12 Years of Residential 'Off-Grid' PV Hybrid System Operation and Evolution in Nemiah Valley, Canada

Andrew Swingler
School of Sustainable Design Engineering
University of Prince Edward Island
Charlottetown, PE, Canada
aswingler@upei.ca

George Colgate
Capital Projects Manager
Xeni Gwet'in First Nation
Nemiah Valley, BC, Canada
george_colgate@wlake.com

***Abstract*—Eleven residential off-grid photovoltaic (PV) hybrid power systems have been deployed and operated since 2006 in the First Nation community of Xeni Gwet'in located in Nemiah Valley, Canada. This paper reviews the operation and evolution of three system designs. Notable experiences, lessons learned and challenges with respect to reliable hybrid system operation are discussed. Finally, an example illustrating an observed reduction in winter battery capacity is presented, discussed in detail and the concept of closed loop charging control is introduced.**

Keywords – hybrid power; solar PV; lead-acid batteries; off-grid; battery performance; partial state of charge

I. Introduction

This paper reviews the deployment and operation of eleven residential off-grid PV hybrid systems (and one temporary genset-only hybrid system) over the last 12 years in Nemiah Valley, British Columbia, Canada (51.5N,123.8W). Since 2006 eleven long-term residential PV hybrid systems have been commissioned within the dispersed aboriginal community of close to 200 people within a twenty-kilometer long valley. From 2006 to 2009 four early PV-genset residential hybrid research/pilot systems of three types were designed and commissioned. In 2017, after approximately ten years of continuous operation, seven additional hybrid systems were redesigned and deployed. The new PV hybrid system design incorporates lessons learned from the previous ten years of hybrid system experience and feature a number of improvements. However, even with significant system design improvements, challenges remain with respect to effective battery management of the 48Vdc battery banks in the low-sun winter months due to what appear to be periods of incomplete charging. Incomplete charging is of concern as it's listed as one of the five common failure mechanisms of flooded lead acid batteries in [1]. In the case of stationary power systems it's possible that acid stratification may also accompany incomplete charging as another failure mode.

The seven new systems feature numerous reliability and safety design improvements with respect to service access and enclosure, thermal regulation, remote communications and data monitoring, simplified PV interconnection, alarms and overall PV array size. While initial operation since April 2017 suggests that generator reliance has been substantially reduced as compared to previous systems, low battery state-of-charge, inherent partial state of charge operation and resulting battery performance remain a concern during the winter season.

This paper initially reviews the past experience with the initial pilot PV-hybrid systems. Challenges with monitoring the long-term performance of hybrid systems in the field are also discussed. A summary of lessons learned follows and a new and improved PV-hybrid system design is then presented. Finally, the technical challenges of managing hybrid system batteries during winter periods of low sun are illustrated with six months of example field data from the winter of 2017/18. The explored example documents a significant decrease in effective battery capacity, details a recovery strategy and then follows the battery's recovery.

II. Hybrid System Evolution 2006-2008

A. *Initial PV Hybrid System - 2006*

The initial PV hybrid system installed in 2006 was dimensioned with a 2 kW_{pk} solar PV array and a 48V 400Ah flooded lead-acid battery in order to meet a predicted small 240/120V AC residential load requirement of ~5 kWh/day (Fig. 1). The system was also designed with an integrated enclosure complete with an automatic 5.5 kW propane genset to provide supplemental energy for the low-sun winter season as well as any additional energy generation as

Figure 1. The original 2006 hybrid system in 2017.

required. Initial design analysis for this system can be found in [2]. Due to the relative large size of the PV array the genset was rarely called to start in the summer season. During its first winter season an intermittent data logging system showed early signs of battery capacity reduction and incomplete charging during periods of low sun and regular genset operation. Experiments in 'fast-charging' were performed by setting aggressive charging parameters to encourage fuel-efficient genset-based charge reconciliation. For example, constant current charging at 50A to 64V showed improvements in battery performance and charge acceptance by providing necessary overcharge and mitigating partial stage of charge (PSoC) operation. Unfortunately, much of this ad-hoc field experience of more than a decade ago is anecdotal and remains undocumented. Similar experiences with incomplete charging in a laboratory environment are discussed in [3]. Additionally, the main operational challenge with the initial hybrid system related more to the immediacy of reliable automatic genset starting in cold winter weather conditions rather than the longer-term impacts of sub-optimal battery performance.

As of 2018 the initial system remains operational and has experienced no hardware failures with the exception of exhausted batteries and genset failure. The batteries have been replaced at least twice and the system is on its third propane genset. As of August 2017 the system has provided 13210 kWh according to the pay-as-you-go smart meter infrastructure installed. This corresponds to an average of 3.3kWh per day over the last eleven years and likely corresponds to ~5kWh per day while residents were at home.

B. Interim Hybrid System - 2008

In early 2008 an interim hybrid system with no PV was installed at another residence for eight months. In this temporary test a small, low-cost, outdoor and exposed-to-the-weather 200Ah, 48V flooded lead-acid battery bank was operated with only an inverter/charger and automatic genset control in charge-cycling mode. The hybrid system provided continuous 120V AC power to a residence with an approximately 10 kWh per day load. The propane genset supplied all of the energy yet operated for only a few hours per day. In order to provide a consistent overcharge of approximately 10% while minimizing genset run time, a 50A constant current single-stage cycle-charging regime starting on a low voltage trigger of 46V and charging up to 64V was implemented. Resulting charge is shown in Fig. 2 where the unconventional charging also served to keep the batteries warm over the winter. This was followed by less

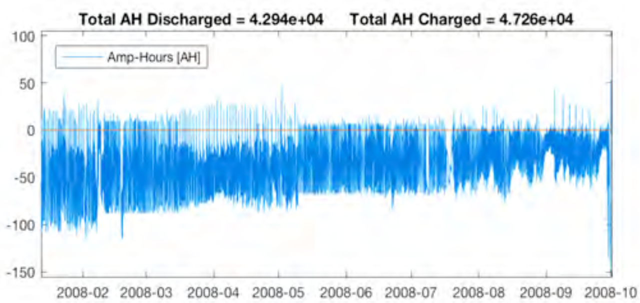

Figure 2. Interim hybrid system battery charge cycling – 2008.

aggressive automatic genset control based on amp-hours set points. The control was then returned to voltage-based set points until the battery capacity faded. In October 2008 the system was retired after the batteries had supplied 42900 Ah, or 215 equivalent *full discharges* in eight months. Considering the batteries were not operated according to any kind of manufacturers recommendations, were overcharged at high currents, ran hot and also ran dry a number of times; we were surprised by the successful result. The experience also suggested that more aggressive charging might be of some net positive benefit to system performance when attempting to fully charge batteries with the limited availability of a genset or winter solar energy.

C. Three additional PV Hybrid Systems - 2008

In 2008 the community commissioned the procurement of three additional PV hybrid systems. The new systems were engineered with the philosophy of being locally reproducible by community members and were constructed as simple wooden outdoor appliances with an integrated battery bank and genset. The three new systems featured 1kW$_{pk}$ of PV, 400Ah of flooded lead acid batteries and the commercial version of same 5.5kW propane genset as used previously. The new commercial genset featured a robust internal genset starting-battery charging system and a larger starting battery in order to increase starting performance.

The three additional systems were commissioned in late 2008 and all four original PV hybrid systems have been operating continuously since; with only short periods of down time for maintenance. The interim genset-hybrid discussed previously was decommissioned and replaced by one of the new PV hybrid systems. The three new systems were configured with a new 'boost' charge mode which was included as a new feature within the newer power conversion equipment. Boost charging allows the first hour of the absorption charge to operate at a higher constant voltage set point in order to aid in proper charge reconciliation and encourage necessary overcharge.

While anecdotal observations of incomplete battery charging during the winter season continued to persist over the years, the main practical issue was, again, related to aging genset performance and reliability. This could have been compounded by increased genset operating hours due to reduced winter battery performance. It should be noted that the belt-driven propane gensets have proven surprisingly reliable; surviving for years (4000-5000 hours have been seen on retired gensets!) with very little maintenance and starting, for the most part, reliably in sub -30C temperatures. However, relative to the rest of the system (batteries included) a generator failure is critical. A hybrid system can provide continuous AC power with no PV and weak batteries but it can't supply power reliably with a genset that doesn't operate.

Each of the hybrid systems has experienced at least one battery replacement in the last 10 years and the health of the current batteries remains unknown. There have been at least five genset replacements and a number of genset repairs since 2006. Due to the remoteness of the community and number of people involved over the years, accurate record keeping has proved challenging. As of August 2017 the system that replaced the interim genset hybrid has supplied 23900 kWh over nine years or 7.3kWh/ day average. Another system connected to three small residences has supplied 33500 kWh and the third system connected to a single residence has supplied approximately half that load. The four original PV hybrid systems continue to provide 24/7 access to AC power a decade after their installation.

III. Lessons Learned 2006-2017

A. System Performance

An important lesson learned over the last 12 years relates to the difficulty in assessing system performance. An underperforming hybrid system in the field with weakened batteries and/or malfunctioning PV may go unnoticed as long as the genset starts reliably. Any lack of system performance and subsequent increase in fuel consumption and generator wear may remain undetected until there is a critical failure of the genset or batteries.

All the PV hybrid systems discussed in this paper are community owned and the residents are not involved in their day-to-day operation. The systems are likely visited only a few times a year to top up battery water and change genset oil. A propane vendor automatically fills the propane tank periodically. From a performance monitoring perspective it would be useful if the system controller could report on the following simple system metrics over selected months and years:

$$Load_{Energy} \text{ (kWh)}$$

$$PV_{Energy} \text{ (kWh)}$$

$$\text{Genset (hours)}$$

$$\text{PV Fraction} = PV_{Energy} / Load_{Energy} \quad (1)$$

Underperforming systems suffering from poor battery performance and/or reduced PV energy generation will show an unexpectedly low PV fraction. Also, underperforming systems will result in higher-than-expected genset run hours due to a less effective utilization of the available PV energy. These two metrics provide arguably the most elegant insight towards rapid assessment of system performance.

The most reliable long-term performance indicator in the four initial systems proved to be robust and necessary AC energy meter used for billing. Data on genset and PV energy supplied is measured but not archived and performance assessment based on the above is not possible.

B. Sytem Hardware

The PV and power electronic components have proven to be impressively reliable with virtually zero failures. As mentioned previously the majority of the hardware issues were related to genset reliability and end of battery life. The following is a compilation of lessons learned in list form:

a) Propane fuelled gensets reliably start when cold if properly maintained and a large tank surface area is used. Oversize the starting battery for the genset to aid in cold weather starting. Ensure the genset has a robust built in charging system for the starter battery.

b) Derate the maximum genset load to 50-75% due to the constant load associated with battery charging. Initial charge cycling operation at full genset power resulted in premature genset failures.

c) An accessible enclosed system is prefered form a service perspective.

d) Systems are tolerant to operating with depleated batteries due to the availablity of the dispatchable genset and a very large fuel supply consisting of 1000L tanks (for surface area in cold weather) and automatic refilling.

e) Desiging systems for less than 250 hours per year of genset operation by implementing a larger PV array. This will extend generator life and also mitigate incomplete battery charging.

IV. New System Design - 2017

As part of a larger overall electrification initiative within the community seven new hybrid systems were commissioned for delivery in 2017. With the assistance of HOMER software the systems were designed for an 85% PV fraction and 150 genset operating hours per year. The design consisted of 6 kW_{pk} of PV, 1000Ah of flooded lead-acid batteries and the same 5.5 kW propane genset as used previously. The design load was 15 kWh/day. The components were then engineered into a robust 10’ shipping container as presented in Fig. 3. The shipping container provides ease of service in addition to providing a secure and protected enclosure. The container features voltage controlled exhaust fans on the battery boxes. A

Figure 3. New Containerized Design - 2017

secondary hydrogen alarm system evacuates the entire container with a main exhaust fan if hydrogen concentrations exceeds dangerous levels within the container. Finally, the container features a thermostatically controlled propane furnace to designed to be used in extreme cold conditions. The updated power conversion equipment also features a remotely accessible web-based interface, which enables the system to be remotely monitored and configured. The monitoring system also has the capacity to log system energies as discussed in the previous section to allow for rapid performance assessment.

To further assist with advanced performance monitoring, each system has been equipped with a dedicated battery data logger device. It is hoped that the robust battery data will allow for a clear assessment of ongoing and long-term system performance and health and to aid in set point tuning after their first year of operation.

V. POOR BATTERY PERFORMANCE EXAMPLE

As mentioned, the seven residential hybrid power systems installed in 2017 are equipped with precision battery data logging capability. Analysis of the robust battery data allows for previously difficult, if not impossible, insight into battery bank performance as the hybrid systems operate and age in the field. Fig. 4 illustrates the field operation of one the new systems over its first winter from September 2017 to March 2018. In this example the 48V 1000Ah battery bank consisting of 24 2V cells suffers a severe loss of effective storage capacity due to repeated undercharging. The battery bank subsequently required an

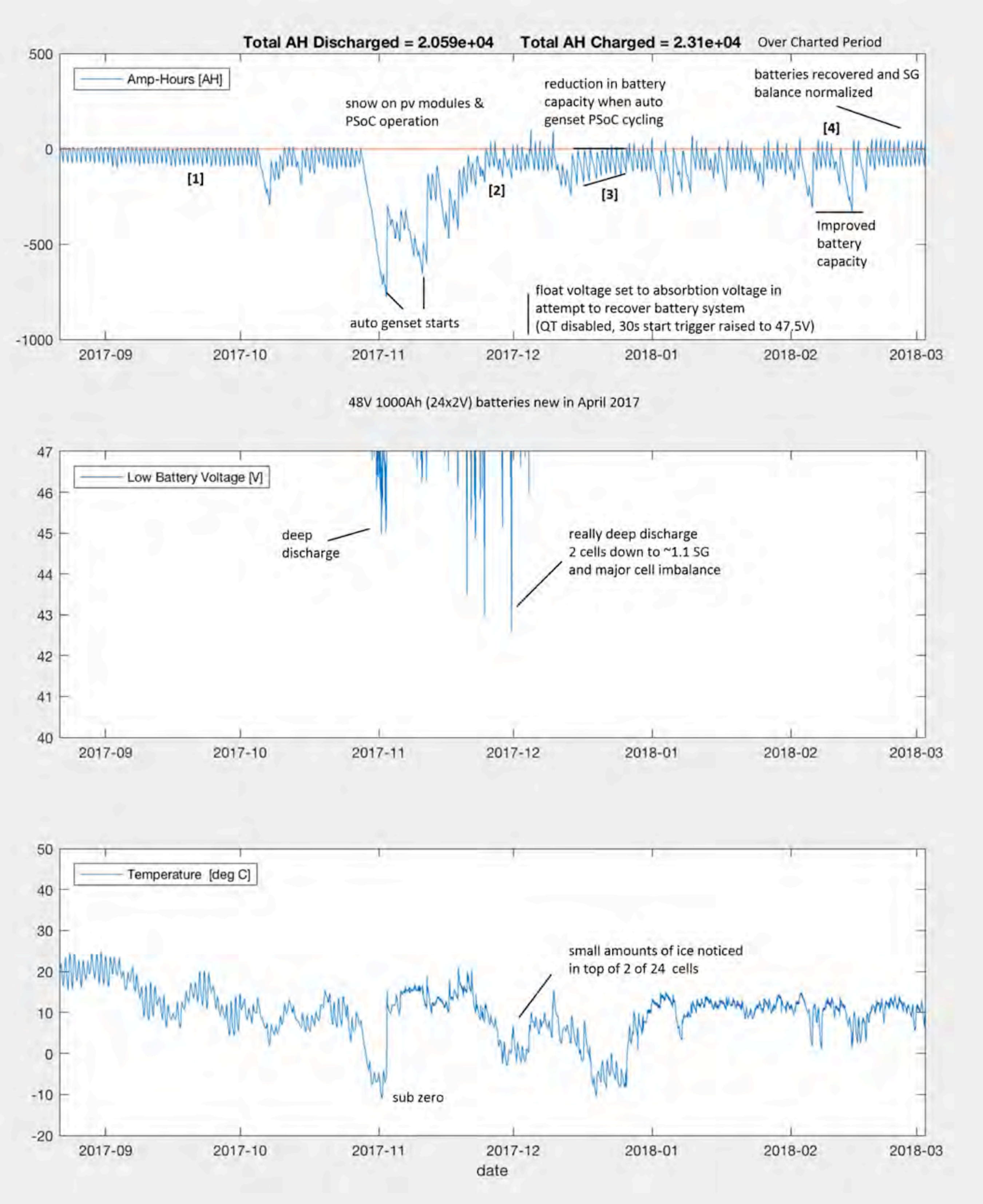

Figure 4. Hybrid system operation over six winter months.

aggressive manual intervention of the charging parameters in order to recover its storage capacity to an acceptable level. While the battery appears to have recovered effectively over the four-month event as illustrated, any permanent life-shortening damage to the battery bank remains unknown. Interestingly, this one detailed example efficiently summarizes general observations, both anecdotal and measured, of hybrid system battery performance in the community over the last 12 years. Battery performance and effective capacity appears to suffer during the winter season due to partial stage of charge (PSoC) operation caused by a combination of lack of sun, premature solar charge regulation and intermittent and incomplete genset-based charging.

In Fig. 4 the *Amp-Hours* trace is a time integration of the battery current and is allowed to climb positive on charging and resets to zero upon subsequent discharge. In this way the time integration of positive *Amp-Hours* might be considered as ‘overcharge’. The middle plot of Fig. 4 shows battery voltage cropped to display only significantly deep discharge conditions thus illustrating what may be considered as notable deep discharge events. Finally, the battery enclosure temperature is shown where the batteries are located in a closed wooden box, which is insulated all five sides except for the top.

In September and October of 2017 the *Amp-Hours* charge reconciliation appears consistent. The operation of the solar charge is shown in Fig. 5 which is a zoomed-in voltage and current snapshot taken at location ‘1’ of Fig. 4. In Fig. 5 the transition to lower constant voltage (CV) float regulation mode can be observed when the battery current falls to the solar charger’s default setting of 2% of the rated battery capacity. Also observed are elevated absorption and float CV set points confirming automatic temperature compensation for the cooler 15C battery and where the original 25C set points are 60.0V and 54.0V respectively. Interestingly, even with elevated temperature compensated CV set points and ample PV energy available, there is an observed reduction in charge reconciliation.

At the end of October a snowstorm covered the solar array and reduced its output power to near zero. The automatic genset controller was in its factory default setting where it was configured to start the genset when the battery voltage fell to less than 44.5 V for 30 seconds and was outside the default restricted ‘quiet time’ hours setting of 9pm and 8am. 44.5V represents a very low battery state of charge and consequently the genset automatically started with the battery in a deeply discharged state as can be seen by the deep discharge and then steep recovery in Fig. 4. The genset then charged the battery bank through the inverter/charger in addition to output of the solar chargers. The controller’s default setting of *stop on absorption* automatically stopped the genset once the battery bank reached the default absorption voltage setting in the inverter/charger of 57.6V. However, at this moment, the

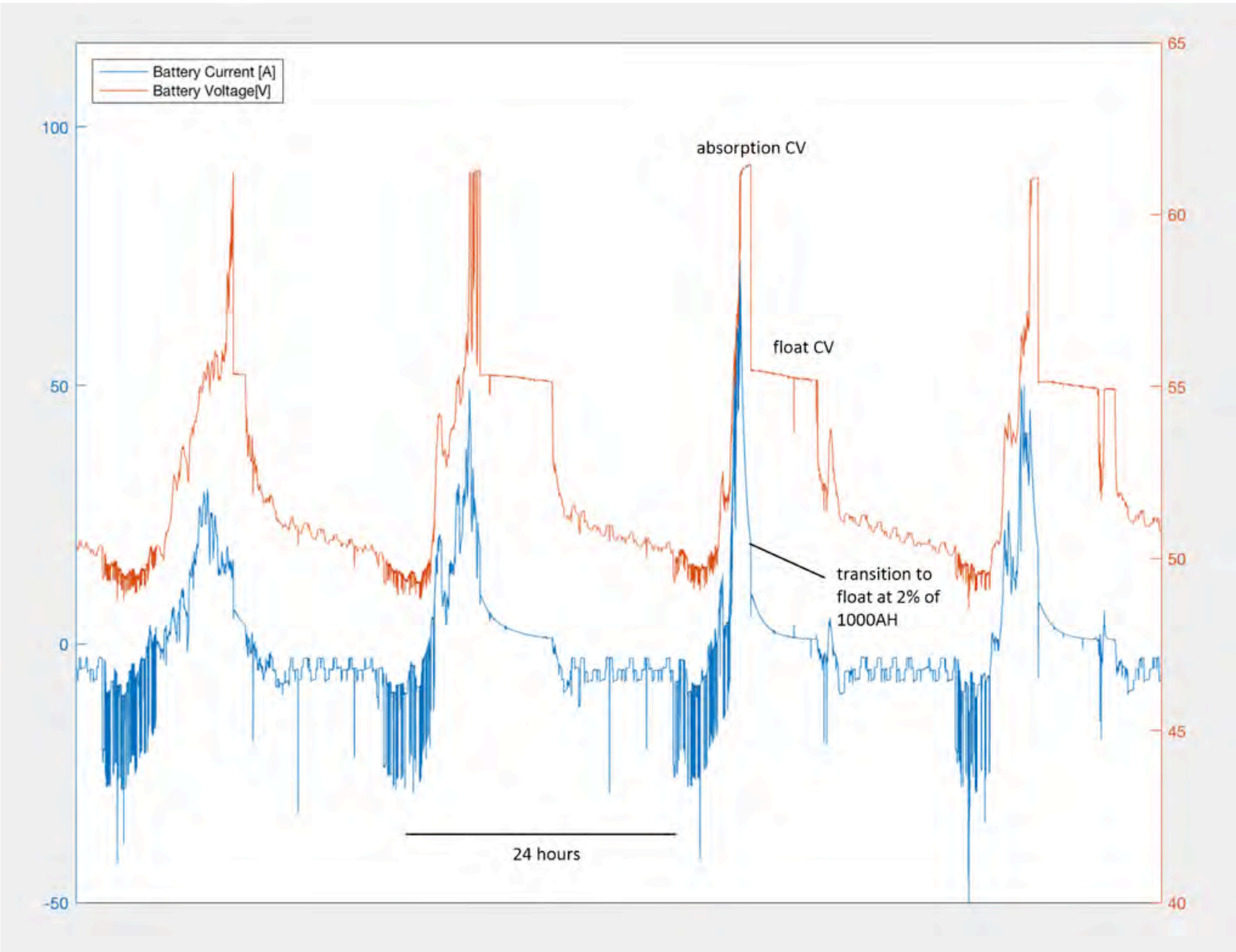

Figure 5. Example battery voltage and current over four days in October 2017. From location 1 of Fig. 4.

battery was far from fully charged (as can be observed by the *Amp-hours* count) and conditions have been established for a challenging future of PSoC operation.

After the initial deep discharge event the solar and automatic genset control system, as configured, is unable to recharge the battery with any kind of effective over-charge reconciliation. The accumulated result is a rapid decline in the effective capacity of the battery. This can be clearly observed in Fig. 6, which corresponds to location 2 of Fig. 4. In Fig 6 a number of interesting details can be observed. operation. The charging system, for all intents, considers the battery as full even though there is considerable charge energy available and the battery is far from charged – or even healthy by this point. This is the repeated process that has occurred in the system and defines extended periods of PSoC operation with no regular over-charge reconciliation. At location '2' of Fig. 4 the usable capacity of the expensive, eight-month-old 1000AH battery is approximately 50AH.

It's worth nothing that automatic genset-based hybrid systems will continue to operate seamlessly with batteries of reduced capacity and even in very poor health due to availability of the supporting dispatchable power. It's likely the system in question would have continued without obvious issue if it weren't for the revealing intermittent AC output, phone call and subsequent expert attention.

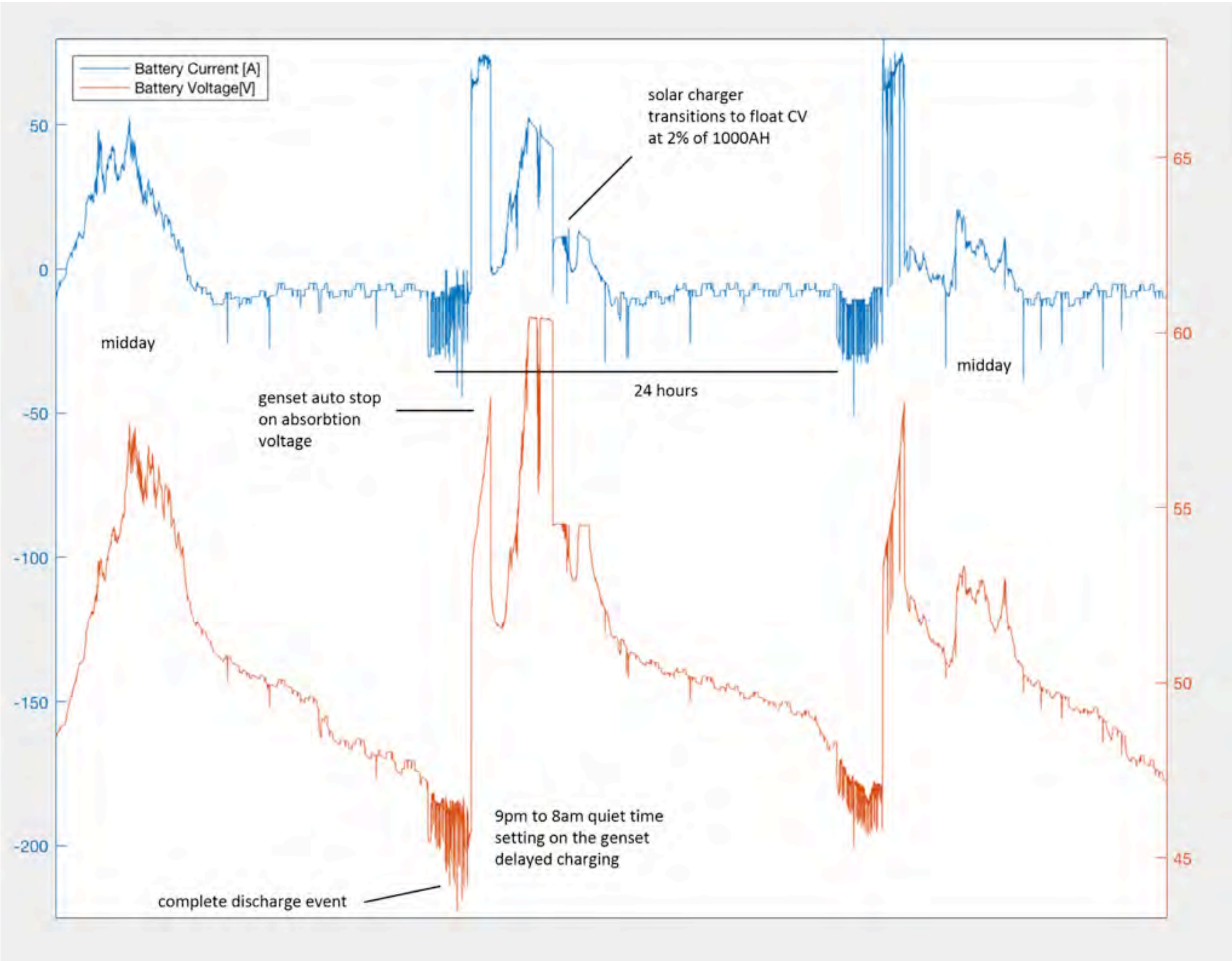

Figure 6. Complete discharge events reduced charge acceptance and effetive capacity over three days. From location 2 of Fig. 4.

Firstly, due to the default quiet time setting of 9pm to 8am an automatic genset-based charge would not prevent an early morning coffee maker load from collapsing the battery voltage to extremely low levels of discharge until after 8am. Ironically it was this abnormally low deep discharge event that alerted local technical experts to the problem. The battery voltage was dropping to below the AC inverter cut out repeatedly shutting down and then restarting the AC power to the residence. The residential AC electricity supply pulsing on and off every few seconds in the dark early morning resulted in a phone call for assistance. Also in Fig. 4, when the genset does start at 8am it reaches absorption voltage in a short period of time thus actively stopping genset-based charging while the battery remains severely discharged. Shortly afterwards solar charging begins and solar charge regulator quickly transitions to absorption and then to a current reduced float CV regulation mode of

In early December 2017 local technical experts investigated the issue. Two of the 24 battery cells were found to be at specific gravity levels of near water and were significantly out of balance with the rest. It has been noticed in previous systems that during deep discharge events and partial state of charge operation a small number of cells 'walk away' to lower specific gravities than the rest. Often the battery bank can be rebalanced or equalized with appropriate amount of so-called overcharge or Amp-hour replenishment. At this point the severity of the reduction in effective battery capacity was not understood. Rather than replace the battery bank we decided to attempt to recover the battery with the following changes. 1) The absorption and float voltages of the solar charger were both set to 60V thereby effectively eliminating float mode of operation and promoting increased over charge and Amp-hour reconciliation. 2) The automatic genset start trigger was significantly increased to 47.5V to avoid deep discharging the unbalanced cells and 'quiet time' was disabled. Simultaneously the automatic genset stop trigger was changed to from *stop on absorption* to *stop on float* thus allowing an absorption charge period; albeit at the expense of increased fuel consumption. While this wouldn't fix the battery bank immediately, the idea was that over time the twenty-four series cells would experience a more aggressive *Amp-hours* reconciliation and eventually recover. In the short term a number of factory equalize charges were performed as observed in Fig. 3. Unfortunately spending an hour (or multiple hours) at an elevated so-called 'equalize' CV voltage was not enough to adequately recover the battery. In retrospect the battery may have been recovered relatively quickly by performing a supervised 20-hour genset-based reconditioning charge at a constant current of 50A for a total of 1000AH returned. However, at the time it wasn't obvious how bad the battery was or even if it would recover. Also, constant current recovery charging with the genset would require significant system set point adjustments and result in significant H2 and O2 generation; this was not appealing to the local technical experts on site. The limitations of CV charging are compared to the benefits of CC charging for batteries exposed to PSoC in [4].

After the system set points were updated there was another period of snow cover and reduced solar energy available as illustrated by location 3 of Fig. 4 and detailed in Fig. 7. This time the automatic genset started reliably at the 47.5V threshold and charged through absorption CV mode and down to the float transition current at which point the generator automatically stopped. While everything looks reasonable in Fig. 7, Fig. 4 shows an obvious reduction in effective battery capacity for each charging cycle with the already reduced battery capacity reducing by another 30+% over six cycles. Again, this reduction in effective battery capacity is familiar result and has been seen repeatedly within other hybrid systems in the community. Hybrid systems operating in a genset charge cycling mode and where a full over charge reconciliation isn't, or can't be, performed regularly appear to struggle with maintaining effective battery capacity. At this point it should be noted that only flooded lead acid batteries, of various brands and sizes, have been used within the community to date.

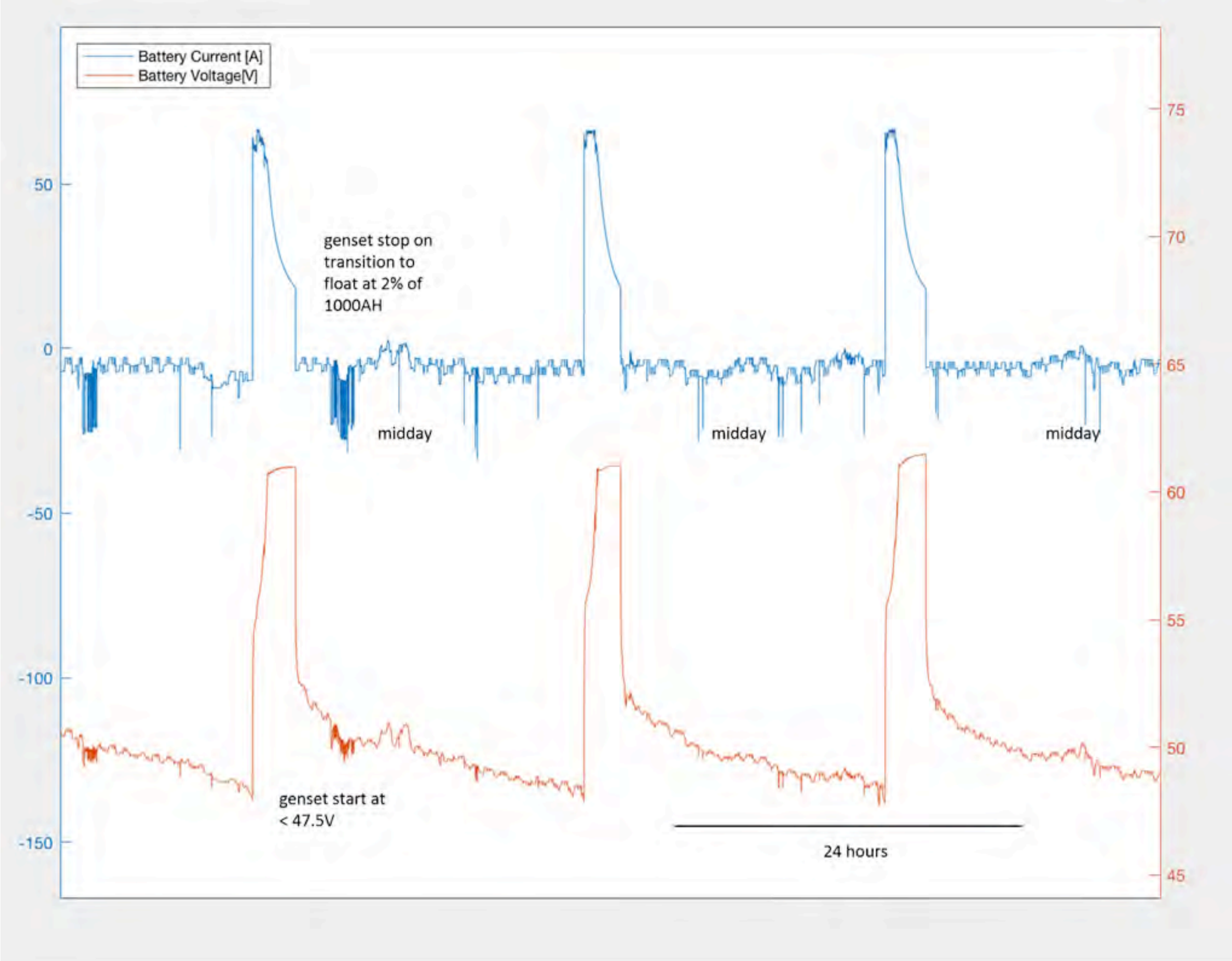

Figure 7. Incomplete genset based cycle charging ultimately resulting in loss of battery capacity. From location 3 of Fig. 4.

Following the PSoC automatic genset cycling at location '3' of Fig. 4, new amounts of overcharge are seen in the *Amp-Hours* trace which indicates the batteries were being consistently reconciled with an increased amount of overcharge. At location '4' of Fig. 4 a number of low sun days trigger the automatic genset to start. One of the genset start events is shown in Fig. 8 where the genset starts and shortly after the solar charging take over. The current remains above 10A and illustrates the effect of operating in absorption CV charge mode for an extended time. The extra charging at the absorption constant voltage for a few hours per day appears to have provided the overcharge critical for recovering the battery bank. The same automatic genset trigger points are used in location 4 and location 3. examined in the spring of 2019 and compared to the prior years' performance.

To avoid deep discharging and also premature genset starts, all the systems have been adjusted to initiate genset charging at 46.5V – two volts above the default set point. Manufacture's suggested charging set points remain in use for both solar absorption and float voltages. While this will almost certainly improve the situation for next year by reducing any deep discharge events and mitigating PSoC operation to some extent, it's not obvious that it is a cure. As

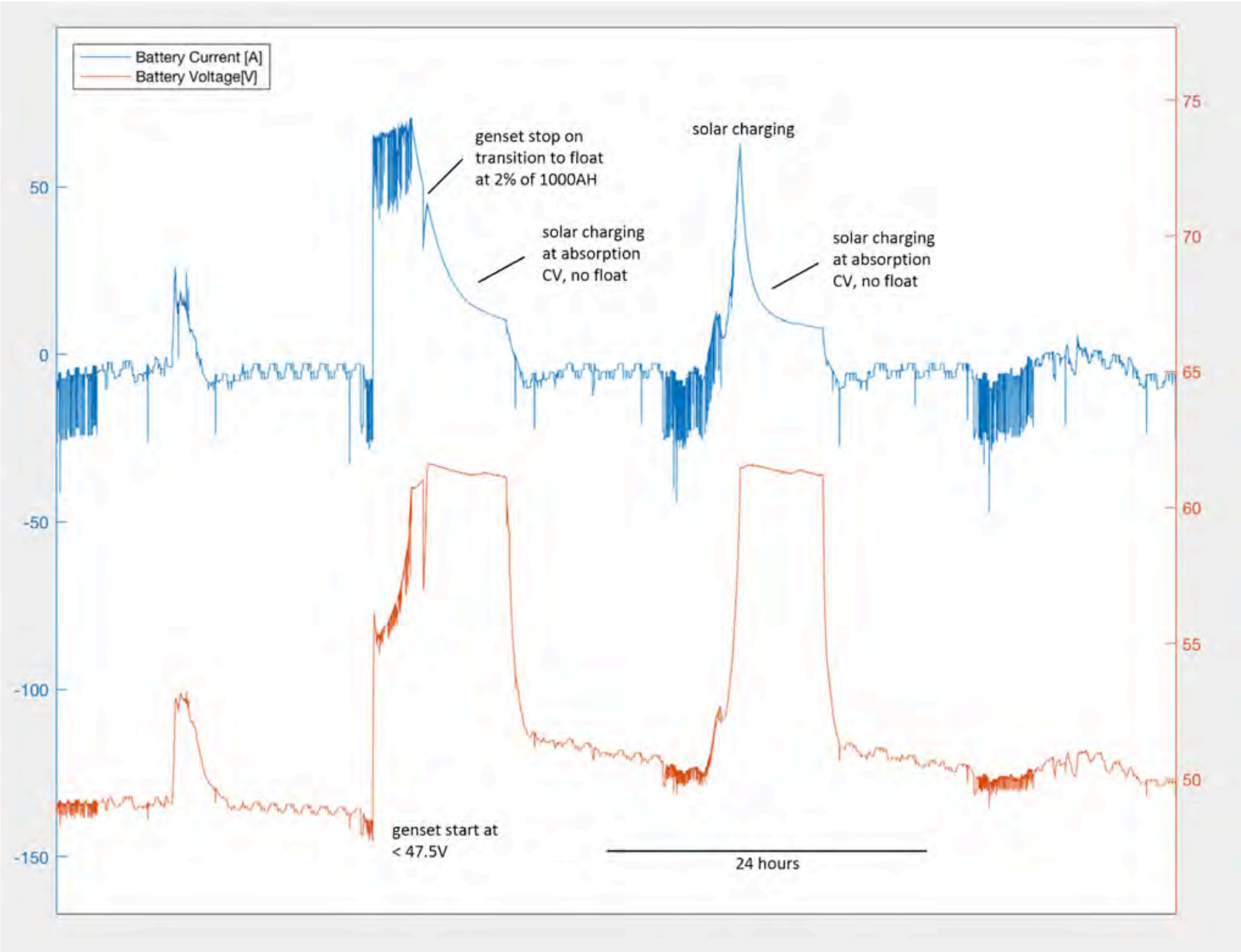

Figure 8. Improved battery capacity and charge acceptance with solar charger not transitioning from absorption to float CV. From location 4 of Fig. 4.

However, location 4 shows significantly improved charge acceptance and indicates an improvement in battery performance and effective storage capacity.

In late February Fig. 4 shows an increase in overcharge reconciliation due to longer sun exposure. In early March local experts revisited the site to take a specific gravity measurement and to reinstate the reduced float voltage thereby reducing the overcharge. The battery bank recovered substantially improving from a specific gravity range (SG) of 0.15, where 22 of the 24 cells were near 1.25 and two at 1.10 in early December 2017, to all of the cells measuring above 1.30 in March 2018. At this point the precision battery data used in this example was also recovered. The SG readings combined with post event data analysis suggest substantial recovery of the battery. However, a capacity measurement was not attempted due to the impracticality of such a test. All, new data will be re- mentioned previously, correcting the undercharge required manual intervention of the system configuration by experts. Ideally the sophisticated charging system of sensors, power electronics and controllers would be self-correcting. Without a self-correcting system or manual intervention we expect to see worsening charge reconciliation and reductions in effective battery capacity in future winter seasons. While the inherent details of insufficient charge reconciliation and battery management will likely go unnoticed by most users – as it may have even in this example if the AC power hadn't started going on and off – anecdotal experience and example data suggest that inherent suboptimal charging and extended periods PSoC may be occurring within hybrid systems operating without charge reconciliation control. PSoC capacity loss is discussed in [5] and specific to off-grid PV in [6] where the authors have proposed a new battery model that incorporates the effects of PSoC in off-grid power system applications.

It is unknown at this point what effects suboptimal charging will have on overall battery life. What is known is that a reduced battery capacity results in less utilization of the solar resource, an increased dependence on the fuel burning genset and a negative overall shift in system economics. Batteries are also expensive and it stands to reason that a battery of a certain capacity should be managed according to recommended charging practices in order to maintain its rated capacity over time - even during the challenging winter months within a residential hybrid system in the Canadian context.

CONCLUSION

Eleven residential off-grid PV hybrid systems have been installed in Nemiah valley between 2006 and 2018. One pilot system was installed in 2006, three test systems were installed in 2008 and seven engineered containerized systems where installed in 2017. Each hybrid system supplies continuous 240/120V AC power to residential loads ranging from 5 to 15kWh per day. As of 2018 all systems are operational.

Lessons learned from the four early test systems were used to guide the design of the later containerized system. Genset reliability was identified the critical to system *up time* and a significant design improvement was the addition of increased solar PV generation in order to reduce genset run hours.

Poor battery performance and incomplete charging during the low-sun winter season was observed over the last 12 years. Precision battery data collected from one system over the 2017-2018 winter has captured one such example of extended partial state of charge operation. Over four months effective battery capacity was severely depleted and then recovered via manual intervention of system control set points. The power conversion and automatic charge control systems were ineffective at maintaining battery performance and health under the observed conditions. Anecdotal experience and experiments combined with recent measured example data suggest that system performance and likely battery life could be improved by implementing closed loop controls based on *amp-hour* charge reconciliation rather than instantaneous voltage and current set points. Closed-loop charge management of lead-acid batteries is not commonly implemented in the off-grid residential hybrid equipment industry today.

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