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Operations, maintenance, and cost considerations for PV+Storage in the United States

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Operations, maintenance, and cost considerations for PV+Storage in the United States

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ABSTRACT

Battery storage systems are increasingly being installed at photovoltaic (PV) sites to address supply-demand balancing needs. Although there is some understanding of costs associated with PV operations and maintenance (O&M), costs associated with emerging technologies such as PV plus storage lack details about the specific systems and/or activities that contribute to the cost values. This study aims to address this gap by exploring the specific factors and drivers contributing to utility-scale PV plus storage systems (UPVS) O&M activities costs, including how technology selection, data collection, and related and ongoing challenges. Specifically, we used semi-structured interviews and questionnaires to collect information and insights from utility-scale owners and operators. Data was collected from 14 semi-structured interviews and questionnaires representing 51.1 MW with 64.1 MWh of installed battery storage capacity within the United States (U.S.). Differences in degradation rate, expected life cycle, and capital costs are observed across different storage technologies. Most O&M activities at UPVS related to correcting under-performance. Fires and venting issues are leading safety concerns, and owner operators have installed additional systems to mitigate these issues. There are ongoing O&M challenges due the lack of storage-specific performance metrics as well as poor vendor reliability and parts availability. Insights from this work will improve our understanding of O&M consideration at PV plus storage sites.

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Nomenclature

AC Alternating current

CM Corrective maintenance

CSP Concentrating solar power

DC Direct current

DOE Department of Energy

EPRI Electric Power Research Institute

kW Kilowatt

kWh Kilowatt-hour

kW$_{DC}$ Kilowatts using direct current

MW Megawatt

MW$_{DC}$ Megawatts using direct current

MWh Megawatt-hour

O&M Operations & maintenance

PM Preventative maintenance

PV Photovoltaics

PVROM Photovoltaic Reliability, Operations, and Maintenance

PVRW PV Reliability Workshop

PVSC IEEE PV Specialists Conference

SEIA Solar Energy Industries Association

UPVS Utility-scale PV plus Storage

U.S. United States

1. INTRODUCTION

In response to supply-demand balancing needs, the use of storage systems in combination with photovoltaic (PV) technologies has evolved rapidly over the past decade. Specifically, storage systems enable capture of energy during sunny periods for use at a later time - during nighttime, during a power outage, or a day without much sun. Matching supply and demand patterns using storage systems can increase the current system efficiency and also lead to lower environmental impacts and lower costs for customers [10]. Additionally, PV plus storage can enhance system resiliency by providing an alternate source of power during outages [19] as well as providing important grid support services such as frequency regulation and voltage support.

Energy storage can be cost-effective even without solar, if savings achieved by peak shaving and load shifting (from peak to non-peak hours) are compelling. However, addition of solar is transformative to the economics because without solar every peak shaved by battery discharge has to be offset by a valley filled to charge the battery back up. The need to re-charge the battery thus limits the amount of cost savings achievable. However, solar allows us to charge the battery without incurring offsetting utility energy and demand charges.

Currently, there are approximately ten types of storage technologies operating worldwide - ranging from pumped storage hydropower to compressed air and battery systems [15]. However, there are two types of technologies that are most frequently present in utility-scale solar plus storage systems: thermal and electrochemical systems [22]. Thermal energy storage, which uses media (e.g., water, molten salt) to store energy in the form of heat, is often coupled with concentrating solar power (CSP) due to its low capital costs and high operating efficiencies [12]. Electrochemical storage, on the other hand, uses battery-based systems (e.g., lithium-ion, nickel-based, etc.) and is often coupled with PV and is especially suited to help maintain the grid's electric voltage and frequency enabled by the fast response of power electronics [16]. This study will focus on battery-based systems at PV sites located within the U.S..

Battery-based UPVS systems can use storage systems coupled on either the direct current (DC) or alternating current (AC) side. With DC-coupled systems, power generated by the PV panels (DC) is fed through a charge controller into the storage system and is available for an inverter to convert to AC as needed. With AC-coupled systems, there are three transformations that occur: 1) power from a PV inverter (in AC) is fed into the utility grid; 2) a rectifier converts the AC grid power into DC for storage within the battery system; and 3) an inverter co-located at the battery converts the DC back into AC when the battery is discharged. The multiple transformations with AC coupling (vs. 1 for DC) increases the part-count and reduces the efficiencies of AC coupled UPVS systems. However, a DC-coupled system generally requires PV, battery, and power conditioning equipment (rectifier/inverter) to be co-located, whereas AC-coupled components could be in different locations on an AC system.

Literature to date on PV plus storage generally provide a broad range of costs associated with operations and maintenance (O&M). For example, commercial and industrial PV plus (electrochemical) storage, the levelized O&M cost per unit of energy throughput ranges from $15/MWh to $57/MWh [13]. Furthermore, reporting of O&M costs are also highly variable, with some reported as dollar values and others being quoted as percent of capital costs [14]. Some costs are reported in $/MWh of energy storage and others in $/kW of power capacity. Energy (kWh) and Power (kW) are related by the charge/discharge rates of the battery, the capacity of the DC/AC inverter, and other AC components such as transformer and power line ratings. Although about 4 kWh of energy storage per kW of power capacity is common, this varies a lot depending on the purpose of the battery system. Given the decreases in capital costs for PV plus storage over time relative to current costs (i.e., 10-52% reduction by 2025; [3]), relative costs of O&M as a function of capital costs make it more challenging to ascertain precise efforts expended on PV plus storage O&M (resulting in a range $0-$7/MWh/year). Additionally, the fixed O&M costs for all battery chemistries are in the range of $6-20/kW/year, with most in the $6-14/kW/year range [1], [6] whereas the variable O&M costs assumed to be approximately 0.3 cents/kWh/year [15]. Generally, these broad ranges lack details about the specific systems and/or activities that contributed to the cost values. This study is to help understand the specific factors and drivers that are contributing to UPVS system O&M costs.

We sought to address these aforementioned knowledge gaps by evaluating the motivation, operations, and effort required to maintain PV plus storage systems. The overall project goal is to capture information from UPVS across the United States. Specifically, we used a combination of questionnaires and semi-structured interviews to collect both qualitative and quantitative data from PV owners and operators across the country. A text analysis of operations and maintenance records was also performed. Our analysis provides insights into: 1) the size and spatial distribution of systems managed; 2) the primary function of the energy system; 3) factors that influenced selection of storage technology; 4) types and scheduling of ongoing O&M activities; 5) approaches to data collection and analysis; and 6) ongoing challenges and needs related to PV plus storage. These findings will help inform best practices and data-driven approaches to improve ongoing integration of PV plus storage systems in support of renewable energy and overall system resiliency goals.

2. METHODS

The team conducted a series of interviews with PV owners and operators in the United States to understand the influence of different O&M cost drivers at PV plus storage sites. O&M tickets contained in Sandia's Photovoltaic Reliability, Operations, and Maintenance (PVROM) database were further evaluated to understand in the field issues related to PV plus storage. Details regarding the data used as well data processing and analysis activities are provided in the following subsections.

2.1. Data Collection

Insights from the literature as well as feedback from subject matter experts from industry and national labs were used to develop and refine a series of questions to guide the data collection. The resulting questionnaire was organized into six sections: Contact Information, Site Details, Selection & Purpose of Energy Storage, O&M Activities, Data Collection & Analysis, and Challenges & Needs. Questions in the first three sections aim to capture details about the perspectives of those providing responses, garner metadata about location and specific technology details, primary function, and selection process of the technology. The remaining three sections capture details about current O&M activities as well as unmet needs at PV sites. A combination of open-ended and multiple-choice questions were used and are listed in Appendix A.

Several approaches were used to recruit participants for the questionnaire including including advertising through trade-related organizations and leveraging contacts from conferences and connections that staff had made working on related PV O&M topics. The questionnaire was shared with site owners and operators within industry working groups such as Sandia's Department of Energy (DOE) Global Energy Storage database, the Solar Energy Industries Association (SEIA), the Electric Power Research Institute (EPRI) Energy Storage Integration Council, and the Sunspec Alliance). We also advertised in industry-focused publications such as PV Magazine and Solar Daily. Social media (i.e., Twitter and LinkedIn) was used to announce the questionnaire as well as message specific individuals to encourage either participation or sharing the announcement with their networks. We also directly contacted major utilities, government agencies (e.g., New York State Energy Research and Development Authority, California Energy Commission), and other national laboratories. Conference presentations at the PV Reliability Workshop (PVRW) and the IEEE PV Specialists Conference (PVSC) were also used to increase project awareness and recruit participants. In total, we estimate over 250 individuals and organizations were directly contacted through this project's recruitment efforts.
Interested parties were able to complete the questionnaire using multiple options per their convenience: 1) complete the online version of the questionnaire (https://survey.alchemer.com/s3/6537904/PV-O-M); 2) populate a Word document version of the

questions (see Appendix A) and send the information back to our team via email; or 3) schedule a 30–60-minute conference call to step through the questions. Most respondents chose to either submit their responses via Word document or via conference call (see Table 2-1).

Table 2-1. Number of responses by submission format.

Submission Format	Number of Responses
Online Questionnaire	2
Word Document Submission	6
Conference Call	6

in addition to interviews, we also leveraged the PVROM database [11], which contains site-level operations, maintenance, and production records from 6 industry partners for more than 50,000 O&M tickets at 837 sites in United States. No targeted data collection of O&M tickets was performed for this study.

2.2. Data Processing

2.2.1. Questionnaire

All collected responses to the questionnaire were reviewed for completeness. After filling in the data gaps, the questionnaires were combined into a single data panel to facilitate analysis. Points of contact were re-contacted to provide answers to missing or incomplete questions; those that remained unanswered and were filled with "N/A" in the data panel. Due to the semi-structured interview format, most responses were extensive and required further processing while others naturally fell into categories pre-existing categories used in the questionnaire (e.g., primary function of storage system). Other responses, such as the warranty coverage, were binned into consistent categories (e.g., “entire system”). Responses to open-ended questions were coded based on similar themes.

2.2.2. Operations and Maintenance Tickets

The O&M tickets contained in PVROM generally capture details related to corrective (CM) and preventative (PM) maintenance activities. Key term identification was used to subset PVROM to focus on tickets referencing storage. In particular, asset labels associated with each ticket were searched using key terms such as “Energy Storage/Battery” or “Battery (Solar + storage facilities)”. Tickets were aggregated by site and month. A simplified set of pre-existing categories related to completion activities such as other, remote troubleshooting, replace/repair, refit (reset), and self-resolved were also applied to each ticket.

2.2.3. Data Analysis

Responses to questions with multiple selections available were tabulated and then divided by the total number of sites and the number of sites by storage technology type. Weighted averages based on the number sites per responses were calculated for questions where only one option was allowed. Responses to qualitative questions were reviewed for themes and aggregated as appropriate (i.e., responses of “None" and "No" were combined to be “No"). Visualizations were also used to identify patterns in responses. In particular, bar charts were used to facilitate relative comparisons across the multiple storage technologies and different types of O&M activities.

3. RESULTS

In this section, we first present our results from the questionnaire across all battery storage technologies and individually by storage technology. Then, we present our results from additional text analysis performed on O&M tickets contained in the PVROM database.

3.1. Questionnaire Findings

3.1.1. Site Details

Fourteen questionnaires were completed, providing insights for 81 sites across 13 states (see Figure 3-1). A majority of sites were located in either California (37%) or North Carolina (18.5%). Most sites were either utility-scale (40.7%) or off-grid/remote (43.2%). The total capacity PV system size across all sites is 51.1 megawatts (MW) with a mean capacity of 3.5 MW per site. These sites were co-located with a total 64.1 megawatt-hours (MWh) of battery storage with a mean storage capacity of 2.9 MWh per site (see Figure B-1). The mean overall age of sites was 5.2 years with a range of 0-11 years.

Sites were installed with either single (55.5%) or combinations (44.5%) of battery storage technologies. Five types of battery storage technologies were reported: lithium-ion (43.2%); lithium-ion with lead-acid and nickel cadmium (43.2%); lead acid (LA, 7.4%); lithium iron phosphate (4.9%); and lithium-ion with lead acid (1.2%). The mean MW/MWh rating is 2 with lithium-ion having the highest average (4.4 MW/MWh, see Table 3-1). Sites with combined technologies such as lithium-ion with lead acid and lithium-ion with lead acid and nickel cadmium reported the highest mean ages (see Table 3-1). The storage occurred behind-the-meter and front-of-the-meter in 81.5% and 6.2% of all sites, respectively. The remaining 12.3% of sites did not report on which side of the meter where the storage occurred.
On average, 50% of the storage technology's energy source is provided by the on-site PV systems with a range of 0%-100%. Sites using either lead acid or lithium-ion with lead acid did not report if the storage's energy source was the site's PV. Of the remaining storage technologies, lithium-ion and lithium-ion with lead acid and nickel cadmium reported on average 70.5% and 45% of the storage energy source coming from the site's PV (see Table 3-1).

3.1.2. Selection and Purpose of Energy Storage

Sites were developed with multiple primary functions in mind. Resiliency (60.5%), fuel savings (43.2%), and demand balancing (18.5%), peak demand shaving (17.3%), and technology demonstration (9.9%) were the five most common functions reported across sites (see Table A1

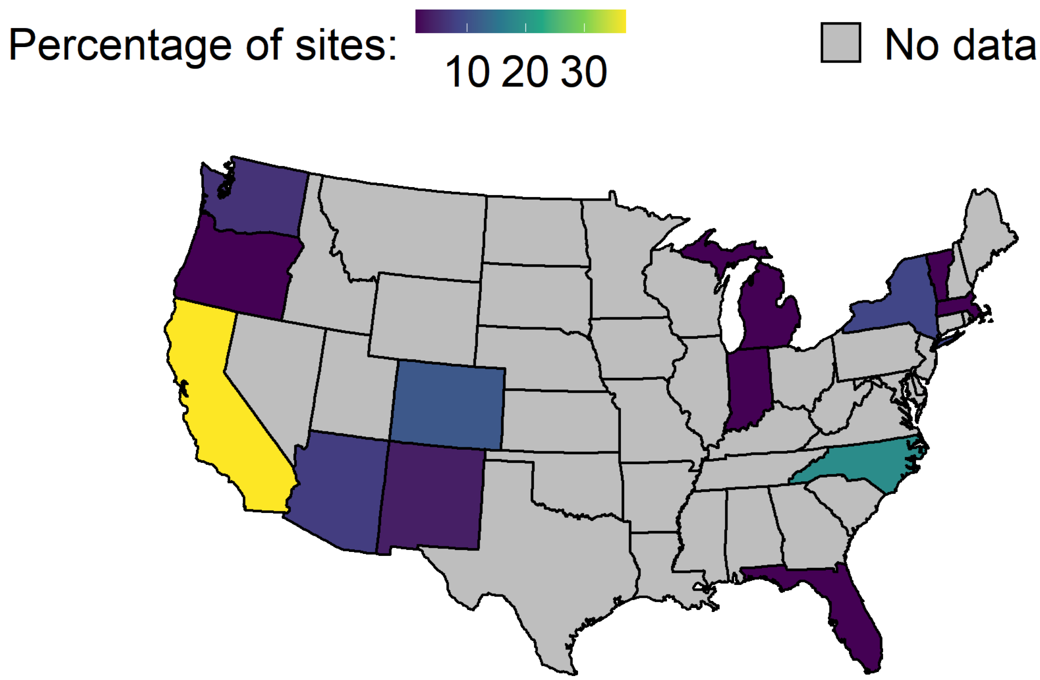

Figure 3-1. Distribution of sites by state from PV plus storage questionnaire.

Table 3-1. Summary of storage technology types represented in the questionnaire responses. Mean reported values are weighted based on number of sites.

Storage Technology	Study Sites (%)	Mean MW/MWh	Mean Age (Years)	Mean Storage Location Relative to Meter (%)			Mean storage energy from site (%)
				Behind	Front	Not Reported	
Lead Acid	7.4	0.2	1.8	100	0	0	—
Lithium-ion	43.2	4.4	3.2	68.8	25	6.2	70.5
Lithium-ion, Lead Acid	1.2	1	7	0	100	0	—
Lithium-ion, Lead Acid, Nickel Cadmium	43.2	0.1	8	100	0	0	45
Lithium Iron Phosphate	4.9	0.3	3.2	50	0	50	33.8
All Technologies	100	2	5.2	81.5	6.2	12.3	50

and Figure B-2). The number of primary functions differs by storage technology (see Figure 3-2 and Table A1). Lithium-ion (7) had the most unique primary functions with demand balancing (40%), technology demonstration (22.9%), and peak demand shaving (17.1%) being the most frequently reported functions across those sites.

Most technologies were selected by respondents after considering 2-9 unique criteria, with Lithium-ion and lead iron phosphate having the most factors (see Table A2 and Figure 3-3). Four options for factors influencing the selection of the storage technology were initially provided within the questionnaire (see Appendix A). However, an additional 11 selection factors were noted by respondents (see Table A2). Technology readiness level (77.8%), technology performance (72.8%) capital costs (70.4%), and O&M costs (59.3%) were the leading factors

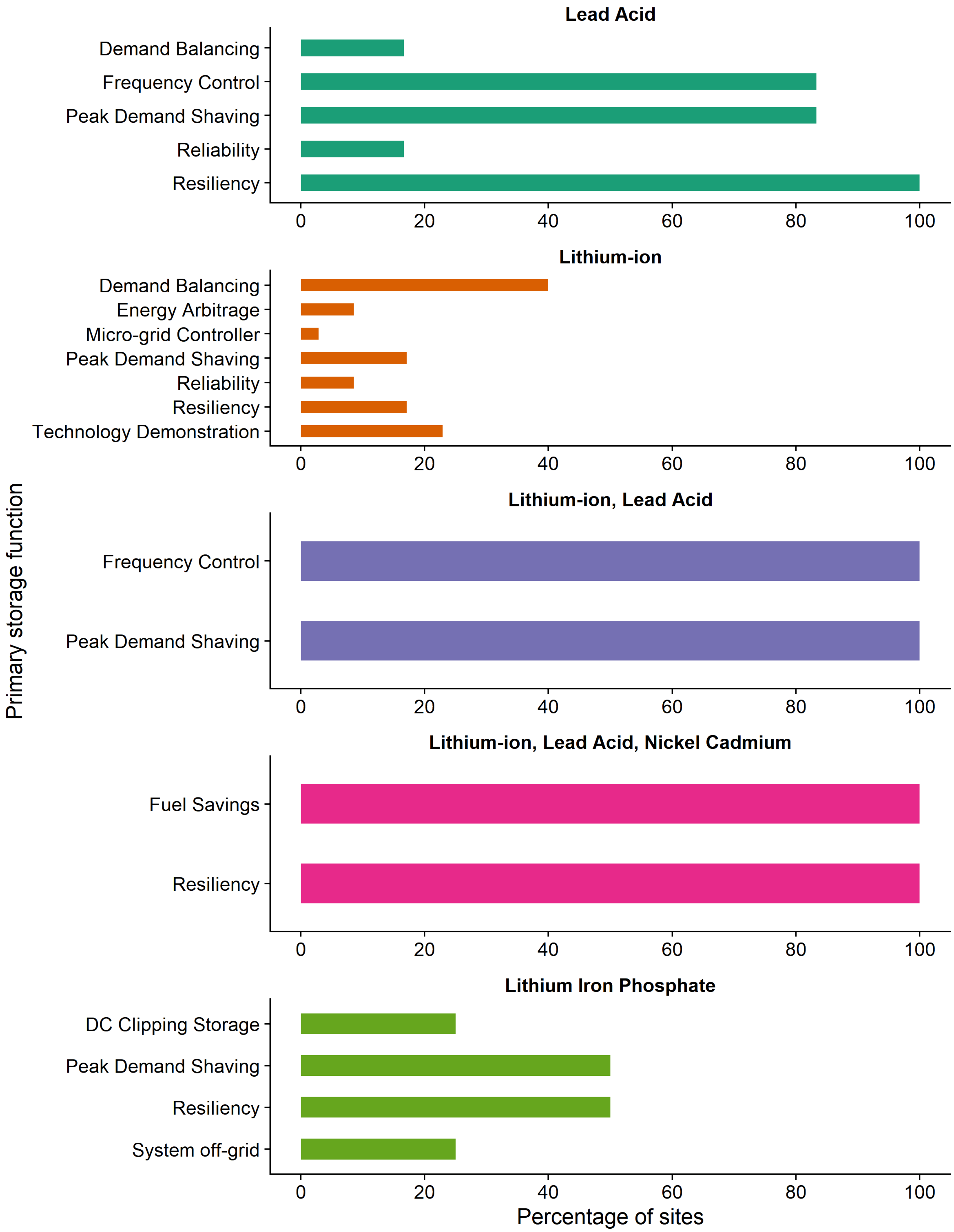

Figure 3-2. Primary functions of energy storage system organized by storage technology type. Values reflect the percentage of sites indicating function is key purpose of the battery storage system. Sites could select multiple functions.

across all technologies. Other notable selection factors focused on safety and long-term financial considerations. Budget limitations (2.9%) and payback period requirements (11.4%) were only factors for lithium-ion. Some respondents reported either mandated payback periods or the shortening of periods during the project design phase were also important considerations. Capital cost was the most considered factor for lithium iron phosphate (75%). Safety regulations were a major consideration for Lead-acid (83%) due to local building codes preventing lithium from being stored on site.

Reported capital costs ranged from $646-$766 per kWh on average across all storage types. Storage technologies using lead acid reported some of the highest and lowest capital costs sites using lithium-ion with lead acid and nickel cadmium having the lowest capital costs reported in this study (see Table 3-2).

Table 3-2. Summary of storage capital costs, expected storage lifetime, and degradation rates by storage technology. Mean reported values are weighted based on number of sites.

	Mean Storage Capital Cost ($ per kWh)			
Storage Technology	Low	High	Expected Lifetime (years)	Degradation Rate (% per year)
Lead Acid	1000	1000	7.5	0.33
Lithium-ion	933	962	10.3	1.01
Lithium-ion, Lead Acid	1000	1000	7	2
Lithium-ion, Lead Acid, Nickel Cadmium	400	600	17	1.76
Lithium Iron Phosphate	700	800	13.8	0.5
All Technologies	646	766	13.1	1.27

A majority of sites reported cycling storage either daily (75.3%) or every few days (18.5%) (see Table 3-3. Sites using lithium ion with lead acid and nickel cadmium or lithium-ion with lead acid storage technologies were were most commonly cycled daily or every few days, respectively. Storage based on either lead acid, lithium-ion, or lithium iron phosphate were cycled across a range of rates (see Table 3-3).

Table 3-3. Storage cycling rates by technology across all sites. Values reflect percentage of sites reporting frequency of system cycling.

Cycling rate	Lead Acid	Lithium-ion	Lithium-ion, Lead Acid	Lithium-ion, Lead Acid, Nickel Cadmium	Lithium Iron Phosphate	All Technologies
Daily	16.7	65.7	—	100	50	75.3
Every few days	83.3	25.7	100	—	—	18.5
5x per month	—	—	—	—	25	1.2
Weekly	—	—	—	—	25	1.2
Not often, no regular schedule	—	8.6	—	—	—	3.7

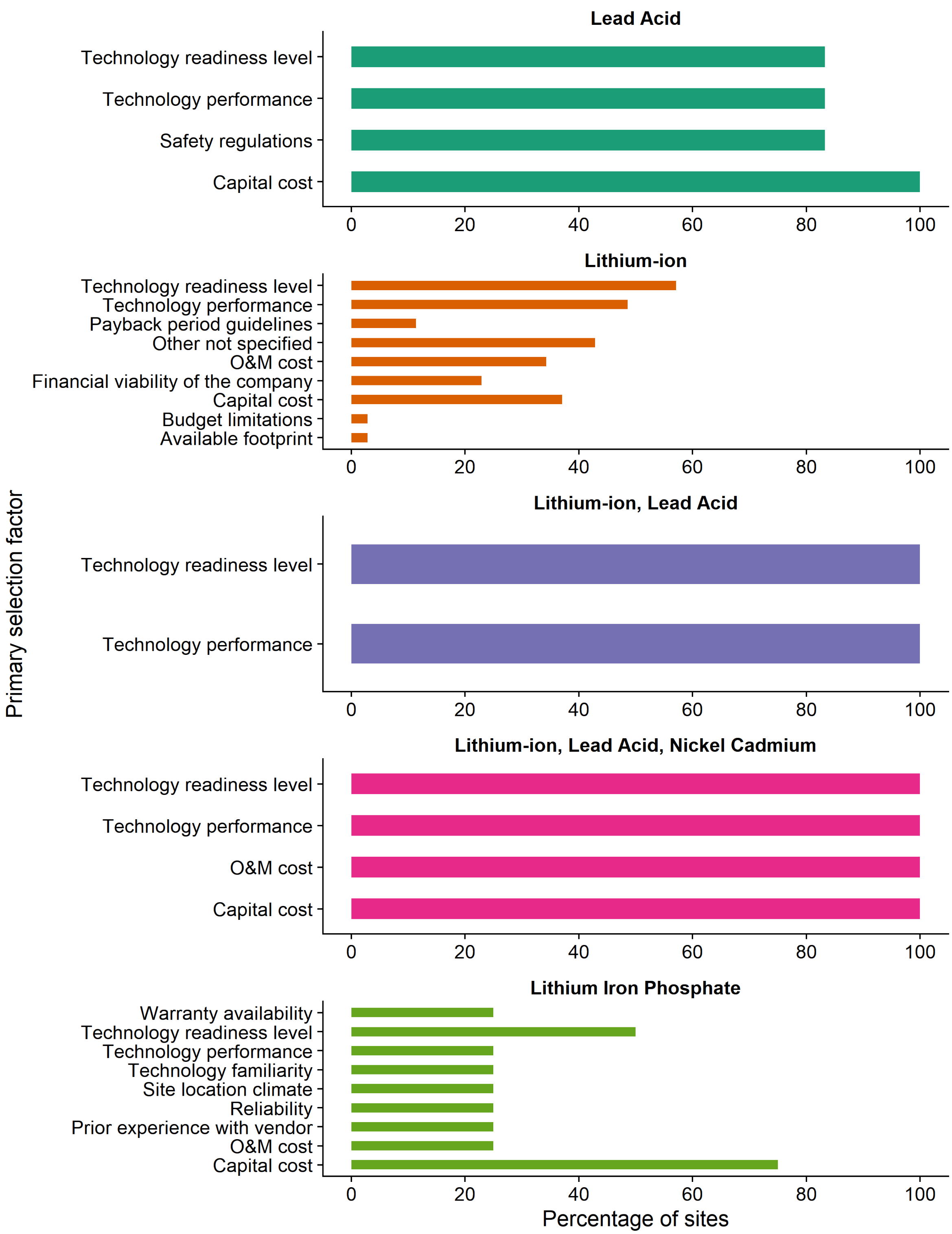

Figure 3-3. Selection factors considered by owner-operators by storage technology type. Values reflect the percentage of sites indicating factor influenced the selection of storage technology type. Owner-operators could select multiple factors for sites.

Factors affecting battery life include: replacement criteria (allowable percent of initial capacity), cycle life, depth of discharge and time spent at low states of charge; total battery “throughput” and calendar life. The mean expected life cycle of the storage technology across all sites is 13.1 years. Sites using lithium-ion with lead acid and nickel cadmium were expected to have the highest (17.0 years) expected life cycles while sites using lithium-ion with lead acid were expected to have the lowest (7.0 years) expected life cycles, respectively (see Table 3-2).

Generally, batteries degrade in terms of capacity and efficiency until criteria trigger a replacement. The mean degradation rate of storage across all sites is 1.27% per year. Sites using lithium-ion with lead acid were expected to heave the highest (2.00% per year) degradation rate while sites using lead acid were expected to have the lowest (0.33% per year) degradation rate, respectively (see Table 3-2).

3.1.3. Operations and Maintenance Activities

Respondents often reported storage system maintenance as being performed by different parties (see Table 3-4). The storage system vendor provided maintenance for 95.1% and in-house technicians were used to provide maintenance for 35.8%, respectively, of all sites. With the exception of sites using lithium-ion with lead acid and nickel cadmium batteries, sites using all other storage technologies types had maintenance performed either in-house or by the system vendor themselves. Both lead acid (16.7%) and lithium-ion (28.6%) also reported using third party contractors to support storage maintenance activities, accounting for 13.6% of all sites.

Table 3-4. Responsible parties for O&M activities as percentages of sites by type of provider and storage technology. Owner-operators could select multiple types of providers.

Provider	Lead Acid	Lithium-ion	Lithium-ion, Lead Acid	Lithium-ion, Lead Acid, Nickel Cadmium	Lithium Iron Phosphate	All Technologies
In-house	83.3	54.3	100	—	100	35.8
System Vendor	83.3	94.3	100	100	75	95.1
3rd Party Contractor	16.7	28.6	—	—	—	13.6
Not reported	—	2.9	—	—	—	1.2

Most sites reported conducting PM activities at least every 3-6 months and an annual basis for all sites (see Figure 3-4). Visual checks, electric checks, and firmware updates were reported to occur every 3-6 months by 33%, 21%, and 21% all sites, respectively. Cooling system checks (26%), electrical checks (20%), and firmware updates (19%) were also commonly performed annually. Cooling system checks and visual checks were performed by 6% of sites on a weekly basis.

Only two types of CM were considered: alarm resolutions, and parts replacement. Corrective activities most often occurred every 3-6 months at sites with both types of activities performed by 17% of all sites. Parts replacement also occurred weekly at 15% of sites, whereas this activity was not reported to occur either a monthly or semi-annual basis. No additional types of corrective activities were reported by respondents.

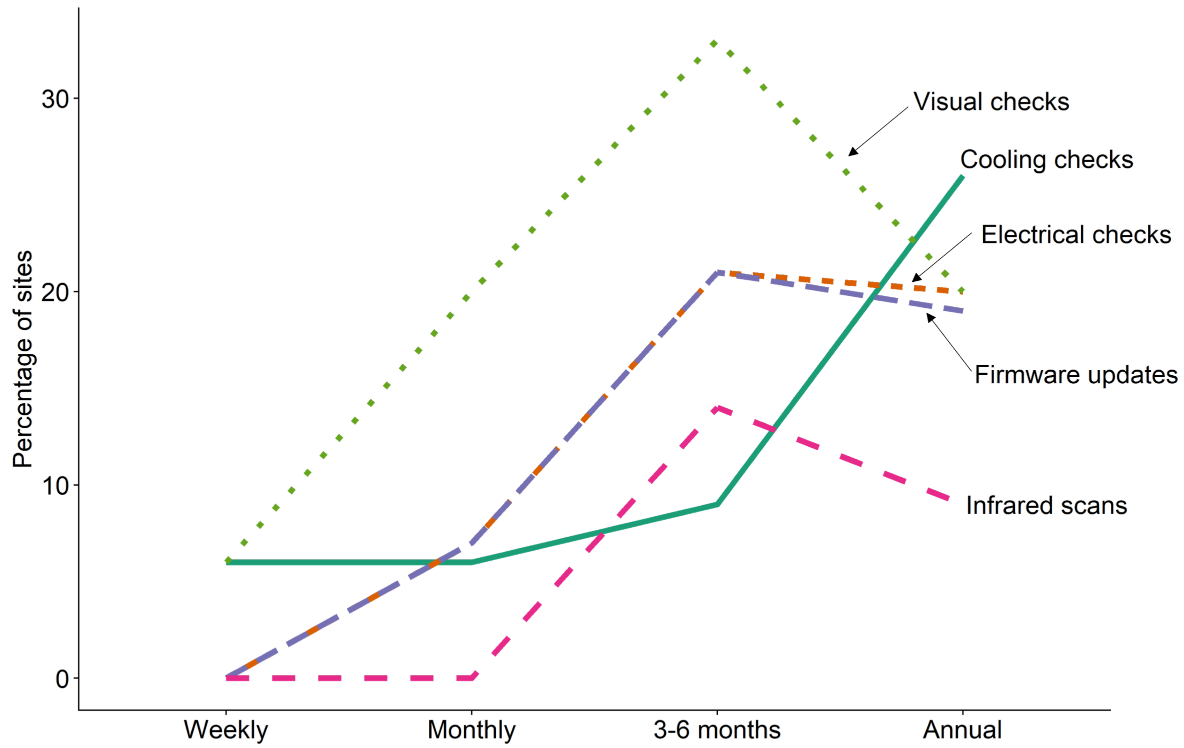

Figure 3-4. Reported preventative O&M activities organized by frequency of activity. Values indicate percentage of sites reporting activity at given frequency.

Respondents generally indicated that there was not much variance in O&M practices across locations in their portfolio, especially when using the same storage technology and supplier. Approximately 35.8% of sites reported either no significant differences in O&M practices by location or unaware of any differences. One respondent remarked about differences across states that were driven by state-specific system design requirements as well as personnel availability for O&M activities. Another respondent remarked on a difference between Lead-acid and Li-ion batteries. In their experience, flooded lead acid batteries needed additional electrolyte checks and maintenance of water levels; these were not needed for Li-ion batteries.

Three warranty periods were captured in this study: 1 year, 1-5 years, and more than 5 years. Approximately 80.2% of all sites reported having a warranty period of at least 5 years (see Table 3-5). A few sites (12.3%) were also covered by one year warranties. Multiple respondents reported having 10-year warranty periods for the batteries. These warranties included both the storage equipment and the workmanship. All sites using lithium-ion with lead acid storage reported being covered by only one year warranties. Conversely, all sites using lithium-ion with lead acid and nickel cadmium storage reported having at least 5 years of warranty coverage.

There were multiple types of components covered by the warranties. Some (17.3%) of sites had warranties that covered the batteries and the control architecture. Other warranties specifically covered only the batteries while others encompassed the entire storage system or major equipment. Sites with one or two-year only warranties noted that while extensions were available, they were considered to be cost prohibitive.

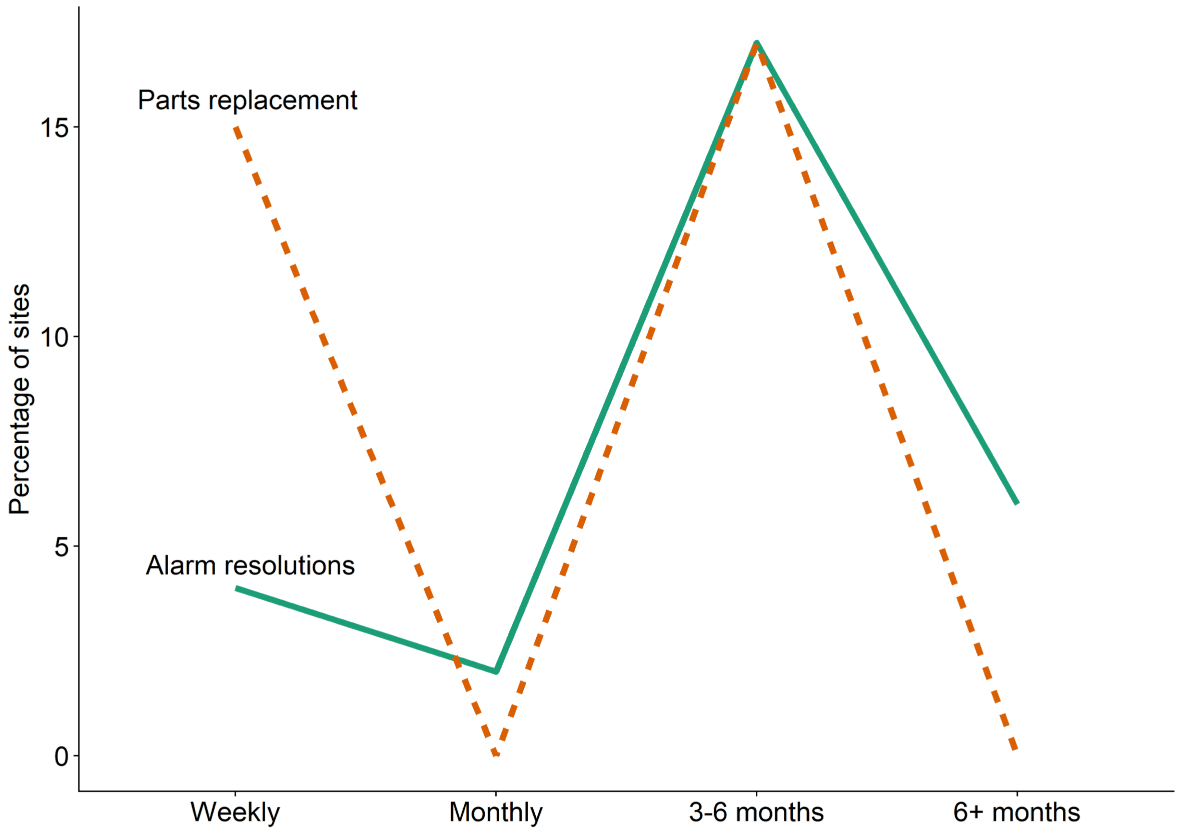

Figure 3-5. Reported corrective O&M activities organized by frequency of activity. Values indicate percentage of sites reporting activity at given frequency.

Table 3-5. Warranty coverage periods by technology across all sites. Values reflect percentage of sites reporting warranty period. Owner-operators could select multiple warranty periods.

Warranty period	Lead Acid	Lithium-ion	Lithium-ion, Lead Acid	Lithium-ion, Lead Acid, Nickel Cadmium	Lithium Iron Phosphate	All Technologies
1 year	83.3	11.4	100	—	—	12.3
1-5 years	—	31.4	—	—	25	14.8
5+ years	16.7	74.3	—	100	75	80.2
Not reported	—	5.7	—	—	—	2.5

As of the date completing the questionnaire, approximately 61.7% of all sites had not filed a warranty claim (see Table 3-6). However, all sites using either lead acid or lithium-ion with lead acid batteries had filed a claim as well as a majority of sites using lithium-ion or lithium iron phosphate batteries. Conversely, no sites using lithium-ion with lead acid and nickel cadmium had reported filing a claim.

Many respondents were either unaware of differences in O&M or insurance costs based on locations (54.3%) or reported roughly the same costs (28.4%). Few sites (7.9%) reported regional costs differences with some locations being up to 10 times higher than other locations in their

Table 3-6. Warranty claims filed by storage technology. Values reflect percentage of sites reporting warranty claim status.

Claim status	Lead Acid	Lithium-ion	Lithium-ion, Lead Acid	Lithium-ion, Lead Acid, Nickel Cadmium	Lithium Iron Phosphate	All Technologies
Yes	100	57.14	100	—	50	35.8
No	—	40	—	100	25	61.7
Not reported	—	2.86	—	—	25	2.5

portfolio. Respondents also reported that choice of vendor (9.9%) or plant production size (1.2%) were additional factors that affected O&M costs. A majority of sites (79%) reported that O&M costs have not changed over time. Some sites (13.9%) fully expect costs to increase, especially after a warranty period expires. Other sites (3.7%) remarked how it was too soon to tell given the relatively young age of their sites.

Approximately half (50.6%) of sites have not had a safety issue at the time of responding to the questionnaire versus nearly a third (30.9%) who had safety issues arise. A notable percentage of sites (18.5%) were unaware of any safety issues. Some sites (12.3%) reported being concerned about fires in general. Other safety issues noted related to venting, a change in safety codes during the design process, and dust. Nearly the same percentage of sites have added additional safety systems (42.0%) compared to those who have not (43.2%). In response to safety concerns, sprinklers, dry hose installation, fire suppression systems, and additional ventilation have been added to the systems. One respondent also noted that they hired fire protection experts to assist with site design to mitigate potential fire risk.

3.1.4. Data Collection & Analysis

Nearly all sites (90.9%) reported using automated systems to collect overall system and storage-specific performance data. A few sites (2.5%) reported manually collected fault codes. Data was most often collected at the 1-minute time step (55.%). Some sites (6.2%) reported other data collection frequencies such as 2-, 5-, 10-, and 15-minute time steps. Other sites (39.5%) did not disclose data collection frequency. Several sites (8.6%) collect multiple power-related parameters including reactive power, the power factor, and apparent power. Some sites also collect information related to clipping energy capture (1.2%), fault codes (2.5%) as well as charging and discharging status (3.7%). A majority of sites (97.5%) did not disclose any differences in the type of information being collected across sites. Other sites (2.5%) indicated there were some differences but did not elaborate.

A majority of sites (59.3%) did not specify how the collected data was used to inform O&M activities. For reporting sites, monitoring site under-performance (34.6%), detecting outages (21%), assisting with corrective maintenance activities (19.8%), and providing insights for failure diagnosis (8.6%) were the most common uses of collected data for helping inform O&M

activities. One respondent noted how the data is also used by third-party O&M providers to help automate dispatching of technicians.

3.1.5. Challenges and Needs

Several ongoing challenges and needs were reported by respondents. Four common themes were identified across reported challenges: new processes needed to set up PV+storage contracts; missing PV+storage performance metrics; limited experience with combining technologies; and long-term vendor availability and reliability. Respondents also shared their needs for helping improve the management of their systems. The needs identified related to: data management and handling; expected versus actual storage lifetimes; long-term field performance; limiting storage technology obsolescence; locally available technicians and parts for servicing O&M needs; and consistency in standards and codes to minimize impacts on equipment availability. These challenges and needs highlight the range of opportunities for continued improvement to ensure long-term success of PV plus storage sites.

3.2. PVROM Summary

3.2.1. Sites Background

Fourteen sites within PVROM currently contain storage-related O&M tickets. These sites are all located within North Carolina and managed by one of our partners. The sites were generally commissioned between Nov 2016 to Dec 2017. Most of the sites have solar capacity of <1000 kilowatts in DC (kW_{DC}) (i.e., 1 megawatt in DC, MW_{DC}), except for two that are $\sim$4000 kW_{DC} (4 MW_{DC}) and $\sim$27000 kW_{DC} (27 MW_{DC}), respectively. The smaller systems use a string inverter while the two larger systems use a central inverter. All of these sites are utility-scale systems, with most having fixed systems; only one site had a tracking system.

3.2.2. Operations and Maintenance Tickets

A total of 152 O&M tickets had pre-existing asset labels pertaining to either “Energy Storage/Battery” or “Battery (Solar + storage facilities)”. Additional details about these tickets are captured below.

Generally, the tickets were evenly distributed across all of the fourteen sites (see Figure B-4) Interestingly enough, the two largest sites had the lowest number of tickets. Rather than fewer issues per se, the relatively low number of tickets at these sites could reflect alternate agreements with O&M services/documentation than the other sites (see Figure B-4). Failures were observed throughout the year, with higher prevalence in winter and spring months and a spike towards the end of summer (see Figure B-5).

A majority of the tickets related to underperformance-related issues (64%), while some discussed production outages (19%) or communications-related outages (16%). The specific completion activity ranged from remote troubleshooting to repairs and self-resolutions to combinations of activities (see Figures 3-6 and B-6).

Some interesting patterns emerge with these different completion activities, including seasonal patterns in timing. For example, refit/reset activities seem to only occur in Sept (could be indicative on an annual rollover) while self-resolutions often occur in January, July, and October (see Figure 3-6).

The beginning and end of each ticket can be used to determine the duration of a completion activity. The tickets lasted in duration from one minute to over 79 days. Summary statistics of the minimum, maximum, and median ticket duration by completion activity types shows a wide variance (see Table 3-7). Remote troubleshooting-related tickets often have the shortest duration, indicating fastest responses with this completion activity. These duration are followed by self-resolved tickets and replacement/repair-related tickets. A small portion of the tickets (<5%) had manufacturer-related warranty claims associated with them.

Table 3-7. Summary statistics of O&M ticket duration by completion activity

	Ticket Duration (minutes)		
Completion Activity	Minimum	Maximum	Median
Other	480	81,120	8,340
Refit (Reset)	114,240	114,240	114,240
Remote Troubleshooting	1	14,880	567
Replace/Repair	75	109,920	3,487
Self Resolved	480	3,360	1,200

3.2.3. Additional PVROM Observations

A manual review of the specific issues identified that most of the tickets (∼52%) discussed alarms, which is consistent with the interview insights. Some of the alarms captured in the tickets include those related to cooling systems (e.g., over temperature faults), operational settings (e.g., under voltage faults), or communications. It was not immediately clear whether all of these alarms affected production. In some cases (e.g., a smoke detector-related alarm), the storage system was automatically tripped as a precautionary measure. In other cases (e.g., discharge-related faults), the timing of the fault did not affect production since the battery was not intended to discharge until a later time.

Statistical analyses (e.g., Weibull distribution or survival fits) were not conducted since there was significant diversity in the level of details captured within the tickets. For example, in contrast to previous O&M analyses, there is a much higher degree of software/controls associated with PV plus battery storage systems. Interpreting these written entries for specific impact (e.g., was it just an alarm or communications issue? Or was there also an underlying hardware problem?) was more difficult to parse with these entries. Future work could ascertain how to address these

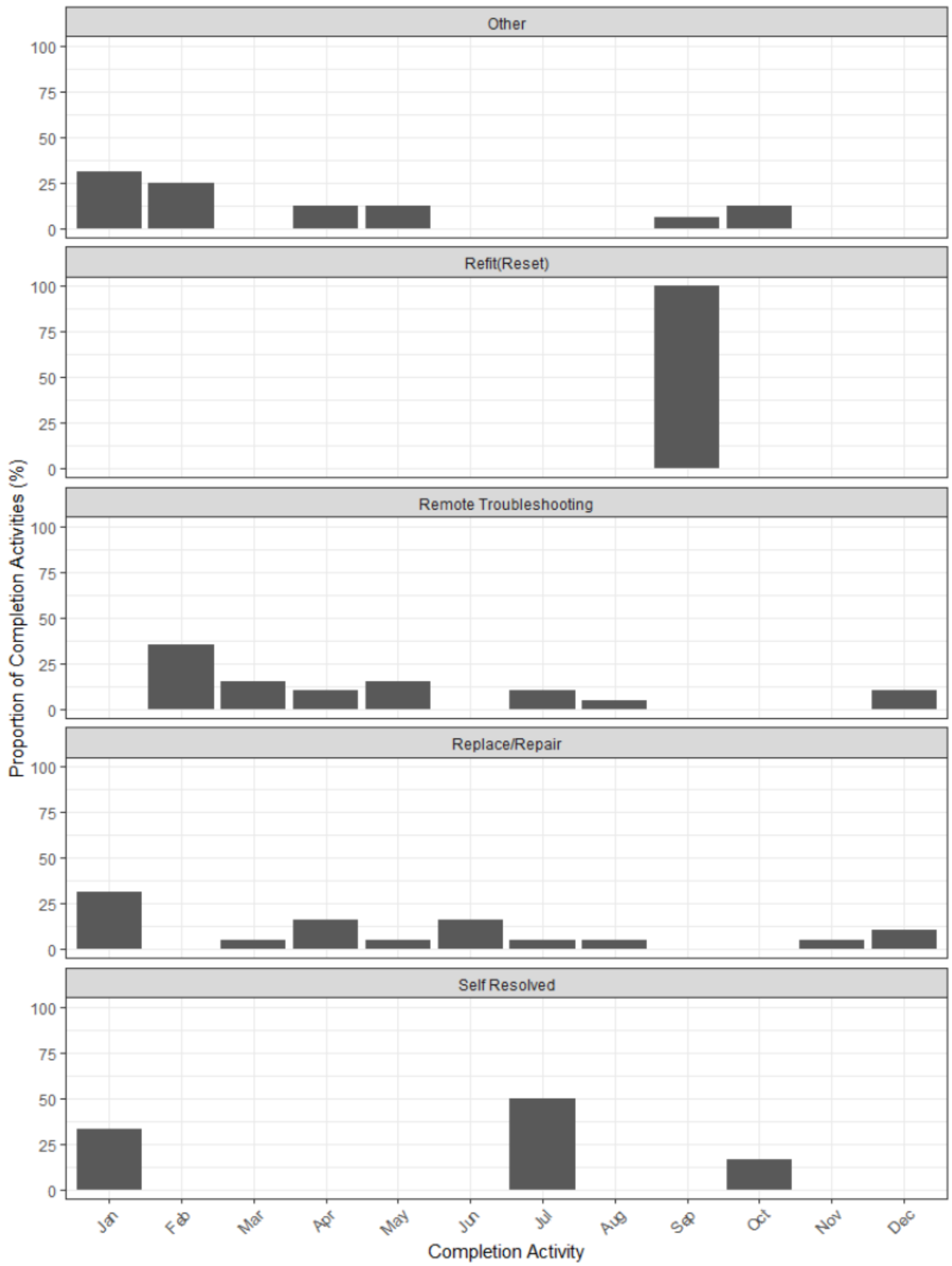

Figure 3-6. Distribution of O&M-related completion activities across the year.

limitations as well as the value of running statistical analyses on these (limited) records or production data collected from partners.

4. CONCLUDING REMARKS

Battery storage systems are increasingly being installed along with PV at sites. Insights from a questionnaires were used to collect key information about PV sites with storage to better understand O&M cost drivers of UPVS systems. Given the significant diversity within industry, a semi-structured interview approach enabled discussion of relevant nuances and various factors that influence decisions about O&M activities for UPVS systems. Results from 81 sites regarding the selection and purpose of energy storage systems, types and frequency of O&M activities, approaches to data collection as well as ongoing challenges and needs at PV plus storage sites were provided. Performance differences across storage technology type (i.e., capital cost, expected lifetime, degradation rate, and frequency of storage cycling) were documented. This work highlighted a number of areas that require further attention such the need for PV plus storage-specific performance metrics, and improving vendor reliability and parts availability, enhancing data collection efforts to support additional statistical analysis, and explore differences in O&M and capital expenditures between single-phase versus multi-phase systems.

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APPENDIX A. Questionnaire

Thank you for taking the time to fill out this questionnaire. This form should take approximately 30-60 minutes to complete.

Study Purpose: Sandia National Laboratories (SNL) and National Renewable Energy Laboratory (NREL), on behalf of the U.S. Department of Energy (DOE), are working to understand the drivers influencing the operations and maintenance (O&M) of PV + Storage systems in the U.S. We are particularly interested in understanding how these technologies were selected, O&M activities being conducted, data collection, and ongoing challenges and needs in this space.

Study Results: The results from this study will be analyzed to understand factors influencing PV + Storage O&M. These summarized findings will be shared through a report and a webinar. Note: Data collected will be retained indefinitely by DOE, NREL, and SNL, and used for meta-analysis and summary findings, but we will not release personally identifiable information (PII), such as individual survey responses, individual names, organization names, site names, site locations, or emails. For more information, see NREL's security and privacy notices: https://www.nrel.gov/security.html.

Once you have completed this questionnaire, please submit the information online or email it back to us: Nicole Jackson (njacks@sandia.gov) or Jal Desai (Jal.Desai@nrel.gov).

Please do not hesitate to reach out to us if you have any further questions or comments about this study. Thank you for your time!

Nicole & Jal

(* indicates high-priority questions)

Section 1: Contact Information

Understanding your role will help us better contextualize the perspectives being shared.

1. Title, Organization (briefly describe your role/title at your organization)*:

Section 2: Site Details

Please provide details about the site and system. Questions in parentheticals indicate some of the details we're interested in capturing.

2. Briefly describe the site(s) that contain PV + Storage. (What states are the site(s) located? Are they utility-scale, residential, etc.? How large are the PV sites?)

3. Briefly describe the storage systems. (What type of storage technologies are used at the site(s) (e.g., Li-ion, Lead-acid, etc.)? What is the kW/kWh rating of PV/energy storage capacity (please

include units)? When did they become operational? Is the storage occurring behind- or front-of-the-meter?)

4. What percentage of the storage technology's energy source is coming from PV at the site(s)?

Section 3: Selection and Purpose of Energy Storage

5. What is the primary function of the storage system? Highlight all that apply.

- Peak demand shaving
- Resiliency
- Frequency control
- Energy arbitrage
- Other:

6. What factors influenced the selection of the storage technology/technologies? Highlight all that apply.

- Technology readiness level
- Technology performance
- Capital cost
- O&M cost
- Other:

7. Please elaborate on the specific factors noted in the previous response. For example, were there certain budget limitations or priorities?

8. What is the capital cost of the energy storage system?

- <$400 per kWh
- $400-$600 per kWh
- $600-$800 per kWh
- $800-$1000 per kWh
- $1000+ per kWh

9. How often is the storage system cycled (i.e., charged and discharged)?

- Daily
- Every few days
- Other:

10. What is the expected cycle life for the energy storage system(s)?

11. What degradation rate is expected for the energy storage system(s)?

Section 4: O&M Activities

Please provide details about specific O&M activities being conducted related to the storage system.

12. Who's responsible for the storage system's maintenance? Check all that apply.

- In-house
- System vendor
- Other

13. What O&M activities have been conducted to maintain the storage technology? Check all that apply.*

- Preventative: Visual checks
- Preventative: Cooling (air filter changes, glycol checks, . . .)
- Preventative: Electrical checks
- Preventative: Firmware/software updates
- Preventative: Infrared scans
- Preventative: Other:
- Corrective:
- Corrective: Parts replacement
  Specify details here:
- Corrective: Other:

14. How often is O&M conducted for the energy storage system? For corrective, please indicate how often you're troubleshooting PV + storage systems. Check all that apply.*

- Preventative: Weekly
- Preventative: Monthly
- Preventative: 3-6 months
- Preventative: Annual
- Corrective: Weekly
- Corrective: Monthly
- Corrective: 3-6 months:
- Corrective: 6+ months

- Corrective:

15. Do your O&M practices vary from location to location? If yes, please describe briefly.

16. Are there warranties currently covering the storage system? Check all that apply.*

- 1-year
- 1-5 year
- 5+ years all sites

17. Please elaborate on the previous question: which components are covered by these warranties?

18. Have you had to file warranty claims? If yes, please briefly describe which components were replaced and the failure causes.*

19. Do your O&M (or insurance) costs differ depending on location? Or have the costs changed over time? If yes, please describe briefly.*

20. If you have observed any safety concerns associated with PV + Storage, please describe them briefly. Also, were there any safety systems added (specifically to the storage technology, such as sprinklers) that are now part of an O&M cost?*

Section 5: Data Collection & Analysis

Please provide details about how the storage system performance is monitored and evaluated.

21. Please describe briefly how data related to PV + Storage performance and maintenance are monitored and captured. (Is the data collection automated or manual? How often is data collected? Is similar information being captured across all sites?)

22. How is the gathered data used to inform O&M activities (e.g., diagnose failures, evaluate contractual agreements, etc.)?

Section 6: Challenges and Needs

Please provide details about any ongoing challenges and needs related to PV + Storage.

23. Are there any other challenges (either current or future) related to PV + storage O&M that you are anticipating? Any specific gaps regarding either installation or long-term projections of PV + storage cost, O&M, etc.?*

24. Are there specific needs (e.g., cost models or predictive maintenance tools) that would improve management of your PV + storage system?*

25. Are you willing to share data about your energy storage system?*

- Yes
- No
- Maybe

26. Are you willing to have a follow-up discussion regarding the responses in this questionnaire? If yes, please provide your name and contact information below. This information will not be shared with anyone outside of the project team.*

APPENDIX B. Supplementary Material

B.1. Additional Figures

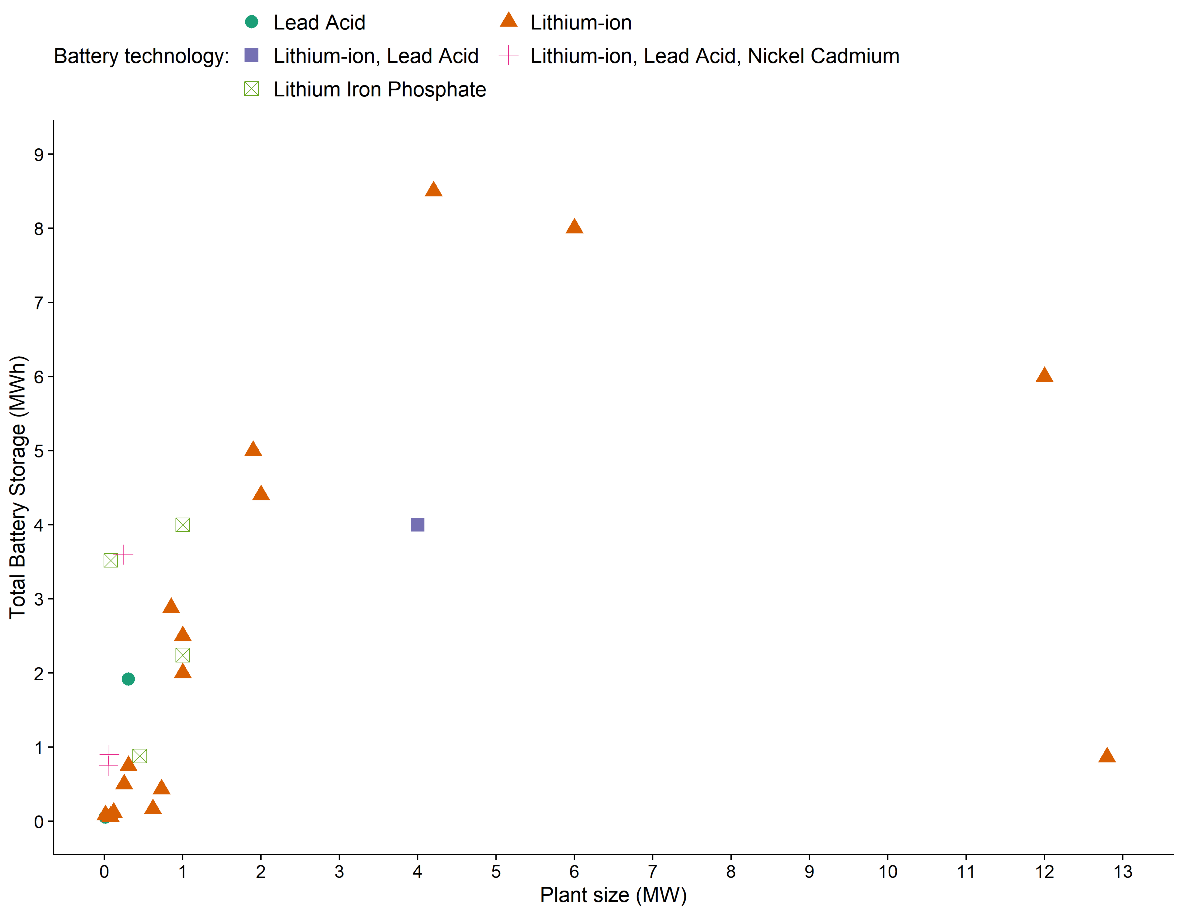

Figure B-1. Comparison of site-level plant size versus battery size by battery technology type.

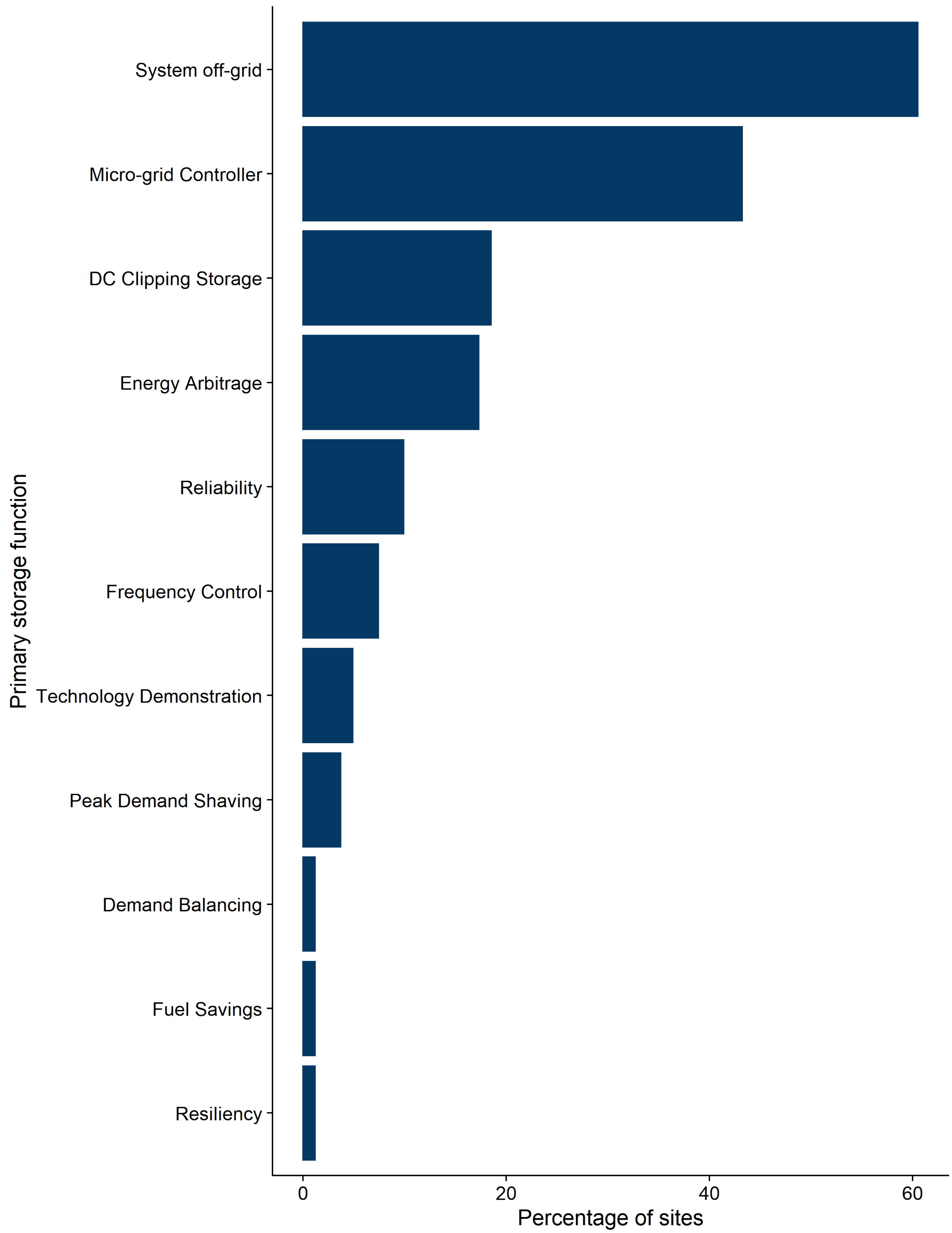

Figure B-2. Overall primary function served by storage system. Values reflect the percentage of sites indicating function is key purpose of the battery storage system. Sites could select more than one purpose.

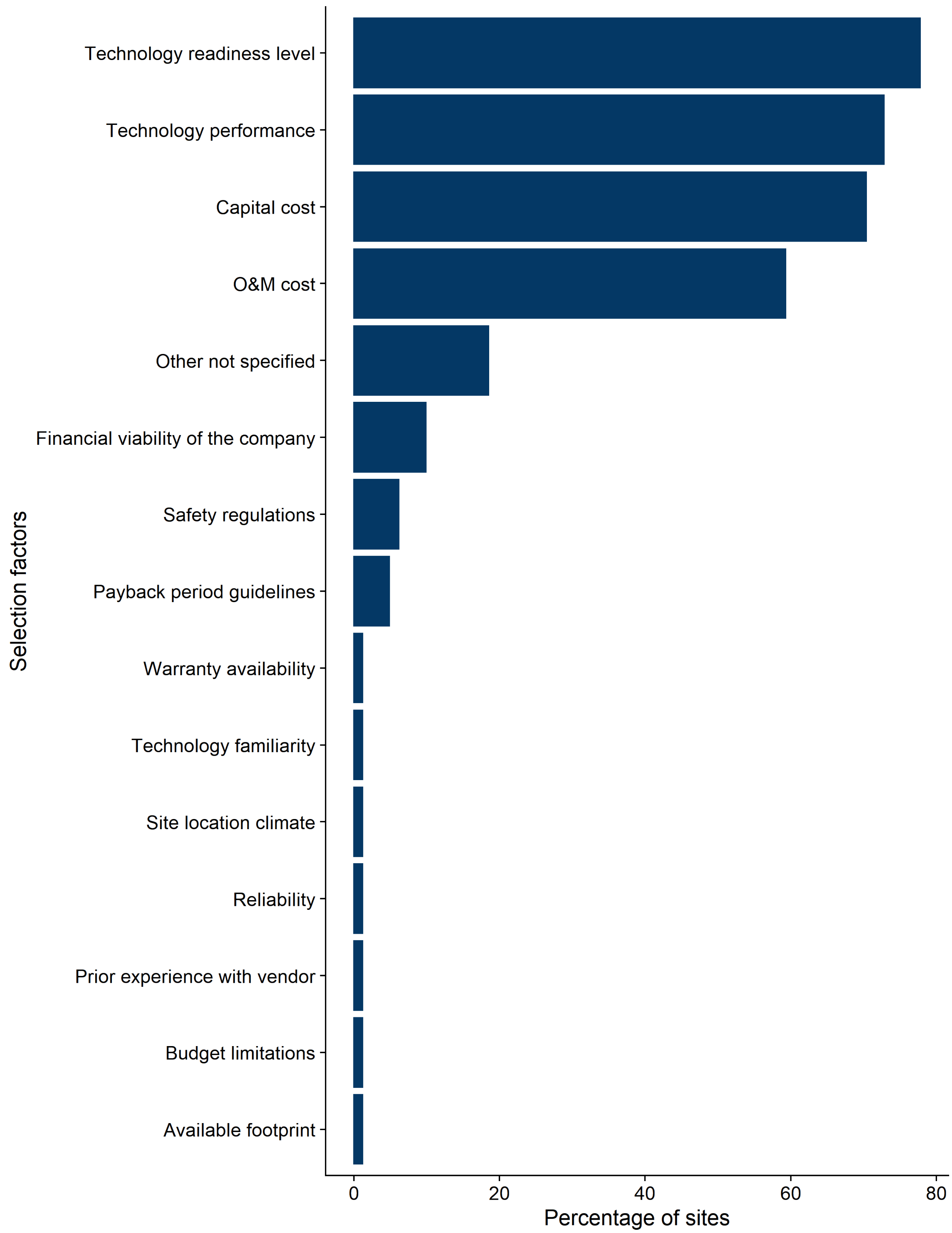

Figure B-3. Selection factors considered for battery storage technology reported. Values reflect the percentage of sites indicating factor influenced the selection of storage technology type. Sites could select more than one factor.

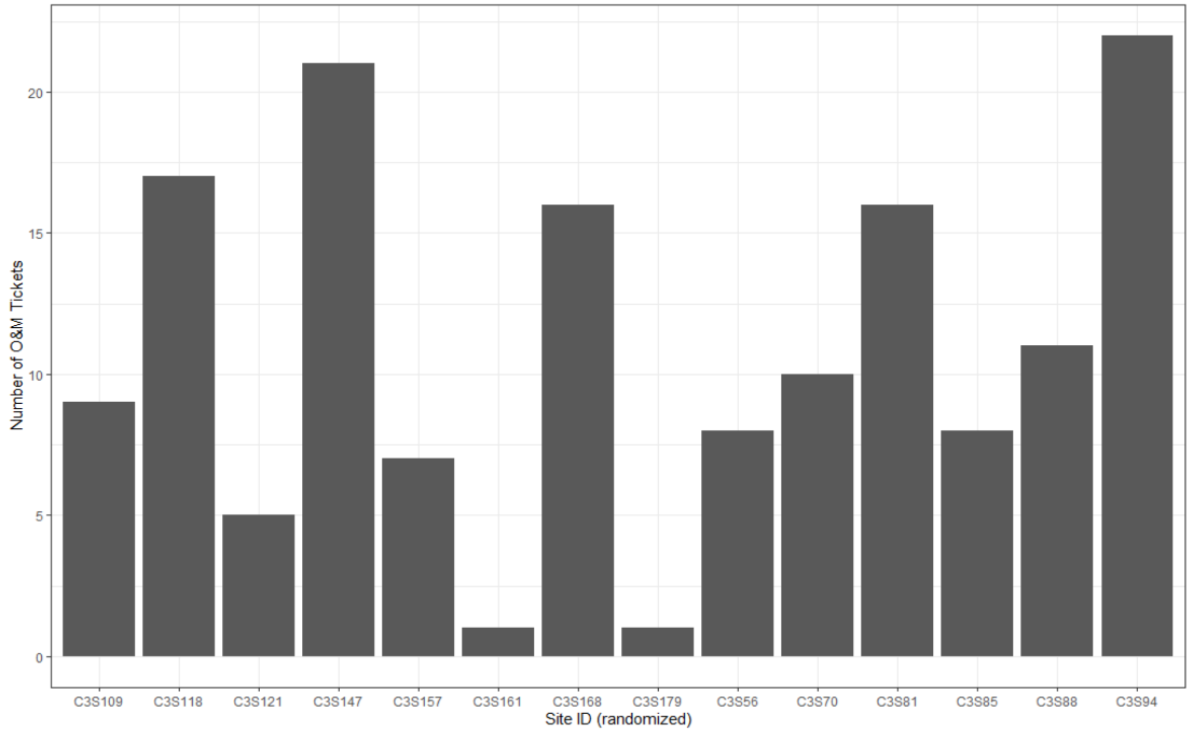

Figure B-4. Number of O&M tickets in PVROM related to PV+Storage by site. Note: site names have been randomized.

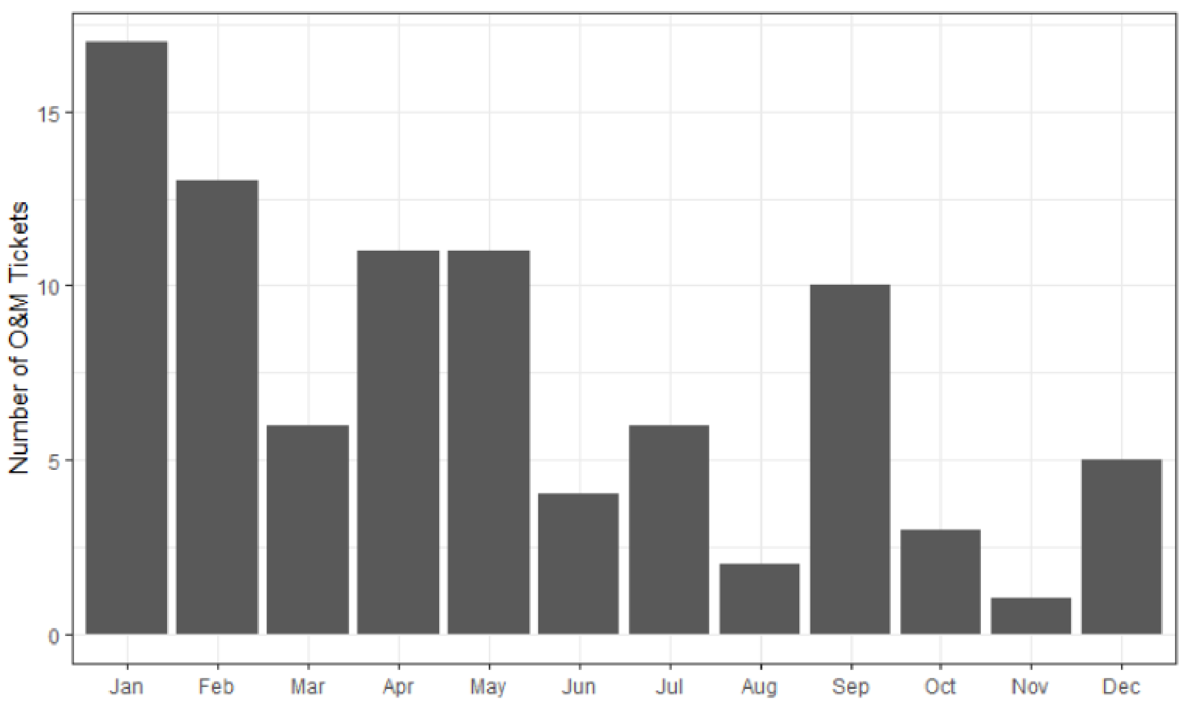

Figure B-5. Number of O&M tickets in PVROM related to PV+Storage by month.

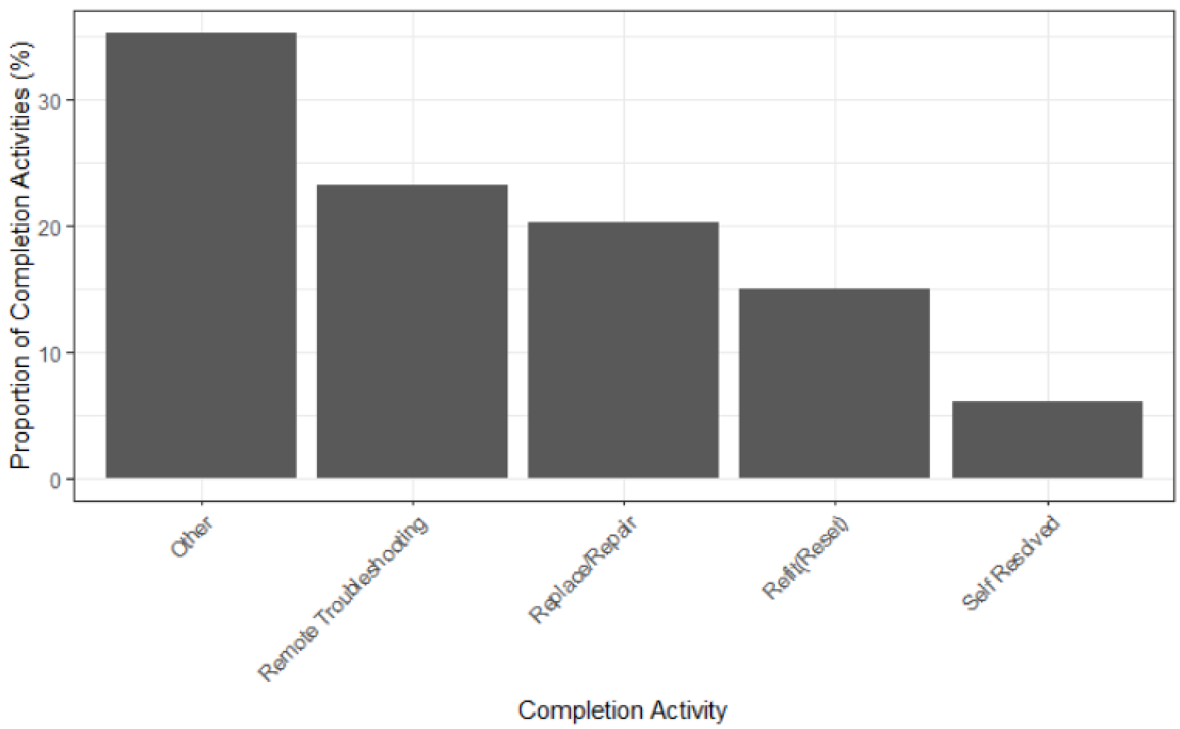

Figure B-6. Completion activities associated with corrective maintenance tickets storage systems.

B.2. Additional Tables

Table A1. Primary functions organized by storage technology type and across all technologies. Values reflect the percentage of sites indicating function is key purpose of the battery storage system. Sites could select multiple functions.

Primary function	Lead Acid	Lithium-ion	Lithium-ion, Lead Acid	Lithium-ion, Lead Acid, Nickel Cadmium	Lithium Iron Phosphate	All Technologies
DC Clipping Storage	0	0	0	0	25	1.2
Demand Balancing	16.7	40	0	0	0	18.5
Energy Arbitrage	0	8.6	0	0	0	3.7
Frequency Control	83.3	0	100	0	0	7.4
Fuel Savings	0	0	0	100	0	43.2
Micro-grid Controller	0	2.9	0	0	0	1.2
Peak Demand Shaving	83.3	17.1	100	0	50	17.3
Reliability	16.7	8.6	0	0	0	4.9
Resiliency	100	17.1	0	100	50	60.5
System off-grid	0	0	0	0	25	1.2
Technology Demonstration	0	22.9	0	0	0	9.9

Table A2. Selection factors as organized by storage technology type and across all sites. Values reflect the percentage of sites indicating factor influenced the selection of storage technology type. Sites could select multiple factors.

Selection factor	Lead Acid	Lithium-ion	Lithium-ion, Lead Acid	Lithium-ion, Lead Acid, Nickel Cadmium	Lithium Iron Phosphate	All Technologies
Available footprint	0	2.9	0	0	0	1.2
Budget limitations	0	2.9	0	0	0	1.2
Capital cost	100	37.1	0	100	75	70.4
Financial viability of the company	0	22.9	0	0	0	9.9
O&M cost	0	34.3	0	100	25	59.3
Other not specified	0	42.9	0	0	0	18.5
Payback period guidelines	0	11.4	0	0	0	4.9
Prior experience with vendor	0	NA	0	0	25	1.2
Reliability	0	NA	0	0	25	1.2
Safety regulations	83.3	NA	0	0	0	6.2
Site location climate	0	NA	0	0	25	1.2
Technology familiarity	0	NA	0	0	25	1.2
Technology performance	83.3	48.6	100	100	25	72.8
Technology readiness level	83.3	57.1	100	100	50	77.8
Warranty availability	0	NA	0	0	25	1.2

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