PNNL-33634

# Native Renewables, Inc. Analysis of Small-Scale Storage Options

## Technical Memorandum

October 2022

Vilayanur Viswanathan
Kendall Mongird
Jessica Kerby

U.S. DEPARTMENT OF ENERGY
Pacific Northwest NATIONAL LABORATORY
Sandia National Laboratories

PACIFIC NORTHWEST NATIONAL LABORATORY
*operated by*
BATTELLE
*for the*
UNITED STATES DEPARTMENT OF ENERGY
*under Contract DE-AC05-76RL01830*

**Printed in the United States of America**

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# Foreword

The U.S. Department of Energy's Energy Storage for Social Equity (ES4SE) Initiative is designed to advance the prosperity, well-being, and resilience of urban, rural, indigenous, and tribal disadvantaged communities. It helps these communities address their energy system challenges by considering energy storage technologies and applications as a viable path forward.

The two-pronged effort features a Technical Assistance (TA) Program and Project Development and Deployment Assistance (PDDA) Program. Under the ES4SE Initiative, Pacific Northwest National Laboratory provides direct TA that gives communities the information, tools, and resources needed to understand their community goals and how energy storage and renewable generation technologies can support their needs and long-term resilience, reliability, and independence goals Sandia National Laboratories then leads the PDDA phase by providing engineering and financial support to deploy energy storage systems in the communities helping convert the TA efforts into tangible results.

The comprehensive and personalized assessments of energy storage feasibility, design, and application provided by the TA Program are intended to not only help communities meet their goals and enable positive outcomes, but also (1) give them a deeper understanding of their energy system challenges and possible solutions, (2) develop a network of people to serve as a valuable resource long after the TA Program is over, and (3) implement solutions to their community-defined challenges.

The results derived from each TA Assessment are reported in technical memoranda such as this one.

More information about the program is available at the following links.
https://www.pnnl.gov/projects/energy-storage-social-equity-initiative
https://www.pnnl.gov/projects/energy-storage-social-equity-initiative/technical-assistance-program

**Cautionary Note:** Lithium-ion batteries are generally safe but can fail due to internal faults or if they are used incorrectly. This can lead to the release of toxic and flammable gases resulting in fire and/or explosion with a risk of death and catastrophic damage to nearby facilities. PNNL follows the best practices for energy storage systems (ESSs) and therefore only recommends ESSs that comply with site-specific code requirements and industry safety standards. The Standard for the Installation of Stationary ESSs (NFPA 855) requires Underwriters' Laboratories (UL) 9540 certification—a global safety certification indicates market products have undergone testing and evaluation confirm they are reliable and meet industry safety standards. UL 9540 is a safety standard for ESSs that operate interconnected to the grid or in stand-alone applications and designates aspects of fire detection and suppression, containment, and environmental performance. Therefore, given performance and especially safety considerations, PNNL only recommends using a certified UL 9540 ESS.

However, PNNL also recognizes the need for assistance for underserved communities that might not be able to pay for or are required to use certified UL 9540 ESS. PNNL reiterates its position to follow safety and applicable codes or best practices and to inform the community about the threats that a noncertified system might pose, but leaves this decision to be made by the community.

# Acronyms and Abbreviations

| | |
|---|---|
| AC | alternating current |
| AGM | Absorbed Glass Mat |
| BMS | battery management system |
| CV | circuit voltage |
| DC | direct current |
| DOD | Depth of Discharge |
| g | gram(s) |
| hr | hour(s) |
| IoT | Internet of Things |
| kW | kilowatt(s) |
| kWh | kilowatt-hour(s) |
| L | liter(s) |
| LCOS | Levelized Cost of Storage |
| LFP | lithium ferro-phosphate |
| $LiFePO_4$ | lithium iron phosphate |
| OCV | open circuit voltage |
| PC | personal computer |
| PNNL | Pacific Northwest National Laboratory |
| PV | photovoltaic(s) |
| SoC | state-of-charge |
| SOH | state-of-health |
| yr | year(s) |

# Contents

# Tables

# 1.0 Introduction

This document presents the results of an analysis of small-scale storage options conducted for Native Renewables Inc. by Pacific Northwest National Laboratory as part of its technical assistance provided under the U.S. Department of Energy's Energy Storage for Social Equity (ES4SE) Initiative.

# 2.0 Analysis of the Levelized Cost of Storage

Details of the Levelized Cost of Storage (LCOS) methodology can be found in the LCOS Section 6 of the *2022 Energy Storage Grand Challenge Cost and Performance Report*.[1] Note that the economic life or the loan term is 10 years in the analysis, in line with the loan duration for small projects, instead of the 20 years for grid-scale storage projects. The following are input values used for the LCOS calculation. Three types of lead-acid batteries and a lithium iron phosphate ($LiFePO_4$)-based lithium-ion (Li-ion) battery were chosen for this analysis.

Table 1. Inputs for LCOS calculation.

| Technology | $/kWh | $/kWh (Battery + Inv. + CC) | Cycles at 80% DOD (350 cycles/yr) | Calendar Life (yr) | DC-DC RTE | AC-AC RTE | Person hours per year | $/yr | O&M $/kW-yr | Years before battery replaced(a) |
|---|---|---|---|---|---|---|---|---|---|---|
| LFP | 534 | 680 | 6,050 | 15 | 0.93 | 0.89 | 3 | 180 | 72 | 17.3 |
| Lead-acid AGM | 238 | 384 | 424 | 10 | 0.85 | 0.82 | 3 | 180 | 72 | 1.2 |
| Lead-acid gel | 315 | 461 | 989 | 10 | 0.85 | 0.82 | 3 | 180 | 72 | 2.8 |
| Lead-acid flooded | 192 | 338 | 1,133 | 10 | 0.85 | 0.82 | 20 | 1,200 | 420 | 3.2 |

AGM = absorbed glass mat; DOD = depth of discharge; LFP = lithium ferro-phosphate; O&M = operations and maintenance; RTE = roundtrip efficiency.

(a) Cycle life at 80 percent DOD for AGM is 424 cycles. At 365 cycles per year, it needs to be replaced every 424/365 years or 1.2 years.

Raw data for cycle life for individual technologies is provided in Table 2.

Table 2. Raw data for battery technologies (AGM, gel, flooded, and LFP).

| Vendor | Model | Type | Cycle Life at 80% DOD |
|---|---|---|---|
| East Penn Deka | 8G8D | Gel | 620 |
| East Penn Deka | 8GGC2 | Gel | 1,213 |
| Deka East Penn | 8G30H-DEKA | Gel | 600 |
| Victron Energy | BAT702601260 | Gel long life | 1,500 |
| Victron Energy | BAT702202260 | Gel long life | 1,500 |
| Victron Energy | BAT412201104 | Gel deep cycle | 500 |
| UPG | K31 Kinetic Series | Gel | 300% over AGM |
| **Average Cycle Life at 80% DOD (Gel)** | | | **989** |

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[1] https://www.pnnl.gov/sites/default/files/media/file/ESGC%20Cost%20Performance%20Report%202022%20PNNL-33283.pdf

| Vendor | Model | Type | Cycle Life at 80% DOD |
|---|---|---|---|
| Victron Energy | BAT412201104 | AGM Deep Cycle | 400 |
| East Penn Deka | 8A8DLTP-DEKA | AGM | 250 |
| OutBack Power | BATTERY-2XS12-190Ah | AGM | 600 |
| Rolls Surrette | S6-460AGM | AGM | 600 |
| Fullriver | FFD200-12 | AGM | |
| Crown Battery | SLIGC2AGM | AGM | |
| Crown Battery | 12CRV8D | AGM | |
| OutBack Power | NSB210FT BLUE | AGM | |
| Interstate Batteries | Deep Cycle 110Ah AGM Battery | AGM | |
| Universal Battery | UB-4D 200 | AGM | 270 |
| Centennial | CB6-400 (6V400Ah) | AGM | 620 |
| **Average Cycle Life at 80% DOD (AGM)** | | | **457** |
| Rolls Surrette | 12-CS-11PS | Flooded deep cycle | 2,800 |
| Rolls Surrette | S6 L16-HC | Flooded deep cycle | 1,000 |
| Trojan | Smart Carbon SPRE 02 1255 | Flooded | 600 |
| **Average Cycle Life at 80% DOD (Flooded)** | | | **1,133** |
| East Penn Deka | DD5300 | LFP | 7,875 |
| Phocos | Phocos Any-Cell LFP 48Volt 5.12 kWh | LFP | 6,750 |
| BigBattery | 48V CNDR Elite - $LiFePO_4$ - 231Ah - 11.8 kWh | LFP | 4,000 |
| BigBattery | 48V HSKY - $LiFePO_4$ - 103Ah - 5.3 kWh | LFP | 4,000 |
| BigBattery | 48V LYNX - $LiFePO_4$ - 103Ah - 5.3 kWh | LFP | 4,000 |
| BYD | 48V 233Ah 11 kWh LFP 150A BMS BYD | LFP | |
| ExpertPower | 48V 100Ah 5 kWh | LFP | 4,000 |
| Fortress Power | eFlex 5.4 and FlexRack 21.6 kWh Bundle | LFP | 8,000 |
| Humless | 5 kWh Battery ($LiFePO_4$) | LFP | 4,000 |
| KiloVault | HAB V4 7.5 kWh | LFP | 6,000 |
| PowerPlus | LiFe Premium P Series | LFP | |
| Atlass ESS | 24V 200Ah 5.1 kWh | LFP | 10,000 |
| LiWerks | U1-24RT | LFP | 4,000 |
| Simpliphi | PHI 1.4 TM Battery | LFP | 10,000 |
| Sonnen | Sonnen eco 10 Gen 3.1 | LFP | |
| **Average Cycle Life at 80% DOD (LFP)** | | | **6052** |

The LCOS results are provided in Table 3. $LiFePO_4$ is the most cost effective, at $0.46/kWh, where the kWh refers to cumulative energy throughput, while lead-acid batteries have an LCOS range of $1.18–$1.24/kWh.

Table 3. LCOS analysis for lithium-ion (LFP) and lead-acid batteries (AGM, Gel, flooded).

| **Technology Parameters** | | | | |
|---|---|---|---|---|
| **Technology** | **LFP** | **Lead-Acid AGM** | **Lead-Acid Gel** | **Lead-Acid Flooded** |
| Power (kW) | 0.0025 | 0.0025 | 0.0025 | 0.0025 |
| Duration (hr) | 4.8 | 4.8 | 4.8 | 4.8 |
| Energy (MWh) | 0.012 | 0.012 | 0.012 | 0.012 |
| | | | | |
| DC-DC RTE (%) | 93% | 85% | 85% | 85% |
| Cycle Life (#) | 6,050 | 457 | 989 | 1,133 |

| Technology Parameters | | | | |
|---|---|---|---|---|
| **Technology** | **LFP** | **Lead-Acid AGM** | **Lead-Acid Gel** | **Lead-Acid Flooded** |
| Calendar Life (years) | 15 | 10 | 10 | 10 |
| | | | | |
| DOD[2] | 80% | 80% | 80% | 80% |
| Rest (hr) | 1.39 | 1.04 | 1.04 | 1.04 |
| One-way inverter efficiency | 98% | 98% | 98% | 98% |
| AC-AC RTE[3] | 89% | 82% | 82% | 82% |
| Max Cycles/year @ 100% DOD | 365 | 365 | 365 | 365 |
| Max Cycles/day @ DOD | 1.25 | 1.25 | 1.25 | 1.25 |
| Cycles per day @80% DOD | 1 | 1 | 1 | 1 |
| | | | | |
| Discharge Time (hr) | 3.20 | 3.20 | 3.20 | 3.20 |
| Charge Time (hr) | 3.60 | 3.92 | 3.92 | 3.92 |
| Hours per Cycle | 9.58 | 9.20 | 9.20 | 9.20 |
| Cycles per day - unlimited | 2.50 | 2.61 | 2.61 | 2.61 |
| Cycles per day - limited | 1 | 1 | 1 | 1 |
| | | | | |
| Cycles per year @ DOD | 365 | 365 | 365 | 365 |
| kWh output per year | 2,920 | 2,920 | 2,920 | 2,920 |
| Output (kWh/kW) - hours | 1,168 | 1,168 | 1,168 | 1,168 |
| Cycle Life (years) | 16.6 | 1.2 | 2.7 | 3.1 |

| Storage Block Replacement | | | | |
|---|---|---|---|---|
| **Technology** | **LFP** | **Lead-Acid AGM** | **Lead-Acid Gel** | **Lead-Acid Flooded** |
| Years of Occurrence to get to 15 years | - | 1.25 | 2.71 | 3.10 |
| | - | 2.50 | 5.42 | 6.21 |
| | - | 3.76 | 8.13 | 9.31 |
| | - | 5.01 | 10.84 | 2.42 |
| | - | 6.26 | 3.55 | |
| | - | 7.51 | | |
| | - | 8.76 | | |
| | - | 10.02 | | |
| | - | 11.27 | | |
| | - | 12.52 | | |
| | - | 13.77 | | |
| | | | | |
| | | | | |
| Present Value ($/kWh) | - | 206.44 | 249.20 | 148.16 |
| | - | 190.75 | 210.00 | 121.78 |
| | - | 176.24 | 176.97 | 100.10 |
| | - | 162.84 | 149.13 | 82.28 |
| | - | 150.46 | 125.67 | |
| | - | 139.02 | | |
| | - | 128.45 | | |

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[2] We recommend Native Renewables, Inc. also run their analysis at 80 percent DOD to align with these numbers. Per our estimation, the cumulative discharge energy at 50 percent DOD does not exceed the energy at 80 percent DOD for lead-acid batteries based on input received from Matt Raiford of the Lead-Acid Battery Council in the year 2020.

[3] AC-AC RTE = DC-DC RTE*(one-way inverter efficiency)$^2$

| Storage Block Replacement | | | | |
|---|---|---|---|---|
| Technology | LFP | Lead-Acid AGM | Lead-Acid Gel | Lead-Acid Flooded |
| | - | 118.68 | | |
| | - | 109.66 | | |
| | - | 101.32 | | |
| | - | 93.62 | | |
| | | | | |
| | | | | |
| Total ($/kWh) | - | 1,577.47 | 910.98 | 452.31 |
| Total ($/kW) | - | 7,571.87 | 4,372.70 | 2,171.08 |

| Capital and O&M Costs | | | | |
|---|---|---|---|---|
| Technology | LFP | Lead-Acid AGM | Lead-Acid Gel | Lead-acid Flooded |
| Storage Block & BOS ($/kWh) | $534.00 | $238.00 | $315.00 | $192.00 |
| Power Equipment ($/kW) | $584.00 | $584.00 | $584.00 | $584.00 |
| | | | | |
| Total Cost ($) | $7,868 | $4,316 | $5,240 | $3,764 |
| Total Overnight CAPEX ($/kW) | $3,147 | $1,726 | $2,096 | $1,506 |
| Total Replacement CAPEX ($/kW) | $ - | $7,572 | $4,373 | $2,171 |
| Fixed O&M ($/kW-year) | $72.00 | $72.00 | $72.00 | $480.00 |
| Electricity Cost (w/ losses) ($/kWh) | $0.034 | $0.037 | $0.037 | $0.037 |

| 10-Year Loan Term | | | | |
|---|---|---|---|---|
| Technology | LFP | Lead-Acid AGM | Lead-Acid Gel | Lead-Acid Flooded |
| CRF | 0.1392 | 0.1392 | 0.1392 | 0.1392 |
| Project Finance Factor | 1.0888 | 1.0888 | 1.0888 | 1.0888 |
| Construction Finance Factor | 1.0440 | 1.0440 | 1.0440 | 1.0440 |
| LCOS ($/kWh) | **$0.44** | **$1.14** | **$0.82** | **$0.79** |

Note that in the above analysis, a 12 kWh battery was procured, with the battery discharged at 80% DOD (or 9.6 kWh per cycle). Repeating the analysis using 80% DOD for LiFePO$_4$ and 50% DOD[4] for the lead-acid battery, with 9.6 kWh discharged per cycle provides the results shown in Table 4.

Table 4. LCOS for 80 DOD for LiFePO$_4$ and 50 percent for lead acid.

| Technology | LFP | Lead-Acid AGM | Lead-Acid Gel | Lead-Acid Flooded |
|---|---|---|---|---|
| LCOS ($/kWh) | **$0.44** | **$1.23** | **$0.88** | **$0.87** |

In both analyses LiFePO$_4$ is the most cost effective, at $0.44/kWh, where the kWh refers to cumulative energy throughput, while lead-acid batteries have a LCOS range of $0.79–$1.23/kWh.

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[4] The cumulative throughput for lead-acid battery at 50% DOD was assumed to be the same as that at 80% DOD.

While the LCOS analysis shows flooded to be the most cost effective among lead-acid batteries (marginally more cost effective than gelled lead-acid batteries), it is recommended to go with the AGM or gel option due to fewer maintenance needs. In general, compared to AGM, gel lead-acid batteries are better suited for deep discharge and so would be the most attractive option among lead-acid batteries. Specifically, the East Penn Deka 8GGC2 6V 180 Ah battery is expected to provide 1,210 cycles at 80% DOD (MK Battery 2018); the Victron Energy BAT412201104 battery offers 1500 cycles (Victron Energy 2018) and is also a promising option. The AGMs offer low cycle life at high DOD and are not an appropriate choice since they need to be replaced once in a little over a year. Among flooded batteries, the Rolls Surrette 12-CS-11P 12V 357 Ah battery offers 2,800 cycles at 80% DOD (Rolls 2019) and hence is an attractive option despite the maintenance requirements related to water topping. Note that while each of these options has < 10kWh of energy, connecting the required number of modules will enable 12 or 19.2kWh of storage, which is a typical size for small residential applications.

There are several general UL standards applicable to batteries. Most of the Li-ion battery modules have various levels of UL listing, ranging from cell-level UL 1873, and UL 1642, to module-level UL 9540. The specific standards for lead-acid batteries are UL 2595, and UL 2436. Standards for charging lead-acid batteries include UL 1236.

# 3.0 Temperature Effect on Operations

## 3.1 Relationship between the State-of-Charge and Temperature for AGM Batteries

The open circuit voltage (OCV) of lead-acid batteries depends on the state-of-charge (SoC) and temperature. At a fixed SoC, lead-acid batteries have a positive temperature coefficient of 0.2 mV/°C (Shamim et al. 2022), which corresponds to an endotherm for reversible heat during discharge and exotherm during charge. As temperature increases, for constant current/constant voltage charge, the voltage for the circuit voltage (CV) phase needs to be adjusted upward to account for this positive temperature coefficient of OCV. However, as temperature increases, the battery resistance decreases, resulting in greater current at fixed SoC and voltage. For AGM, this results in more oxygen generation at the positive during the CV phase and a higher recombination rate of this generated oxygen at the negative. Since the oxygen recombination rate is exothermic, this results in a further increase in temperature. If left unchecked, this may result in a thermal runaway. Hence most AGM battery chargers adjust the voltage in the CV phase downward as battery temperature increases.

## 3.2 Effect of Various Parameters on the State-of-Health for AGM Batteries

The SoC provides information on whether the battery is discharged, partially or fully charged. The SoC does not provide any information on the battery's state-of-health (SoH). If a battery has an initial capacity of 100Ah, when fully charged, it can deliver 100Ah during discharge. However, batteries tend to degrade with their use and over time. If the battery capacity has degraded from 100Ah to 90Ah, we say the degraded battery's SoH is now 90 percent. Now, the fully charged battery (100 percent SoC), can deliver only 90Ah during its discharge (90 percent SoH). The more relevant metric for batteries, in general, is the effect of temperature on the SoH. The higher the temperature, the greater the degradation, as battery degradation rate constant k follows the Arrhenius Equation (1) below (Clark 2002),

$$k = Ae^{-Ea/RT} \tag{1}$$

Where *A* is the frequency factor, also called the pre-exponential factor (assumed to be constant, even though it varies slightly with temperature), *Ea* is the activation energy for the reaction in Joules per mol, *R* is the universal gas constant equal to 8.31 Joules/(°K.mol), and T is the temperature in degrees Kelvin. Higher the activation energy, the lower the rate constant at a fixed temperature. For fixed activation energy, the greater the temperature, the greater the rate constant.

Hence high temperature increases the rate of reaction for the desired charge/discharge process and for degradation processes as well.

For lead-acid batteries, including AGM, prolonged storage at low SoC increases irreversible sulfation on the electrodes. The sulfates have high electronic resistance and may isolate portions of the electrodes by cutting off access to electrons. Hence it is important to apply a full charge periodically to mitigate this issue. For this application, since the battery is being cycled daily, this is not expected to be a significant issue.

Cycling at a high depth of discharge results in lower cumulative energy throughput for lead-acid batteries. Hence it is preferred to oversize the battery while keeping the DOD to < 80 percent. For this analysis, an 80 percent DOD is assumed.

## 3.3 Relationship between the SoC and Temperature for Lithium-Ion Batteries

The OCV of Lithium-ion batteries with $LiFePO_4$ cathode has a flat voltage profile as a function of the SoC in the ~ 20-80 percent SoC range. The temperature coefficient of OCV is moderately negative at < 15 percent SoC and moderately positive at >15 percent SoC ranging from -0.5 mV/°C to +0.2 mV/°C (Viswanathan et al. 2020, Wang et al. 2021). As stated in the lead-acid battery section, lowering of cell internal resistance at high-temperature results in higher current flow at a constant voltage. Hence the CV set point is lowered with increasing temperature.

## 3.4 Effect of Various Parameters on the SOH for Li-Ion $LiFePO_4$ Batteries

Similar to lead-acid, lithium-ion batteries also follow the Arrhenius Equation (1) and have a higher degradation at higher temperatures. For $LiFePO_4$ batteries, storage at a high SoC is not expected to be as detrimental to the SoH as it is for nickel-cobalt-aluminum oxide and nickel-manganese-cobalt oxide cathodes. For the latter, the voltage is higher at full charge, resulting in the parasitic reaction between the electrodes and electrolyte. However, lithium ferro-phosphate (LFP) batteries should not be stored for a prolonged period at close to 0 percent SoC to prevent the dissolution of the copper current collector at the negative electrode.

While cycling at high DOD reduces cumulative energy throughput, the relation is not as steep as for nickel-cobalt-aluminum oxide or nickel-manganese-cobalt oxide cathodes. For this analysis, an 80 percent DOD is assumed.

## 3.5 Thermal Management Solutions

Lead-acid batteries have a high thermal mass, related to their lower specific energy. Their operating range is wide at approximately -20 to 50°C (Battery University 2022), hence no thermal management is needed. However, having heating, ventilation, and air-conditioning that maintains the temperature inside the container in the 15 to 35°C range is expected to improve performance and life, with a recommended tighter range of 20-30°C.

Li-ion batteries with layered cathodes (Yang 2021) have higher specific energy compared to $LiFePO_4$-based cathodes and are typically used in hybrid, plug-in, and all-electric vehicles. The onset of thermal runaway[5] is lower for layered cathodes, and the energy released is also higher for these exotherms. Hence $LiFePO_4$-based cathodes have a lower safety risk. The charging temperature range for $LiFePO_4$-based Li-ion batteries is 0-45°C, while it can be discharged from -20 to 60°C (Battery University 2022). Hence in a hot climate, having HVAC that maintains the temperature inside the container in the 15 to 35°C range is expected to improve performance and life.

# 4.0 Maintenance Procedures

**AGM Maintenance**

AGM batteries do not need topping off of the electrolyte and are maintenance-free. These batteries typically do not have a battery management system that tracks the performance degradation of modules and assesses the SoH of the modules. Accordingly, an inspection is warranted. An inspection of the battery once in 6 months should include:

1. Visual inspection of connections to make sure connectors are free of corrosion
    a. Remove electrolyte spills or buildups or corrosion with a damp sponge using a solution of baking soda (100 g/L) in water, followed by wiping with a damp sponge wetted with water.
2. Visual inspection of module swelling. This is not expected to be an issue if the valves are functioning correctly.
3. Visual inspection of valves to make sure they are seated properly
4. Check and tighten battery connections using a torque wrench. It is recommended that terminals are disconnected, cleaned, and re-torqued as part of regular maintenance.
    a. Under-torquing may lead to loosening of connections during operation followed by a test, with associated heating and cooling. Loose connections may cause arching and/or spark. Over-torquing may damage the terminal by bending or cracking it. Loose or overly tight connections increase connection resistance, with associated poor performance and heating of the connection.
5. Check all cables for signs of chafing, and replace them as necessary
6. Check inverter's cooling vents and clean as needed
7. Check/tighten the inverter's internal AC block connections using appropriate torque.

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[5] Thermal runaway can happen when the battery heat generation rate exceeds the rate at which it can be dissipated. This can lead to extremely high temperatures with the potential for explosion. Hence thermal management is important not just to increase battery life but also to confirm safety.

8. Replacement of battery modules as they approach the end of life
    a. In the absence of the battery management system (BMS) maintaining a record of battery performance degradation, tracking of battery performance is possible if performance data is transmitted to Native Renewables. In the absence of that, once in six months, a technician can look at real-time operation data to estimate the battery's SoH. For example, if the battery is designed to provide 8 hours of operation at a certain average power, and provides less than 60 percent of that, it is time to replace the battery.

**LFP Battery Maintenance**

Li-ion $LiFePO_4$-based batteries have minimal maintenance depending on the BMS capabilities. Some BMS balance the cells within a module, thus requiring minimal maintenance. An inspection of the battery once in six months should include:

1. Visual inspection of connections to make sure connectors are free of corrosion
    a. remove electrolyte spills or buildups or corrosion using baking soda
2. Check and tighten battery connections
3. Check all cables for signs of chafing, and replace them as necessary
4. Check inverter's cooling vents and clean as needed
5. Check/tighten the inverter's internal AC block connections using appropriate torque.
6. Visual inspection of module swelling. Individual cells may swell due to the continuous formation of the solid electrolyte interface, accompanied by the evolution of various gases. Excessive solid electrolyte interface formation is also reflected in the loss of energy capacity of the battery.
7. Analyzing the BMS output to assess the battery SoH. Some BMS may report SoH directly, making this task easier. Assessment of energy available at fixed average power and comparison with initial performance enables estimation of battery SoH for the technician.

A very nice description of BMS for $LIFePO_4$ batteries is available in a study published by Darwin Sauer (2021).

# 5.0 User-friendly and Remote Battery Monitoring

## 5.1 Commercially Available SoC Monitoring Systems

BMSs (Battery Management Systems) are usually proprietary and come as a package from the battery manufacturer to allow both monitoring, controls, and optimization of the system. Battery monitoring without any control functionality, on the other hand, can be achieved with third-party assets, usually tied to the inverters. Some smart-meter makers integrate these monitoring systems into their software packages for mini-grids, for example, SparkMeter. For small-scale, off-grid applications, many monitoring packages are low-cost and app-based to allow monitoring via the user's smartphone or USB-connected PC.

Below is an abbreviated list of commercially available monitoring systems, with a brief description and links to the manufacturer's web page. These are some examples, while many other options are available in the market. Pacific Northwest National Laboratory (PNNL) does not endorse any manufacturer.

### Victron Energy

Supplies both simple SoC monitors and full BMSs, with Bluetooth and Wi-Fi remote monitoring, and USB connection to PCs for in-person monitoring.

**Battery Monitors**[6] – The BMV series of battery monitors are connected via a current shunt to the monitor that displays the following parameters:

- Voltage (up to two batteries)
- Current
- Amphere-hours (Ah) consumed
- SoC
- Time-to-go
- Power consumption (W)
- Battery temperature
- Midpoint Voltage – to alert the user of malfunctioning cells/batteries

The BMV series is Bluetooth enabled to work with the *VictronConnect* smartphone app available for Android and Apple phones as well as Mac and Windows PCs with USB connection.

**Battery Management System**[7] – The next step up in features from Victron Energy is the BMS series, which are designed to work with Victron Energy Lithium batteries and provide over and under voltage protection as well as temperature regulation. These BMS are compatible with up to five parallel strings of batteries with a system voltage of 12, 24, or 48 V depending on the model.

**Panels and System Monitoring**[8] – Last, Victron Energy also supplies an integrated management and monitoring system for both the photovoltaic (PV) panels and the batteries of a system. The Gerbo GX optionally comes with a touchscreen display for on-site monitoring in addition to the default Wi-Fi and LAN monitoring. The system allows for control and optimization of the system as well as monitors the following parameters:

- Battery SoC
- Power consumption (W)
- Power harvest from PV, generator, and mains
- Temperature.

### OutBack Power

OutBack Power FLEXnet DC[9] and MATE[10] – The OutBack Power FLEXnet DC system monitor, when used in conjunction with the OutBack Mate system controller designed to work with OutBack inverters/chargers, monitors and provides on-screen display of the following parameters:

- SoC
- Status: charging/discharging

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[6] https://www.victronenergy.com/upload/documents/Datasheet-BMV-700-series-EN.pdf

[7] https://www.victronenergy.com/upload/documents/Datasheet-BMS-overview-EN.pdf

[8] https://www.victronenergy.com/upload/documents/Datasheet-Cerbo-GX-GX-Touch-EN.pdf

[9] https://www.outbackpower.com/downloads/documents/system_management/flexnet_dc/specsheet_english.pdf

[10] https://www.outbackpower.com/downloads/documents/system_management/mate/mate_specsheet.pdf

- Power production/consumption (current, cumulative, and historical up to 128 days)
- Voltage
- Daily lowest SoC
- Current (total and average)
- Total battery amps
- Averaged battery amps
- Averaged battery volts
- DC amp-hours IN per shunt
- DC amp-hours OUT per shunt
- DC kWh IN per shunt
- DC kWh OUT per shunt
- Last cycle amp-hours
- Last cycle watt-hours
- Last cycle amp-hour
- Charge factor
- Last cycle watt-hour
- Charge efficiency
- Total number of days full
- Cumulative battery amp
- Hours removed.

A DB9 jack is available to connect the MATE to a PC to run the WinVerter management software. The system is also compatible with the OPTICS (OutBack Power Technologies Intuitive Communication System) app for smartphones and PCs.

### Schneider Electric

Schneider Electric[11] – Conext Battery Monitor is compatible with 24 and 48V battery banks and provides data on runtime hours, SoC, voltage, and current as well as midpoint voltage collection to signal battery performance issues. The onboard display can be used as a standalone monitor or connected to the Conext Gateway and Insight monitoring and controls software.

### SimpliPhi

SimpliPHI Power[12] – EnergyTrak Energy Management Software Platform with multi-layered monitoring and control. A scalable system allows batteries and inverters to be incrementally added to increase output or resilience. IP 65 rated indoor/outdoor, AC/DC coupled, On/Off-grid. Integration of system components for streamlined programming and performance, including an integrated BMS. Control/monitor ESS system through a mobile app for remote operation and monitoring. 10-year warranty. SimpliPHI uses LFP or $LiFePO_4$ batteries. SimpliPHI hosts free training webinars to familiarize customers with their systems and maintains an archive of past training sessions on its web page.

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[11] https://download.schneider-electric.com/files?p_enDocType=Technical+leaflet&p_File_Name=DS20200117-Conext-Battery-Monitor.pdf&p_Doc_Ref=DS20200117-Conext-Battery-Moni&_ga=2.3338096.1743696632.1660679389-913502743.1657230904&_gac=1.138152324.1660679389.EAIaIQobChMIqb-W4pDM-QIV_iGtBh0cfAiyEAAYAyAAEgKcsfD_BwE

[12] https://simpliphipower.com/

## 5.2 Trade-off Analysis on Remote vs. In-Person Data-Collection

While wired monitoring systems using RS232/RS485 cables were originally used for solar plus storage systems, the advent of wireless monitoring systems has highlighted various drawbacks of wired systems, such as increased installation costs as well as the cables' exposure to the elements Ansari et al. 2021). Wireless monitoring systems are capable of providing real-time data over secured networks less vulnerable to physical security concerns and require very little maintenance (Ansari et al. 2021). Modern BMSs and battery monitoring devices now include onboard memory to store data when connections are severed (Samanta and Williamson 2021). There are currently five different wireless communications protocols upon which a wireless monitoring system can operate: Bluetooth, Zigbee, Wi-Fi, Internet of Things (IoT), and Cloud-based, their attributes are summarized below (Samanta and Williamson 2021):

Bluetooth

- Low data transfer rate
- Low range
- Prone to communication failure
- Low power consumption
- Low cost

Zigbee (IEEE 802.15.4)

- Low cost
- Low power
- Limited additional real-world testing

Wi-Fi

- Not capable of large volumes of data
- Scalable

IoT

- Scalable
- Reliable
- Low-cost
- Low interference
- Immature cybersecurity measures

Cloud-Based

- Continuous and accurate monitoring
- IoT-based

# 6.0 Battery Recycling

Lead-acid battery recycling is well established, with about 99% of the lead being recycled. The infrastructure is in place. About 10 percent of the lead-acid battery capital cost can be recovered via recycling.

There are a few recyclers that employ proprietary processes such as mechanical separation, hydrolysis or pyrolysis to recover materials from disassembled Li-ion modules. Because $LiFePO_4$ based batteries have only lithium as a recoverable metal of value, it costs about 50–70 cents per pound to recycle $LiFePO_4$-based batteries (2021 Energy Storage Cost and Performance Report, PNNL, yet to be released) (Ansari et al. 2021). The recycling infrastructure is a work in progress for Li-ion batteries, including $LiFePO_4$-based batteries. Native Renewables, Inc. should work with the manufacturer to explore recycling options at the end of the project life.

# 7.0 Container Options

This section summarizes vendors that offer containers for off-grid storage, most of whom also offer the entire solution inclusive of solar panels, batteries, charge controllers, and inverters. There are many manufacturers available that provide this kind of solution; below are a few examples.

- **BOXPOWER** – Currently working on a similar project with Native Renewables Inc. to electrify 24 homes in the Navajo Nation, Kayenta Chapter.[13] Website: www.boxpower.io
- **Amicus Cooperative** – consists of a group of solar providers throughout the U.S. Website for providers in Arizona: https://www.amicussolar.com/our-member-owners/Arizona/
- **Phocos** – provides an integrated solution for off-grid PV solar + storage, including the Any-Grid Hybrid inverter charger, which consists of a built-in charger for the battery, along with an inverter. Charging of the battery occurs by power flow directly between solar panels and battery via the built-in charger which has a bi-directional dc buck/boost converter. Battery discharge flows through this bi-directional converter, and through the inverter to power the AC loads. Website for provider:

  https://www.ecodirect.com/Phocos-Any-Grid-5kW-48V-Hybrid-Off-Grid-Inverter-p/phocos-psw-h-5kw-120-48v.htm
- **Commodore Independent Energy Systems** – provides integrated solutions. Some details are provided below. Website: https://www.commodoreaustralia.com.au/
- **SunWize** –

  Enclosures:
  SunWize Power and Battery manufactures a wide range of proprietary enclosures, with many standard designs as well as custom manufacturing capabilities. Most of their enclosures are NEMA3R rated for outdoor use and feature standard fitment options for control panels to mount the solar charge controllers and breakers, etc. To learn more about their enclosure options, click on this link - enclosure catalog. To shop their pole, skid, and ground-mounted enclosure options, click the link below.

  https://www.sunwize.com/product-category/enclosures/
- Control Panels:
  When purchasing solar charge controllers, another option to consider is a fully pre-wired control panel. Their QC-tested control panels can save time and money, and result in a more reliable system. These control panels have many of the Morningstar controller options

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[13] Received pricing information for MiniBox single unit and 100 units

available and easily mount in almost any of their enclosures (see catalog link below for details).

https://www.sunwize.com/product-category/power-system-parts/controlpanels/

## 8.0 Charge Controller and Inverter

Pure sine wave inverters with total harmonic distortion of less than 5 percent are recommended to prevent heating of equipment, communication interferences, overvoltage and failures. Inverters for homes should be UL 1741 listed, while inverters for UPS need a UL 1778 listing. Other key metrics for an inverter are (Unbound Solar 2023):

- Efficiency
- Self-consumption
- Ability for short-term overload
- Battery charge output current
- Temperature range of operation
- Warranty – 3 to 5 years is typical

Some of the manufacturers of high-quality inverters are as follows:

- SMA
- Schneider Electric
- Morningstar
- Outback Power
- Victron Energy

## 9.0 Case Study for Off-Grid Solutions

An off-grid case study is presented in (Discover 2019)[30]. The system consists of:

- 3x 42-48-6650 Discover Advanced Energy System 48V, 20 kWh Li-ion ($LiFePO_4$) battery.
- Charge controllers
- Battery inverter
- 5.2 kW PV panels
- 8 kW generator.

A 1-year and 2-year check-in showed the customers were happier with this technology in replacing an 18 kWh flooded lead-acid battery option, mainly related to higher efficiency and higher DOD.

Another off-grid case study involved Victron inverters and charge controllers with a 13.3 kWh battery (2x 42-48-6650 Discover Advanced Energy System 48V system), along with a 2.4 kW PV array. Communication between the battery BMS and Victron Energy equipment was done via the Discover LYNK Gateway Communication device (vicron energy n.d). Additional examples of off-grid installations are available in (Discover n.d.).

Certificates of compliance for various Discover battery and Schneider Electric inverter combinations with power ranging from 4–13 kW and energy ranging from 6–20 kWh are also available.

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**Pacific Northwest National Laboratory**

902 Battelle Boulevard
P.O. Box 999
Richland, WA 99354

1-888-375-PNNL (7665)

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