ELECTRIC POWER RESEARCH INSTITUTE

Guidelines for Assessing End-of-Life Management Options for Renewable and Battery Energy Storage Technologies

Technical Brief

Deployment of new renewable and battery energy storage technologies, or creation of fleet replacement strategies using these technologies, should consider the new asset's decommissioning and end-of-life (EoL) management requirements. Widespread recognition exists that enhanced EoL management of energy technologies will be a key future need to reduce waste, increase material reuse and circular economies, maximize environmental and resource stewardship, and provide additional financial value. However, most energy facilities are not designed or managed for ease of repowering or disassembly, or site restoration.

Figure 1. EoL management is increasingly important for PV modules, wind turbine blades and battery energy storage systems.

As a result of the above needs, these industries have seen rapid increases in related research, development of logistics, and market assessments. Laboratory, pilot testing, and scale-up efforts for recycling and reclamation processes are ongoing around the world [1,2,3,4,5]. New entrants into this market, as well as departures, are expected in upcoming years as the volume of renewable materials reaching EoL increases and a wider range of business models become economic. However, only a limited number of EoL management processes are currently in place across the range of technology vendors and project developers, and the extent to which they meet utility sustainability, certification, and liability requirements varies. Compilation of best practices and guidelines for decommissioning continues to be a strong need for electric utilities.

As EoL volumes of solar photovoltaics, wind turbines, and electric vehicle and grid-scale battery energy storage systems increase, electric utilities that own and operate these systems have questions about how to responsibly and cost-effectively manage these materials. The EPRI Renewables and Battery End-of-Life Strategic Initiative [6] was created to support the electric power industry in proactively managing technology EOL issues, developing sustainable solutions, and avoiding unintentional potential environmental liabilities in the future.

A common question posed to EPRI staff and utility members is how to begin the process of determining the final disposition of renewable and battery technologies. There is a need to share lessons learned that have been gained from other utilities that have already gone through this process. This technical brief discusses the basic decommissioning process and considerations that are common to renewable and lithium ion battery technologies, lists possible actions at the point of technology procurement, then describes technology-specific procedures once assets reach end of life. It is intended as a starting point for information gathering on recycling, reuse or second life, or disposal options. A related EPRI deliverable summarizes examples of current service providers in this arena [7].

The technologies of focus include:

- Solar photovoltaic (PV) modules;
- Wind turbine blades; and
- Stationary battery energy storage systems.

Note that electric vehicle and stationary storage system battery modules will be handled in a similar manner at the point of recycling or disposal once they are removed from their platforms. Guidance provided here for module management is relevant to both application types. It is possible that utility-owned or customer electric vehicle fleets are more likely than stationary systems to be managed through the vehicle manufacturer or resale agents before reaching the point of final disposition. This technical brief thus focuses on decommissioning of stationary energy storage platforms, although several battery and vehicle manufacturer, research and industry consortia, including EPRI, are actively engaged in electric vehicle end-of-life management.

Common Overall Procedures

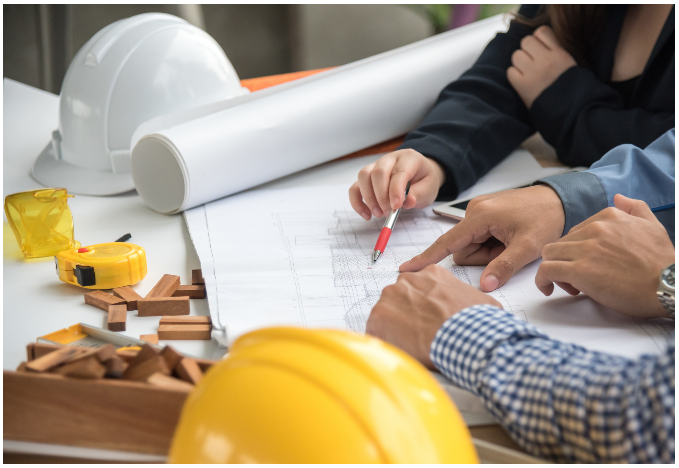

Figure 2. Key steps at EoL include reviewing decommissioning plans, contractual arrangements, and regulatory requirements.

Once a system is determined to have reached EoL, a series of steps common to all technologies should next be considered. These are included below:

- Review any previously created plans for repowering or decommissioning that were considered at the point of procurement for the site of interest, or for other facilities. It is currently not well known how many solar PV, wind turbine, and battery energy storage installations have an associated decommissioning plan, whether a required document or an informal internal company plan. A recent EPRI report says plans are common for solar PV [8], although the facilities reviewed were more recent projects. It is possible plans were less commonly created for older projects, or for certain technologies. EPRI has summarized themes in plan components, cost ranges, and relevant regulatory actions in several reports. [8,9,5].
- Gather site and system details, and other information that describes the facility and might be requested by service provider. These could include: system specifications; decommissioning site area size and layout, including access points; electrical, civil and structural drawings; any non-standard sizing or modified system parameters; weights and quantities of liquid volumes and/or refrigerants; list of equipment to be removed, recycled or disposed of; materials safety data sheets (MSDS) and any other available compositional information; amount and composition of bulk materials for removal; general information about state of health and damage. It is recommended to collect and save this information at the point of installation, for ease of access as the system matures.
- Consider the desired outcome, which could range from repowering a subset of the renewable or storage technology, repurposing of the site, or site restoration to original "greenfield" condition. Repowering or repurposing can be attractive options for systems that are underperforming or have incurred damage, or systems that are expensive to maintain. Determining preferred options may include modeling to assess the costs of repowering, repurposing, or site restoration against the potential performance, environmental, or economic benefits. Factors in the decision process may also include contractual obligations; permit or land lease requirements; capital, financing, and labor costs for equipment replacement; end-of-life management costs for equipment and materials taken out of service; as well as long-term business interests and resource needs. Environmental impacts may also be a consideration, including emissions reductions generated by the system; temporary pollutant and greenhouse gas emissions from equipment and vehicles required for system removal, off-site transportation, and materials processing and disposal; habitat and species protection; ecosystem services; and site conservation or preservation objectives.
- Develop a scope of work & technical requirements for the project. Engage with several service providers for detailed descriptions of service and cost estimates. Due to the range of services offered and business structures across the companies working in this space, careful consideration should be made of total costing and service package. Service providers may only deal with project management logistics, or subsets of logistics (e.g., on-site system disassembly, transportation) while others will also perform refurbishment or recycling in-house. It is common for a utility to work directly with a project management/logistics or engineering firm, who may in turn hire subcontractors to perform certain aspects of the work, and then transfer the valuable components to recycling companies (e.g., the battery modules would go to a battery recycler). Those recycling companies may disassemble the component, distribute salvageable materials for recycling, and dispose of the remaining material. Utilities may have requirements on subcontractor characteristics, or the investment recovery process for removed equipment or materials, that need accommodation.
- Determine required permits, custody and liability at each step of system dismantling, removal, component disassembly, recycling and disposal. These could include general permits (e.g., traffic control, demolition permit) or items specific to the technology being removed. Determine who is responsible for meeting regulatory requirements for transport, hazardous waste, or other issues. Be aware transport of some or all material may occur across state or country boundaries depending on the location of the recycler's facilities. Ensure the entity to receive any salvage credit from the decommissioned equipment and/or scrap materials is clearly determined.
- Perform site walk-through and/or share imagery with selected provider(s) to refine logistical and financial estimates. Double check that any site design or specification paperwork accurately matches the final installed equipment or take note and adjust plans accordingly. The design paperwork can sometimes reflect generational updates in technology, but not the exact models or designs that are installed. Carefully confirm packaging and transportation service vehicles are appropriate for the equipment and component sizes. Document the differences for owner and service provider records.

- Confirm a decommissioning work plan across all relevant partners. Arrangements should be made for security, health and safety, emergency response, technology de-energization, disconnection, disassembly, removal, packaging/labeling, handling and transport of the system components. Removal/recovery of fire suppressants and HVAC refrigerants may need to be considered. Determine if other testing is required for the key technology components (e.g. Resource Conservation and Recovery Act (RCRA) hazardous material classification testing such as Toxicity Characteristic Leaching Procedure (TCLP) analyses) or bulk materials (e.g., asbestos, contaminated concrete).
- Provide site access and safety training to the service providers. Supervise de-energize/disconnect, disassembly, removal and packaging. It is not uncommon for this phase to be concentrated in several long consecutive days. Check expected time frames for deconstruction equipment and transport vehicle arrivals and rental times. Inaccurate estimates in the time needed for disassembly and removal, and associated delays that can result in unexpected rental costs, are not uncommon due to the limited experience most vendors have with removing renewable and battery systems.
- Once the process is complete, documentation of the final disposition of the materials (e.g., delivery and recycling) should be provided to the owner. Final location should clearly match the transportation document signed before the material is sent to a recycling facility.

Possible Actions at Procurement

A utility can take several actions at the point of facility design and procurement to reduce risks and influence options for asset management (e.g., sale, life extension, repowering, and retirement). These include the following:

- Request information on EoL management processes from both the technology manufacturer and the developer or engineering firm that will design and construct the site. Is manufacturer takeback recommended or available? What is the product bill of materials? Does the firm have relationships/recommendations for certain EoL service providers that have experience with their technology? Consider requesting from the manufacturer a checklist of the equipment in the facility along with the manufacturer's recommended recycling facility for each component.
- Ensure a decommissioning cost estimate is calculated and the net salvage value is determined as a % of total installed project costs. This could involve engaging professional engineers, who can accurately break down work scope, and potentially researchers or service providers who are projecting markets and costs out to the time of expected end of system life. Underestimates of the dismantling time and associated labor and equipment rental costs are a common source of error [9]. On the other hand, some EoL service providers may provide higher estimates of overall decommissioning and recycling costs, as they are less familiar with the procedures for certain technologies due to a limited number of facilities reaching EoL. Another option to consider is that some technology manufacturers may directly include takeback and/or recycling and disposal costs as part of the project development budget due to the value they can recover from materials extraction at end of life or due to material scarcity concerns. Estimates can be used to help justify the amount of relevant financial assurance needed for a project.
- Consider what financial assurance mechanisms are required or desired by the financier, insurance firm, parent company, or other project partners. Some form of financial assurance typically must be in place at the inception of project construction or operation. For example, PV plant decommissioning guidance on best practices provided by some state or local authorities recommends reserve, trust, or escrow accounts; surety bonds or letter of credit; or parent guarantees are created to support plant decommissioning [8]. These mechanisms can help protect a utility in the event a partner responsible for decommissioning or recycling goes out of business and is no longer available to fulfill their planned role.
- Plan for cost estimates to be reviewed and updated as EoL is approached. Second life markets are expected to expand for technologies such as batteries, and even established markets will be affected by global changes in demand and material recovery developments. The relative costs of EoL options may change as recycling processes for renewables and batteries improve and as investments are made in dedicated recycling facilities. Greater certainty in decommissioning costs and process efficiency improvements may reduce costs as the industry becomes more experienced.
- Consider including contractual terms that clearly define EoL responsibilities for relevant parties at the point of procurement. During project development, decommissioning plans can delineate the EoL responsibilities of the asset owners, including eventual removal, restoration, and disposition processes to be conducted at the end of the project's operational lifetime or if the project is determined to be abandoned. While decommissioning responsibilities belong to the asset owner and are accounted for as a liability, these responsibilities can be assigned to others others—such as engineering, procurement, and construction (EPC) or operations and maintenance (O&M) contractors—as a way of allocating risks to more experienced service providers. If it is expected to be available when the system reaches EoL, inclusion of manufacturer takeback as a management option should be considered.
- Consider the tax and contractual implications of various EoL decisions. For example, if a project receives the federal investment tax credit (ITC) or accelerated depreciation benefits, failure of the facility in the first 5 years of the planned operating life, resulting in early decommissioning, may reduce or remove eligibility for those incentives. Additionally, ownership transfers, such as partnership flips, could be jeopardized by early project decommissioning, leaving the original system owner with EOL management responsibility. Ensure the decommissioning planning process includes consideration of the requirements of such incentives and contract agreements, and the implications thereof, if the preference of site management changes (e.g., lifetime extension, refurbishment, or repowering becomes desirable instead of decommissioning at a set time).
- Review existing and pending regulatory requirements for material management after decommissioning (e.g., landfill bans, fees during purchase that are required to support EoL management) to set expectations. Currently in the U.S., these requirements are more common on a local or state level, and not federal level. The exception are facilities

located on federal property and controlled by the Bureau of Land Management or other agencies. Re-review should occur in advance of initiating repowering or decommissioning, due to the rapid evolution of waste management practices for some of the technologies of interest. In some locations, New York for example, the state is beginning to harmonize varying local or municipal requirements [9], though this is not yet common. In the event any deviation occurs from a particular standard, a clear justification should be provided to ensure all parties understand why a particular task was not implemented or considered.

- Consider selecting technologies, manufacturers or project management/engineering firms that have demonstrated or are developing EoL management processes rather that those that leave this up to the buyer to determine. These could include manufacturer takeback protocols or extended producer responsibility commitments; provision of compositional or hazardous waste classification data; design features of the components or overall system that facilitate repowering/repair as well as disassembly; established relationships with recycling firms; or experience with reuse of system components.
- Preferentially consider service providers that have certifications for environmentally responsible recycling. For example, e-waste recyclers may hold Sustainable Electronics Recycling International (SERI) Responsible Recycling (R2) Standard [10] or e-Stewards [11] certifications. Entities following International Standards Organization (ISO) 140001 Environmental Management System Standards [12] are also desired. Not only does this mean the firms meet specific operational guidelines, it also may imply they have additional experience with EoL management as the holding of such certifications can act as a driver for customer selection of their technology or service.
- Create a decommissioning plan, even if not required and only for internal use. Common elements of decommissioning plans include descriptions of the project and site; expected facility lifetime; cost estimates; plan for notification of relevant authorities, partners, and emergency response agencies; summary of relevant regulatory and permit requirements; typical removal and demolition elements; disposition of key components (e.g., battery modules, turbine blades, and PV modules); and plans for site restoration. Examples of decommissioning plans range from several pages to detailed versions with engineering drawings and tabulated cost estimates.

Technology-Specific Considerations

Solar PV Modules

Several voluntary industry standards or certifications exist to delineate important aspects of environmental, occupational health and safety, and social responsibility leadership as it relates to renewable energy technologies. In the absence of a strong regulatory presence, these certifications and standards may encourage sustainable material decisions, as well as other life cycle aspects such as system design to facilitate recycling and reuse. Another benefit of manufacturer or EoL service provider certification is that it provides differentiation between vendors that can be considered during technology or EoL service procurement. In addition to the more general SERI R2, e-Stewards, and ISO 14001 Environmental Management System recycling standards mentioned above, several voluntary programs exist for solar PV modules. Electric utilities considering EoL

Figure 3. Solar PV modules stacked after removal.

manufacturers, developers, or service providers could choose to preferentially select those holding such designations.

- The NSF International/ American National Standards Institute (NSF/ANSI) 457 Sustainability Leadership Standard for PV Modules and Inverters was facilitated by the Green Electronics Council (GEC) and NSF International [13]. The standard establishes corporate performance metrics and sustainability performance criteria used to demonstrate leadership. Performance objectives were created for PV modules and inverter manufacturers. An audit process is used to demonstrate compliance at ratings of gold, silver, and bronze. The NSF/ANSI 457 standard is listed on the Electronic Product Environmental Assessment Tool (EPEAT) registry [14], an online eco-label tool intended to help purchasers compare electronic products based on their environmental attributes (e.g., toxicity of materials, recyclability).
- The Silicon Valley Toxics Coalition (SVTC) developed the Solar Scorecard to document transparent environmental and social justice practices in the solar industry [15]. The rankings are based on voluntary answers provided by PV module manufacturers to survey questions about their business practices. Scorecard metrics relevant to EoL management practices include: extended producer responsibility requirements to takeback modules and ensure they are recycled; use of recycled materials during manufacturing; compliance with ISO 14001 Environmental Management Standard; reporting of associated landfill waste; and analysis of disposal and recycling processes.

- In 2016 the Solar Energy Industries Association (SEIA) created a member-based National PV Recycling Program to network recycling companies that responsibly manage modules and other PV system components [16]. Certain recycling partners are designated as "preferred" through an evaluation process to ensure practices meet SEIA's standards. For example, modules and components must be processed in the United States and hold a recycling certification.

A recent EPRI report identified a wide range of decommissioning cost estimates detailed in decommissioning plans for large-scale PV [8]. Some plans optimistically predicted a positive plant salvage value at decommissioning valued at up to $70.5/kW_{DC}$ of cost that would be recouped, whereas most plans assumed a net expenditure. The upper end of the range was $141.6/kW_{DC}$. The mean decommissioning cost estimate across the 25 plans that EPRI reviewed was $21.6/kW_{DC}$. Sources of variation among estimates included equipment salvage value, module disposal/reuse/recycling plans, and site restoration requirements. A separate 2018 EPRI study estimated the cost to decommission a conceptual 11 MW_{AC} (13.2 MW_{DC}) facility [17]. Assuming modules are landfilled, the negative net salvage value would be $69/kW_{DC}$, or 4.8% relative to the installed cost. If modules are instead assumed to be recycled at a price of $10/module to $30/module, the decommissioning estimate increased to $95/kW_{DC}$ to $153/kW_{DC}$.

Wind Turbines

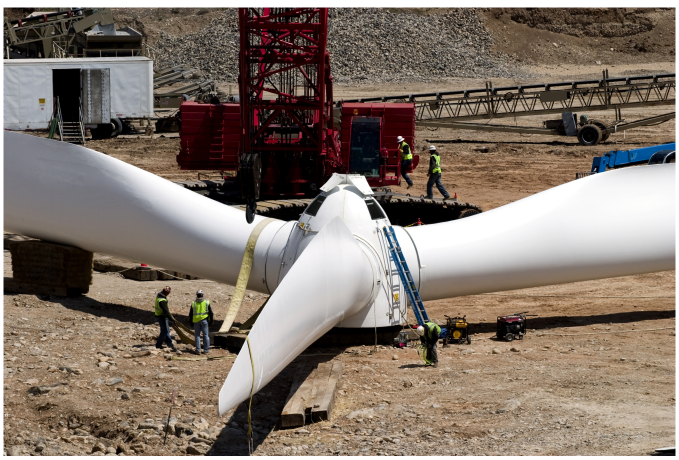

Figure 4. Wind turbine blades being removed.

The regulatory requirements differ for EoL management of wind turbines installed in onshore and offshore locations. For example, decommissioning of offshore facilities must follow international standards set by the United Nations Convention on the Law of the Sea through the International Maritime Organization and by the Oslo and Paris Convention for the Protection of the Marine Environment of the North-East Atlantic [9]. In the United States, it is the Bureau of Ocean Energy Management which requires that conceptual decommissioning plans and preliminary cost estimates be included in the construction and operations plans for farms proposed for federal waters. Meanwhile, onshore wind farms do not have a specific standard for decommissioning and vary widely by location.

A recent EPRI report summarizes a range of gross cost estimates for decommissioning for more than 25 facilities in the United States from $100,000 - $700,000 per turbine. Salvage values for bulk components can reduce the net costs in comparison. Rotor blades are usually fabricated from fiber-reinforced composites, for which recycling and reuse options are generally in the early stage of development [4]. Thus, current U.S. decommissioning plans reviewed by EPRI either specified that blades will be landfilled or did not specify the disposition of the blades.

Some direct reuse options for end-of-life wind turbine blades currently being investigated include their use as structures, such as transmission towers, pedestrian bridges, and building roofs, as well as their use in reclamation of coal mines. Recycling of end of life blades generally begins with size reduction through cutting, shredding or grinding. Subsequent options being studied include pelletization for use in new composites, grinding into fibers and powders for use as filler, and chemical or thermal processing to decompose the blades into useful components. One recently commercialized recycling option involves processing end-of-life blades into raw material feed for production of Portland cement in kilns.

Stationary Battery Storage Systems

Figure 5. Cutaway of a typical stationary battery energy storage container.

Many system details, from battery energy density and module and total system weights, are important metrics in cost estimation as they directly affect the labor and logistics required for dismantling, packaging, transportation, and recycling stationary battery energy storage systems. A typical cost breakdown for a lithium ion battery system is as follows: Roughly 40% of cost accrues to on-site dismantling and packaging, 30% to transportation costs, and 30% to recycling costs. EPRI estimated recycling costs from a 1MWh system for a variety of lithium ion battery chemistries (summarized in Table 1) [18] and has recently expanded that methodology to look at other technologies. Moving forward, cost savings due to the increased scale of EoL volumes and process improvements may balance expectations of increased labor and other inflation costs.

Table 1. Estimated decommissioning and recycling costs for various lithium ion battery chemistries.

Chemistry	Estimated Recycling Costs	
	Price per pound	Price per kilogram
NCA – Nickel Cobalt Aluminum Oxide	$1.00	$2.20
NMC – Nickel Manganese Cobalt Oxide	$1.00	$2.20
LMO – Lithium Manganese Oxide	$2.50	$5.50
LFP – Lithium Iron Phosphate	$2.50	$5.50
LTO – Lithium Titanate	$1.00	$2.20

Once removed from the system, battery modules are transported to specialized recycling and material recovery facilities. Using current commercial recycling processes for lithium ion batteries, these modules are typically first shredded, resulting in a combination of fine solid material called "black mass". This is a combination of lithium, manganese, cobalt, and other desired elements, as well as plastics and carbon. Subsequent processing uses a hydrometallurgical or pyrometallurgical approach, or combination thereof to extract the elements of interest from the black mass. Advanced techniques, which will shift towards direct cathode recycling or highly refined product approaches, remain in the research and development phase and are not commercially available.

References

1. EPRI. *Program on Technology Innovation: Feasibility Study on Photovoltaic Module Recycling in the United States*. Palo Alto, CA: 2018. 3002012461.
2. EPRI. *Insights on Photovoltaic Recycling Processes in Europe*. Palo Alto, CA: 2017. 3002008846.
3. EPRI. *Novel PV Recycling Processes*. Palo Alto, CA: 2018. 3002014487.
4. EPRI. *Wind Turbine Blade Recycling: Preliminary Assessment*. Palo Alto, CA: 2020. 3002017711.
5. EPRI. *End-of-Life Management for Lithium Ion Battery Storage*. Palo Alto, CA: Expected 2021.
6. EPRI. *Renewables and Battery End-of-Life Strategic Initiative*. Palo Alto, CA: 2019. 3002016314.
7. EPRI. *End-of-Life Service Providers for Renewable and Battery Technologies*. Palo Alto, CA: 2021. 3002020492.
8. EPRI. *Decommissioning Plans for Large-Scale Solar Plants: Issues, Uncertainties and Opportunities*. Palo Alto, CA: 2020. 302019089.
9. EPRI. *Decommissioning Plans for Wind Farm: Issues, Uncertainties and Opportunities.* Palo Alto, CA: 2020. 3002019651.
10. SERI. "R2". Accessed February 8, 2020 at https://sustainableelectronics.org/r2/.
11. e-Stewards. "e-Stewards". Accessed February 8, 2020 at http://e-stewards.org/.
12. ISO. "ISO 14000 Family, Environmental Management". Accessed February 8, 2020 at https://www.iso.org/iso-14001-environmental-management.html.
13. NSF International. "Solar PV Modules – Sustainability Leadership Objectives," May 7, 2020. Accessed February 5, 2021 at https://blog.ansi.org/2020/05/solar-pv-sustainability-leadership-ansi-457/.
14. Electronic Product Environmental Assessment Tool (EPEAT) registry (www.epeat.net).
15. SVTC. "Solar Scorecard 2018-19". Accessed February 5, 2020 at http://www.solarscorecard.com/2018-19/.
16. SEIA. "SEIA National PV Recycling Program". Accessed February 5, 2020 at https://www.seia.org/initiatives/seia-national-pv-recycling-program.
17. EPRI. *PV Plant Decommissioning Salvage Value: Conceptual Cost Estimate*. Palo Alto, CA: 2018. 3002013116.
18. EPRI. *Recycling and Disposal of Battery-Based Grid Energy Storage Systems: A Preliminary Investigation*. Palo Alto, CA: 2017. 3002006911.

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3002020594 March 2021

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