DEMONSTRATION OF A UTILITY-SCALE LITHIUM-ION BATTERY SYSTEM WITH A WIND TURBINE

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Two lithium-ion batteries with a total power output of 400 kW and an energy storage capacity of 744 kWh have been connected to the grid adjacent to an 800 kW wind turbine at a site four kilometers east of Regina, Saskatchewan. This is one of the first utility scale turbine and battery installations in North America. Data from the wind-battery system are being monitored continuously to evaluate its performance and the value of the wind-storage system. The reliability and durability of the wind-storage system are also being assessed.

The focus of this paper is to quantify the effectiveness of the battery's smoothing and dispatching capabilities and to assess the value of dispatching energy at peak times. Preliminary data show that the smoothening algorithm appears to reduce ramp rates by 65%, and that the system is capable of dispatching 400 kW for 90 minutes, three times per day.

Keywords: wind turbine, lithium-ion battery, energy storage, smoothening, smoothing, dispatch

INTRODUCTION

Wind turbines are viewed as variable energy sources that can provide electrical energy reliably on an annual basis. They cannot, however, provide power reliably on-demand because the output depends on wind velocity, which can be extremely variable. As well, risk levels relating to power system reliability are elevated when penetration of wind generation is high in an electrical grid [1]. If there is a risk that system stability cannot be maintained, wind energy production is often curtailed, resulting in loss of revenue. This wind volatility prevents utilities from achieving higher levels of wind penetration in their generation portfolios.

Technologies such as energy storage can be used to increase the penetration of wind power into the grid. Ramp rates of power generation can be smoothened, and energy can be dispatched during peak times when electrical prices are usually highest. Using energy storage in this manner increases the predictability and reliability of wind energy systems. This paper shows the effectiveness of a utility-scale lithium-ion battery storage system coupled to a wind turbine to reduce wind turbine power fluctuations and to dispatch power at peak times when the power has the highest value. A preliminary assessment of revenue streams for energy storage in a local context is also presented.

In Saskatchewan, the total electrical generation capacity was 4,094 MW in 2012 and consisted of 41.2% coal, 30.5% natural gas, 20.8% hydro, 4.8% wind, with the remaining 2.7% being supplied by various independent power producers [2]. The capacity factor of the 198 MW of installed wind generation is nearly 40%. Peak generation in January 2012 was 3,365 MW, with coal and gas representing 71.7% of net generation capacity. Wind generation will increase to 9.1% of net generation capacity in 2017 with the installation of a 175 MW wind farm; however, no wind or solar projects are anticipated beyond this time.

In the neighboring province of Alberta, coal and gas accounted for 84% of generation capacity of 13,898 MW in 2011; the peak load was 10,599 MW [3]. Wind represented 6% of capacity in 2011, but its share is expected to increase to 13% by 2020. System stability and the possible need for transmission reinforcements are concerns regarding increasing the penetration of wind power into the grid. In addition, an important problem for wind and solar is that backup generation is required when the wind isn't blowing and the sun isn't shining.

California has attained 20% renewable energy generation on their grid, and has mandated a requirement of 1,325 MW of storage to reach 33% renewable penetration by 2020, with 200 MW to be installed by the end of 2013 [4]. The California storage initiative should help it achieve its renewable energy goals and have a huge impact on the storage industry.

A 2008 study by the Pembina Institute suggested that "adding power storage to the grid will allow our future base load and peak power needs to be met primarily with renewable power sources, including those that have variable outputs like solar, tidal, wave and wind power" [5]. The study suggested that storage would firm up variable power sources and bring stability to the grid, "allowing better management of peak demands, reducing transmission needs, and improving power quality and frequency regulation." It appeared to the author that "about 20% of the wind farm's nameplate megawatt capacity in battery storage with six to eight hours of storage time is needed to firm up power from a wind farm so that it can deliver its average load (capacity factor) at any time." One case cited in the study suggested that reduced line losses were greater than the parasitic losses of the battery when used to improve power factor.

A subsequent study on energy storage in Alberta focused on making intermittent power dispatchable [3]. It suggested that "storage can be used to implement two basic dispatch strategies in the energy market: time shifting and firming." Time shifting, or arbitrage, involves charging the energy storage device when the price of power is low and selling when the price is high. "Firming would allow a wind producer to make a firm quantity offer into the energy market two hours (say) before delivery." In Alberta, a wholesale market, or power pool, exists for electricity and is operated by the Alberta Electric System Operator (AESO). The AESO is responsible for the operation of the wholesale market and sets an hourly real-time price for electricity. It also procures a variety of arrangements called Ancillary Services (AS) to ensure system reliability. In 2012, the competitive pricing system resulted in purchase prices that ranged from $0.01/MWh to $1000/MWh, with an annual average of $64/MWh [6]. A wind producer can make a firm quantity offer into the energy market two hours prior to the delivery hour, although in 2011 wind producers were not obliged to make firm offers.

First Nations desire to develop practical methods of wealth creation that honor First Nations' traditions and collective ownership. Thus, when Natural Resources Canada (NRCan) issued a request for proposals on SMART grid technologies in 2009, Cowessess First Nation (CFN), in collaboration with the Saskatchewan Research Council (SRC), developed a proposal to install an 800 kW wind turbine with a lithium-ion battery system that could store 744 kWh of electricity and deliver a maximum power of 400 kW. The site is located four km east of Regina, Saskatchewan, Canada, and a previous study indicated that the average annual wind speed at 50 m is 6.97 m/s [7]. The project was developed with financial support from the Clean Energy Fund, CFN, SRC, Aboriginal Affairs and Northern Development Canada, and the Saskatchewan Go Green Fund.

The purpose of this paper is to demonstrate the benefits of lithium-ion batteries as storage for wind power and general electrical grid applications. The objectives are as follows:

1. To demonstrate the reliability and durability of a wind-battery system.
2. To identify potential fiscal value for energy supplied by the batteries.

Investigations focused on determining the effectiveness of algorithms used to smoothen the volatile output of the wind and to determine the value of dispatching energy at peak times during the day. The paper describes the system installed and presents field data on wind smoothening and peak dispatch, as well as data on system availability, capacity factor, capacity credit, and overall efficiency. Means of evaluating round-trip efficiency are also discussed. To put storage into context, the paper compares means of estimating the value of energy at peak dispatch with measures used to determine the value of peak electrical loads like demand charges and demand reduction initiatives.

DESCRIPTION OF EQUIPMENT

Two Saft Intensium lithium-ion batteries with ABB PSC 100 inverters and a transformer from Cooper Power Systems were installed in December 2012, as shown in Figure 1. Key reasons for selecting lithium-ion batteries over other storage technologies were that they contain no liquids, require low maintenance, have long life with deep cycles, come in a compact package, and the batteries can be re-cycled at the end of useful life. The batteries chosen have an approximate 15 year lifetime when performing three full discharges per day.

The two batteries, which are operated in a master / slave configuration, together contain 4,872 cells made of nickel-cobalt-aluminum-lithium-ion and store 744 kWh of electrical energy. Power output can be set from 0 to 400 kW; hence, 400 kW can be dispatched for 112 minutes. Charging from the grid at rates ranging from 0 to 400 kW is also possible to maintain battery state of charge. The cells are housed in modules that are stacked in racks within two 6 m (20 ft) containers.

Preliminary modelling indicated that the batteries could be capable of reducing volatility by up to 70% on an annual basis.

Figure 1: Saft Lithium-ion Batteries

An 800-kW Enercon E53 wind turbine was installed on a 73 m tower in March 2013, as shown in Figure 2. Although this was the only wind turbine of this size available in Canada, it was an excellent match for the wind-battery project, given the average projected wind speed of 7.5 m/s (16.8 mph) at 73 m based on a previous wind resource assessment. The cut-in speed is 2.5 m/s (5.5 mph), and the maximum power of 800 kW is delivered at 13 m/s (29 mph).

The RETScreen-4 wind energy project modeling software estimated the average annual energy production of the turbine to be 2,500 MWh at a capacity factor of 35.5%; however, the addition of the battery system reduced the estimated energy output to 2,207 MWh at a capacity factor of 31.5% [8]. Hence, overall losses due to the battery system were projected to be 11.7%.

Figure 2: Enercon E53 Wind Turbine, Site Building and Battery System

MONITORING RESULTS

A monitoring system was installed to evaluate the performance of the system. Meters measuring energy and power were installed at the grid connection (or point of common coupling), the turbine, the battery, the HVAC (heating, ventilating, and air conditioning) systems, and the site building. As well, the master and slave batteries are monitored for power, state of charge, and operating temperature. Enercon uses a separate Supervisory Control and Data Acquisition (SCADA) system to monitor the turbine, and the batteries are monitored separately by Saft. A 50 m anemometer tower is located 230 m from the turbine to provide wind velocity (elevations of 10, 20, 30, and 50 m), ambient temperature, and relative humidity, and barometric pressure. Since the site is unmanned, a camera was mounted on the anemometer tower to monitor construction and provide site security.

Commissioning of the turbine-battery system was completed in April 2013; the turbine availability and turbine-battery capacity factor are shown in Table 1. The average turbine availability of 97.2% was excellent over the first seven months of operation. The monthly capacity factor of the wind-battery system dropped from 39.5% in April to 17.6% in August and rose to 29.2% in October. This is consistent with the annual variation in wind speed, which drops in the summer by about 2 m/s (4.5 mph) compared to the spring, fall, and winter. The overall capacity factor of the turbine-battery system was 29.9%; however, it is expected to rise over the winter. Note that this does not include power consumed by the site building.

The availability of the master and slave batteries is shown in Table 2. The combined availability of about 70% is viewed as good, given that this is one of the first installations of this kind. It should be noted that the reduced availability is not due to the batteries or inverters, but due to the auxiliaries. The HVAC system in the slave battery had an electrical fault that spuriously caused it to shut down, and issues related to multiple layers of communication and controls contributed to additional shut downs.

Table 1: Turbine Availability and Turbine-Battery Capacity Factor (Billing Meter)

2013 Month	Turbine Availability (%)	Turbine-Battery Capacity Factor (%)
April	92.0	39.5
May	95.9	42.9
June	99.4	23.9
July	94.3	23.6
August	100.0	17.6
September	100.0	32.7
October	99.0	29.2
Overall	**97.2**	**29.9**

Table 2: Battery Availability

2013 Month	Master Battery (%)	Slave Battery (%)
July	54.7	80.4
August	98.5	44.5
September	77.2	63.9
October	64.1	79.8
Average	**73.6**	**67.2**

Table 3 summarizes the wind turbine energy production and the losses from the batteries and building. The overall efficiency was 93.2% from April to October. Hence, losses were 6.8%, which are less than the initial projection of 11.7% mentioned above.

Table 3: Turbine-Battery Energy Production and Losses

Production (MWh)	Consumption (MWh)	HVAC and Building Losses (MWh)	Site Efficiency (%)
1,258	30	43	93.2

A measure of the turn-around efficiency of the batteries and HVAC system has yet to be determined, given the three modes of operation: smoothening, dispatch, and smoothening plus dispatch.

Figures 3 to 6 show the effectiveness of the smoothening algorithm and controls provided by Saft and ABB to attenuate the volatility of the wind and dispatch electricity. As shown in the Figure 3, the amplitude of the power output from the turbine varies by as much as 300 MW over a 3 minute period at an average power output of 400 MW. Hence, the batteries reduce the wind volatility significantly, which should improve grid stability.

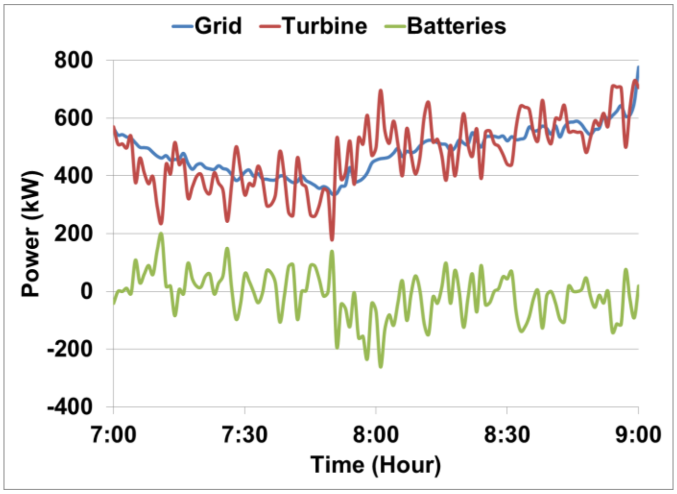

Figure 3: Smoothening Turbine Output

Figure 4 shows the batteries dispatching 400 kW at 9:00 and 15:00 with the turbine shut down. Note that a 90 minute dispatch was scheduled for each time period, but the dispatch at 15:00 was curtailed after about 36 minutes because the battery state of charge (SOC) was below 10%. Without the turbine available to charge the batteries, the batteries relied on the grid. However, the grid charge was limited by the control system to 50 kVA.

Dispatch with smoothening is shown in Figure 5 with fairly steady power output from the turbine of 800 kW and the batteries limited to 200 kW. Power output is limited to 1 MW by the control software to meet the requirements of the Power Purchase Agreement with SaskPower. The SOC of the batteries reduces steadily from 80% to 54% over the one-hour dispatch.

Note that the two output transients of about 300 kW at 8:00 are almost eliminated by the smoothing effect of the batteries.

Figure 6 shows the batteries' effectiveness in smoothening the wind power under volatile wind conditions (which appear to be somewhat typical). The wind turbine's power output varied between 800 kW and 200 kW over an initial 30-minute period. The batteries provided up to 300 kW of power over this period are smoothened the output of the system by approximately 65%. Equation 1 demonstrates the method used for measuring reduced volatility. Similarly to the above case, dispatch was limited again to 200 kW after 17:30 because of the 1 MW limit on the output. Smoothening was measured using Equation 1.

$$S = \frac{\sum_{n=1}^{n}\left(\frac{\Delta Ps_n}{\Delta t}\right)}{\sum_{n=1}^{n}\left(\frac{\Delta Pi_n}{\Delta t}\right)} \qquad (1)$$

Where:

S indicates smoothening,
Ps is the smoothened power output of the system, and
Pi is the initial (turbine only) power output of the system.

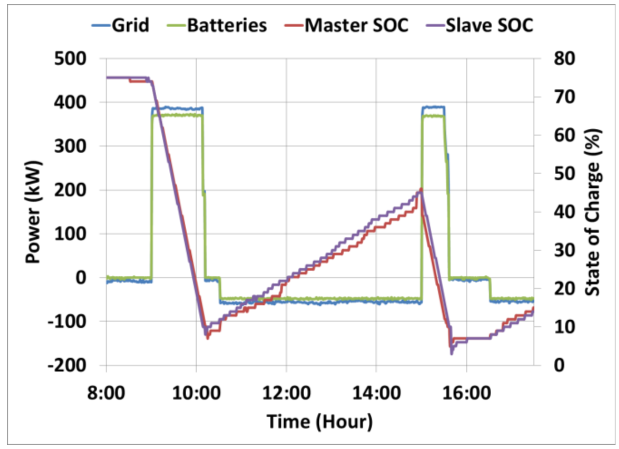

Figure 4: Dispatch and Charging

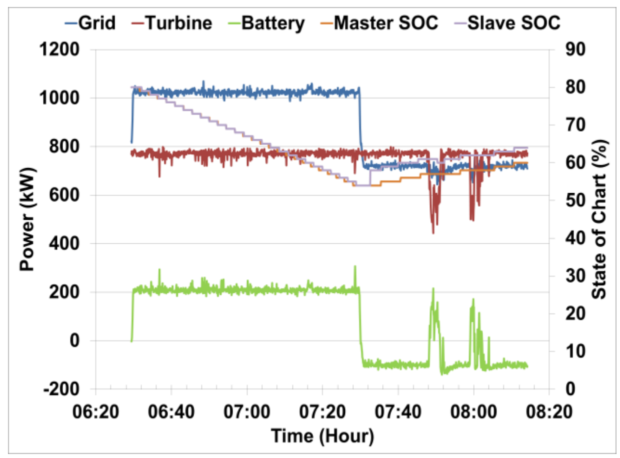

Figure 5: Dispatch and Smoothening

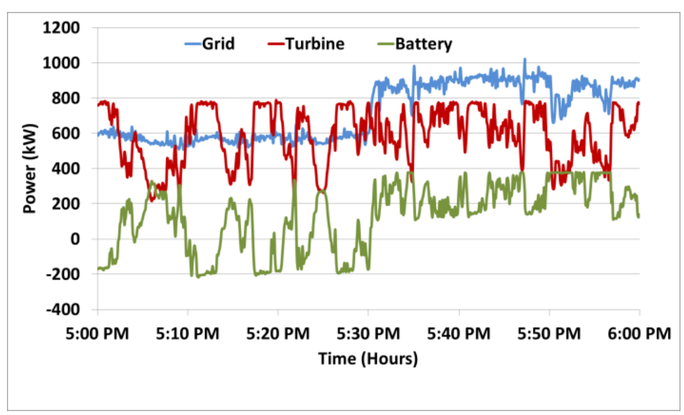

Figure 6: Smoothening and Dispatch

A 24-hour operating period is shown in Figure 7, with 90-minute dispatches scheduled at 9:00 and 15:00. For this case the wind velocity ranged from 4 m/s (9 mph) to 14 m/s (31 mph). Smoothening took place throughout the operation, including dispatches at 9:00 and 15:00 and charging from the grid at 19:00.

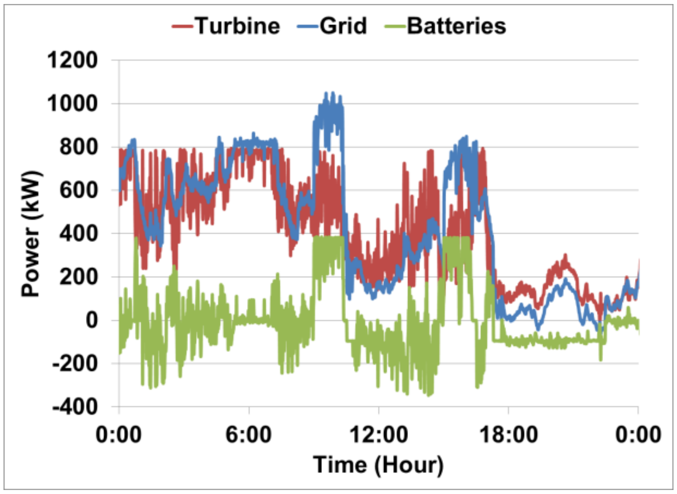

Figure 7: Dispatch and Smoothing

ANALYSIS OF RESULTS

This section evaluates some of the benefits of batteries on the electric system, and attempts to put boundaries on the added value of dispatching electricity on short notice three times per day, every day of the year. This would involve both "time shifting" and "firming" as mentioned earlier. Other benefits of storage are reported to be smoothening, improved stability, improved power quality (frequency, voltage), fast regulation, load-following capability, and spinning reserve. Batteries can also provide transmission and distribution system support and can defer electrical system upgrades.

Although a utility scale wind-battery system has been demonstrated in this project, the system is considered to be small by utility standards. However, the technology can be replicated and scaled up to, say, a 100 MW wind farm with a 50 MW/100 MWh battery system. The system could consist of 50, 2-MW wind turbines; each with a battery system that would provide a total of 1 MW of power and 2 MWh of energy.

For a larger system, the improved capacity credit of the turbine due to the battery is shown in Figure 8. The turbine by itself would have a capacity credit of only 8%, assuming a loss of load expectation (LOLE) of 0.5 days/year and Saskatchewan's generation capacity and profile as of 2012. The LOLE is a measure of the duration that generation capacity falls short of the demand load. The battery, because it can deliver consistent power at any time (when charged), would have a capacity credit of 65%. Together the turbine and battery as a system have a capacity credit of 30%.

In order to understand some of the financial benefits of timed dispatch, a review was made of two local programs used to price and control added loads: demand charges for loads above 50 kVA; and a demand response program used to reduce at least 5 MW of load, given notice of either 12 minutes or 120 minutes.

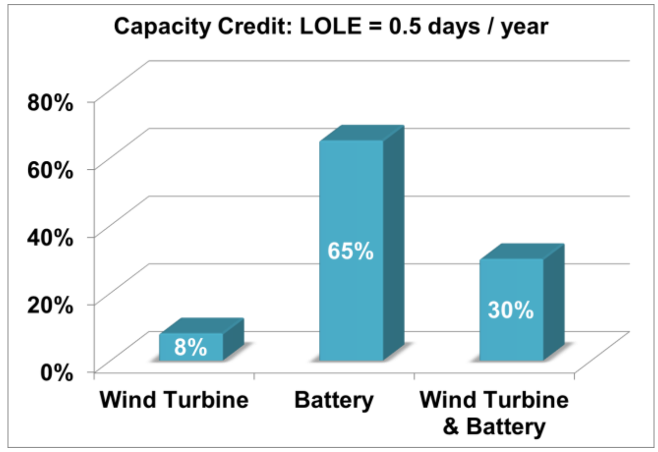

Figure 8: Capacity Credit

Most utilities use demand charges to price the added capacity required to meet added load. For example, if a 400 kW electric motor was connected to the grid, the annual demand charge from the utility could amount to $48,000. The current demand charge structure is $11.40/kVA over 50 kVA. Assuming that the 400 kW motor utilizes 525 MWh annually, then the average rate would be valued at $91/MWh. Note that CFN's Power Purchase Agreement (PPA) with SaskPower provides a rate of about $100/MWh for energy produced at the site. (Rates have yet to be developed that specifically value the attributes of storage.) This case is an over-simplified comparison with battery dispatch, because no credit is given for time shifting or firming. Similarly, the utility does not know how long the motor will operate for, but it must have the capacity available to serve it.

The Demand Response Program, operated by SaskPower, is based on shedding a minimum 5 MW's to a maximum of 60 hours/year. Based on notifications of 12 minutes and 120 minutes, the annual payments are $52,000/MW-year and $20,000/MW-year. Hence, for the maximum 60 hours per year, the average rates for notifications of 12 minutes and 120 minutes for load shedding are valued at $867/MWh and $483/MWh, respectively.

The province of Alberta has a power pool that buys power from various sources to supply the electrical grid throughout the year. The rates paid to power producers in 2012 are presented in Figure 9. The prices range from $0.01/MWh to $1,000/MWh [6], which are similar to the above rate analysis for demand charges and load shedding. The figure shows that the prices paid to producers were higher than $800/MWh 35 times and were at the minimum of $0.01/MWh 39 times; the annual average was $64/MWh.

Table 4 presents the revenue that the 400 kW/744 kWh battery would have received from the Alberta pool in 2012 if storage were eligible for payment. Cases are provided for dispatching 700 kWh at the evening peak and at the maximum daily peak (which doesn't necessarily occur at 18:00 hours).

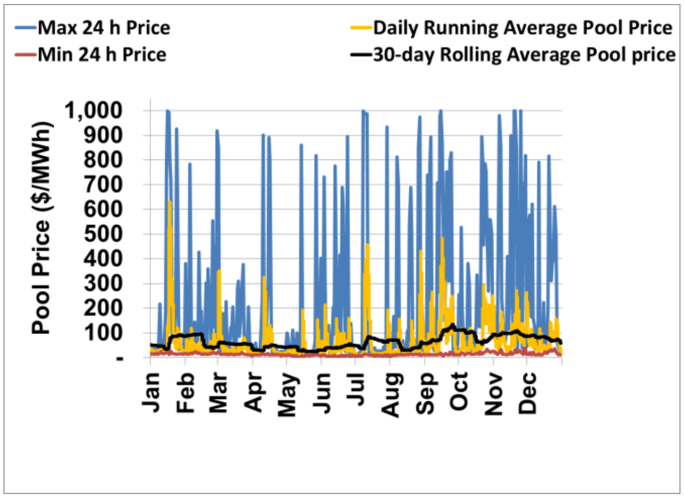

Figure 9: Alberta Power Pool Prices, 2012

Table 4: Possible Revenue Due to Peak Dispatch

Alberta Pool Price	2012 Peak Dispatch of 700 kWh	
Average at 17:00 peak	$32,500	$127 /MWh
Average at maximum daily peak	$59,100	$231/MWh

This analysis suggests that the value of the electricity dispatched at the peak ranges, on average, from $127 to $231/MWh, or $27 to $131/MWh of additional value above the CFN PPA of $100/MWh.

CONCLUSIONS AND RECOMMENDATIONS

Based on the monitoring and analysis conducted for the wind turbine and lithium-ion battery demonstration, the following conclusions can be drawn:

1. The reliability and durability have been demonstrated over the seven months of operation as follows:
    a. Turbine availability 97.2%
    b. Battery availability 70.4%
    c. Site efficiency 93.2%
    d. Average capacity factor April to October 29.9%
    e. Smoothening reduction in volatility 65.0%
    f. Timed dispatch 400 kW for 90 minutes
2. Commercialization of electrical energy storage is imminent and replication on a clear track, depending on the value attributed to dispatching at peak times, valuing additional storage capabilities such as smoothening, and decreased capital cost of storage as technologies continue to mature.

It should be noted that seven months is not enough time to demonstrate the reliability and durability of a new technology. However, the key parameters are being monitored to establish the technical viability of the turbine-battery system over the long term.

The following recommendations are made based on the first seven months of operation:

1. Continue to operate and monitor the reliability and durability of the system over the next five years.
2. Continue to assess the value of peak dispatch and extend the analysis to other benefits like smoothening the output, increasing grid penetration, and improving stability, spinning reserve, load following, and power factor control.
3. Install a 200 kW solar addition at the CFN site to investigate the benefits.
4. Increase the storage capacity from 744 kWh to 1 MWh.
5. Investigate scaling up the system to a 100 MW wind farm with 100 MWh of storage and a power output of 50 MW.
6. Reduce parasitic loads on the battery system.
7. Improve availability of the battery system by resolving issues with auxiliaries.
8. Test new algorithms for discharge / charge / smoothening.
9. Apply sensitivities such as reduced capital cost of storage to determine the required incentives to make energy storage viable.

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REFERENCES

[1] P. Hu, R. Karki, and R. Billinton, "*Reliability Evaluation of Generating Systems Containing Wind Power and Energy Storage*," IET Generation, Transmission & Distribution, 2009, Vol. 3, Iss. 8, pp. 783-791.

[2] D. Kozoriz, "*Supporting Local Energy Production: SaskPower's Net Metering & Small Power Producer's Programs*," Northern Greenhouse Workshop, November 8, 2012.

[3] A. Reynolds, "*Energy Storage*," Alberta Innovates Technology Futures, Version 1.1, October 27, 2011.

[4] B. Sweet, "*California's First-in-Nation Energy Storage Mandate*," IEEE Spectrum, October 25, 2013.

[5] R. Peters, "*Storing Renewable Power*," Pembina Institute, June 2008.

[6] Alberta Electric System Operator. (2013). Retrieved April 29, 2013, from http://ets.aeso.ca

[7] S. Shewchuk et al., "*The Cowessess First Nation Wind Resource Assessment*," SRC Publication No. 12218-1C07, May 2007.

[8] "RETScreen Software Online User Manual," Natural Resources Canada, ISBN 0-662-36820-7, 2004.

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