WHITE PAPER

Renewable Energy's End-of-Life Challenge: Identifying Recycling Options for Batteries, Solar Panels and Wind Turbines

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Renewable energy technologies are revolutionizing energy production and storage, but the associated assets have limited end-of-life potential. By 2050, these assets are expected to generate significant amounts of waste. While recycling methods currently exist, scientists are exploring new materials and techniques to streamline processes.

Although natural gas has usurped coal as the largest source of electricity generation in the U.S., renewable sources of energy are gaining ground. These developments bode well for proponents of emissions reductions, but life-cycle analyses show end-of-life opportunities for wind and solar assets could lead to new forms of waste and pollution.

Wind turbines, solar panels and the battery storage systems that support renewable energy are impermanent, and three data points underscore the conundrum facing energy providers and utilities across the U.S. According to the Electric Power Research Institute, there will be an estimated 4 million tons of wind turbine blade waste and 10 million tons of solar photovoltaic (PV) waste in the U.S. by 2050. Similarly, there will be 20 million tons of lithium-ion battery waste in the U.S. by 2050.

These forecasts highlight a drawback of renewable energy generation, especially for the solar, wind and battery storage assets that power these systems. Conversely, these estimates highlight an opportunity to identify viable end-of-life disposal and recycling systems for renewable energy assets.

Recycling methods for solar panels, wind turbines and lithium-ion batteries exist, but pinpointing the optimal approach is complicated, often due to the chemical composition of the renewable energy asset. For example, some recycling methods for wind turbine blades produce hazardous particulate matter or toxic byproducts. Other methods that are less toxic can be difficult to scale up, making it difficult to establish recycling facilities nationally or near end-of-life renewable assets. Taking into account environmental and operational challenges associated with recycling renewable energy technology, owners and operators of renewable energy facilities will need to choose between various disposal methods. Ideally, when more recycling facilities — specifically designed for renewable assets — are established, costs associated with recycling will go down because asset owners won't have to ship retired assets long distances.

Wind Turbines

Approximately 90% of a single wind turbine comprises easily recyclable materials, including metals and concrete. Accounting for 10% of the overall materials used to build a wind turbine, the blades are often the most difficult component to recycle.

Identifying solutions to effectively recycle turbine blades is complex because the turbine blades are made from epoxy-fiber composite. The carbon fibers or fiberglass used to make wind turbine blades can be recycled into other materials and deliver a high-recovery value. However, recycling can be problematic due to the thermoset epoxy's resistance to melting. To facilitate the recycling of wind turbines, four approaches are emerging. Wind turbine blades can be recycled using a combination of mechanical, thermal, co-processing and chemical approaches. Most recycling facilities will mechanically break down wind turbine blades before executing a thermal, chemical or co-processing approach.

Using the following methods, asset owners can recycle wind turbine blades:

- Mechanical recycling: This recycling method involves crushing the blades into small fragments that can be used in insulation, artificial wood or plywood. Mechanical recycling is cost-effective and the resulting material can be incorporated into various consumer products. However, a drawback of this process is the generation of hazardous particulate matter.
- Thermal recycling: This approach includes decomposing epoxy from carbon and glass fibers using high temperatures, either in the absence or presence of oxygen. This process will create clean fragments of carbon or glass fibers, and the byproducts of this recycling method have a higher economic value. Thermal recycling uses high temperatures, which can be expensive. Additionally, the high temperatures required during thermal recycling can degrade the fibers and reduce tensile strength.
- Co-processing: This method includes shredding and burning turbine blades. It offers several advantages, including the fact that the fly ash generated from the burning process can substitute for nearly 30% of the coal fly ash used in cement manufacturing. Moreover, the incineration process not only generates energy but is also cost-effective. However, there are some drawbacks associated with the burning process. Wind turbine blades are often made from fiberglass, which is incombustible. Also, the epoxy used in wind turbine blades produces toxic byproducts when combusted.
- Chemical recycling: This recycling method involves chemically decomposing the epoxy while facilitating the recovery of carbon and fiberglass. Unfortunately, this process is very complex and difficult to scale up. Furthermore, it necessitates the use of toxic solvents and high temperatures. Conversely, recycling processors can anticipate reclaiming 90% of fibers with tensile strength exceeding 85% of the original material. This method stands out for its superior economic value compared to the other three recycling processes.

Researchers and scientists are currently investigating approaches to enhance wind turbine blade recycling. Some companies are exploring the benefits of thermoplastic epoxy, a material that melts at lower temperatures in acidic conditions. Using this material makes it easier to repair blades and recover fibers. While scientists continue to investigate various recycling methods for wind turbines, asset managers may want to consider alternative solutions for decommissioned wind turbine blades. Blades can be repurposed into various new structures, including pedestrian bridges, playgrounds, or materials for flooring and roofing. These practical and alternative applications can contribute to sustainable practices while reducing waste from wind turbines.

Solar Photovoltaics Modules

Two types of modules lead the solar panel market: crystalline silicon (c-Si) and thin cell modules. Both types of modules utilize three main components: glass, ethylene-vinyl acetate (EVA) and solar wafers. These solar wafers contain high-value materials such as cadmium, copper, silicon, silver, tin and zinc. When solar wafers from c-Si panels can be recovered without any degradation or damage, they can potentially be reused to create new panels. Unlike wind turbine blades, there are two approaches to recover the high-value materials found in solar panels. First, recycling facilities can extract rare minerals and metal from solar wafers. The second option is to recover the entire wafer, typically through mechanical or chemical recycling processes.

Recovering high-value metals from solar PV panels involves a combination of various recycling methods, adding complexity to the economics and operations required to recycle these panels. EVA is a thermoset polymer, which is challenging to separate from glass and solar cells during recycling. Also, high-value metals account for less than 10% of the entire module. Scientists and engineers continue to research closed-loop manufacturing processes to reuse materials while mitigating increased CO2 emissions, material scarcity, supply constraints and energy consumption, but closed-loop manufacturing is not yet a reality within the solar PV industry. Infrastructure technology firms are researching materials that could support close-loop manufacturing of solar panels, with more research and development expected in the coming years.

While there is no single method to recycling solar PV modules, these renewable assets can be recycled using a combination of the following methods:

- Mechanical recycling: During this process the solar PV module will be crushed before glass is recovered through attrition, vacuum blasting or other methods. This approach is advantageous, because glass can be recovered without the use of chemicals or high temperatures. Unfortunately, up to 40% of the original material becomes waste due contamination and this method produces hazardous particulate matter. Another method of mechanical recycling includes hot-wire cutting to remove glass without shredding the solar panel. This approach recovers the solar wafer with minimal damage and doesn't require the use of chemicals or high temperatures.
- Thermal recycling: During thermal recycling, solar modules withstand temperatures ranging from 450 degrees Celsius to 650 degrees Celsius to facilitate burning the EVA layer off the solar wafer. At 650 degrees Celsius, recycling vendors can expect a 91% recovery rate for clean glass, but temperatures exceeding 450 degrees Celsius have negative consequences, including the degradation of solar wafers. Unfortunately, this method also produces emissions and chemical compounds, including methane, carbon monoxide, carbon dioxide and hydrogen fluoride. An alternative approach known as electrothermal heating generates heat using an alternating magnetic field. Electrothermal heating can reduce emissions while yielding clean glass. However, it's worth noting that electrothermal heating will crack solar wafers and requires additional processes to recover raw materials.
- Chemical recycling: When solar PV modules are chemically recycled, various acids and chemicals are employed to extract and purify valuable metals from the solar wafer. While these chemical processes effectively recover high-value minerals, the acids and chemicals involved in this process are hazardous, making it difficult to implement chemical recycling at a commercial scale. Likewise, the EVA layer of a c-Si panel can be removed from the solar wafer using a chemical bath at low temperatures. The resulting solar wafer is almost identical to commercially sold products, but this process produces toxic gases.

While a combination of these processes is necessary to recycle a solar panel, all solar panel recycling efforts will require either mechanical or thermal processes to remove the EVA layer. Although each approach has its limitations, scientists are actively exploring different materials and manufacturing methods for solar PV modules with the aim of streamlining and simplifying the recycling process. One potential improvement scientists are exploring is utilizing a thermoplastic layer, which could be easier to recycle than a thermoset polymer. Additionally, vacuum pressure can be used to reduce soldering and lamination. Focusing on material choices during the production process has the potential to reduce waste generated by solar panels when they reach the end of their life cycle.

Lithium-Ion Batteries

While there are numerous types of battery chemistries, two types are commonly used in energy storage and would be regularly used to support energy storage for renewable assets. Unlike other batteries, lithium iron phosphate (LFP) batteries don't require cobalt, which is a costly component. Over time, nickel manganese cobalt oxide (NMC) batteries have been developed to incorporate more nickel and less cobalt, helping to reduce costs.

Recycling lithium-ion batteries has some obvious advantages, including mitigating potential supply chain issues while reducing the fossil fuel consumption required for mining and refining critical raw materials. Unfortunately, recycling lithium-ion batteries poses challenges, including the use of hazardous chemicals and requiring higher temperatures.

The following methods can be used to recycle lithium-ion batteries:

- Thermal recycling: This recycling method utilizes controlled incineration to deactivate the battery. Waste leftover from the incineration process is smelted to recover raw materials. This approach to lithium-ion battery recycling is highly efficient and requires very little physical space. However, it's important to consider that exposing LFP or NMC batteries to high temperatures can generate hydrogen fluoride, an inorganic compound that is both highly corrosive and poisonous. Additionally, a portion of the lithium found in batteries is lost during the typical thermal recycling process.

- Chemical recycling: By leaching the lithium-ion batteries in acid, rare and raw metals can be recovered and recycled. However, before leaching the battery in an aqueous solution, a pre-treatment process is required to classify, separate and discharge the battery properly. Avoiding the pre-treatment process could result in the battery short-circuiting or exploding. Although chemical recycling allows facilities to recover a significant amount of metals and raw materials, this recycling method also generates hazardous chemicals and it is difficult to implement on a commercial scale.
- Direct recycling: The process of direct recycling employs both thermal and chemical processes to recover and regenerate cathode material. The cathode material can be used again in new batteries, thus promoting circularity while mitigating potential environmental damage from mining. Unfortunately, to implement this process on a commercial scale, batteries need standardized chemistry. Presently, most batteries have different chemistries, which makes it challenging to adopt this approach.

While all three approaches could be used to recycle lithium-ion batteries, thermal and chemical recycling methods can be employed without direct recycling, but this depends on how the recycling facility deactivates batteries.

The Infrastructure Investment and Jobs Act and the Inflation Reduction Act (IRA) have changed the economics of renewable asset recycling. While not explicitly providing funding for recycling facilities, these laws provide tax abatements for utilities and developers who purchase batteries, wind turbines and solar panels that use materials sourced or recycled in the United States. The developers seeking these abatements as well as end-of-life disposal opportunities will be searching the market for recycling facilities. In the current market, transporting and recycling renewable energy technologies isn't cost competitive when compared to landfill tipping fees, even with the cost to recycle renewable assets and technologies is expected to go down in the next decade. Whether a recycling firm wants to establish a new facility or an asset owner wants to dispose of renewable assets, distance is often a priority. The most cost-effective recycling option typically depends on the distance from the project site to the recycling facility. Since passage of the IRA, more than $2 billion has been invested in recycling efforts for renewable assets, with funding coming from both governmental and private sources.

Market demand for recycling facilities is set to grow. When recycling methods become more economically viable and recycling facilities promulgate, asset owners will have more options to explore. Currently, utilities and asset owners concerned about recycling can allocate funds for end-of-life decommissioning and recycling of major components by incorporating a standardized clause in power purchase agreements.

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