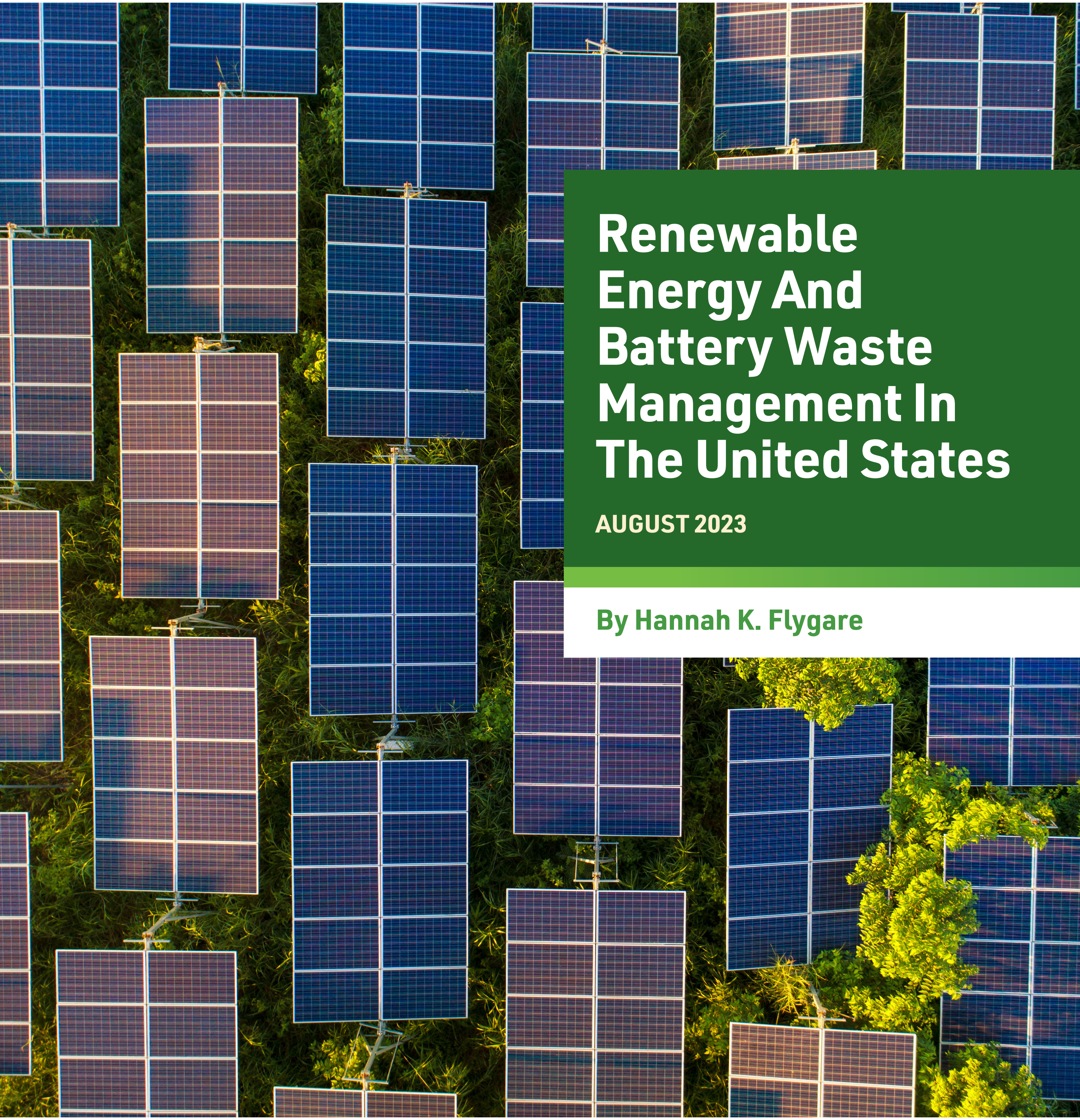

Renewable Energy And Battery Waste Management In The United States

AUGUST 2023

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Executive Summary

Due to the concerns surrounding climate change and its consequences, governments and the private sector are looking to decarbonize the energy and transportation sectors. This means building wind energy, solar energy, and electric vehicles (EVs) at unprecedented rates. At the same time as manufacturing and installation rates are increasing, large amounts of solar panels, wind turbines, and lithium-ion batteries (LIBs) are reaching the end of their useful life. Most wind turbines, solar panels, and LIBs are not recycled despite there being growing demand for the materials that these waste streams contain such as copper, lithium, silver, and cobalt. In fact, the International Energy Agency (IEA) predicts that all of these materials will not be manufactured in sufficient quantities to meet demand by as soon as 2030.[1]

Recycling is one way that society can mitigate shortages and meet the demand for critical minerals in the long-term. While it may seem like the obvious solution, it cannot stop near-term shortages. Additionally, it requires advanced machinery, energy, and reagents which together can add up to cost more than new materials. Cost is not the only issue; for some of the recycling steps, research is on-going. This report outlines the technical and economic hurdles facing the solar, wind, and LIB recycling industries and discusses policy options to address them.

The major technical hurdles facing solar panel recycling are first, that the initial separation of the outer glass from the solar cells is difficult and second, that there is not a commercialized method for silver recovery. The major economic hurdle is that it is anywhere from three to nine times more expensive to recycle solar panels than to landfill them. There are no technical challenges facing wind-turbine recycling. The economic challenges of wind turbine recycling are first, that recycling is more expensive than landfilling, and second, that the product of recycling (ground-up fiberglass) has a low monetary value. The major technical hurdles facing LIBs are first, that LIBs are difficult to disassemble and second, that LIBs are not standardized so mixing battery waste makes final material separation difficult. The economic hurdles facing LIB recycling are first, high transportation costs; second, the most valuable recoverable battery materials are being engineered out of battery designs; third, high labor costs in the U.S.; and fourth, complicated separation requires high energy input and reagents that are costly.

Policies to encourage solar panel recycling are recommended due to the hazardous materials present in solar waste (lead, cadmium, and arsenic) that could contaminate groundwater. The scarcity and potential depletion of silver reserves is another compelling reason. No policy or legislation is recommended for recycling wind-turbine blades because fiberglass is inert and poses no environmental threat. Landfilling of LIBs should be banned due to hazardous flammable electrolytes and the lack of domestic critical mineral supplies. Legislating manufacturer/retailer responsibility at end-of-life for LIBs could also be considered in this case, similar to legislation governing lead-acid batteries. Standardizing LIBs, as was done with lead-acid batteries, is another interesting policy option that could be explored by the national government. A summary of the findings can be found in Table 1 below.

Table 1: Summary of policy options for solar panels, wind turbines, and lithium-ion batteries at end-of-life.

	Technical hurdles	Economic hurdles	Policy Options	Rationale
Solar	Separation of glass and solar cells (EVA layer dissolution) Silver recovery has not yet been commercialized	Cost to recycle ($15-$45) is greater than cost to landfill ($1-$5) Cost of recovered materials is less than cost to recycle Most valuable material (silver) is being engineered out of newer designs	Mandate recovery of aluminum casing and copper wiring Provide grants for silver recovery research/ commercialization	Toxic lead is contained in the solder connecting the cells together. Copper is valuable. Silver reserves are scarce and might be depleted by 2041
Wind	Fiberglass can only be downcycled into products requiring less material strength	Cost to landfill blades is $55/ton, with added $15 for in-tact blades. Grinding blades before transport is the cheapest option. Ground blade material cost more than new raw materials for cement and other reuse applications (currently, others are paid to take it)	None recommended.	Landfilling wind turbines poses no environmental threat. Landfill space is not scarce. There is no market for ground fiberglass
Lithium-ion Batteries	EV battery disassembly can take hours, and the differences in LIBs from one brand to the next makes the process difficult to automate Mixing multiple EV battery chemistries makes separation difficult	Transportation costs are high due to hazardous waste classification (up to 40% of total cost) Most valuable material (cobalt) is being engineered out of newer designs, so recycling profits are projected to decrease Labor costs are high in the U.S., driving up overall recycling costs Typical separation methods (with reagents/ heat) are costly due to consumption of energy/ reagents	Mandate manufacturer/ distributor take-back at EoL Investigate standardizing LIB design to improve recyclability	Batteries must be classified as hazardous waste because they can ignite and start landfill fires (landfills usually give off methane)

Background

MATERIAL MANAGEMENT IS NECESSARY TO MEET CLIMATE CHANGE TARGETS

Climate change has become a stark reality in the last decade as the frequency of costly, extreme weather events has increased. The International Panel on Climate Change's 2020 report predicts that even in the best-case scenario (limiting planetary warming to 1.5°C) global warming from human-generated carbon emissions will result in a 7-10% loss of livestock, and an increased number of deadly heat waves, droughts, and severe weather events.[2] Continuing to emit carbon at current levels only makes these predictions worse, putting many lives at risk, which is why policymakers across the globe have been steadily increasing funding to decarbonize the energy and transportation sectors. The U.S. government recently approved the Inflation Reduction Act which contains the biggest government investment into clean energy and electric vehicles that the country has ever seen. Increased investment into wind, solar, and electric vehicles has caused demand projections to skyrocket. Lawmakers must prepare now for the waste these products will generate in twenty years when they reach End of Life (EoL).

THE BASICS OF GOOD MATERIAL MANAGEMENT

Good material management involves considering a product's whole lifecycle from cradle-to-grave (from inception to EoL). There are three phases of a product's life that producers must consider: creation, useful life, and EoL. Materials are chosen based on the product's intended purpose and cost. EoL options are determined by safety considerations (such as, will this product contaminate a landfill, or spontaneously ignite on a hot day?) and what economic value, if any, can be extracted from the product. There are three common EoL options: recycling, repurposing, and landfilling. Ideally, every product would be repurposed and then recycled to extract as much value as possible. Repurposing and recycling, however, are not always options due to safety concerns, a lack of opportunity to repurpose, inherent material properties, and the economics of recycling (recycling processes are sometimes possible but require too many reagents or too much energy to be practical).

Of the four major classes of materials (metals, polymers, ceramics, and composites), metals are the most recyclable and composites are the least. This is because the chemical bonds in a metal object (metallic) have different physical properties from the chemical bonds in a composite object (ionic or covalent). Metallic bonds make it so that old metal products can be easily melted and remolded into new products; the new metal object can be forged to have the same strength and durability as the old. Products made out of composite materials cannot be melted and remolded. As the name suggests, a composite is made of two or more different materials that, when combined, have different physical properties than either of the two or more starting materials. For example, most fiberglass is made of silicon oxide (glass) and various metal oxides (calcium, magnesium, lithium, aluminum oxide).[3] The silicon oxide and metal oxides combine together in an irreversible chemical reaction that creates long fibers. Once these fibers are broken, they lose their strength forever.

Renewable energy technologies and batteries are complex with components made from each of the four material types. EoL options are explored in the section below using a cradle-to-grave perspective to optimize material circularity and economic value.

Solar Panels

OVERVIEW OF SOLAR PANEL RECYCLING

Solar Panel Waste

The cumulative global amount of solar panel waste by 2030 is expected to be around 8 million tons[4], one million of which (~12.5%) will be generated in the U.S.[5] By 2050, the global amount is projected to grow almost by a factor of ten to 78 million tons.[6] According to the world bank, global municipal solid waste amounted to 2.01 billion metric tons* in 2021 alone.[7] Solar waste volumes are quite small when compared to total waste volumes. The overall percentage of cumulative global solar waste by 2030 (about 40 years of waste) only amounts to approximately 0.36% of all global waste generated in a single year (based on global waste in 2021).

Solar Panel Materials

Solar panels are composed of glass, aluminum, polymers, silicon, and various metals. There are two main types of solar panels: CdTe thin-film and crystalline silicon (c-Si). In 2021, c-Si panels comprised 95% of the solar panel market, while thin-film panels made up the other 5%.[8] Both types of panels are primarily glass by weight (thin-film: 80-85% glass, crystalline silicon: 68-72% glass), and contain only a small amount of metals; only 3-5% of the total weight comes from copper, silver, zinc, lead, tin, and other metals combined.[9] For c-Si panels, most of the material resell value (35-40%) is derived from the crystalline silicon, which makes up only 3-4% of the panel by weight. The next most valuable material is silver (9-23%), followed by glass (11-15%), aluminum (5-12%), and copper (5-12%).[10] For thin-film panels, glass makes up 47-54% of the material resell value, followed by aluminum (28-37%), polymers (5-12%), and tellurium (3-6%).[11]

Reasons to recycle

There are two compelling reasons to recycle solar panels. The first is the scarcity of silver; some estimate that silver production will peak in 2030[12] and known deposits could be depleted by 2041.[13] Additionally, solar panels contain lead, cadmium, and arsenic which could leach into and contaminate groundwater.[14]

** One metric ton (metric ton = 1000 kg) is equivalent to 1.1 tons (ton = 2000 lbs)*

Recycling Process

Although the exact process to recycle thin-film modules differs from c-Si solar modules, the three stages of recycling for both types of modules are the same. First, the aluminum frame surrounding the panel is removed. Next, the glass is separated from the solar cells by dissolving the binder (known as the EVA layer) that holds them together. And last, the cells themselves are treated with chemicals or burned to extract the remaining materials.

CURRENT STATE OF RECYCLING SOLAR WASTE IN THE US

Less than 10% of solar panels in the U.S. are recycled. There are no federal laws or regulations prohibiting solar panels from being landfilled in the United States. According to an article published in *Chemical and Engineering News* in 2022, landfilling costs $1-$5 whereas recycling costs anywhere from $15-$45.[15] The article goes on to say that most solar panels are not truly recycled, rather the frame and junction box are removed from the panel, and the remaining glass and solar cells are then crushed and sold as low-grade glass cullet.[16] There are few places in the U.S. that truly recycle solar panels. In fact, as of December 2022, commercial recycling processes could not completely recover all valuable materials, and only a few companies were able to remove the glass and recover the silicon and some metals contained in the solar cells. The Solar Energy Industries Association (SEIA), the national trade association for solar companies in the U.S., has created a National PV Recycling program to get solar panel owners in touch with responsible EoL management companies. So far, it has vetted many recycling companies but only partnered with four.[17] Though not a SEIA partner, a company called First Solar also does complete raw material recovery (as opposed to rudimentary methods producing low-grade contaminated glass) but only processes thin-film CdTe modules (just 2.4% of the solar panel market).[18]

Because it is the more expensive EoL option, the recycling industry remains rudimentary in both its methods and processing capacity. This is true across the globe. Even in China, the manufacturing capital of the world, recycling facilities only disassemble and refurbish panels, but lack the capability to refine solar waste into usable raw materials.[19] The processes are still being developed, which is why the U.S. government is aiming to expand its solar recycling capabilities through research and commercialization of better technology.

CHALLENGES FACING CURRENT RECYCLING TECHNIQUES

There are several challenges with the current recycling process that need improvement to reduce pollution or increase material recovery. Currently, the glass crushing process produces harmful dust and creates noise pollution.[20] Additionally, all methods currently used to dissolve the EVA layer produce harmful biproducts including lead and large amounts of toxic organic waste.[21] Rong Deng, a solar panel recycling expert at the University of New South Wales says that, "if there's any breakthrough technology in this area, it will be an easier way to get rid of the glue (EVA) layer".[22] Finally, as of 2020 there is no commercialized method for recovering silver, and other integrated metals from spent solar panels cells.[23] ROSI, a French company is changing this for silver, however, with an innovative etching technology that allows it to extract the silver circuitry.[24]

ECONOMIC BARRIERS TO RECYCLING SOLAR WASTE

There are four end of life options for solar panels:

- Landfill
- Export as e-waste
- Partial recycling (unspecialized glass or e-waste recycling)
- Maximum material-recovery recycling

Recycling is currently not the most economic option. The major economic hurdle facing solar panel recycling is that the value of recovered materials is not yet greater than the cost to recycle. One study performed by Tao et al. estimated that the combined value of recovered glass, aluminum, and copper (anywhere from 30-60% of total material value) amounts to approximately $3 of economic value per panel for a 60-cell Si module.[25] With costs of $15-$45, recycling processes currently result in net losses rather than net profits.[26]

The cheapest EoL option for solar panels is to landfill them. The same study also estimated that it costs less than $1 per panel to send solar panels to a landfill.[27] This study agrees with a National Renewable Energy Laboratory (NREL) study that estimated the total recycling cost to be $15-45 per panel and the total cost to landfill to be less than $1 for non-hazardous waste landfills and less than $5 for hazardous waste landfills.[28] The consensus is that landfilling is the most economic option, which explains why more than 90% of solar panels in the U.S. end up in landfills today.[29]

SUPPLY CHAIN CONSIDERATIONS

In terms of the solar panel supply chain, three areas stand out as potential bottlenecks that could limit the proliferation of solar energy. These areas are raw materials for initial solar panel manufacturing, recycling infrastructure, and reaching a critical mass of waste for recycling.

Raw Materials

There are several raw materials that are predicted to be underproduced by 2030. The IEA predicts that copper could be in short supply by as soon as 2024.[30] As stated above, silver is another raw material of concern and known reserves could be depleted as soon as 2041.[31] The solar industry accounted for 25% of global silver demand in 2022, a number that will only increase as solar panel production increases.[32] While recycling is necessary to ensure the longevity of the solar industry, mining will need to increase in the near-term because recycling only ensures supply chain security in the long-term.[33] The International Renewable Energy Agency (IRENA) estimated in 2018 that the ratio of waste solar panels to new installations was approximately 0.1%.[34] Thus, only 0.1% of new solar panels could be manufactured with waste panel materials if all materials could be fully recovered. By 2050, however, IRENA predicts that the ratio of waste panels to new installations will be over 80%.[35] Particularly in the cases of silver and dysprosium where material scarcity is a concern, recycling can play a valuable role in creating supply chain circularity and sustainability in the long-term.[36]

Recycling Infrastructure

As for solar panel recycling infrastructure, there are very few commercial businesses that specialize in recycling solar panels. Most PV recycling companies in Europe and the U.S. only recycle the aluminum frame, glass, and copper wiring; they contract out the electronic waste recycling and glass recycling processes.[37] It appears that only one commercial company, ROSI (France), recovers silver during its recycling process. Once again, this is an issue because of the scarcity of silver. Additionally, not recovering the silver reduces the payback for recyclers, making recycling less lucrative. Researchers Meng Tao at Arizona State University and Rong Deng at the University of New South Wales are in the process of developing cheaper methods to increase material recovery.[38]

Reaching a critical mass of waste

One reason that recycling industries are so difficult to build is that it takes time for waste volumes to accumulate, and even more time for waste volumes to stabilize. Department of Energy's Solar Energy Technologies Office Photovoltaics End-of-Life Action Plan alludes to this problem by stating, "PV waste volumes in the short term are likely to be low and sporadic which further makes building a profitable industry difficult".[39] This makes pay-back more difficult to achieve.

The principle of economies of scale suggests that solar panel recycling will get cheaper as more and more panels can be recycled. The Spanish company, Iberdrola SA, estimates that it could be profitable when waste volumes reach 10,000 tons a year in Spain, which Iberdrola thinks could happen as soon as 2027.[40] This would be a rapid increase in waste volumes (in-line with IRENA predictions), which stood at approximately 2,000 tons per year as of May 2022.[41] The same concept applies to the U.S., although no profitability threshold estimates seem to exist.

While the U.S. is waiting to reach a critical mass, it is possible that countries with lower labor costs will attract waste volumes away from the U.S. market, thereby making it impossible for American recycling companies to become profitable. This creates environmental problems for certain countries and discourages material recovery advances in the long-term.

While most recycling plants may not currently recover all raw materials from solar panels, the infrastructure to partially recycle them sets developed countries apart from developing countries. Unfortunately, old solar panels often get resold to developing countries that do not have the infrastructure to recycle them.[42] Currently 80% of e-waste, which includes solar panels, is shipped to Asia where most of it is not handled properly due to lack of infrastructure.[43] As long as this option remains, the U.S. solar panel recycling industry will grow slowly, and its progress toward implementing better material recovery processes will be hindered as a result.

Another danger of waiting to reach a critical mass is that countries that manufacture large volumes of solar panels will gain the competitive advantage. This is because scraps from solar panel production are another input stream into recycling plants. Most solar panel manufacturing is concentrated in China (84% of U.S. solar panel market), with the exception of thin-film solar panel manufacturing which is concentrated in Ohio (16% of U.S. solar panel market).[44] While China manufactures and owns the majority of solar panels in the world (installed capacity of 306,973 MW), the U.S. has the second most solar power in the world (95,209 MW). With this amount of solar power concentrated onshore, it is worth noting that solar panel recycling revenue is predicted to reach $1.8 billion by as soon as 2031.[45]

Additionally, China does not currently refine solar panel waste; it only does initial panel separation and repair.[46] Because solar panel recycling is projected to be a profitable industry in the future, the U.S. should consider what it must do now to grow the industry onshore, or risk losing it. In particular, the fact that the U.S. has a manufacturing advantage, and therefore recycling advantage, in thin-film solar panels should not be overlooked.

POLICY OPTIONS

In order to increase solar panel recycling in the U.S., the government would need to provide incentives to make recycling the more favorable economic option. A paper by Waltzberg et al. (2021) published in Nature Energy, Role of the social factors in success of solar photovoltaic reuse and recycle programmes, attempted to model nine different policy scenarios and their overall effect on EoL management for solar panels.[47] The four scenarios, a through d, ordered highest to lowest by predicted 2050 solar panel recycling rate were, "Landfill ban (a), high material recovery (96%) andU.S.$18 per module recycling costs (b), lower recycling costs (US $18 per module) (c), [and] higher landfill costs (US $2.75 per module) (d)".[48] The other five scenarios are irrelevant to this discussion because those policies were not predicted to meaningfully impact recycling rates.

The landfill ban option was predicted to increase material circularity and recycling the most. It is ultimately the costliest option for roof-top solar panel owners and would increase the price of solar energy for consumers. NREL estimates that it costs $30 on average to recycle one solar panel. The average U.S. home needs a 6kW system of 15-19 solar panels[49] to cover its energy needs, which results in additional recycling costs of $450 to $570 dollars. Owners would be responsible for covering this cost. Given that a 6kW solar panel system costs anywhere from approximately $13,000 to $20,000[50], this would only increase overall costs by three to four percent. As for consumers, because solar farms would now be required to not just decommission but also recycle solar panels (solar farms already include a decommissioning facility in order to receive government permits to build and operate), they would also incur additional costs. They would pass these costs along to consumers, which would increase the overall price of solar energy. This option is predicted to achieve a recycling rate of approximately 73% by 2050.[51]

The next option is high material recovery and subsidizing the recycling costs to $18. In addition to subsidies, this option requires government grants to build recycling plants to boost material recovery. This would shift costs to all taxpayers who would provide the funds for the subsidies and grants. The cost of solar electricity would still increase, but to a lesser extent than in the scenario of a landfill ban. This option is predicted to achieve a recycling rate of approximately 55% by 2050.[52] Subsidies by themselves without higher material recovery are predicted to increase recycling rates to approximately 44% by 2050, and higher landfill costs increase recycling rates to approximately 40%.[53]

Policies governing EoL management for solar panels should move society closer to achieving the same environmental goals that drove the adoption of renewable energy in the first place. These goals are: 1) to minimize the human contribution to climate change, 2) to achieve energy independence through eliminating dependence on foreign oil, and 3) to minimize pollution and preserve nature. The need for thoughtful and rational policy is clear, as some policies have inadvertently increased pollution in the past (encouraging old-panel re-use has increased solar panel pollution in developing countries).[54] Additionally, it is important to consider trade-offs: recycling requires more energy and takes away economic resources from other government programs, while landfilling takes up more space and increases the risk of environmental contamination.

According to Robert Nicholson, Senior Manager of Sustainability at the SEIA, solar panel manufacturers do not want to reuse solar panel glass until glass recyclers are able to guarantee its purity. Without the guarantee of purity, the cost-savings do not outweigh the risks. Some recycling companies are working to provide this guarantee, but no glass recyclers currently do. The aluminum frame is easily removed and recycled. While a total landfill ban results in the most recycling, it is clear that policymakers should thoroughly consider the reality of what material re use will actually look like before passing any regulations. In the case of solar recycling, recycling only the aluminum and copper is feasible right now and results in 10-24% of the value of the panel. Governments should also consider funding research into silver recovery, which would boost value recovery to 19-52% and resolve concerns of the depletion of silver reserves. When silver recovery is possible, this should be mandated as well. As most commercial solar farms already have plants to decommission solar panels, EoL responsibility should be legislated for rooftop solar manufacturers.

WIND TURBINES

OVERVIEW OF RECYCLING WIND TURBINES

Current State of Wind Turbine Waste

The amount of wind turbine blade waste to be generated by 2050 is small when compared to municipal solid waste as a whole, however, wind turbine waste is projected to increase rapidly between now and 2050. In a 2017 study done by Pu Liu and Claire Y. Barlow, it was estimated that the global cumulative amount of wind turbine waste will be approximately 500 thousand metric tons by 2030.[55] The same study projects that global wind turbine waste will grow to two million metric tons annually by 2050, 16% of which will be generated in the U.S.56 According to the EPA, the U.S. landfilled 146.1 million tons of MSW in 2018.[57] To put this into perspective, if the U.S. had disposed of the two million metric tons of wind turbine blade global waste in 2018, the overall MSW in the U.S. would have only increased by 1.5%.

Wind Turbine Materials

\According to Siemens Gamesa, wind turbines are, on average, 85% recyclable.[58] The reason for this can be explained by looking at what kinds of materials make up a wind turbine. Wind turbines are approximately 83-86% metal and 14-17% various composite materials.[59] Most of a wind turbine's metal is located in the tower and the gearbox. The remaining ~15% of composite materials are located in the wind turbine blades, which are primarily made of fiberglass or carbon fiber, various epoxies, and wood.

Reasons to Recycle

The best reason to recycle wind turbine towers is that they are made of metal, which is highly recyclable. Copper wiring has a high resell value and has obvious electrical applications once recycled. As for the blades, there are no compelling reasons to recycle wind turbine blades. Fiberglass is inert and poses no environmental risk when landfilled. Additionally, fiberglass can only be downcycled. Downcycling occurs when a used item is remade into an item of lesser value. There are a few commercial companies currently doing this, though the economics is unprofitable without government subsidies. There are now fully recyclable blades. Siemens Gamesa installed the first wind turbines with fully recyclable blades in Germany in August of 2022[60].

Recycling Process

At EoL, the wind turbine is either disassembled using cranes to remove the blades or knocked down. The blades and tower are then cut and transported via semi-truck. The steel and aluminum are sent to foundries where they are reprocessed[61], while the blades go to landfills or to companies who recycle the fiberglass. Such companies can sometimes grind the blades on-site before transportation as well.

END OF LIFE OPTIONS FOR WIND TURBINES

The current EoL options for wind turbine blades are:

- Landfilling
- Downcycling
- Repurposing

All three options require the blades to be cut and transported, however, these costs can vary depending on the state of the wind turbine before it is transported (i.e., shredded blades versus blades cut into large, transportable pieces).

Option 1: Landfilling

The cheapest option is currently landfilling shredded material, with a landfill fee of approximately $55/ton.[62] Although it costs $90 per ton to shred wind turbine blades and only $25/ton to cut the blades (but leave them otherwise intact), the cost to transport shredded material is so much cheaper per ton ($14/mi-ton for a cut blade vs $0.12/mi-ton of ground-up blades) that it makes shredding the blades worth the upfront cost.[63] Additionally, large blade pieces incur a tip fee of $15/cubic yard when landfilled that shredded blades are not subject to.[64] The issue with landfilling blade material is that it is not a sustainable solution in the long-term, however, as stated above, wind turbine blade waste is a very small portion of the overall MSW problem. Additionally, with the creation of fully recyclable blades, this problem may take care of itself in the long-term.

Option 2: Downcycling

The second EoL option is downcycling the blade material. Old wind turbine blades cannot be recycled into new wind turbine blades because of the material properties of the wood, resins, and either glass fiber or carbon fiber that make up the blade. Instead, these materials can be kept out of landfills by reusing them in other products such as cement, lawn chair furniture, and manhole covers. Veolia and Global Fiberglass Solutions, for instance, are two companies pursuing this option. Both companies specialize in cutting, transporting, and grinding wind turbine blades. The resulting ground material is then used in the downcycled products mentioned above. Currently, Veolia's business model requires turbine blade owners to pay them to take and process the blades, and Veolia subsequently pays cement manufacturers to make cement with the material.[65] Veolia does not disclose the price they charge to take the blades or the price at which they sell the ground blade material, but it is clear from the direction of cash flow in this model that the ground blade material is still more expensive than the traditional raw materials used for cement. While the economics by themselves do not incentivize downcycling wind turbine blades, there are environmental benefits to downcycling wind turbine blades, particularly when used in cement manufacturing.

Cement manufacturing is one of the most carbon-intensive industrial processes today producing approximately 8% of global emissions on its own according to a Princeton review.[66] In a study done by Quantis US, it was reported that seven tons of wind turbine material can replace five tons of coal, 2.7 tons of silica, 1.9 tons of limestone, and nearly one ton of additional minerals.[67] Overall, this reduces emissions by 27% when compared to cement manufacturing without wind turbine blade material.[68] This use case could take care of all wind turbine waste, given that more than four billion metric tons of cement is manufactured every year.[69]

Option 3: Repurposing

Repurposing wind turbine blades is a useful EoL option because, after landfilling cut blades, it requires the least amount of work (shredding wind turbine blades uses more energy than repurposing because grinding is an energy-intensive process). Wind turbines have already been successfully repurposed as bike rack shelters, pedestrian bridges[70], and even public playgrounds for children.[71] While the simplicity of repurposing is appealing, it is not a complete solution by itself. This is due to a lack of demand; there are more wind turbine blades to dispose of than projects that could potentially repurpose them. In a 2021 Business Insider study, Chris Howell, the senior director of operations at Veolia, explains, "these other uses do not provide the scale necessary to manage the current volumes needed for sustainable wind turbine blade management."[72] Repurposing wind turbine blades is thus a good option when available, but does not scale to the extent necessary to repurpose all wind turbine blades that will be decommissioned in the future.

POLICY OPTIONS

Given that wind turbine blade recycling is not economic, and there are no compelling environmental reasons to recycle wind turbines, no policy is needed to govern wind turbine blade EoL. It should instead be left to market forces to determine the best EoL outcome. There are two case studies that illustrate this below.

Wyoming provides an interesting case study of wind turbine recycling policy in a location where landfill space is abundant. The Casper, Wyoming landfill received upwards of 1,100 wind turbine blades in 2020 which generated $600,000 in revenue. Cynthia Langston, the solid waste division manager at the time said, "It's great revenue especially when revenues are down because of the oil and gas industry...We do not have landfill space issues at the City of Casper".[73] Not everyone agreed with Langston, however, and in 2021 Wyoming State Senator Eric Barlow introduced a bill to allow private coal companies to use the wind turbine blades as mine reclamation fill (purchasing fill dirt is the costliest part of mine reclamation)[74]. This is not mandatory, and no landfill ban has been imposed, so market forces will decide if the blades are landfilled or used as mine fill. These two EoL options are remarkably similar – in both cases, the wind turbine material ends up buried in the ground – and serves to illustrate that burying wind turbine blades does not pose an environmental threat. This is not surprising given the fact that fiberglass is inert.

Colorado is another interesting case study. The Logan County landfill in Logan County, Colorado became the first landfill in the U.S. to ban wind turbine blade waste in March of 2022. This caused wind turbines to pile up across the border in the neighboring town of Sidney, Nebraska. The reason for the ban was fear of water contamination, even though fiberglass is inert and is currently not known to pose any environmental threats.[75] The situation in Nebraska is supposedly temporary until recycling measures can be put in place. Nebraska is currently reviewing legislation to consider banning wind turbine blade waste from being disposed of in landfills. This will result in increasing the cost of EoL for wind energy, which is a disincentive to build more wind in Colorado.

Lithium-Ion Batteries

OVERVIEW OF LITHIUM-ION BATTERY WASTE

Current State of Lithium-ion Battery Waste

Lithium-ion battery (LIB) waste volumes are predicted to grow rapidly throughout the next two decades, and it is already predicted to reach 1.6 million metric tons globally by 2030.[76] Not only does LIB waste require special handling to dispose of safely, but it also contains valuable materials that will need to be recycled in order to meet LIB demand in the near future. For example, the IEA predicts that copper, cobalt, and lithium will not be mined in sufficient quantities to meet 2030 demand.[77] The strong and growing demand for lithium-ion batteries comes primarily from electric vehicles (EVs) becoming more affordable via economies of scale and government subsidies.[78] In 2021, EV purchases in the U.S. doubled, jumping from 316,000 vehicle purchases in 2020 to roughly 645,000 vehicle purchases in 2021.[79] According to Statista, EV demand is expected to quadruple by 2027.[80]

Lithium-ion Battery materials

LIBs are typically composed of many separate battery cells all linked together. Inside each battery cell, LIBs have four main components: 1) the anode, 2) the cathode, 3) the separator, and 4) the electrolyte. The anode is made of a thin copper strip, known as a current collector, that has been covered in a slurry of graphite powder.[81] The anode is a thin aluminum strip that is covered in a slurry of active material (a compound material that includes lithium). The separator is a semipermeable polymer membrane between the anode and the cathode across which a voltage can be generated. The electrolyte supplies the lithium ions that are shuttled from the anode to the cathode when the battery is discharged.

Reasons to Recycle Lithium-ion Batteries

LIBs are classified as hazardous waste because they contain flammable electrolytes which can ignite and cause fires. Since they must already be handled separately, aggregating and recycling is a

logical next step. Additionally, the U.S. could improve its national security by recycling and keeping LIB materials onshore. As the House Energy and Commerce Committee noted in an April 2023 hearing memorandum, "China dominates global production of battery cells, including 70 percent of cathodes, 85 percent of anodes, 66 percent of separators, and 62 percent of electrolytes; China has 78 percent of the world's cell manufacturing capacity for EV batteries; Three-fourths of the world's lithium-ion battery megafactories are located in China."[82] In terms of raw materials, China produces 75% of the graphite supply (no U.S. production), South Africa produces 31% of the world's manganese (no U.S. production), Australia produces 58% of the lithium supply (some U.S. production), and the Democratic Republic of the Congo produces 61% of the cobalt supply.[83] While the U.S. does not have a comparative advantage in mining because it takes decades for a new mine to begin production, recycling is a long-term alternative that has a lower upfront capital investment cost and could provide material security.

Lithium-ion Battery Recycling Methods

Depending on the recycling method, varying amounts of these materials can be recovered. There are three main methods for recycling LIBs, namely: pyrometallurgy, hydrometallurgy, and what is known as the direct method.[84] The products that can be recovered using pyrometallurgy are the least valuable in terms of quality. This method is also the costliest[85]. Hydrometallurgy is currently the least expensive option and involves using solvents to dissolve and leach valuable materials from the battery cell (aluminum, copper, lithium, cobalt, etc.)[86]. Direct-method recycling is able to recover the most material, and results in closed-loop cathode recycling, meaning that the cathode can be immediately used in a new battery.[87] This method is more expensive than hydrometallurgical recycling in the current economic climate, but it could potentially be a more attractive investment in the long-term as battery material composition changes (see economics section for more details).[88] Direct-method recycling has not yet been commercialized.

CURRENT STATE OF RECYCLING IN THE UNITED STATES

As of 2019, only 5% of lithium-ion batteries were recycled in the U.S.[89] A large reason for this is the lack of established channels and infrastructure to collect, sort, store, and recycle the batteries.[90] Most LIBs processed in the U.S. are not truly recycled, they are simply shredded onshore and then shipped abroad, usually to China, for further material processing. There are only two companies currently recycling LIBs in the U.S.: Inmetco (pyrometalurgy) and Li-cycle (hydrometallurgy).[91] Hydrometallurgy will soon be the most widely used battery recycling technology in the U.S. when two additional companies become operational, namely Redwood Materials which should be operational in 2023,[92] and Ascend Elements, which should be operational in late 2023. Li-Cycle is also scheduled to build additional plants in the U.S.[93] The total capacity in North America is currently 20,500 tons; an additional 40,000 tons of planned capacity is set to triple this amount.[94]

CHALLENGES FACING CURRENT RECYCLING TECHNIQUES

There are two hurdles in the recycling process itself which make it both difficult and costly.[95] The first is removing the outer casing and the individual cell casings. This is difficult to automate because there are multiple EV battery designs each of which has its own dimensions and configuration. Two of the three methods (pyrometallurgy and hydrometallurgy) overcome this hurdle by removing only the outer casing and grinding up the individual cells, casings and all. Direct recycling extracts all materials to treat them separately, so grinding the individual cells is not an option. Instead, each individual cell must be disassembled to preserve the cathode. This requires complex assembly lines and sophisticated robotic machinery, driving up the cost. Despite this challenge, direct recycling methods have been developed and, according to Linda Gaines at the ReCell Center (a national collaboration among scientists, academia, and industry funded by the

Department of Energy and created specifically to perform research on how to improve current battery recycling methods), some have already applied for government grants to commercialize their technology. For instance, Princeton New Energy received funding and is building a plant in Texas.

The second hurdle is the variations in battery chemistry. Each manufacturer has its own proprietary chemistry which it does not disclose to recycling companies. Recycling companies could recycle each battery type separately if it were not for the already-small volumes of battery waste that make it hard to get the industry going in the first place. Recycling companies must process multiple chemistries together in the same recycling stream to make recycling economic. It is essentially impossible for third-party battery recyclers to operate without access to proprietary battery chemistry information. With so much variation in battery chemistry (lithium-phosphorus, lithium-manganese, and lithium-cobalt being among the most popular) and varying volumes of each type of battery being recycled in a given batch, the recycling process becomes too impractical to actually consider investing in. It would need to change for each individual batch in order to recover the most valuable materials. The only way to process multiple brands of batteries (again, necessary due to the economics of the small initial volumes) without knowing the proprietary battery chemistries would be to purchase and continuously run expensive mass spectrometers. Even then, there would constantly be modifications needed to run the distillation columns correctly. This all amounts to too much room for error, and is essentially an impossible task, which is why the recycling industry for LIBs has yet to take off.

ECONOMIC BARRIERS TO RECYCLING LIB WASTE

There are three major areas that drive up the cost of LIB recycling and have hindered investment into this sector: high transportation costs, high labor costs, and trend toward decreasing the value of recoverable materials.

High Transportation Costs

The first is that transportation costs are high (a literature review of EV transportation costs at EoL found that transportation is on average estimated to be 41% of the overall recycling cost)[96] because used LIBs are classified as hazardous waste.[97] This means they require special handling in transit which drives up the cost. Additionally, they must only be taken to hazardous waste landfills which are less prevalent, meaning distances between the LIB and the landfill are greater than for non-hazardous waste.

High Labor Costs in the United States

The second economic barrier is labor costs. Labor costs in the U.S. are high ($20 USA versus $2 China and $10 Korea)[98] making it much cheaper to recycle LIBs in China or Korea. As mentioned above, transportation costs are high as well, which might explain why so few LIBs make to a recycling plant in the first place.

In 2019, the Energy Department's Office of Energy Efficiency and Renewable Energy estimated that recycling LIBs in the U.S. could potentially provide one-third of the cathode material needed to meet U.S. LIB needs in 2030.[99] However, because cheaper labor gave East Asia a comparative advantage, two-thirds of global battery recycling capacity is currently located there (207,500 tons of capacity, most of which is concentrated in China).[100] By comparison, as of 2021, North America had roughly one tenth of this capacity (20,500 tons of capacity). Because so much more capacity already exists in East Asia, the U.S. was losing a substantial amount of LIB waste. In 2020, China banned all imports of solid waste, including LIBs. This, combined with high transport costs, means that right now there is an opportunity to grow a LIB recycling industry in the U.S.[101] This possibility is further supported by one study that showed that, while recycling in China had higher profit margins, recycling LIBs in the U.S. can still be profitable.[102]

Value of Recoverable Materials is Decreasing

The last economic barrier to LIB recycling is the decreasing amount of cobalt in batteries. Cobalt is the highest-value material that can be recovered from recycling LIBs.[103] Cobalt is a rare element and many cobalt mines have been exposed for human rights violations and unsafe work practices.[104] For these reasons, the LIB industry is slowly moving away from cobalt and toward other elements such as phosphorus.[105] This reduces the overall value that can be captured from recycling LIBs in the long-run and thus disincentivizes new entrants. The direct recycling method is predicted to become more profitable than the current low-cost leading method, hydrometallurgy, in the long-run because its end-product will be regenerated cathodes rather than raw battery materials that will be worth less due to lower cobalt content in the future.[106]

POLICY OPTIONS

Existing Policies Addressing Recycling Economics

In 2021, the Biden Administration published a National Blueprint for Lithium Batteries in which it listed five goals, namely:

1. Secure access to raw materials. Find alternatives to Co and Ni
2. Grow U.S. materials-processing base,
3. Stimulate the U.S. electrode, cell, and pack manufacturing sectors,
4. Enable U.S. end-of-life reuse and critical materials recycling at scale, and
5. Maintain/Advance U.S. battery technology leadership through R&D, STEM education and workforce development.[107]

The U.S. has almost no regulation at the federal level surrounding the disposal of LIBs beyond the Environmental Protection Agency classifying them as hazardous waste.[108] On December 23, 2022, the Strategic EV Management Act passed as part of the National Defense Authorization Act 2023.[109] This law expands the reuse and recycling of spent LIBs in the U.S. government's federal vehicle fleet.[110] This policy includes that a cost-benefit analysis be performed on EVs and the internal-combustion engine vehicles in the fleet. It also requires that EV batteries in the federal fleet be recycled responsibly, which will bolster the domestic recycling industry. One study done on recycling in the UK found that both direct recycling and hydrometallurgical recycling were profitable when done domestically.[111] It should also be noted that minimizing material transportation at EoL would reduce transportation emissions and lessen the overall environmental impact of LIBs.

According to a recent study published in ACS Energy Letters, there are only two federal laws that are relevant to consumer EV battery recycling: the Resource Conservation and Recovery Act (RCRA) and the Mercury-Containing and Rechargeable Battery Management Act.[112] The first law, the RCRA, specifies how various waste types should be recycled.[113] The second law requires all lead-acid and nickel-metal hydride battery vendors to accept and recycle spent batteries. This has led to a greater than 95% recycling rate for lead-acid batteries in the U.S.[114]

By contrast, the European Union recently introduced a comprehensive regulatory framework for Lithium-ion battery recycling. Their framework includes:

1. Mandating a carbon footprint declaration for all LIBs
2. Labeling requirements for LIB manufacturers
3. Creating minimum recycling targets
4. Requiring minimum amounts of recycled material in new LIBs

5. Requiring that all battery manufacturers have a "due diligence" policy to account for negative environmental externalities associated with LIBs
6. Requiring that manufacturers make it possible for consumers to easily remove and replace old batteries, and
7. Enabling collection of waste LIBs free of charge for end users.[115]

At the state-level, both California and New York have laws requiring manufacturers to accept and recycle rechargeable batteries.[116] Although neither has laws specific to LIBs, many believe a manufacturer take-back policy similar to the Mercury-Containing Rechargeable Battery Management Act could be very successful. In March of 2022, the Lithium-ion Battery Recycling Advisory Group, commissioned by the CalEPA, published its findings and policy recommendations for EV battery recycling policy in the state of California. The report recommends that whoever handles out-of-warranty EV batteries (EV batteries that are still under warranty are already covered by warranty regulation programs) at EoL should be responsible for ensuring that it is properly recycled.[117] Much like Mercury-Containing Rechargeable Battery Management Act, the report specifies that these EoL managers will likely be EV battery suppliers, EV dismantlers, or the vehicle manufacturers.[118] As of January 2023, there does not appear to be legislation in the works in New York State. A bill that would create extended producer responsibility was introduced in the California State Legislature in early 2022, however, no advancements in the process have occurred since April 2022.[119]

Existing Policies Addressing Process Hurdles

The federal government has sponsored the ReCell center for Advanced Battery Recycling to "grow a sustainable advanced battery recycling industry".[120] The ReCell Center researches battery recycling methods to improve the process and make it more economic. Process improvement is a crucial way that the U.S. aims to reduce the overall recycling cost and grow the domestic recycling industry. In an interview (conducted for this research) with Linda Gaines, former Chief Scientist of the ReCell center, she expressed concern over two of the EU policies, namely the requirement for recycled material in new batteries and the labeling requirement. In her view, the recycled material mandate runs the risk of delaying production of EVs and other technologies that rely on LIBs in the event that not enough recycled material is available because it is still in service. As for labeling requirements, LIB manufacturing companies' may feel that it puts their proprietary information at risk. The fifth point in the EU framework, requiring manufacturers to have a due diligence policy, is most closely aligned with the state and federal trend toward manufacturer responsibility at EoL.

Recommended Policy Action

It is recommended that states pass laws making it illegal to dispose of EV LIBs in landfills, as in the case of lead-acid batteries.[121] Additionally, and in line with the CalEPA recommendations, it is recommended that EoL responsibility be legislated for out-of-warranty batteries as belonging to LIB manufacturers, dismantlers, or retailers (the responsible party depends on if the LIB is replaced before or at the EV's EoL). Another factor that contributed to the high recyclability (>95%)[122] of lead-acid batteries was their standardization. For this reason, it is also recommended that the national government commission the ReCell Center to explore standardizing LIBs.

Conclusion

Recycling solar panels, wind turbines, and LIBs is a complex issue with both economic and technical process hurdles to overcome. The major issues facing solar panel recycling in the U.S. are lack of commercial processes to recover silver and the fact that most waste is currently being exported. That means that it will take a longer amount of time to reach the critical mass of waste needed to make recycling cost-effective. The best option for recycling solar panels is most likely to recover the aluminum frame, copper, and silver. While not immediately economic, these materials are valuable, and it is worth subsidizing recycling efforts to secure the supplies of these materials.

There are no major issues with wind turbine recycling. As fiberglass poses no known threat to the environment, no subsidies or policies are needed to keep wind turbines out of landfills. If landfill space becomes scarce, the market price to landfill wind turbines will increase to a point where eventually recycling will become the economic option.

As for LIB recycling, governments should legislate EoL manufacturer responsibility. This would solve the problem of multiple chemistries being recycled, it would keep manufacturer data private, and would keep needed battery materials onshore. Several vehicle manufacturers already have a battery take-back policy, so this policy is in-line with what is currently happening with EV battery recycling in the U.S. right now.

Recycling certain materials is environmentally friendly and, especially for metals, it is good material management in the long-term. Its impact on material supply is limited in the short-term but increases supply chain security as recycling volumes grow in the long-term. Like all industries, recycling in the U.S. will need time to grow. To have the capacity to recycle at high volumes in the future, it is necessary to invest in recycling infrastructure now.

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Endnotes

1. *Reliable supply of minerals – The Role of Critical Minerals in Clean Energy Transitions – Analysis - IEA*. (n.d.). Retrieved August 29, 2022, from https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions/reliable-supply-of-minerals
2. Hoegh-Guldberg, O., D. Jacob, M. Taylor, M. Bindi, S. Brown, I. Camilloni, A. Diedhiou, R. Djalante, K.L. Ebi, F. Engelbrecht, J. Guiot, Y. Hijioka, S. Mehrotra, A. Payne, S.I. Seneviratne, A. Thomas, R. Warren, and G. Zhou, 2018: Impacts of 1.5°C Global Warming on Natural and Human Systems. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. In Press.
3. Chawla, K. K. (2001). Glass Fibers. *Encyclopedia of Materials: Science and Technology*, 3541–3545. https://doi.org/10.1016/B0-08-043152-6/00630-6
4. Tao, M., Fthenakis, V., Ebin, B., Steenari, B. M., Butler, E., Sinha, P., Corkish, R., Wambach, K., & Simon, E. S. (2020). Major challenges and opportunities in silicon solar module recycling. *Progress in Photovoltaics: Research and Applications*, *28*(10), 1077–1088. https://doi.org/10.1002/PIP.3316
5. *End-of-Life Solar Panels: Regulations and Management | US EPA*. (n.d.). Retrieved April 1, 2023, from https://www.epa.gov/hw/end-life-solar-panels-regulations-and-management
6. Weckend, S., Wade, A., & Heath, G. (2016). *End-of-Life Management Solor Photovoltaic Panels*. IRENA, IEA-PVPS. https://www.irena.org/publications/2016/Jun/End-of-life-management-Solar-Photovoltaic-Panels
7. *Trends in Solid Waste Management*. (n.d.). Retrieved November 21, 2022, from https://datatopics.worldbank.org/what-a-waste/trends_in_solid_waste_management.html
8. *Special Report on Solar PV Global Supply Chains*. (n.d.). Retrieved November 11, 2022, from www.iea.org/t&c/
9. Ibid.
10. Ibid.
11. Ibid.
12. Sverdrup, H., Koca, D., & Ragnarsdottir, K. V. (2014). Investigating the sustainability of the global silver supply, reserves, stocks in society and market price using different approaches. *Resources, Conservation and Recycling*, *83*, 121–140. https://doi.org/10.1016/J.RESCONREC.2013.12.008
13. *Reliable supply of minerals – The Role of Critical Minerals in Clean Energy Transitions – Analysis - IEA*. (n.d.). Retrieved August 29, 2022, from https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions/reliable-supply-of-minerals
14. Nain, P., & Kumar, A. (2020). Initial metal contents and leaching rate constants of metals leached from end-of-life solar photovoltaic waste: An integrative literature review and analysis. *Renewable and Sustainable Energy Reviews*, *119*, 109592. https://doi.org/10.1016/J.RSER.2019.109592
15. Mark Peplow, special to C&EN. (2022). Solar panels face recycling challenge. *C&EN Global Enterprise*, *100*(18), 24–28. https://doi.org/10.1021/CEN-10018-COVER
16. Ibid.
17. *SEIA National PV Recycling Program | SEIA*. (n.d.). Retrieved January 20, 2023, from https://www.seia.org/initiatives/seia-national-pv-recycling-program
18. Ibid.
19. Chowdhury, M. S., Rahman, K. S., Chowdhury, T., Nuthammachot, N., Techato, K., Akhtaruzzaman, M., Tiong, S. K., Sopian, K., & Amin, N. (2020). An overview of solar photovoltaic panels' end-of-life material recycling. *Energy Strategy Reviews*, *27*, 100431. https://doi.org/10.1016/J.ESR.2019.100431
20. Ibid.
21. Ibid.
22. Mark Peplow, special to C&EN. (2022). Solar panels face recycling challenge. *C&EN Global Enterprise*, *100*(18), 24–28. https://doi.org/10.1021/CEN-10018-COVER
23. Tao, M., Fthenakis, V., Ebin, B., Steenari, B. M., Butler, E., Sinha, P., Corkish, R., Wambach, K., & Simon, E. S. (2020). Major challenges and opportunities in silicon solar module recycling. *Progress in Photovoltaics: Research and Applications*, *28*(10), 1077–1088. https://doi.org/10.1002/PIP.3316
24. Ibid.
25. Ibid.

26. Mark Peplow, special to C&EN. (2022). Solar panels face recycling challenge. *C&EN Global Enterprise*, *100*(18), 24–28. https://doi.org/10.1021/CEN-10018-COVER

27. Weckend, S., Wade, A., & Heath, G. (2016). *End-of-Life Management Solor Photovoltaic Panels*. IRENA, IEA-PVPS. https://www.irena.org/publications/2016/Jun/End-of-life-management-Solar-Photovoltaic-Panels

28. Curtis, T. L., Buchanan, H., Heath, G., Smith, L., & Shaw, S. (2021). *Solar Photovoltaic Module Recycling: A Survey of U.S. Policies and Initiatives*. www.nrel.gov/publications.

29. Ibid.

30. *Reliable supply of minerals – The Role of Critical Minerals in Clean Energy Transitions – Analysis - IEA*. (n.d.). Retrieved August 29, 2022, from https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions/reliable-supply-of-minerals

31. Ibid.

32. Basov, V. (2022, September 14). *Silver demand for solar panels is expected to grow by 15% in 2022 | Kitco News*. Kitco News. https://www.kitco.com/news/2022-09-14/Silver-demand-for-solar-panels-is-expected-to-grow-by-15-in-2022.html

33. Ibid.

34. Weckend, S., Wade, A., & Heath, G. (2016). *End-of-Life Management Solor Photovoltaic Panels*. IRENA, IEA-PVPS. https://www.irena.org/publications/2016/Jun/End-of-life-management-Solar-Photovoltaic-Panels

35. Ibid.

36. van Exter, P., Bosch, S., Schipper, B., Sprecher, B., & Kleijn, R. (2018). *Critical metals for renewable energy: mapping supply and growing demand*. Ministry of Infrastructure and Water Management. https://www.metabolic.nl/publication/metal-demand-for-renewable-electricity-generation-in-the-netherlands/

37. Mark Peplow, special to C&EN. (2022). Solar panels face recycling challenge. *C&EN Global Enterprise*, *100*(18), 24–28. https://doi.org/10.1021/CEN-10018-COVER

38. Ibid.

39. Energy Technologies Office, S. (2022). *Solar Energy Technologies Office Photovoltaics End-of-Life Action Plan*.

40. Holger, D. (2022, May 5). The Solar Boom Will Create Millions of Tons of Junk Panels - WSJ. *Wall Street Journal*. https://www.wsj.com/articles/the-solar-boom-will-create-millions-of-tons-of-junk-panels-11651658402

41. Holger, D. (2022, May 5). The Solar Boom Will Create Millions of Tons of Junk Panels - WSJ. *Wall Street Journal*. https://www.wsj.com/articles/the-solar-boom-will-create-millions-of-tons-of-junk-panels-11651658402

42. Ibid.

43. *Electronic Waste Facts*. (n.d.). Retrieved March 24, 2023, from https://www.theworldcounts.com/stories/electronic-waste-facts

44. *OFFICE OF ENERGY EFFICIENCY & RENEWABLE ENERGY Key Findings and Opportunities*. (n.d.).

45. Sawlani, N. (2023, May 5). *Solar Panel Recycling Market Size is Expected to Reach $1.8 billion by 2031, Rising at a Market Growth of 37.0% CAGR During the Forecast Period.* Transparency Market Research Inc. Accessed June 20, 2023: https://finance.yahoo.com/news/latest-solar-panel-recycling-market-133300106.html

46. Chowdhury, M. S., Rahman, K. S., Chowdhury, T., Nuthammachot, N., Techato, K., Akhtaruzzaman, M., Tiong, S. K., Sopian, K., & Amin, N. (2020). An overview of solar photovoltaic panels' end-of-life material recycling. *Energy Strategy Reviews*, *27*, 100431. https://doi.org/10.1016/J.ESR.2019.100431

47. Walzberg, J., Carpenter, A., & Heath, G. A. (2021). Role of the social factors in success of solar photovoltaic reuse and recycle programmes. *Nature Energy 2021 6:9*, *6*(9), 913–924. https://doi.org/10.1038/s41560-021-00888-5

48. Ibid.

49. *How Many Solar Panels Do I Need? | Solar Calculator*. (n.d.). Retrieved February 3, 2023, from https://www.solarreviews.com/blog/how-many-solar-panels-do-i-need-to-run-my-house

50. Parkman, K. (2022). *How Much Do Solar Panels Cost? (2023) | ConsumerAffairs*. Consumeraffairs.Com. https://www.consumeraffairs.com/solar-energy/how-much-do-solar-panels-cost.html

51. Walzberg, J., Carpenter, A., & Heath, G. A. (2021). Role of the social factors in success of solar photovoltaic reuse and recycle programmes. *Nature Energy 2021 6:9*, *6*(9), 913–924. https://doi.org/10.1038/s41560-021-00888-5

52. Ibid.

53. Ibid.

54. *Solar Panels Are Starting to Die, Leaving Behind Toxic Trash | WIRED*. (n.d.). Retrieved March 24, 2023, from https://www.wired.com/story/solar-panels-are-starting-to-die-leaving-behind-toxic-trash/

55. Liu, P., & Barlow, C. Y. (2017). Wind turbine blade waste in 2050. *Waste Management*, *62*, 229–240. https://doi.org/10.1016/J.WASMAN.2017.02.007

56. Ibid.

57. *National Overview: Facts and Figures on Materials, Wastes and Recycling | US EPA*. (n.d.). Retrieved December 9, 2022, from https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/national-overview-facts-and-figures-materials

58. *Commanding circularity: Siemens Gamesa announces Recyclable Blade for onshore wind power projects*. (2022, September 22). Siemens Gamesa. https://www.siemensgamesa.com/newsroom/2022/09/092222-siemens-gamesa-press-release-onshore-recyclable-blade

59. Mone, C., Hand, M., Bolinger, M., Rand, J., Heimiller, D., & Ho, J. (2015). *2015 Cost of Wind Energy Review*. www.nrel.gov/publications.

60. Lewis, M. (2022, August 2). *World's first wind turbine with recyclable blades is up and spinning*. Electrek.Co. https://electrek.co/2022/08/02/worlds-first-wind-turbine-with-recyclable-blades-is-up-and-spinning/

61. *Can wind turbines be recycled?* (n.d.). Retrieved April 1, 2023, from https://www.engie.com/en/activities/renewable-energies/wind-energy/recycling-wind-turbines

62. Cooperman, A., Eberle, A., & Lantz, E. (2021). Wind turbine blade material in the United States: Quantities, costs, and end-of-life options. *Resources, Conservation and Recycling*, *168*, 105439. https://doi.org/10.1016/J.RESCONREC.2021.105439

63. Ibid.

64. Ibid.

65. Kosciulek, A., & Nixdorf, K. (2021, December 11). *How One Company Keeps Wind Turbine Blades to Keep Out of Landfills*. Business Insider. https://www.businessinsider.com/wind-tubine-blades-landfill-recycle-world-wide-waste-2021-12

66. Ramsden, K. (2020, November 3). *Cement and Concrete: The Environmental Impact – PSCI*. Psci.Princeton.Edu. https://psci.princeton.edu/tips/2020/11/3/cement-and-concrete-the-environmental-impact

67. Mitch Jacoby. (2022). Recycling wind turbine blades. *C&EN Global Enterprise*, *100*(27), 26–30. https://doi.org/10.1021/CEN-10027-COVER

68. Ibid.

69. Tiseo, I. (2022, November 28). *Global cement CO_2 emissions 1960-2021 | Statista*. https://www.statista.com/statistics/1299532/carbon-dioxide-emissions-worldwide-cement-manufacturing/

70. Katsikopoulou, M. (2021, September 27). *denmark is repurposing discarded wind turbine blades as bike shelters*. https://www.designboom.com/design/denmark-repurposing-wind-turbine-blades-bike-garages-09-27-2021/

71. Jackson, A. K. (2021, November 16). *Recycled Wind Turbine Playground*. TheCoolist. https://www.thecoolist.com/recycled-wind-turbine-playground/

72. Kosciulek, A., & Nixdorf, K. (2021, December 11). *How One Company Keeps Wind Turbine Blades to Keep Out of Landfills*. Business Insider. https://www.businessinsider.com/wind-tubine-blades-landfill-recycle-world-wide-waste-2021-12

73. Cotton, M. (2020, September 24). *An update on Casper's landfill wind turbines project*. Wyoming News Now. https://www.wyomingnewsnow.tv/2020/09/24/an-update-on-caspers-landfill-wind-turbine-project/

74. Johnson, G. (2021, February 28). *Wyoming coal mines eyed for disposal of old windmill parts | AP News*. AP News. https://apnews.com/article/industrial-waste-wyoming-gillette-085d653f2f46a279236b7633a7b6014f

75. Ozaki, A. (2022, March 4). *Hundreds of old wind turbine blades in field near Sidney, NE*. KETV Omaha. https://www.ketv.com/article/hundreds-of-old-wind-turbine-blades-in-field-near-sidney-ne/39271654

76. Crownhart, C. 2023, *How old batteries will help power tomorrow's EVs*. MIT Technology Review. Retrieved June 21, 2023, from https://www.technologyreview.com/2023/01/17/1065026/evs-recycling-batteries-10-breakthrough-technologies-2023/

77. *Reliable supply of minerals – The Role of Critical Minerals in Clean Energy Transitions – Analysis - IEA*. (n.d.). Retrieved August 29, 2022, from https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions/reliable-supply-of-minerals

78. Consortium for Advanced Batteries, F. (2021). *NATIONAL BLUEPRINT FOR LITHIUM BATTERIES EXECUTIVE SUMMARY*.

79. *Electric Vehicles - US | Statista Market Forecast*. (2022, December). Statista. https://www.statista.com/outlook/mmo/electric-vehicles/united-states#unit-sales

80. Ibid.

81. *Anode Materials for Li-ion Battery Manufacturers | Targray*. (n.d.). Retrieved December 28, 2022, from https://www.targray.com/li-ion-battery/anode-materials

82. Rodgers, C.M., April 24, 2023. *Hearing entitled, "Exposing the Environmental, Human Rights, and National Security Risks of the Biden Administration's Rush to Green Policies"*. House Energy and Commerce Committee.

83. *Critical Minerals and U.S. Public Policy - EveryCRSReport.com*. (n.d.). Retrieved April 1, 2023, from https://www.everycrsreport.com/reports/R45810.html

84. Lander, L., Cleaver, T., Rajaeifar, M. A., Nguyen-Tien, V., Elliott, R. J. R., Heidrich, O., Kendrick, E., Edge, J. S., & Offer, G. (2021). Financial viability of electric vehicle lithium-ion battery recycling. *IScience*, *24*(7). https://doi.org/10.1016/J.ISCI.2021.102787

85. Ibid.

86. *Hydrometallurgical processing of Li-ion batteries*. (n.d.). Retrieved December 28, 2022, from https://www.futurelearn.com/info/courses/ewaste-and-battery-recycling-technology-design-challenges/0/steps/292427

87. Lander, L., Cleaver, T., Rajaeifar, M. A., Nguyen-Tien, V., Elliott, R. J. R., Heidrich, O., Kendrick, E., Edge, J. S., & Offer, G. (2021). Financial viability of electric vehicle lithium-ion battery recycling. *IScience*, *24*(7). https://doi.org/10.1016/J.ISCI.2021.102787

88. Gaines, L., & Wong, Y. (n.d.). *How to Maximize the Value Recovered from Li-Ion Batteries: Hydrometallurgical or Direct Recycling?* Retrieved December 28, 2022, from www.electrochem.org/online-store

89. Office of Energy Efficiency and Renewable Energy. (2019). Research plan to Reduce, Recycle, and Recover Critical Materials in Lithium-Ion Batteries. In *US. Department of Energy*. https://about.bnef.com/electric-vehicle-outlook/

90. Ibid.

91. Baum, Z. J., Bird, R. E., Yu, X., & Ma, J. (2022). Lithium-Ion Battery Recycling~~O~~verview of Techniques and Trends. *ACS Energy Letters*, *7*(2), 712–719. https://doi.org/10.1021/ACSENERGYLETT.1C02602

92. *Redwood Materials establishing operations in Berkeley County with largest economic development announcement in state history | S.C. Governor Henry McMaster*. (2022, December 14). https://governor.sc.gov/news/2022-12/redwood-materials-establishing-operations-berkeley-county-largest-economic-development

93. Randall, C. (2022, October 21). *Ascend Elements to make battery materials in Kentucky* – electrive.com. Retrieved June 20, 2023 from https://www.electrive.com/2022/08/03/ascend-elements-to-manufacture-battery-materials-in-kentucky/.

94. Baum, Z. J., Bird, R. E., Yu, X., & Ma, J. (2022). Lithium-Ion Battery Recycling~~O~~verview of Techniques and Trends. *ACS Energy Letters*, *7*(2), 712–719. https://doi.org/10.1021/ACSENERGYLETT.1C02602

95. Ibid.

96. Evergreen, S. (2022). *Lithium costs a lot of money—so why aren't we recycling lithium batteries? | Ars Technica*. ArsTechnica. https://arstechnica.com/science/2022/04/lithium-costs-a-lot-of-money-so-why-arent-we-recycling-lithium-batteries/

97. Slattery, M., Dunn, J., & Kendall, A. (2021). Transportation of electric vehicle lithium-ion batteries at end-of-life: A literature review. *Resources, Conservation and Recycling*, *174*, 105755. https://doi.org/10.1016/J.RESCONREC.2021.105755

98. *EverBatt: A Closed-loop Battery Recycling Cost and Environmental Impacts Model Energy Systems Division*. (n.d.). Retrieved October 26, 2022, from www.anl.gov.

99. Ibid.

100. Office of Energy Efficiency and Renewable Energy. (2019). Research plan to Reduce, Recycle, and Recover Critical Materials in Lithium-Ion Batteries. In *US. Department of Energy*. https://about.bnef.com/electric-vehicle-outlook/

101. Baum, Z. J., Bird, R. E., Yu, X., & Ma, J. (2022). Lithium-Ion Battery Recycling~~O~~verview of Techniques and Trends. *ACS Energy Letters*, *7*(2), 712–719. https://doi.org/10.1021/ACSENERGYLETT.1C02602

102. Bird, R., Baum, Z. J., Yu, X., & Ma, J. (2022). The Regulatory Environment for Lithium-Ion Battery Recycling. *ACS Energy Letters*, *7*(2), 736–740. https://doi.org/10.1021/ACSENERGYLETT.1C02724/ASSET/IMAGES/LARGE/NZ1C02724_0002.JPEG

103. Lander, L., Cleaver, T., Rajaeifar, M. A., Nguyen-Tien, V., Elliott, R. J. R., Heidrich, O., Kendrick, E., Edge, J. S., & Offer, G. (2021). Financial viability of electric vehicle lithium-ion battery recycling. *IScience*, *24*(7). https://doi.org/10.1016/J.ISCI.2021.102787

104. Lima, M. C. C., Pontes, L. P., Vasconcelos, A. S. M., de Araujo Silva Junior, W., & Wu, K. (2022). Economic Aspects for Recycling of Used Lithium-Ion Batteries from Electric Vehicles. *Energies 2022, Vol. 15, Page 2203*, *15*(6), 2203. https://doi.org/10.3390/EN15062203

105. Frankel, T. C. (2016, September 30). *Cobalt mining for lithium ion batteries has a high human cost - Washington Post*. https://www.washingtonpost.com/graphics/business/batteries/congo-cobalt-mining-for-lithium-ion-battery/

106. Hays, B. (n.d.). *Lithium ion batteries going cobalt-free nickel next on the chopping block - UPI.com*. Retrieved December 29, 2022, from https://www.upi.com/Science_News/2022/04/13/cobalt-free-lithium-ion-auto-batteries/1731649255014/

107. Gaines, L., & Wong, Y. (n.d.). *How to Maximize the Value Recovered from Li-Ion Batteries: Hydrometallurgical or Direct Recycling?* Retrieved December 28, 2022, from www.electrochem.org/online-store

108. Consortium for Advanced Batteries, F. (2021). *NATIONAL BLUEPRINT FOR LITHIUM BATTERIES EXECUTIVE SUMMARY*.

109. *Used Lithium-Ion Batteries | US EPA*. (n.d.). Retrieved January 14, 2023, from https://www.epa.gov/recycle/used-lithium-ion-batteries

110. DeFazio, P. A. (2022). *Titles - H.R.7776 - 117th Congress (2021-2022): James M. Inhofe National Defense Authorization Act for Fiscal Year 2023*. http://www.congress.gov/

111. Quinn, M. (2021, December 21). *Senate passes bill to increase EV battery recycling as part of defense budget*. Utilitydive.Com.

112. Lander, L., Cleaver, T., Rajaeifar, M. A., Nguyen-Tien, V., Elliott, R. J. R., Heidrich, O., Kendrick, E., Edge, J. S., & Offer, G. (2021). Financial viability of electric vehicle lithium-ion battery recycling. *IScience*, *24*(7). https://doi.org/10.1016/J.ISCI.2021.102787

113. Bird, R., Baum, Z. J., Yu, X., & Ma, J. (2022). The Regulatory Environment for Lithium-Ion Battery Recycling. *ACS Energy Letters*, *7*(2), 736–740. https://doi.org/10.1021/ACSENERGYLETT.1C02724/ASSET/IMAGES/LARGE/NZ1C02724_0002.JPEG

114. Resource Conservation and Recovery Act (RCRA) Laws and Regulations. U.S. EPA, https://www.epa.gov/rcra (accessed Nov 19, 2021).

115. Bird, R., Baum, Z. J., Yu, X., & Ma, J. (2022). The Regulatory Environment for Lithium-Ion Battery Recycling. *ACS Energy Letters*, *7*(2), 736–740. https://doi.org/10.1021/ACSENERGYLETT.1C02724/ASSET/IMAGES/LARGE/NZ1C02724_0002.JPEG

116. *Batteries: deal on new EU rules for design, production and waste treatment | News | European Parliament*. (n.d.). Retrieved January 3, 2023, from https://www.europarl.europa.eu/news/en/press-room/20221205IPR60614/batteries-deal-on-new-eu-rules-for-design-production-and-waste-treatments

117. Bird, R., Baum, Z. J., Yu, X., & Ma, J. (2022). The Regulatory Environment for Lithium-Ion Battery Recycling. *ACS Energy Letters*, *7*(2), 736–740. https://doi.org/10.1021/ACSENERGYLETT.1C02724/ASSET/IMAGES/LARGE/NZ1C02724_0002.JPEG

118. Kendall, A., Slattery, M., & Dunn, J. (2016). *Lithium-ion Car Battery Recycling Advisory Group Final Report*.

119. Ibid.

120. *AB2886 | California 2021-2022 | Recycling: electric vehicle lithium-ion batteries. | TrackBill*. (n.d.). Retrieved January 14, 2023, from https://trackbill.com/bill/california-assembly-bill-2886-recycling-electric-vehicle-lithium-ion-batteries/2231335/

121. *About - ReCell Center*. (n.d.). Retrieved January 13, 2023, from https://recellcenter.org/about/

122. *Spent or Used Lead Acid Battery Storage & Transport Regulations*. (n.d.). Retrieved April 1, 2023, from https://www.unisegproducts.com/usa/products/lead-acid-battery-container/spent-lead-acid-battery-regulations/

123. Bird, R., Baum, Z. J., Yu, X., & Ma, J. (2022). The Regulatory Environment for Lithium-Ion Battery Recycling. *ACS Energy Letters*, *7*(2), 736–740. https://doi.org/10.1021/ACSENERGYLETT.1C02724/ASSET/IMAGES/LARGE/NZ1C02724_0002.JPEG

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