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Compressed air storage and wind energy for time-of-day electricity markets

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Abstract

As renewable energy generating capacity increases on electricity grids, technology is needed to balance the supply and demand of energy. In order to manage the demand side of electricity, time-of-day (TOD) tariffs are a simple economic mechanism that encourages consumers to smooth the diurnal demand profile by shifting consumption to off-peak times. The management of supply by renewable energy generators can be achieved using energy storage. This study investigates the use of compressed air energy storage (CAES) to de-couple a wind energy converter (WEC) from the electricity grid and manage its power output. Numerical and thermodynamic models simulate the operation of the system. One year of operation is simulated using 10 minute WEC time-step data for varying CAES capacities in order to optimize the economic performance of the total system. By selling electricity according to TOD tariff schedules, the income generated by a 0.8 MW WEC using a 4 MWh CAES system is increased by 30%. The CAES has a round-trip efficiency of 66% and annually experiences 450 deep cycles as it stores 25% of the energy generated by the WEC.

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1. Introduction

The growing demand for renewable energy generation is increasing the penetration rate of wind energy converters (WEC) around the world. As WEC generating capacity increases, the electricity grid must respond in order to ensure that the demand for electricity is constantly and equivalently supplied. In order to meet this flexibility, control systems are needed to balance supply and demand through procurement of energy services [1]. Energy storage systems will play an important role in the energy future by providing an array of services such a time-shifting energy or ramp rate compensation. Compressed air energy
storage (CAES) is well suited to accommodate increased penetration of renewable energy generators, especially from WEC [2-4]. Although most existing WEC generating capacity is supported by electricity grid mechanisms other than energy storage (e.g. gas peaking plants), this report examines the financial benefits that that may be gained by adding a CAES system. By taking advantage of time-of-day (TOD) electricity rates, an energy storage system improves the revenue generated from the WEC by time-shifting electricity from off-peak to meet on-peak demands. This report presents a scenario where a 0.8 MW wind turbine is coupled with a 0.5 MW, 4 MWh CAES system. The operation of the CAES system is simulated using real WEC production data and TOD electricity schedules. The model optimizes the CAES system to enhance revenue of the WEC.

2. Background

2.1. Time-of-day electricity rates

Although TOD rates are common for electricity consumption, some jurisdictions offer similar varying rates for energy generation using feed-in-tariffs (FIT). Offering higher tariffs during times of peak demand creates benefits for system operators and rate payers alike by creating higher system efficiencies and creating demand driven electricity markets [1, 6, 7]. The value of energy during off peak periods decreases because demand is low and base-load generators can operate in stable conditions. System operators pay higher rates for dispatchable energy when demand increases during the day in order to avoid ramping up base-load generators. Typically, FIT rates that vary according to the TOD are reserved for generation technologies that can adjust their output, such as fossil fuel generators, hydroelectricity, and biomass. Jurisdictions that currently have TOD FIT rates include Portugal, Slovenia, Hungary, and Spain [6], where rates vary from 41% of normal tariffs during “deep off-peak”, to 140% during on-peak hours. In Nova Scotia, Canada, TOD tariffs are only available for residential rate payers who use electric thermal energy storage. The energy charges for residential consumers are shown in Table 1. During the majority of the year the price during peak times is the standard residential tariff, and the incentive is only available during off peak times. However, in the winter season the price of electricity varies from 51 to 130% the standard residential tariff.

Table 1. Time-of-day tariffs for Nova Scotia residential customers [8]

| Time-of-day       | Weekdays (Dec – Feb) | Weekdays (Mar – Nov) | Weekends and Holidays |
|-------------------|----------------------|----------------------|----------------------|
| 07:00 to 12:00    | $ 0.17133 /kWh       | $ 0.13336 /kWh       | $ 0.07166 /kWh       |
| 12:00 to 16:00    | $ 0.13336 /kWh       |                      |                      |
| 16:00 to 23:00    | $ 0.17133 /kWh       |                      | $ 0.07166 /kWh       |
| 23:00 to 07:00    | $ 0.07166 /kWh       |                      |                      |

Fig 1 demonstrates Nova Scotia’s distinct peaks in electricity demand throughout the day and year. December through March have two distinct peaks, while the remainder of the year has a single peak, hence the extra pricing structures for these winter months. In contrast, the typical diurnal WEC generation profile peaks in Nova Scotia peaks at night, and does not align with that of demand. This, and the lack of ability to dispatch wind energy, eliminates advantages of TOD electricity rates with WECs. However, a TOD FIT rate for non-dispatchable generators would be justified if a CAES system was employed. A WEC would charge the CAES during off-peak hours. During on-peak hours, the CAES would discharge while the WEC directly fed the electricity grid. This leads to two principal benefits for system operators:
i) increased time shifting of energy would ease the strain during peak demand, and ii) base-load generators would operate in more stable conditions during off-peak periods without having to compensate for variable renewable energy generators.

Fig. 1. Nova Scotia provincial diurnal demand profile throughout the year, data taken from [9,10]

2.2. Isothermal Compressed Air Energy Storage

Recent private research efforts are underway to develop a unique, simultaneous, two-fluid CAES system that approaches an isothermal process during compression and expansion [5]. This avoids the freezing characteristics and use of natural gas combustors found in conventional CAES. Quasi-isothermal compression is achieved by injecting finely atomized water into the cylinder of a reciprocating compressor to absorb the thermal energy. Water and oil are suitable liquids for injection due to their specific heat capacity and density properties. The fine water droplets enhance surface area, enabling high rate heat transfer and compression ratios up to 30 [11].

The energy density of isothermal CAES depends on the thermodynamic efficiency. As the thermodynamic efficiency decreases from 100%, a temperature change occurs throughout compression and expansion. This results in some of the energy taking the form of sensible heat in both the water and the air. Thermodynamic efficiency can be varied according to the volumetric fraction of water and the size of water droplets injected during compression. As the thermodynamic efficiency increases, the amount of air and water required for storage increases because there is a lower temperature change, thereby lowering the energy density of the system.

In order to achieve an energy density practical for use, an ideal thermodynamic efficiency is used to balance the temperature increase with energy density. For example, a high energy density can be achieved with a low thermodynamic efficiency, but storing high temperature fluids and gasses inevitably results in heat losses. According to [5] the ideal thermodynamic efficiency is 90%, which is achieved by spraying 2.5% by volume water as 100 μm droplets into a cylinder running a compression ratio of 14.1 at 20 Hz, resulting in a temperature increase of approximately 20 K. The rate of heat transfer is significantly faster than the compression process, at approximately 0.001 seconds.
2.3. Recent Literature

Research by [3] compares the coupling of a large scale wind farm with natural gas combined cycle and conventional CAES to provide 400 MW of base load generating capacity. The variable heat rates of the gas turbines and supporting thermal generating stations operating in spinning reserve mode are considered. Results show that the required wind capacity for the CAES far exceeds that of the combined cycle, at 1110 MW and 482 MW respectively, in order to meet base load generation requirements. In the CAES system, wind supplies 80% of total electricity and the CAES supplies the remaining 20%, versus 47% from wind and 53% from natural gas in the combined cycle case. CAES has four times less CO₂ emissions than the combined cycle case and nine times less than the conventional base load case. The capital cost of CAES is found to be twice that of combined cycle, but increases in natural gas prices (double the current $5-6/GJ) and CO₂ taxes ($90-100/t) could reduce this margin.

A study by [1] considers the economics of a wind farm coupled to CAES which charges from wind and/or the grid when electricity export is less profitable. The electricity market was in France, where grid flexibility is typically provided by on-line generators that adjust energy deliveries, and additional support is provided through the procurement of contractual reserves. This type of grid management necessitates stand-by generating capacity to balance supply and demand. Using energy storage to manage variable generation from wind power avoids the provision of additional stand-by capacities. The wind farm capacity is 2 GW with a capacity factor of 26%. The storage facility uses conventional CAES and is rated for 1440 MW during compression and 1200 MW during expansion, with a capacity of 10 hours. A numerical model optimizes CAES charging from wind and grid electricity in order to maximize profits of the system. The study concludes that under the current pricing scheme the wind-CAES system results in negative profits.

Research by [14] asks the question of whether large scale wind-CAES projects can compete in day-ahead markets. Day-ahead dispatch schedules optimize profits based on wind forecasts. Dispatch charge algorithms are run hourly based on parameters such as efficiency, state-of-charge, energy capacity, and discharge power. Eight different price scenarios are used based on wholesale prices of electricity for balancing and day-ahead markets. The high cost of a CAES facility (at $750,000/MW) is calculated to be unjustifiable in all of the pricing scenarios considered. However, it should be noted that the market prices are based on a period of time when cheap natural gas was available, and auxiliary grid services offered by energy storage systems are not considered.

3. Method

3.1. Wind Energy Converter Model

The WEC model used in these simulations is based on one year of data collected from September 2011 to August 2012 from a 0.8 MW Enercon E-53 WEC located in Nova Scotia. Newly installed turbines of this type will now receive a FIT of $0.131/kWh [12]. This is on par with the residential tariff, justifying the use of the TOD FIT proposed for this research. Based on the wind data the WEC achieves 41% capacity factor and produces 2.9 GWh annually. The data used for this model is a 10-minute time series of average power production at the grid interconnection, the point at which revenue is assessed.

3.2. Energy Storage System Model

3.2.1. Operating Model

The isothermal CAES system is modeled in MATLAB to interact directly with the WEC. The model simulates a year of operation using 10 minute time-steps. Depending on the TOD, season, and the state-
of-charge, the system will charge, discharge, or sit in stand-by to optimize the income from electricity sales. The CAES system operational characteristics are shown in Table 2.

Table 2. CAES operational characteristics

| Characteristics                  | Value           |
|---------------------------------|-----------------|
| Round trip efficiency           | 66 %            |
| Operating pressure range        | 50 - 200 bar    |
| Charge power                    | 0 – 500 kW      |
| Ramp rate (zero to full power)  | 10 minutes      |
| Discharge power                 | 500 kW          |
| Energy capacity                 | 1 – 8 MWh       |

The charge power is variable in order to accommodate variable output from the wind turbine. The discharge power is held constant in order to maximize efficiency. The simulation is run 8 times in order to examine the effect of varying the energy storage capacity by 1 MWh increments. As the simulation takes place, the CAES management system considers three factors. Depending on the TOD and season, the control system determines if the grid is on-peak or off-peak. If the state-of-charge (SOC) is greater than zero during on-peak, the system will discharge at full power and the power output from the WEC is fed directly into the grid. Conversely, if the SOC is greater than zero during off-peak conditions, the system will charge at whatever power is available from the WEC, up to the maximum of 0.5 MW. Any power produced beyond 0.5 MW is fed directly to the grid. If the CAES is fully charged (SOC = 100 %) during off-peak periods, the power from the WEC is fed directly to the grid. Fig 2 shows the simplified system control flow chart and charge-discharge regime represented in MATLAB.

Fig. 2. CAES system control strategy

**OFF-PEAK GRID CONDITION**

If \( P_{WEC} > 0.5 \text{ MW} \),

\[
\begin{align*}
P_{\text{charge}} &= 0.5 \text{ MW} \\
P_{\text{WEC,export}} &= P_{\text{WEC}} - 0.5 \text{ MW}
\end{align*}
\]  

(1)

The charge energy is the product of power, time step (10 minutes), and efficiency, \( \eta \). This is added to the total energy stored in the system:

\[
E_{\text{charge}} = P_{\text{charge}} \times \frac{1}{6} \text{ hours} \times \eta_{\text{charge}}
\]  

(2)

\[
E_{\text{stored},i+1} = E_{\text{stored},i} + E_{\text{charge}}
\]  

(3)

The income generated during this time step is calculated using the off-peak tariff, \( R_{\text{off-peak}} \), as:

\[
\text{Income} = P_{\text{WEC,export}} \times \frac{1}{6} \text{ hours} \times R_{\text{off-peak}}
\]  

(3)

**ON-PEAK GRID CONDITION**
During peak conditions, all wind energy is sent directly to the grid:

\[ P_{\text{WEC,export}} = P_{\text{WEC}} \]  

As long as there is energy stored in the system, discharge occurs:

\[ \text{If } SOC > 0 \quad P_{\text{discharge}} = 0.5 \text{ MW} \]  

The energy discharge and total energy stored are therefore:

\[ E_{\text{discharge}} = \frac{P_{\text{discharge}} \times \frac{1}{6} \text{ hrs}}{\eta_{\text{discharge}}} \]  

\[ E_{\text{stored,}i+1} = E_{\text{stored,}i} + E_{\text{discharge}} \]  

The income generated during this time step is calculated as:

\[ \text{Income} = \left( P_{\text{WEC,export}} \times \frac{1}{6} \text{ hrs} + E_{\text{discharge}} \right) \times R_{\text{on-peak}} \]

The model runs a year-long simulation and stores 10 minute time-step data for each of the variables described above. The economic benefit of the CAES is calculated based on the FIT rate for the off-peak at $0.131/\text{kWh}$ periods and a corresponding multiple for on-peak given by the ratios found in Table 1.

### 3.2.2. Thermodynamic Model

The thermodynamic model used in this analysis is based on information from [5] to determine the physical characteristics of the optimized CAES system. The temperature of water and air is assumed the same, due to the fast rate at which heat transfer equilibrium is reached (approximately 1 millisecond in a 50 millisecond compression process). A heat and mass transfer analysis is conducted for the compression, storage, and expansion stages. The work by the system determines the amounts of air and water required to store the necessary energy.

### 4. Results

#### 4.1. Wind and CAES System

Fig 3 illustrates the operation of the WEC and CAES system for two day periods during A) peaking months (Jan – Feb) and B) non-peaking months (Mar – Nov) for a 4 MWh system. During off-peak hours, most of the power from the WEC is directed to the CAES for charging (shown in red). If the output from the WEC exceeds the maximum charge power (500 kW) then the excess is fed directly to the grid (shown in green), as it is during peak hours. The CAES discharges (shown in teal) whatever energy is stored (shown in purple) during peak hours. Fig 3 (A) shows that there are two periods each day where the CAES system discharges corresponding to the high-peak periods that are applicable from December through February. Even though the period from 12:00 to 16:00 is technically on-peak, the value of electricity increases between the hours of 16:00 to 23:00, so the CAES enters charge mode. In Fig 3 (B), the operation is very similar except that there is a single charge and discharge cycle each day.

#### 4.2. CAES Capacity Optimization

The operational profiles for the entire year of simulation are analysed based on the revenue increase as a result of each system (the systems are varied from 1 MWh to 8 MWh). The system costs are calculated based on a fixed cost for the compressor/expander/generator ($1M/MW$) and incremental costs for the amount of energy storage capacity ($0.15M/MWh$) [5]. The base case for wind energy sales directly to the
grid at the present FIT rate is approximately $372,000 of revenue annually. In every case, the CAES increases the annual revenue from energy sales, starting at a 3% increase of $12,500 for a 1 MWh system. As additional storage capacity is added, the additional revenue continues to increase. Beyond 4 MWh, the cost of additional capacity is no longer justified because the additional revenue that is generated begins to level out due to WEC limitations. The optimized 4 MWh system results in a 30% annual revenue increase of $112,000 and a simple payback period of 10 years.

Fig. 3. Operation of wind CAES system for 24 hour periods in A) winter (peak season) and B) summer (off-peak season)

4.3. Operational Characteristics of a 4 MWh CAES System

The system will undergo 450 charge and discharge cycles each year. The average energy stored in the system when it reaches peak hours is 2.5 MWh. Fig 4 shows the energy throughput for the CAES and WEC system. The CAES system operates relatively consistently throughout the year compared to the WEC. Although the amount of energy cycled through the CAEs is roughly 1/4 to 1/3 compared to the WEC, the resulting revenue is approximately ½ due to its enhanced value during on-peak periods.

Fig. 4. Total energy throughput of the WEC and CAES system
4.4. Thermodynamic Analysis

The 20 degree temperature increase in each stage of compression to 200 bar requires 3360 kJ per kg of air. After efficiency losses, the recoverable expansion energy is 2200 kJ per kg. The size of the energy storage depends on the recoverable work per unit mass of air stored. The amount of work per kg of air stored is equal to the total input during compression (3360 kJ/kg), or 0.9325 kWh/kg. Losses will occur during expansion, so the total amount of energy that is retrievable is 0.7564 kWh/kg. The amount of air and water required for a 4 MWh system is therefore 5300 and 110000 kg respectively. A tank of 34 m³ is used to store air over a pressure range of 50 to 200 bar. The energy density and specific energy are approximately 25 Wh/L and 32 Wh/kg, respectively, calculated based on a volumetric balance of plant of 10% and a mass balance of plant of 10%.

5. Conclusion

Isothermal CAES is an effective method for energy storage. In this report, a system is designed to make the energy output from a WEC partially dispatchable. This allows the system (WEC + CAES) to feed electricity into the grid according to a TOD FIT. Based on the economic assumptions used in this report, the additional revenue from the time shifting of energy to peak hours adds up to $111,600 per year or an approximate 30% increase in gross revenue.

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