Enabling Solar Generation and Reducing Diesel Consumption at the Redwood Gate Ranch Microgrid with Aqueous Hybrid Ion (AHI) Batteries

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Abstract

This paper details a commercial microgrid project that was deployed at an off-grid ranch near Jenner, California in February 2014. The project consists of a hybrid solar/diesel generation system combined with a 54 kWh Aqueous Hybrid Ion (AHI) battery set. This novel energy storage solution will enable the user to achieve a much lower levelized cost of electricity (LCOE) than a stand-alone diesel or hybrid system employing other types of batteries by enabling the maximum solar contribution to the energy mix, minimize the use of the diesel generation as well as ensuring the diesel generator runs at its most efficient state. Preliminary data are included here to both demonstrate system functionality as well as illustrate the value proposition of using AHI batteries in micro and off-grid applications.

Aqueous Hybrid Ion (AHI) Battery Technology

Recently there have been multiple reports in the academic literature that illustrate the promise of using lithium potassium and/or sodium intercalation materials in water based electrolytes.[1-6] The best of these results show that some intercalation electrode materials are completely stable through many thousands of cycles and in some cases are capable of very high charge/discharge rates. AHI batteries as developed at Aquion Energy are aimed at exploiting these performance attributes by leveraging intercalation electrode materials that are fully stable in an aqueous environment. Commonly available precursors are used to synthesize the necessarily low-cost materials, including a cubic spinel λ-MnO_2 cathode, a sodium titanium phosphate/activated carbon composite anode, a sodium sulfate (neutral pH) aqueous electrolyte, and a synthetic cotton separator. Initial work relied on an anode comprised of only activated carbon, which was found to be electrochemically stable.[7] To increase energy density and decrease voltage swing during use, however, $NaTi_2(PO_4)_3$, has been added to the system.[8, 9]

AHI batteries have a cost-optimized electrode configuration focused on providing optimal value for stationary applications that have charge/discharge durations that are typically greater than 4 hours. Under long-duration testing, units have proven to be robust under a variety of operating conditions; they have been cycled thousands of times to 100% depth of discharge with minimal degradation and have also demonstrated the ability to stand at a partial state of charge with minimal self-discharge or loss in function. Additionally, AHI batteries do not require costly thermal management or fire suppression systems. They do not require maintenance and are safe and easy to handle because they do not contain or produce any hazardous materials, corrosive acids or noxious fumes at any point during storage or use.

Figure 1 shows representative discharge curves for the AHI chemistry under constant current charge/discharge conditions for multiple rates. As can be seen in the data, the voltage swing encountered during use is below a 2:1 V_{max}:V_{min} ratio.

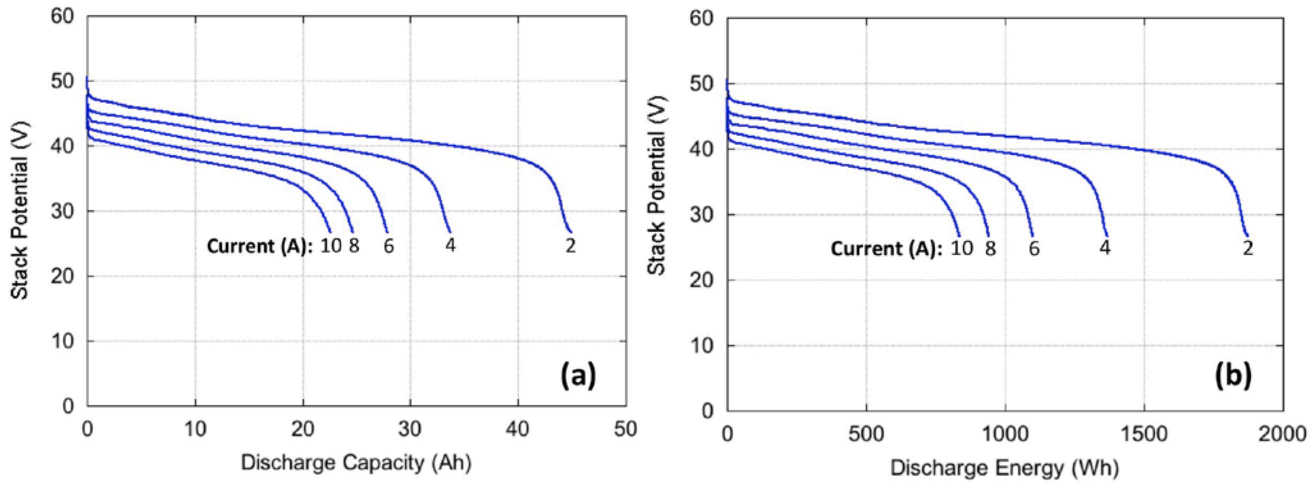

Figure 1: Constant current discharge data from prototype AHI battery strings (twenty eight 44 Ah cells connected in series); (a) String voltage vs discharge capacity at currents ranging from 2 to 10 A. (b) String voltage vs discharge energy at currents ranging from 2 to 10 A.

Figure 2 shows the cycle life stability of the both the chemistry and a large format test device. The materials themselves have been tested in a thin-electrode coin cell environment and show less than 5% capacity fade over 3000 cycles (>80% SoC swing), and a large format test has been ongoing at 40˚C.

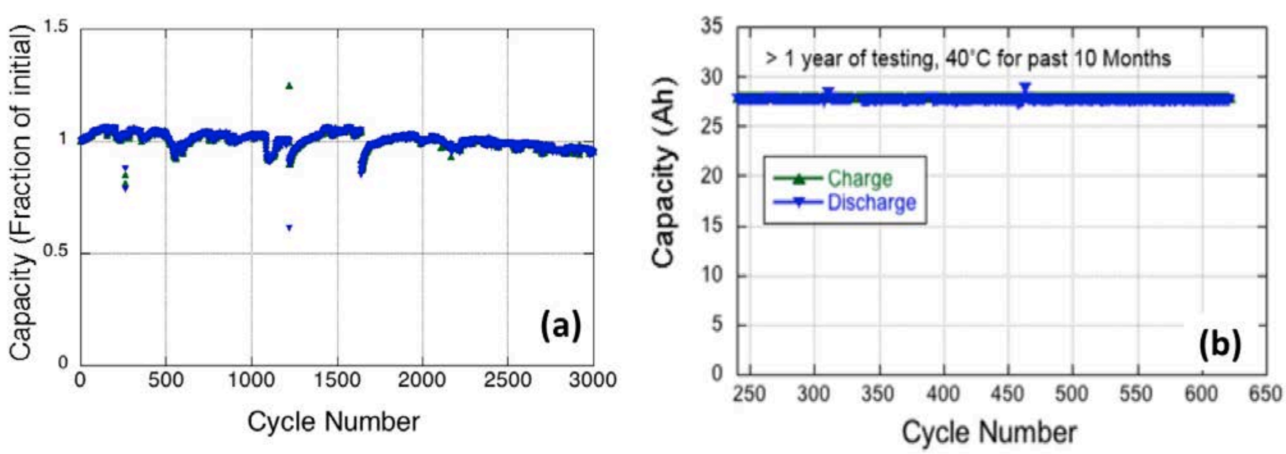

Figure 2: (a) Cycle life testing from an AHI coin cell featuring a MnO_2 intercalation cathode and a $NaTi_2(PO_4)_3$ anode. The noise in the data is due to thermal variation and test stop/start over the 8 months of testing. (b) Cycle life results from a large format (28 Ah) test cell of the same configuration. This unit has been under constant deep cycling at a C/5 rate for over 10 Months at 40˚C.

The chemistry has been found to be very robust in the face of a common lead-acid abuse test; the partial state of charge (PSOC) pulse test. Specifically, a large format AHI pack has been undergoing constant high current pulsing around ~50% state of charge at 40˚C. Every 1000 pulses, two deep "reference" cycles are performed to probe available energy at a 6 to 8 hour discharge rate. Over the 10 months of testing thus far encountered, there has been virtually no loss in pack energy.

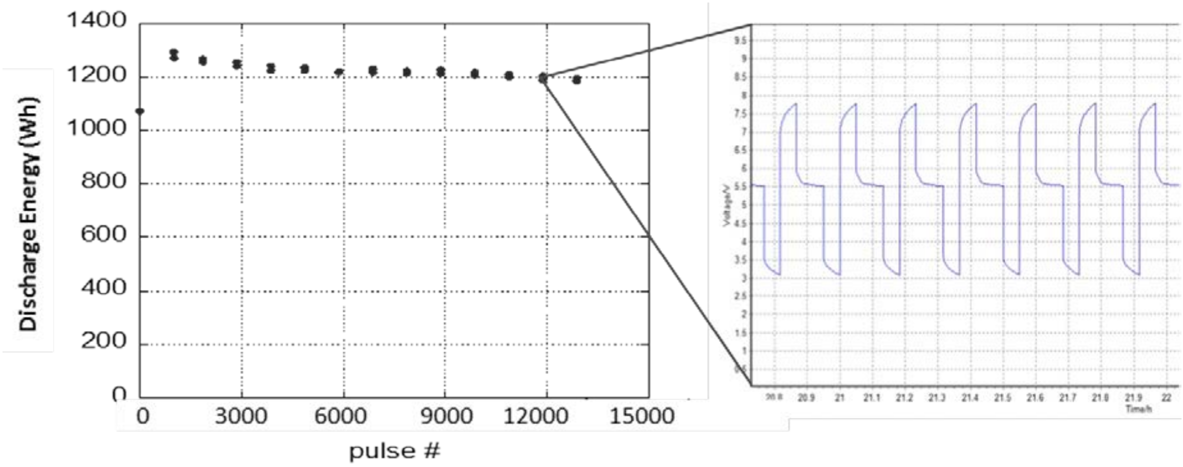

Figure 3: Sandia Partial State of Charge (SOC). Pulse: The batteries are cycled between 45-55% SOC using ±10A load (inset figure), with two full (100% DoD) cycles every abuse 1000 cycles. Over 13,000 cycles and 10 months of testing at 40˚C has resulted in very little loss in string-level discharge energy.

Production AHI batteries were also tested under a typical microgrid duty profile, in this case a 24-hour charge/discharge power vs time profile provided to Aquion by a large scale microgrid developer based in Australia. The power, energy, voltage, and current responses to this application are shown for one cycle in figure 4.

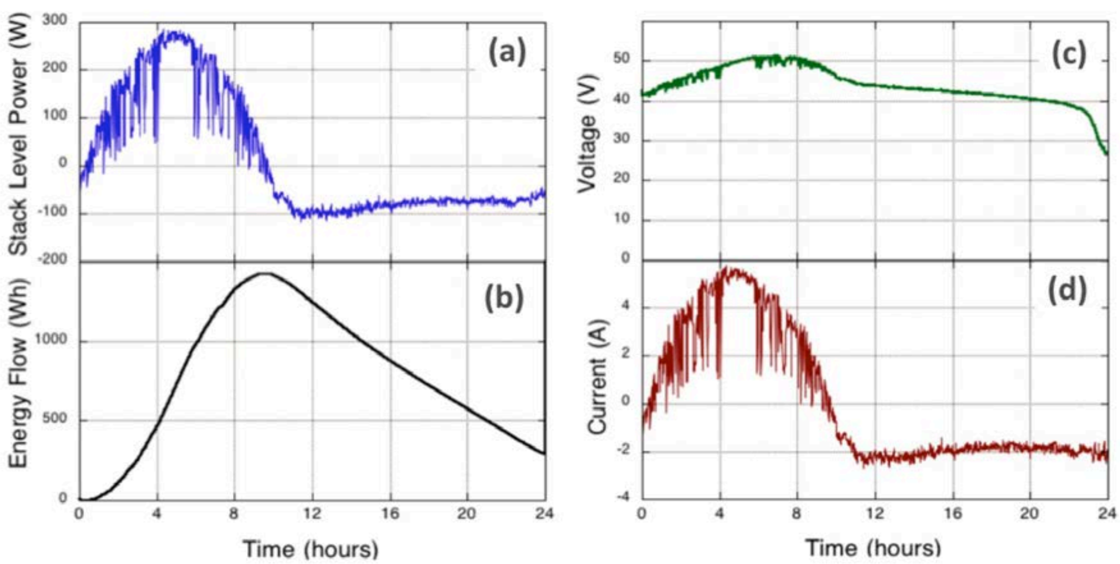

Figure 4: A 24-hour power vs time duty cycle used to represent the load encountered by an energy storage system that is employed to "baseload" a PV array by charging during the day and discharging at night. The power (a), stack energy (b), voltage (c) and current (d) are all shown. These data were collected from an actual AHI battery stack (alpha class).

A battery pack was exposed to over 125 continuous days of this duty profile and was found to deliver the requisite energy each cycle with a round-trip energy efficiency exceeding 80%, as indicated in Figure 5.

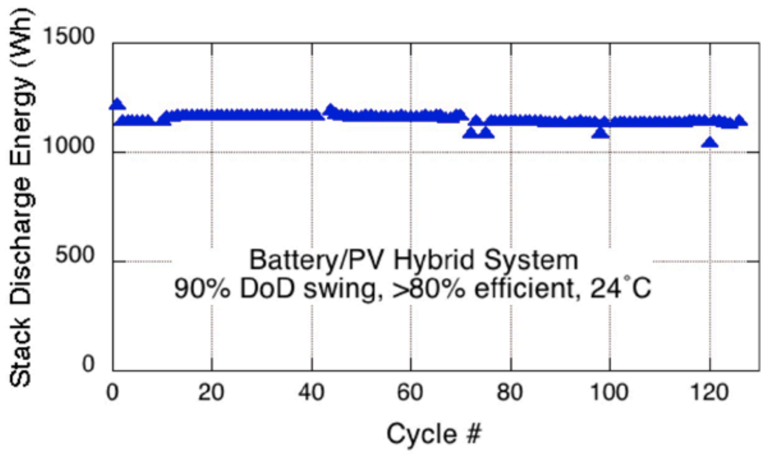

Figure 5: Energy delivered as a function of day (cycle #) for the 24-hour PV/battery hybrid duty cycle shown in Figure 4. This test is ongoing and the system remains stable. The several data points that are off-trend are a result of temporary test system shut downs.

AHI Battery Configurations

The commercial AHI batteries used in the Jenner microgrid contain four series connected cells as the most basic building block. The battery design is shown below in Figure 6, with a rendering of the internal structure and components of the battery detailed in Figure 7. The batteries are assembled into series connected stacks of seven to eight batteries depending on desired voltage. Figure 8 shows a module, which consists of 12 stacks that have been assembled on a standard pallet and fitted with sensing and controls able to interface with industrial power control electronics via ModBus. Stacks are designed to be connected directly to standard off grid power control electronics that operate below 60 Vdc and operate without any active management, monitoring or control. Modules are designed to support much larger systems with the ability to support massive series/parallel configurations and a DC bus of up to 1000 Vdc.

Figure 6: AHI 4-cell battery

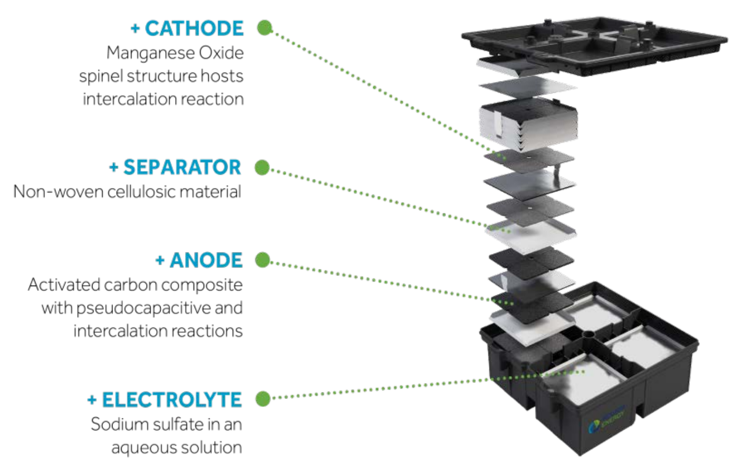

Figure 7: AHI battery internal configuration

OPERATION & PERFORMANCE	
Energy Capacity	19.2 kWh at C/20 rate
Cycle Life	>3,000 cycles
Usable SOC Window	100%
Operating Temp Range*	-5 to 40° C
Round Trip DC Efficiency	>85% at C/20 rate
Voltage Range	Configurable to 624 Vdc/unit
Charge/Discharge Modes	CC, CP, CV, AC ripple tolerant

PHYSICAL CHARACTERISTICS		
Height	1,079 mm	42.5 in
Width	1,016 mm	40.0 in
Depth	1,321 mm	52.0 in
Weight	1,256 kg	2,770 lbs

Figure 8: AHI palletized battery module comprised of 12 stacks wired in series or parallel

Microgrid Application

Redwood Gate Ranch is a 500-acre mountainside ranch in a remote, off-grid location near Jenner, California, in the western Sonoma County coastal hills overlooking the Pacific Ocean. The ranch is located outside of the area serviced by the region's electric utility. The site was originally powered by a small solar system comprised of 8 PV panels and 12 lead acid batteries to provide power for a small cabin and to replace a gasoline generator used to power a water pump. A recently constructed 3,000 square foot residence at the ranch increased the energy load and added a requirement for continuous access to reliable power.

During construction, the owners powered the site with a 30kW diesel generator. They planned to move the generator to a back-up role in a solar hybrid microgrid once construction was complete. The goal of the microgrid was to allow the residence to be energy self-sufficient using solar generation as the primary source of power. The owners talked to PG&E, the local electric company, about having power lines installed to the ranch to tie into the main grid to manage instances when solar wasn't available and reduce the need for storage. Extending grid service to the ranch came with an estimated expense of between $150 - $200K, as well as liability for any future maintenance costs. This led the owners and their system designer to the conclusion that the energy storage component of the microgrid should be sized to support about three days of anticipated load in order to minimize diesel consumption.

Battery System Selection

The project integrator and solar system designer evaluated several potential energy storage systems based on upfront cost, cycle life, temperature performance, efficiency and safety. They hoped to maximize solar energy produced by deploying a solar array large enough to serve loads directly during daylight hours and simultaneously charge a battery bank that would be providing three days of autonomy and serving daily loads during non-sunlight hours.

Lead acid solutions were evaluated and found to require significant oversizing to avoid deep cycles or stands at partial states of charge. Lithium Ion solutions were also evaluated, but required costly HVAC and fire suppression systems in order to provide long duration charge/discharge cycles consistent with the intended use. AHI batteries were ultimately selected because of their combination of safety, cycle life and abuse tolerance, and ability to support active management of solar generation at the ranch under a variety of conditions. In addition to attractive cost and performance characteristics, the designers were also excited by the sustainable, non-toxic nature of AHI batteries relative to the other types of batteries considered.

Project Summary

System Configuration:

The final design of the solar hybrid microgrid included a 10.8 kW stationary photovoltaic array and a 54 kWh AHI battery pack. Average daily energy consumption was estimated at about 24 kWh with an average daily peak of 4 kW. The system is sized to support >14 kW of instantaneous power in order to serve the maximum anticipated load. Loads include the main house, workshop/garage, guest house, pool filtration, and water pumping. The living spaces use a wood burning stove as the primary heat source and a propane-fueled in-floor radiant heat back up system. Water is heated by a solar thermal system. The system uses control software that enables integration, controls, optimization, automation, and networking of the microgrid components.

Microgrid System Components

- Three AHI battery modules (54 kWh)
- 30 kW Inverter
- 40 270W PV modules
- Solar panel mount
- Battery combiner box
- Solar combiner box
- 30 kW backup diesel generator

Figure 9: Images of the batteries, inverter, and the external solar array

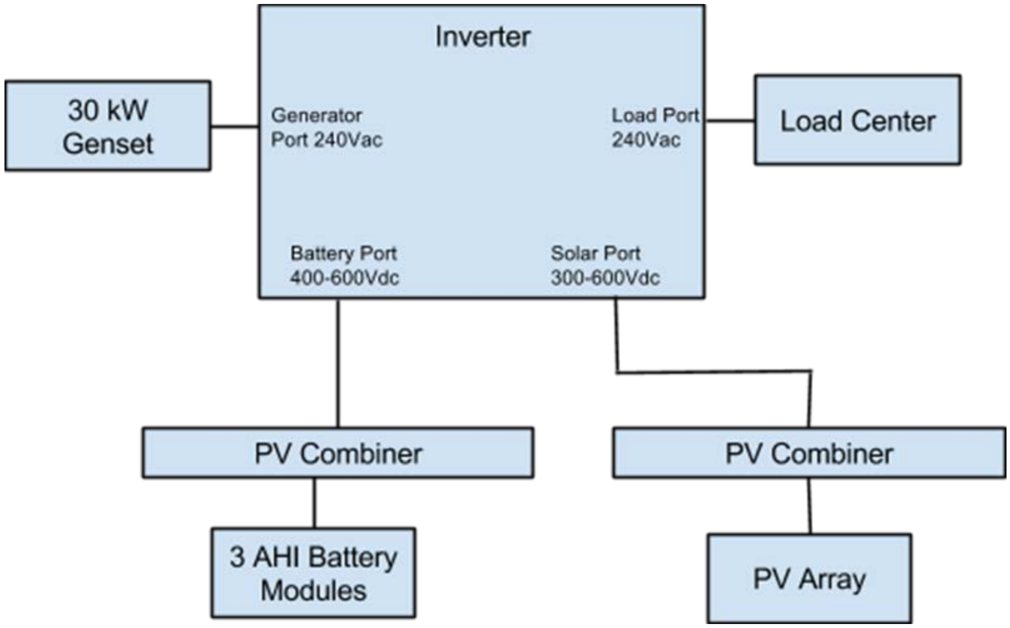

Figure 10: Block diagram of Redwood Gate Ranch microgrid

Figure 11: Screenshot of web interface

System Analysis

Table 1 shows summary results of system performance analysis conducted by Aquion using HOMER, a common microgrid modeling tool. The system as built was compared against two hypothetical cases: 1.) continuing to provide power the site with only the diesel generator that and 2.) deploying the same microgrid with lead acid instead of AHI batteries. The estimated cost of diesel delivered to the site was $1.32/L ($5/gallon). The results of the analysis show how AHI energy storage and solar panels drastically reduce diesel consumption and enable the overall best levelized cost of electricity (LCOE). The upgrade costs an additional $64,000 but is projected to save over $27,000 per year in diesel fuel costs, a payback period of less than three years. A lead acid based microgrid solution has a slightly lower upfront cost, but a much less attractive LCOE because of the number times the lead acid batteries would need to be replaced over the life of the project.

	Initial Capex	Diesel (L/yr)	Diesel ($/yr)	Renewable %	LCOE
Diesel-Only	$20,000	20,300	$26,800	0%	$4.51
PbA+Solar+Diesel	$73,300	170	$230	92%	$0.87
AHI+Solar+Diesel	$80,500	65	$90	97%	**$0.77**

Table 1: Economic analysis of solar/battery microgrid vs diesel stand-alone

Conclusion

AHI's significant performance and safety advantages over other commercially available battery systems enable remote microgrids like Redwood Gate Ranch to economically produce the majority of their energy from solar. Rapid price declines in solar combined with increasingly high diesel prices mean that stand-alone diesel generation is no longer cheaper than generation from solar-heavy microgrids in many cases. Because they are safe, reliable, sustainable, and still cost effective, AHI batteries offer a strong value proposition to commercial microgrid operators for these types of projects.

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