

Achievements of an ABSOLYTE® Valve-Regulated Lead-Acid Battery Operating in a Utility Battery Energy Storage System (BESS) for 12 Years

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At a time when ways are being sought to reduce our dependence on foreign oil, to curtail carbon emissions into the environment, to improve the quality and reliability of our electrical grid, to make greater use of renewable energy resources, and to save money during tight economic times, it is appropriate to report on the achievements and successes of an effort initiated over a decade ago that accomplishes all of these goals.

In 1996, Exide Technologies in collaboration with the General Electric Company, the Department of Energy and Sandia National Laboratories designed and installed a 1MW/1.4MWh Battery Energy Storage System (BESS) at the facilities of Metlakatla Power and Light (MP&L) at the island village of Metlakatla, Alaska [1]. The purpose of this installation was to stabilize the community's utility grid providing instantaneous power into the grid when demand was high from local industry, and to absorb excess power from the grid to allow its hydroelectric generating units to operate under steady-state conditions. The BESS replaced a large 5.0MVA/3.3MW diesel generator that operated very inefficiently, shifting a greater portion of the utility's base load from the less expensive hydro and onto the diesel just to provide an adequate load-following rate. A secondary purpose was to demonstrate the technical and economic justification for a BESS in the operating environment of an electric utility, where battery performance, maintenance and life are critical factors. The BESS was constructed using standard commercially proven components – Exide's ABSOLYTE® IIP VRLA batteries and GE's industrial AC drive technology. Return on investment (ROI) calculations for the BESS were initially based on a battery lifetime of 8 years. The BESS was made operational on February 3, 1997. In September 2008, after 11-½ years of continuous operation at MP&L, Exide replaced the BESS's battery with another ABSOLYTE® battery system. This paper looks at the economic and environmental benefits of having the BESS, and the performance and condition of sample field-aged cells selected at random from the original battery set during its replacement.

Economic and Environmental Benefits of the MP&L BESS The economic benefit derived from the BESS can be linked directly to the costs "avoided" by not having to operate the diesel generator to maintain power quality and frequency control on the MP&L grid. These include the cost of the fuel oil consumed, the expense to transport and store the oil on the island, and the periodic maintenance of the diesel. These operational costs for 1996, the year before the BESS was installed, were extrapolated through to September 2008 to estimate the total costs if the BESS had not been installed; and then compared to the operational costs, including the replacement battery, with the BESS installed. Fuel oil consumption in 1996 without the BESS was 476,000 gallons. Annual fuel oil costs were based on the historical spot market prices reported by the Energy Information Administration of the US Department of Energy [2], rising from less than \$20 per barrel when the BESS was initially installed to more than \$90 per barrel in 2008. Since Metlakatla is located 25 miles from Ketchikan on Annette Island, fuel for the diesel must first be barged from the mainland and then transported through pipe across the island to the facility. In addition to the obvious environmental concerns, delivering this fuel adds another cost to each gallon of fuel consumed. This delivery surcharge was calculated as a constant from the difference between actual price paid per gallon of fuel oil by MP&L in 1996 and the average 1996 spot market oil price. Finally, operating continuously, the diesel requires a minor overhaul every three years at a cost of \$150,000 and a major overhaul costing \$250,000 every six years – a total for the period that the BESS was operational of \$1.1 million.

Operating costs with the BESS installed included operating the diesel generator 15 days each year for periodic battery equalization charging, planned BESS battery and inverter maintenance, and regularly scheduled checks on diesel and generator operation and function. Fuel oil consumption was estimated at 50 gallons per hour. Although none were actually performed, one minor overhaul and one major diesel overhaul were included in the cost benefit analysis. And, since the battery can be considered to have been consumed over time in operation, the cost of the replacement battery, including all new replacement battery modules, shipping to Metlakatla, labor of two Exide installers to supervise, complete, inspect and test the installation, shipping and recycling of the spent battery, and operation of the diesel while the BESS was off-line for six days was included in the analysis. The net benefit of the BESS as summarized in *Table 1* was a savings of **more than \$6.6 million.**

	<i>Operating Cost Without BESS</i>	<i>Operating Cost With BESS</i>
Fuel Oil At Spot Market Price	\$4,864,133	\$183,865
Surcharge To Deliver Fuel To Island	\$2,038,700	\$78,000
Diesel Maintenance	\$1,100,000	\$400,000
Battery Replacement	N/A	\$681,890
Diesel Operation During Battery Changeout	N/A	\$20,875
Total Operating Cost (1997-2008)	\$8,002,833	\$1,364,630

Table 1. Estimated operating costs with and without the BESS show a savings to MP&L of more than \$6.6 million.

In addition to the obvious reduction in noise pollution achieved by not operating the diesel and the avoided risk for spillage by not having to transport and store more than 5.3 million gallons of diesel fuel, the environmental benefit can be assessed by the carbon footprint reduction realized in operating the BESS. By going from burning 476,000 gallons of diesel fuel per year to less than 18,000 gallons, MP&L’s CO₂ emissions were reduced from 5,272 tons per year to less than 200 tons per year – a reduction of almost 59,000 tons of CO₂ since the BESS was installed [3]. These were all factors cited by the community of Metlakatla in receiving the grant from the Alaska Commerce, Community and Economic Development Agency (AS 37.05.317) to replace the battery and continue operating the Battery Energy Storage System at MP&L [4].

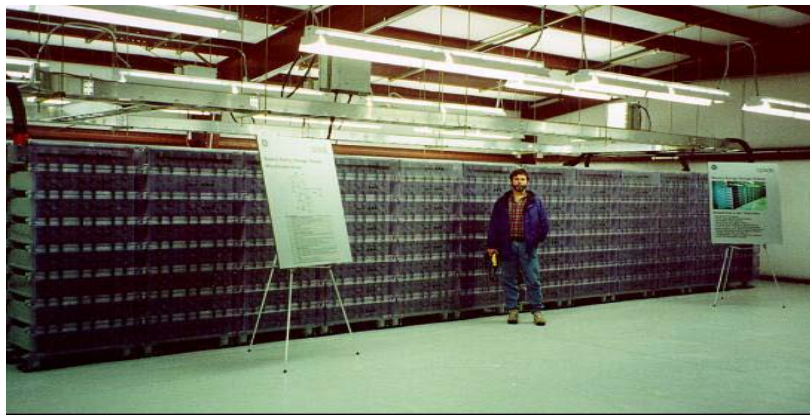


Figure 1. The battery at the MP&L BESS consists of 378 Exide ABSOLYTE® IIP VRLA 100A75 modules connected in series. The modules are arranged in two back-to-back rows, each row comprised of twelve stacks of modular trays eight high, separated by an aisle to minimize cable runs between the battery and the PCS equipment. The BESS is housed in a 40x70 foot building with a fan and heater to warm and dehumidify the building.

The MP&L BESS Battery The battery installed at the MP&L facility in 1996 (*Figure 1*) consists of 378 Exide ABSOLYTE IIP 100A75 VRLA battery modules arranged in a single series-connected string providing a nominal 756-volt rating. The 100A75 module has a C/8 rating of 3,600Ampere-hours; its rating at the intended 90-minute discharge rate for this application is 2,000Ah / 3.87kWh. The entire system is rated at 1.4MWh at a 1.0MW discharge rate. Maximum discharge rate is limited by the Power Conversion equipment to support a continuous load of 800kVA and pulse loads of up to 1,200kVA. The PCS allows bi-directional power flow between the ac equipment and the battery in less than a quarter-cycle. An automatic generation control (AGC) system provides computerized control and dispatch of MP&L’s resources for optimum efficiency. The BESS is designed to be connected continuously to the grid and to maximize utilization of MP&L’s hydroelectric generation capacity. The operating strategy for the BESS is to have the battery discharge into the system to satisfy short-term demand “peaks” and to accept excess power in the system as recharge without causing the battery to overcharge. To achieve these conditions, Exide proposed that the battery be maintained at 60-80% state-of-charge (SOC) – in this condition, the battery is at its lowest internal resistance allowing for efficient discharge at a relatively high voltage and the least amount of ohmic heating, and charge acceptance is essentially 100% allowing the control algorithm to be based on “counting” ampere-hours in/out of the battery to balance and maintain its SOC over time. The battery is operated continuously in this partial state-of-charge condition for periods of up to six months. Twice each year, the battery is provided an equalization charge to bring it back to a fully charged condition and to reset the control algorithm state-

of-charge counter. It is these long periods of operation in a partially discharged state that is of greatest interest and concern, particularly as it relates to battery performance and life.

During the MP&L battery replacement, 36 individual cells were randomly selected for electrical testing and physical examinations at Exide’s laboratories. The objectives of these tests and examinations were to determine if long-term continuous operation in a partially charged state, as required for optimum efficiency in the BESS, had any serious operational or life effects on the battery cells, and to characterize the condition of the various materials and components internal to the cell. The testing plan called for: (i) determining the actual state-of-charge of the cells removed from the BESS; (ii) demonstrating the recovery of cells operated for long periods of time in a partially charged condition with appropriate charging; (iii) characterizing the overall performance capabilities of these field-aged cells; and (iv) analyzing the internal materials and components to determine the “ageing” effects of partial state-of-charge operation.

Electrical Evaluations Upon receipt at Exide’s laboratories and without any conditioning charge, the open circuit voltage and C/8 discharge capacity of the cells was measured. The average cell Open Circuit Voltage, 2.069 volts, was consistent with actual capacity, 60%, delivered by the cells when discharged at the C/8 rate (**Figure 2a**). The battery control algorithm at the MP&L BESS is set to maintain the battery at between 60 and 80% state-of-charge, and this data shows that the algorithm logic achieved this state-of-charge target. Following this initial “as received” discharge, the cells were given an equalization charge and again discharged at the C/8 discharge rate (**Figure 2b**). The cells recovered immediately to an average capacity of 89% of rated, with several cells delivering greater than 100% of the rated capacity. These results show that the operating parameters for the BESS were successful in maintaining the battery at the desired SOC and that, based on the electrical performance of these field-aged cells following an adequate equalization charge, there appears to have been no irreversible deterioration of the battery as a result of operating in a partial state-of-charge condition for almost 12 years.

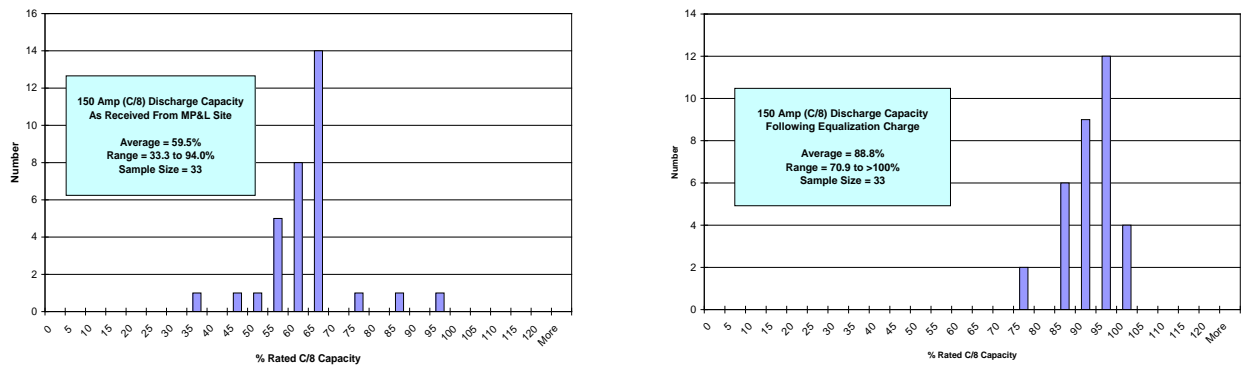


Figure 2a/b. The discharge capacity of sample MP&L cells “as received” from the site averaged 60% at the C/8 discharge rate, showing the BESS control algorithm was maintaining the battery at the desired state-of-charge. Following an equalization charge, the capacity of the cells increased to nearly 90%, demonstrating their recovery from the partial state-of-charge operating regime.

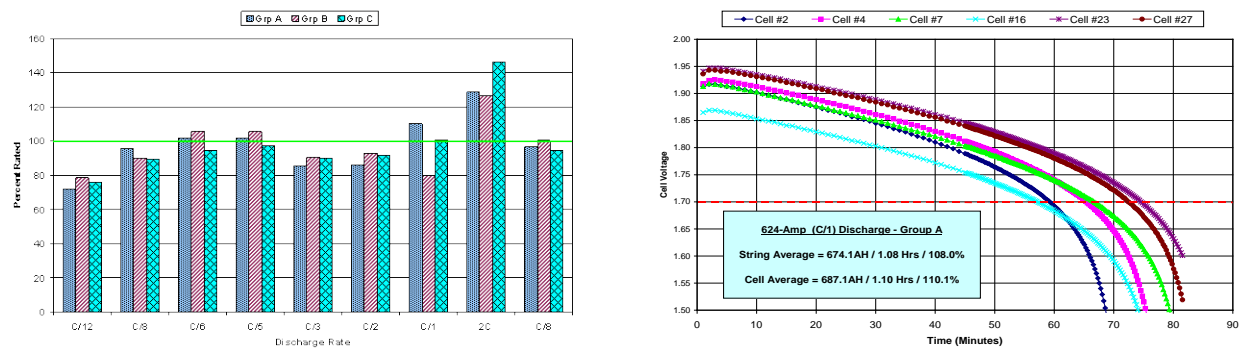


Figure 3a/b. Characterization discharges of the MP&L field-aged samples indicate an overall better than 95% of rated capacity from the C/12 to 2C discharge rates. Even at the higher 1-hour discharge rate (624 Amps), cell voltage is strong and consistent.

From this original test group, three sets of six cells each were subsequently selected representing the low, middle and upper segments of the distribution curve, capacity discharged at currents ranging from the C/12 to the 2C rates, and then compared to the cell's nominal published ratings. Overall, the cells achieved a performance at all discharge rates of greater than 95% (**Figure 3a**). Even at a higher discharge current (i.e., the C/1 rate of 624 Amps), the samples delivered 100% or greater than rated (**Figure 3b**). These results indicate that any short-term capacity deterioration from operating for long periods in a partially discharged state was readily reversed; and, the excellent performance of these samples at the higher discharge rates suggests that these cells are performing at very near full rated capability and are not suffering from any accelerated ageing effects as a result of their use in this BESS application.

Cell Teardown and Examination Detailed examination of the cell's jars, covers, seals, pressure relief vents and current carrying hardware (**Figure 4**) showed all to be in very good to excellent condition. The cell's plate assemblies were in excellent condition with all plates aligned and adequately compressed, with no separator damage or plate growth. The separator material was uniformly moist throughout and measurement of the electrolyte gravity indicated the material to be free of any stratification (**Table 2**). Active material composition and electrolyte concentration were consistent with the condition of the cell and electrical testing conducted.



Figure 4. Examination of the internal lead hardware of the MP&L field-aged cells shows no signs of unusual corrosion or accelerated deterioration.

	<i>Top</i>	<i>Middle</i>	<i>Bottom</i>
As Received #1	1.210	1.211	1.212
As Received #2	1.196	1.195	1.195
Initial Capacity Test - Low	1.206	1.211	1.212
Initial Capacity Test - High	1.289	1.291	1.290
Cycled Group A	1.285	1.286	1.288
Cycled Group B	1.306	1.310	1.311
Cycled Group C	1.290	1.292	1.288

Table 2. Specific gravity measurements made on electrolyte samples taken from the top, middle and bottom sections of separator material from MP&L field-aged cells shows no signs of stratification.

Surprisingly, the condition of the cell's positive plates and grids was exceptionally good, considering the cell's 12 years of operation at the BESS (*Figures 5a/b*).

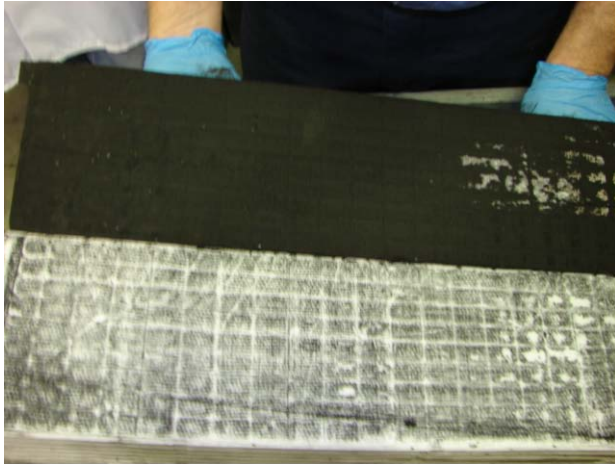


Figure 5a. Positive plates from a field-aged MP&L cell “as removed” from the site shows a small amount of white surface sulfate, typical for a partially discharged cell. After an equalization charge and a few cycles, this sulfate was reconverted to lead dioxide, and the plates had the normal dark brown color of a fully charged plate.

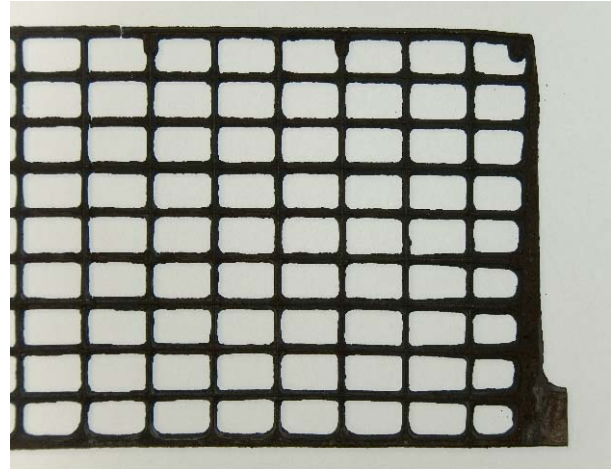


Figure 5b. Close-up view of the upper section of a grid from a 12-year old MP&L cell shows it to be fully intact and free of cracks and breaks. It is typical at this age for positive grids to become brittle and fragile, and to easily crumble with handling.

By design, the capacity and life of an ABSOLYTE® cell is defined by the cell's positive electrode. During discharge, the cell's positive active material is converted from lead dioxide to lead sulfate. The color of the lead dioxide of a fully charged positive plate is a dark chocolate brown; the color of a discharged positive plate containing some amount of lead sulfate is more of a reddish brown and may have areas on the surface of the plate that are gray to white. Cells examined in the “as operated and received” condition from MP&L were still a very dark brown color; however, on some of the plates there were small patches of white surface sulfate as shown in *Figure 5a*. Chemical analysis of this active material indicated as much as 20% lead sulfate, which is consistent with their partial SOC operation at the BESS. Positive plates from cells that were given an equalization charge and cycled were dark brown in color and free of any white surface sulfate; the chemical analysis indicated the composition to be greater than 90% lead dioxide – all consistent with the observed electrical performance recovery of these cells.

Another surprising observation made during the teardown examinations was the overall strength and integrity of these positive plates. Furthermore, measurements of the width of these positive plates made at several locations from the top to the bottom of the plate showed no signs of positive grid growth. Typically as a lead-acid battery ages, the positive active material becomes soft and the positive grid becomes brittle and fragile – the result of corrosion. As seen in *Figure 5b* the positive grids from these 12-year old MP&L cells were fully intact with the grid wires free of cracks and breaks, appearing as if they were removed from a much newer cell than the actual 12-year age of these MP&L samples.

Operational Age of the BESS Battery From practical history, it is known that the MP&L BESS had been operating for 11 years, 7 months and 20 days – well beyond the 8-year life used to justify its installation. The operational age of the MP&L BESS however, can be best assessed by the electrical performance, the total capacity discharged and the condition of the internal components of its cells. Discharge capacity testing done on the field-aged samples from the MP&L BESS indicated the cells capable of greater than 95% of rated – well above the minimum 80% typically used to define end of life. Total capacity discharged, or “*throughput*” is used to define battery lifetime in cycling applications. The anticipated life of the ABSOLYTE® 100A75 module is 1200 cycles at the C/8 rate to 80% depth-of-discharge or a total lifetime throughput of 3,456,000AH. Data collected from the BESS during the first 47 months of operation indicated a monthly average discharge capacity of 25,500AH. At that monthly discharge rate, the MP&L BESS would have accumulated 3,562,350AH of discharge throughput while in operation for the 139.7 months until it was shutdown to replace the battery. Although the Exide ABSOLYTE® VRLA battery achieved

103% of its design cycle life, it was still capable of delivering greater than 95% of its rated capacities even up to the 2C discharge rate. This indicates that the operating conditions in this BESS application were less severe than in a typical cycling application.

The final technique to assess the operational “age” of a lead-acid battery is to measure the amount of positive grid corrosion that has occurred. The design lifetime for the ABSOLYTE® product is based on a positive grid corrosion rate of 0.0025-0.0030 inch per year under recommended float charge conditions. With consideration for the load currents at which the MP&L BESS was projected to be operated, it was estimated that the positive grids should have 40-50% of the cross sectional area of the grid’s members remaining at the end of the battery’s life. The short distance internal radius of the vertical grid members (the direction of current flow) of the positive grid of an ABSOLYTE® cell is approximately 0.070 inches, yielding a calculated cross sectional area of 0.015 square inches. Assuming that there should be 45% cross sectional area remaining at the end of life in the BESS application, the end-of-life cross sectional area is calculated to be 0.007 square inches leaving a hard metal radius of 0.047 inches. Thus the corrosion layer thickness at the end of life should be 0.023 inches. At a corrosion rate of 0.0025-0.0030 inches per year, it was estimated to take approximately 8.3 years to develop the corrosion layer thickness calculated for end of life. This calculation was the basis for Exide’s 8-year warranty for the ABSOLYTE® battery at the MP&L BESS.

Measurements of the corrosion layer made on grids from sample cells removed from the MP&L BESS after 30 months of operation (**Figure 6a**) showed a thickness of 0.006 inches, resulting in an actual corrosion rate of 0.0024 inches per year [5]. From these measurements, it could be projected that it would take about 10 years to reach the corrosion conditions indicative of battery end-of-life. It was these interim corrosion measurements that supported the decision to continue to operate the MP&L BESS battery beyond its original design life.

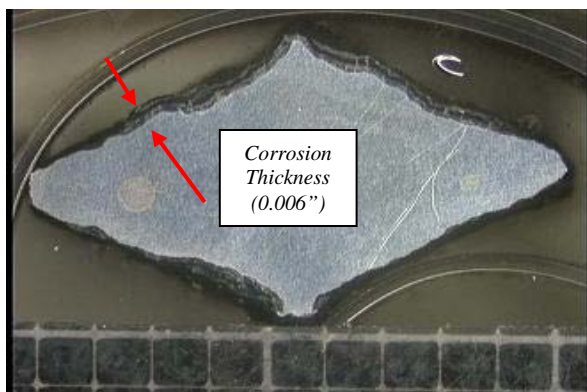


Figure 6a. Photomicrograph of a positive grid section from an MP&L BESS cell after 30 months of operation. The measured corrosion layer thickness, 0.006 inches, projected a 10-year life before reaching end-of-life conditions.

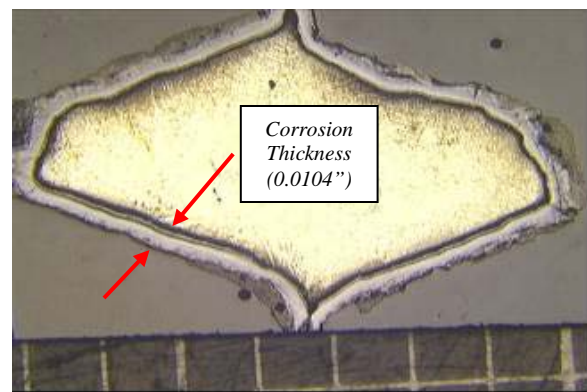


Figure 6b. Photomicrograph of a positive grid section from an MP&L BESS cell after 11.6 years of operation. The 0.0104-inch thick corrosion layer uniformly surrounds the hard lead metal center.

In a similar manner, the corrosion layer on the positive grids from several field-aged cells sampled from the decommissioned MP&L BESS battery was measured. In total, 120 measurements were made on 30 grid sections from 6 different cells. The average of these measurements resulted in a corrosion layer thickness of 0.0104 inches, yielding a corrosion rate of 0.0009 inches per year. These measurements and observation of the condition of the positive grids clearly indicate that positive grid corrosion was less than initially anticipated, and suggests that the battery could have continued to operate in the BESS for a few more years.

Summary and Conclusions. The Battery Energy Storage System (BESS) installed at Metlakatla Power & Light has proven itself to be a success – economically, environmentally and technically. The equipment installed at the BESS has operated flawlessly. All of the concerns expressed at the start of this project have been addressed and have been definitively shown not to be an issue. The Exide ABSOLYTE® Valve-Regulated Lead-Acid battery surpassed all expectations. Not only did the battery meet all of the anticipated challenges of the installation, it even supported the entire system during several unexpected local power blackouts. Battery life exceeded the estimates used to justify the system by 50%, operating acceptably for nearly 12 years versus the initially anticipated 8 years. Testing and examination of cells following the battery’s replacement indicate that they were in excellent condition and may have

been able to operate even longer with appropriate conditioning charging. Indeed, the BESS has shown itself to be industrially robust and able to be operated and maintained just like any other piece of industrial equipment. Battery Energy Storage is totally viable, and can now be considered part of an environmentally friendly energy system in utility, industrial and even residential applications.

Best of all for the small Indian community of Metlakatla has been the economic benefits realized. Over the twelve years that the BESS has been installed and operating, the community has saved over \$6.6 million. By taking the action to replace the battery, the citizens of Metlakatla will continue to accrue these savings well into the future ensuring stable and efficient electric service using predominantly renewable sources.

References

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