A Circular Economy Approach to Solar Photovoltaics in Maryland

SCHOOL OF PUBLIC POLICY
CENTER FOR GLOBAL SUSTAINABILITY

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Executive Summary

Maryland has established itself as a national climate leader through ambitious targets set in the Climate Solutions Now Act (CSNA). The CSNA outlines goals to cut greenhouse gas emissions 60% by 2031 and achieve net-zero emissions by 2045, establishing an urgent need for rapid and large-scale expansion of renewable energy sources and reduction in dependence on fossil fuels. With rising energy demands from electrification, a sufficient renewable energy supply is essential to reach these targets and maintain resilience, which presents the challenge of significantly scaling up sources like solar.

Solar energy is a key component of Maryland's renewables strategy, supporting the transition away from fossil fuels and delivering economic, environmental, and health benefits. With a dedicated carveout in the Renewable Portfolio Standard (RPS) and prioritization in the Climate Pollution Reduction Plan, solar energy is integral to Maryland's climate goals. However, deployment rates currently fall short of the required pace, according to data from the State Energy Data System (SEDS) and the Solar Energy Industries Association (SEIA).

Accelerating the expansion of solar power will require addressing the full lifecycle of renewable technologies, including end-of-life (EoL) solutions for decommissioned solar panels. As solar photovoltaic (PV) generation expands, it will generate a predictable waste stream as panels retire. A circular economy approach to managing these retirements can help maximize benefits while reducing impacts. Modeling results presented here indicate that effective EoL policies could prevent 45% of the waste from decommissioned solar panels from being landfilled. With solar PV systems' relatively long lifespan, Maryland has the opportunity to iteratively develop best-practice waste management methods, leveraging stakeholder input and learning from other jurisdictions with solar PV management policies.

Effective EoL management will require coordination among a diverse group of stakeholders, including state and local governments, to ensure a cohesive approach. The U.S. policy landscape on EoL solar management is still evolving, positioning Maryland to lead in establishing standards that could influence national policy. The CSNA established a working group within the Maryland Commission on Climate Change (MCCC) to explore policy options for EoL solar management. This report responds to that mandate, offering recommendations to guide Maryland toward effective solar waste management aligned with circular economy principles.

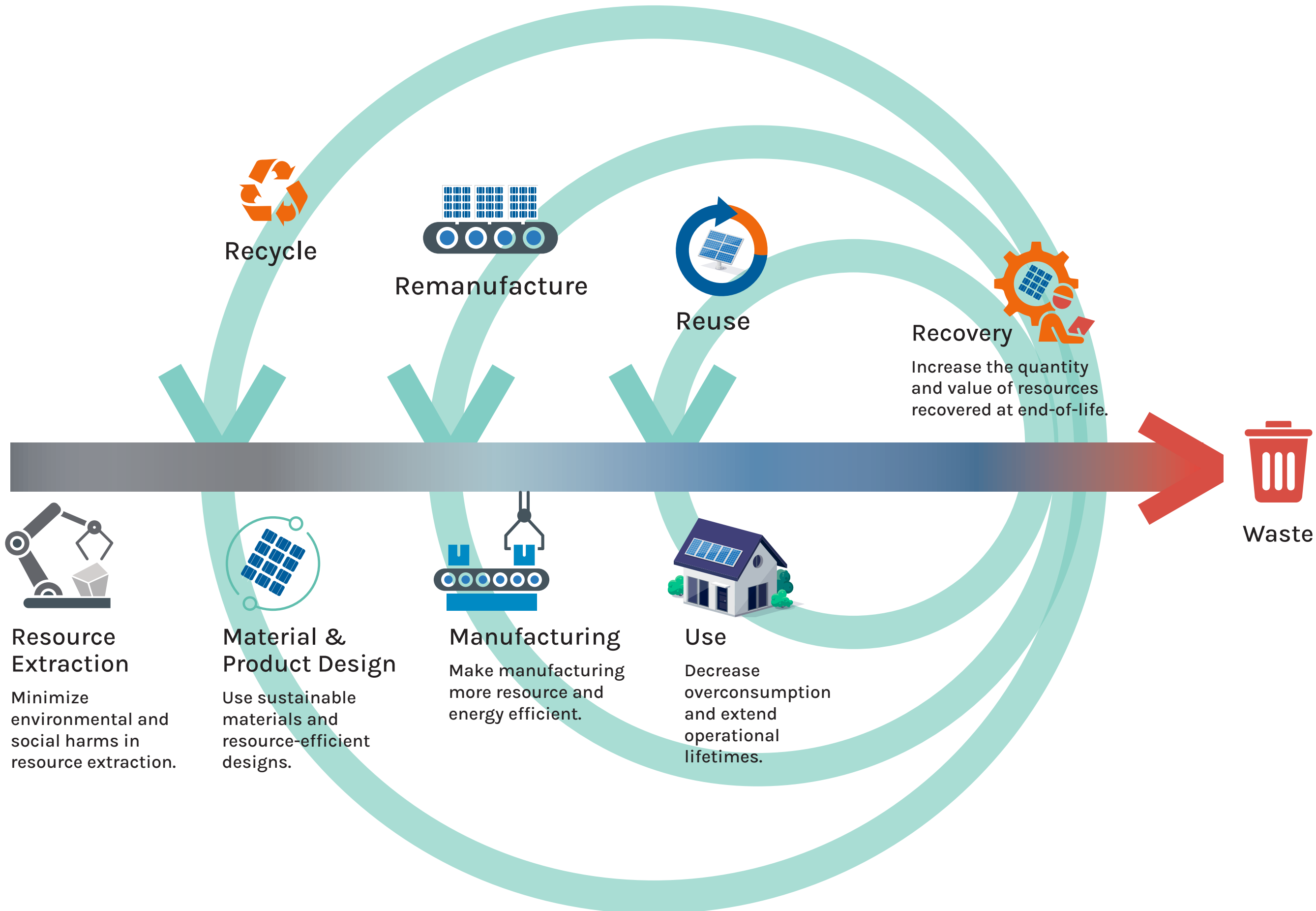


Figure E1. Schematic of a linear vs a circular economy. The central line represents the steps in the current linear paradigm often summarized as "take-make-waste", while the arrows and descriptions indicate ways to introduce circularity into each step of the product life cycle.

Through the Solar Photovoltaic Systems Recovery, Reuse, and Recycling Working Group, the CSNA directed an investigation into policy options for solar PV management in Maryland. This report provides an analysis of these options, starting with an exploration of how circular economy principles can be applied to solar photovoltaics to manage waste and mitigate supply chain risks. It reviews policy frameworks from other U.S. and international jurisdictions and examines the policy context within Maryland. Additionally, the report models nine different scenarios for the solar PV industry in Maryland based on three deployment trajectories and three policy approaches, along with their impacts on solar waste generation in the state. The report concludes with several recommendations on how Maryland can move towards a best-practices circular economy approach for solar PV management.

1. **Increase Stakeholder Engagement:** Maryland should broaden stakeholder engagement with groups such as solar recyclers, installers, homeowners, community and commercial solar operators, and local governments to better inform EoL solar policy. Increased collaboration, especially with residential solar and local sustainability offices, would improve data collection on the PV waste stream, recycling rates, and EoL costs.

2. **Pursue a Regional Approach:** Maryland can coordinate with nearby states to address EoL solar challenges, as near-term, in-state volumes may not justify a dedicated recycling center. A regional strategy could enhance compliance with landfill bans and support shared recycling facilities, potentially in North Carolina or Virginia.

3. **Implement a Landfill Ban with Incentives:** To curb out-of-state landfilling of EoL solar panels, Maryland should consider a landfill ban paired with financial incentives that favor reuse, remanufacturing, and recycling. In the short term, the state can support e-waste recyclers to manage solar panels, while developing cost-effective, long-term transport options to regional facilities.

4. **Address Immediate Needs:** The Maryland Department of the Environment (MDE) can bridge current policy gaps by guiding residential, commercial, and community solar owners on EoL options, while helping county landfills and existing recyclers manage solar panel disposal requests until a comprehensive state policy is established.

5. **Support Electronics Recyclers:** Maryland could expand its recycling capacity by providing financial and technical assistance to existing e-waste recyclers certified under R2 standards. This interim support would enable recyclers to handle EoL solar waste streams more effectively.

6. **Leverage Workforce Development Synergies:** Maryland should integrate EoL management skills into solar workforce training programs, including reuse and circular economy practices. This will prepare the workforce to manage future solar EoL challenges as the renewable energy sector grows.

7. **Embed the Waste Hierarchy:** Maryland should promote the reuse of solar panels as a primary option, with landfilling as a last resort. Establishing a reuse market, which could help make solar accessible to a wider consumer base, requires testing and recertification processes to ensure consumers are getting reliable and economically viable energy resources.

8. **Revisit Policies Annually:** With rapid advancements in solar technology and EoL options, Maryland should review and adjust its EoL policies annually. Adaptable approaches will help the state stay aligned with evolving federal standards and industry practices, fostering a resilient solar recycling framework.

Maryland's leadership in EoL solar management offers an opportunity to set a national example in circular economy practices. By effectively managing the lifecycle impacts of renewable technologies, the state can support its ambitious climate targets, ensuring a sustainable energy transition that addresses both climate goals and environmental stewardship.

Introduction

Maryland has the most ambitious state-level climate goals in the United States, targeting 60% reduction in gross greenhouse gas (GHG) emissions by 2031 and net-zero emissions by 2045.[1] Meeting this goal will require a rapid expansion of renewable energy to both replace existing fossil fuels and to meet rising electricity demand due to electrification of transportation, buildings, and industry.[2,3] Solar power will play an essential role in this transition, as recognized by the explicit targets in Maryland's Renewable Portfolio Standard (RPS), which aims for 14.5% of the state's electricity consumption to be supplied by solar by 2030.[4] However, this rapid growth in solar power raises new questions about how Maryland will manage the life cycle of solar panels, particularly during decommissioning when solar panels reach the end of their operational life.

Managing the end-of-life of solar photovoltaic (PV) panels involves a range of different actors across the solar industry, as well as federal, state, and local governments. The policy landscape around solar PV management is developing rapidly at all levels of government, alongside ongoing technological change as solar PV devices continue to improve. To effectively manage solar technologies over time, it will be essential for Maryland to engage with all of these processes and develop a holistic approach that can address every stage of the technology life cycle, such as in a circular economy.

The Climate Solutions Now Act of 2022 (CSNA) established the Solar Photovoltaic Systems Recovery, Reuse, and Recycling Working Group under the Maryland Commission on Climate Change to investigate policy options for solar PV management in Maryland.[5] In this report, we respond to the charge in the CSNA and present analysis of different policy options. First, we describe how circular economy principles can be applied to solar photovoltaics to better manage waste and reduce supply chain risks. We provide an overview of policy frameworks currently in use to enact these principles in various jurisdictions in the US and around the world and discuss the current policy context in Maryland. Then, we present an analysis of the solar PV systems currently deployed in the state, and model how different potential trajectories for Maryland's solar industry would affect the generation of solar waste in the state. Finally, we describe the potential impacts of solar waste in Maryland and provide recommendations for how Maryland can manage solar waste with a focus on circular economy principles.

Photovoltaics in the Circular Economy

The U.S. economy currently functions primarily through linear “take-make-waste” processes where virgin materials are used to manufacture products and the products are landfilled at end of life. This system is the dominant paradigm for the solar photovoltaic market, with less than 10% of decommissioned solar panels reused or recycled as of 2019, while the vast majority of panels ended up in landfills or long-term storage.[6] Landfilling solar panel waste permanently removes valuable materials from the solar PV supply chain[9] and can contribute to pollution, particularly if solar waste is mismanaged.[7,8] An alternative to this is a circular economy, or a system that retains the value of materials for as long as possible by re-using products that are still functional, recovering materials at the end of life, and minimizing new material extraction and landfilled waste.[10,11] As Maryland increases its deployment of solar photovoltaic panels to meet its renewable energy goals, these circular economy principles can provide a holistic life cycle management approach to ensure the system is sustainable.

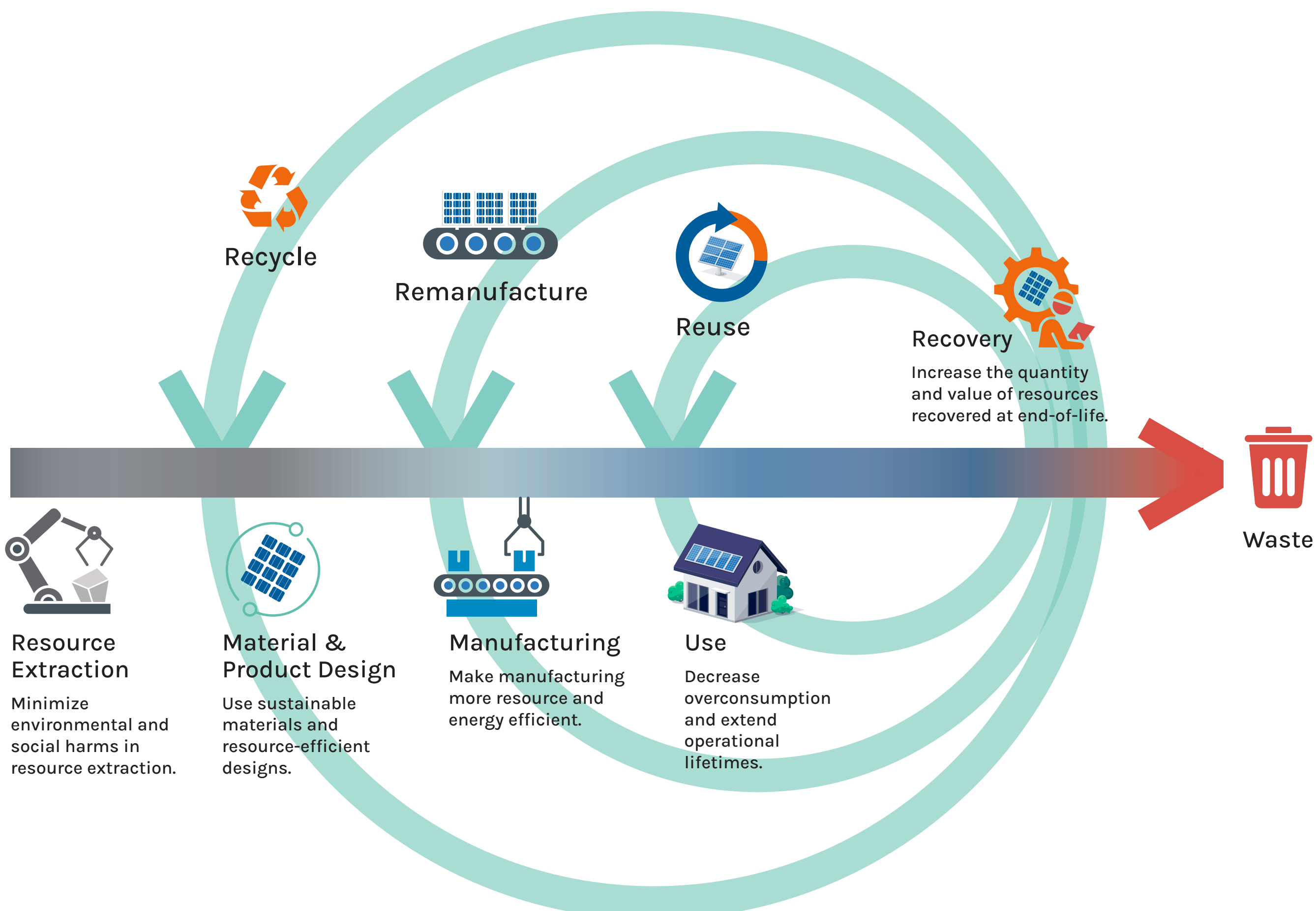


Figure 1. Schematic of a linear vs a circular economy. The central line represents the steps in the current linear paradigm often summarized as “take-make-waste”, while the arrows and descriptions indicate ways to introduce circularity into each step of the product life cycle.

A solar PV circular economy would incorporate concepts of material reduction, reuse, repair, remanufacture, and recycling throughout the value chain, from research and design to end-of-life (Figure 1). This would mean designing panels when they are manufactured to facilitate repair processes and disassembly, such that pieces of a panel can be reused in new panels (also known as remanufacturing) or broken pieces can easily be separated into constituent materials for recycling. In Table 1, we define how we interpret the different end-of-life (EoL) management strategies for solar in this report.

Term	Definition
Recovery	Any and all methods to use a solar panel or its components after its expected lifetime. Repairing, reusing, remanufacturing, or recycling a solar panel are all forms of recovery.
Reuse	Continuing to use a solar panel beyond its initial project lifetime. Examples include continued use of the panel on-site past the end of an economic contract, or resale of a panel after its removal from its original site to a new buyer.
Repair	Replacing or fixing any component of a module during its period of use *without* removing it from its place of operation. Examples include re-wiring the panel to the rest of the array, or cleaning or replacing the glass after weathering.
Remanufacturing	Dismantling a solar panel or module and using the functioning components to produce another panel without further processing, after its removal (demounting) from its place of operation. Examples include cleaning and removing the glass sheets from a panel and installing them on another panel, or sending a functioning module with corroded aluminum frames back to the panel manufacturer to be re-fitted with new frames.
Recycling	Removing and dismantling a panel into its components and breaking down/crushing the components into their individual materials for resale in any market. For instance, this could involve demounting and dismantling the aluminum frames from a module and sorting them to be melted and reused along with soda cans, auto parts, or any other aluminum components. For glass, it could mean removing the glass of a panel and adding it to the existing glass recycling stream with window panes and glass bottles, for ultimate resale as stock material for manufacturers in any industry.

Table 1. Definitions of end-of-life management options for solar PV panels.

The further back into the value chain that materials return, the greater the cost both financially and environmentally. Therefore it is preferable in a circular economy to prioritize material reduction, reuse, and repair before recycling, which is the least circular process. This prioritization is known as the waste management hierarchy. Current solar panel research, investment, and policies often narrowly focus on recycling as the alternative EoL option to landfilling, but promoting sustainability and a circular economy should involve the entire panel lifecycle.

Examining the economics of EoL utility scale solar projects can demonstrate the financial benefits of different circular EoL approaches. Figure 2 shows the results of a financial model developed by NREL, with a partial picture of the cash flow of an idealized solar power plant. The Decommission scenario refers to a base case in which a utility-scale solar power plant is decommissioned, panels taken down and the site deconstructed, after the intended 25 year project lifetime. The Extend scenario assumes a "stay-in-place" scenario in which the original solar panels and balance of systems equipment are left for an additional amount of time beyond the initial 25 year project lifetime. The Refurbish case assumes that where applicable, panels will be refurbished and the solar power plant will regain some power output lost to degradation of panels. For the Repower scenario, the panels of the solar power plant are wholesale replaced, thus restoring the original power output.

This model demonstrates that extending a project could lead to a lower cost of electricity over the entirety of the project, primarily due to avoiding the capital costs of a new installation. However, the

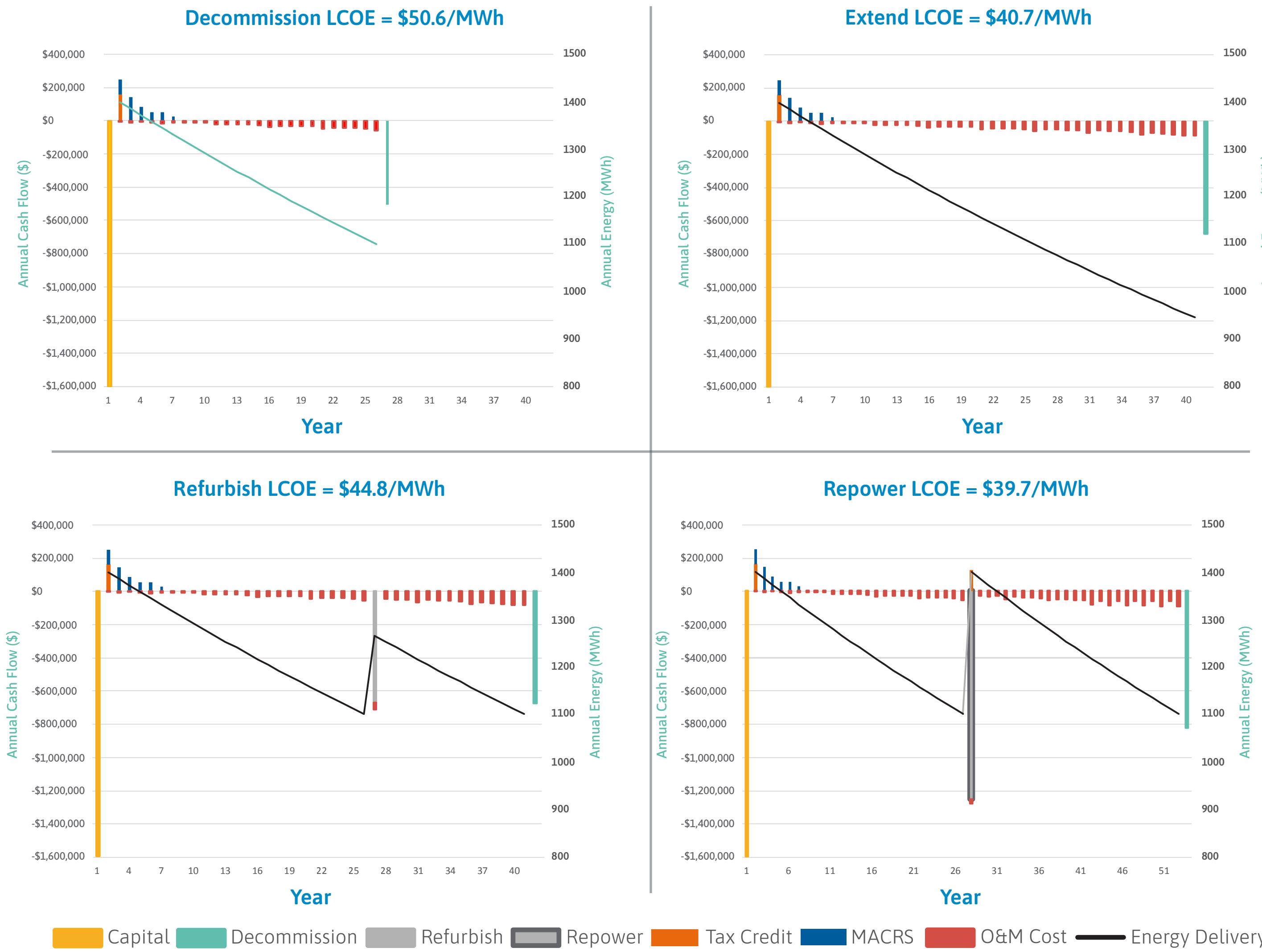


Figure 2. Representative cases of cash flow analysis based on different end-of-life options. Financial model developed by National Renewable Energy Laboratory (NREL) and updated by the authors.[12] Note that this only includes a few revenue sources, and it does not include revenue from selling energy generated. O&M = Operations and Maintenance. MACRS = Modified Accelerated Cost Recovery System, a method of depreciation. Further details are provided in the technical appendix.

utility-scale solar project owner may find the lower power output of aging solar panels does not provide enough return to keep the project online as is. This suggests a role for policy to incentivize less panel turnover and more “stay in place” projects that create less waste. The lowest cost of electricity across the entire project is achieved when the panels are replaced wholesale, as shown in the “Repower” scenario. The benefits of this case include leveraging the existing balance of systems equipment and location while also resetting the power output with new panels operating at peak efficiency.

Across the entire solar panel and system lifecycle, there are opportunities to consider circular economy concepts, and in doing so, we can examine a full spectrum of policies that approach material management holistically, rather than just at a product’s end of life. While there may be current technical barriers that make it difficult to refurbish or reuse solar panels, new policies can help guide the design of products to favor easier waste management or create incentives for reuse markets.This kind of broad strategy considering the entire lifecycle of panels will require engaging with stakeholders to ensure a coherent plan for each stage of the value chain. By doing so, Maryland can become a leader in taking a comprehensive approach to solar PV systems EoL management.

Policy and Financing Approaches for a PV Circular Economy

In this section, we describe existing approaches to regulating and financing end-of-life management of solar PV panels. These approaches are summarized in Table 2.

Policy	Description	Benefits	Challenges
Extended Producer Responsibility (EPR)	Holds producers responsible for EoL management of goods they manufacture	• Pushes producers to make their products more recyclable • Embeds circularity into product life cycle	• Difficult to track responsibility throughout the life of panels (25+ years) • Difficult to regulate global manufacturers at a local or state scale
Universal Waste Designation	Classifies solar modules as a sub-class of hazardous waste with streamlined regulations for handling and management	• May make handling solar panels deemed to be hazardous easier and more economic for recyclers • Follows EPA action for federal rule designating solar panels as UW	• Solar EoL handlers may still have to determine if panels are hazardous or not • Could increase costs for recyclers if simplified storage, transport, and recycling requirements are not included
Landfill Ban	Prohibits disposal of solar modules in landfills	• Promotes more circular EoL options for solar panels	• Presumes other EoL options, like recycling, are available • Solar panel waste potentially transported out of state
Advanced Recovery Fee	Consumers are charged an up-front recycling fee upon purchasing panels	• Provides funding to support recycling • Costs are fully known at point-of-sale	• Could disincentivize solar adoption by increasing costs
Adoption of Industry Standards	Establishes standardized best practices for recycling and other forms of EoL management	• Provides clear guidance on expectations for recyclers • Third party certification can give consumers confidence in those that comply with standards	• Compliance with standards is voluntary, and not all actors may choose to comply

Table 2. Summary of common policy approaches to solar PV EoL management.

Extended Producer Responsibility

Extended Producer Responsibility (EPR) is a policy design used for management of multiple consumer goods where the producer of the good is held responsible, financially and/or physically, for collection and potentially disposal of the product after its useful life.[6] EPR programs already exist in the United States for certain electronic devices.[6] These programs require manufacturers to register with the state, and the manufacturers are often regulated to collect a certain portion of their sold goods for recycling or reuse.[6] A well-designed EPR program aims to incentivize producers to design products that are more sustainable and easier to recycle or reuse, in addition to creating a compliance mechanism that enforces recycling and/or reuse. [6]

European Union

The European Union (EU) revised its Waste Electrical and Electronic Equipment (WEEE) regulations in 2012, which govern EoL of solar panels as well as other forms of Electrical and Electronic Equipment (EEE) waste.[13] The regulations set targets for EEE waste collection, recovery, and recycling through an EPR program.[14,15] Producers are directed to establish take-back programs, making them liable for collection, treatment, recovery, and disposal costs for solar panels, with target compliance rates that were phased in over time (Table 3).[14] A 2017 report showed recyclers mainly adapted existing electronics recycling operations, given that glass and aluminum constitute a large fraction of the mass of a solar module.[16] As of 2020, some European jurisdictions saw recycling rates above 90%, with recycling costs lower than $1 per module.[9] Overall, the EU has seen increased collection of EEE waste and EoL solar, as well as more recycling and reuse of EoL solar panels.[17,18]

The regulation explicitly states that producer responsibility schemes should be implemented at the EU level as opposed to the national level.[14] However, as policy has evolved, some nations in the EU have adopted more detailed systems and policies for EoL solar management that fit within the overall EU WEEE regulation.[13] Germany differentiates between solar companies selling to private households, which is categorized as business to consumer (B2C) and larger scale solar power plants operated by an independent company, categorized as business to business (B2B).[19] For B2C, Germany operates a collective producer responsibility system.[19] In this system, a clearinghouse does some of the administrative tasks required of an EPR program - collecting data on what products are on the market and which producers are registered within that market.[19] Additionally, residential solar customers cannot be charged for EoL collection and treatment.[20] This represents a more collective system of responsibility that centralizes some classic activities of an EPR program like solar panel collection, tracking of products and producers, and distributing and sharing financial obligations.[19] For B2B, arrangements can be made between the two parties while still following overall WEEE regulation.[19]

A key piece of the EU policy is that the regulation shifted over time from solely a recycling requirement to a requirement that modules be prepared for reuse as well, thereby moving towards a more circular approach to end-of-life management.[14] Additionally, the EU established a Restriction of Hazardous

Substances (RoHS) in Electrical and Electronic Equipment policy, which aims to reduce the amount of toxic substances used in electronic manufacturing to reduce negative environmental and human health impacts and to promote recyclability.[21]

Year	Recovery Rate	Recycling Rate	Panels Prepped for Reuse/Recycling
2012 - 2015	75%	65%	-
2015 - 2018	80%	-	70%
2018 -	85%	-	80%

Table 3. European Union targets for re-use and recycling of solar panels under their Waste Electrical and Electronic Equipment regulations.[14]

Washington State

Washington state is the only state in the US with an EPR program for solar panels.[6] The state's 2017 policy is broad, covering small rooftop systems to larger utility-scale systems.[6] It applies to in-state manufacturers plus distributors and installers who take legal responsibility for imported panels. Manufacturers are required to finance the takeback and recycling system at no cost to the owner of the PV module.[6] However, the Department of Ecology recently requested the state delay implementation of the law because some manufacturers have chosen to not sell solar panels in Washington rather than comply with the EPR program.[22]

Considerations for a Maryland EPR

Other states have previously or may be actively considering an EPR policy mechanism for EoL solar management. Although detailed studies on the efficacy of the EU and Washington EPR programs are not yet available, lessons can still be learned from both. While Washington state might see solar energy businesses leave as manufacturers decide it is too costly or difficult to comply with the EPR program,[6] the EU EPR covers multiple nations, making it more difficult for entities who choose not to comply and sell instead to a neighboring jurisdiction. In short, success of an EPR program in the US may be contingent on its scale being regional or national. Additionally, to ensure greater circularity and push for more advanced recycling and recovery, recycling and recovery requirements based on mass should be considered carefully; a recycling requirement of 75% by mass may lead to only the glass and some aluminum being recycled, leaving silicon and other metals to be landfilled.[23] A mass-based requirement may therefore fail to alleviate concerns around solar PV supply chains, which primarily focus on higher value materials. Lastly, some in the EU recognized that different solar sectors required different solar EoL arrangements, leading to separate treatment of B2C and B2B arrangements. This suggests a potential benefit to having separate processes and policies for residential versus utility-scale solar.

Universal Waste Designation

Under the Resource Conservation and Recovery Act (RCRA), solar panels are classified as solid waste that may or may not be hazardous.[24] It is the responsibility of the solar panel waste generator to determine whether the panels are hazardous through their knowledge of panel components or through a toxicity characteristic leaching procedure (TCLP) test. If a solar panel fails the TCLP test, then it would have to be handled, transported, and managed under hazardous waste procedures, which are more rigorous and stringent than non-hazardous waste procedures.

Because solar panels are becoming more common and handling them as hazardous waste can be time intensive and costly, the Environmental Protection Agency has begun to develop a federal rule to classify hazardous solar panels as universal waste (panels that pass the TCLP test could still be considered non-hazardous). Universal waste is a subcategory under hazardous waste that is considered lower risk compared to other hazardous wastes and thus has streamlined management requirements. The goals of classifying solar panels as universal waste would be to provide a clearer system for panel handling, ease regulatory burdens for disposal and recycling, promote collection and recycling, and reduce the number of panels going to landfills. Some states like California and Hawaii have already designated solar panels as universal waste at the state level.[25,26] However, in 2023 there were efforts in California to establish alternative management standards for recycling solar panels determined to be universal waste. The proposed amendment would allow for the use of heat, chemicals, and water for the recycling of universal waste-designated solar panels – processes that are currently not allowed under the universal waste regulations.[27] While a universal waste designation could be helpful in easing regulatory burdens, barriers may still exist for EoL solar panel management that are not fully addressed through the designation.

Landfill Diversion Policy

Landfill diversion policies (also known as landfill bans) for solar panels prohibit the disposal of panels in municipal non-hazardous waste landfills.[6] By eliminating this low-cost option for landfill disposal, such diversion policies can help keep panels out of landfills altogether by making the market choose between costly hazardous waste landfills and recycling.[6] There are currently no federal or state laws directly banning the disposal of solar panels in landfills in the US. Arizona's legislature considered a landfill diversion bill in 2020, but the bill did not make it out of committee.[28] One state in Australia, Victoria, has a landfill ban for EoL solar waste and other Australian states are considering the same.[29] A notable number of US states do prohibit disposing of certain electronic devices in landfills.[6] In many such cases, the landfill ban is paired with an EPR or EPR-like program in which manufacturers register and provide takeback opportunities;[6] recognizing the potential synergies of a landfill ban coupled with product stewardship programs.[30] However, there are additional considerations that must be addressed to ensure these potential benefits are achieved. Specifically, some in the solar recycling industry have expressed concern about recyclers who end up recycling very little and landfilling many materials of a solar panel.[31,32] Additionally, there is a risk that panels could simply end up in long term storage if they are prohibited from being landfilled and recycling is not economical.[6] Working with recyclers, waste management professionals, and other relevant stakeholders will therefore be vital to ensure a landfill ban is effective and outcomes are monitored and verified.

Advanced Recovery Fee

An Advanced Recovery Fee (ARF) system allows retailers to charge consumers a recycling fee at the time of purchase, and that fee is used directly to support recycling entities and efforts.[33] Governments are often the responsible party for recycling in an ARF system.[34] California is the only state to use this policy structure for its e-waste program.[35] The Solar Energy Industry Association (SEIA) has expressed support for an ARF system for solar panels for the residential solar sector.[36] The New Jersey Solar Panel Commission also put forward an ARF as a potential solution for financing EoL management of solar panels.[37]

California's program demonstrates what an ARF policy could look like for solar panels. The fees collected from purchases of new products are used to fund recycling of retired products, emblematic of a pension system.[34] Importantly, the fee is administered at the point of sale, so the full cost is known to consumers up-front.[38] The fee revenues are then used by the state for recycling efforts as well as inspections and compliance activities.[38] Depending on the size of the fee, this approach could raise concerns that the higher up front price could slow solar deployment on the consumer side.

Industry Standards

The solar PV industry is currently undergoing standards development as it pertains to end of life solar management and recycling processes. Specifically, the SEIA is developing multiple standards related to EoL solar; SEIA 601 covers decommissioning, SEIA 602 addresses equipment needed for solar panel recyclers, and SEIA 603 addresses EoL management more broadly.[39] In addition, the R2 standard from Sustainable Electronics Recycling International (SERI) now contains Appendix G specifically for Photovoltaic Modules.[40] There are multiple facilities in Maryland currently certified to the R2 standard,[41] but given the recent development of the additional PV standard requirements, none of those facilities are certified to Appendix G.

While some standards only focus on EoL, other standards might help push for more sustainable manufacturing of panels at the same time.[42] The NSF/ANSI 457 standard covers EoL management along with design and manufacturing of solar modules.[42] This standard promotes circular economy by having manufacturers provide take-back options and seek opportunities to refurbish, repair, and resell modules.[42] Pushing for the adoption of NSF/ANSI 457 can help consumers' trust in solar PV by identifying manufacturers that are incorporating more environmentally responsible processes into their manufacturing.[42] Lastly, the state can follow the example of the EPA as it uses specific ecolabels to help guide procurement.[43]

Policies Under Development

Multiple US states have created commissions and working groups, and are drafting reports on best practices for solar PV recycling.[6] Often, such groups and reports provide recommendations to the state, suggesting actions or policy changes to address solar PV waste that may also be relevant for the Maryland context. Additionally, work is ongoing at the federal level regarding solar panel recycling.

North Carolina

In a report about decommissioning renewable energy technologies, the North Carolina Department of Environmental Quality found reuse and recycling markets to still be in development.[44] Additionally, they found the waste hierarchy detailed above to be appropriate for EoL solar panels.[44] While recycling was limited and costly at the time of writing (2021), refurbishment and reuse were broadly described as "economically advantageous".[44] Lastly, the report does not recommend a manufacturer stewardship program, but it does recommend exploring it as an option in the future.[44]

New Jersey

New Jersey established a commission to study solar recycling policy, and they released a report in late 2023 with findings and recommendations.[37] They recommended the construction of solar panel recycling facilities within the state, and adoption of an EPR or ARF model to govern EoL solar panels.[37] Additionally, continuing to use panels beyond an arbitrary lifespan is recommended.[37] Lastly, the commission recommends reusing panels by transporting them to areas with less access to new solar energy, which could be domestic or international locations.[37]

Federal Government

The EPA is currently undertaking a rulemaking process to designate solar panels as universal waste.[45] At the same time, the Department of Energy (DOE) has put out an Action Plan for EoL photovoltaics.[46] Beyond supporting research and development in solar recycling, the Action Plan sets a target of reducing recycling cost from the current value of $15-$45 per module to approximately $3 per module by 2030.[46] Additionally, they are gathering data to better understand the current waste stream, targeting data on 10 MW of EoL solar and a database with relevant information for solar EoL handlers.[46]

Maryland Policy Context

Policy for Utility-scale Solar PV

The EoL of utility-scale solar projects in Maryland is currently governed by the Public Service Commission (PSC), the body which approves decommissioning plans.[47] PSC regulations require that all solar projects greater than 2 MW must have a plan for equipment removal when the project reaches its end of life.[47] To inform the approval of these decommissioning plans, the Department of Natural Resources (DNR) Power Plant Research Program (PPRP) evaluates potential project impacts and makes recommendations to the PSC about what must be included in any license conditions when a Certificate of Public Convenience and Necessity (CPCN) is granted.[47]

While Maryland does require decommissioning plans for utility-scale solar projects, they are approved on a case-by-case basis. Therefore, further clarification and standardization may be helpful for PPRP, PSC, and project developers. Many states more specifically define what decommissioning entails and thus what elements would need to be included in a decommissioning plan.[48] Regardless, any new end-of-life solar panel policy should recognize that utility-scale solar projects are currently approved with at least a skeletal plan for end-of-life treatment of those panels.

Decommissioning plans can have various levels of EoL detail. For example, within some applications for a CPCN, solar project developers note they will maximize the reuse and recycling of solar components in their decommissioning plans.[49] Other utility-scale solar array plans state they will work with recycling centers and manufacturers to recycle the PV modules.[50] Recognizing the value of resale, some plans specify that the panels will likely be resold on a secondary market.[49] Reselling modules can help projects cut down on decommissioning costs and is preferable for some compared to recycling.[51]

Policy for Commercial, Community, and Residential Solar

Newer community solar and commercial solar arrays are growing in size, with some large enough that they are required to obtain a CPCN. However, many are small enough to avoid the CPCN process; therefore, they may not be subject to the same requirements for decommissioning and end of life management of panels. In some instances, private lease agreements may still include decommissioning plans, although they are not subject to a consistent regulatory process like the CPCN. Counties may also have policies governing decommissioning for commercial and other ground mounted solar arrays. Residential solar may be subject to some policies at the county level for larger arrays, but EoL management is often handled by the homeowner or panel leasing company. In these solar sectors (commercial, community solar, residential), state policy could serve to push for more reuse, repair, and recycling of panels. However, different solutions may need to be tailored to each sector, as each has unique patterns of financing, ownership, and management.

Related Policies

The Maryland Department of the Environment currently administers multiple EPR or EPR-like programs; one program covering paint[52] and another covering electronics[53] could offer important insights for a potential EPR program for solar in Maryland. Additionally, HB 468, which passed this year, directs a commission to explore the viability of an extended producer responsibility program for lithium batteries.[54]

EPR for Paint

In the 2024 Legislative Session, the legislature established an EPR program for paint.[55] The bill requires producers of architectural paint to submit a plan to the Maryland Department of the Environment (MDE) by July 1, 2025 for a Maryland Paint Stewardship program.[55] A nonprofit, PaintCare, will operate the stewardship program as a third party organization, providing pickup locations at retail stores and EoL management for paint.[52] The program is aimed at reducing public financial responsibility while maintaining government oversight.[52]

Electronics Recycling

MDE also operates an electronics recycling program that directly involves the manufacturers of covered electronic devices.[53] Manufacturers of qualifying electronics register with the state, and the registration fee can be reduced for manufacturers that offer MDE-approved, free take-back options directly to consumers.[53] In their take-back program, they must offer educational materials and a no-cost method of returning the covered electronic device.[53] In short, this program does not require every manufacturer to take back their products, but manufacturers are financially incentivized to do so by a large registration fee reduction.

Proposed Legislation

There are four pieces of legislation previously proposed in Maryland related to solar panel stewardship and recycling, which fall into two categories. Three of the bills were introduced in 2018, 2019, and 2020, with the aim of setting up a Solar Photovoltaic Recycling Fund to be housed in the Maryland Department of the Environment (MDE).[56–58] Another bill introduced in 2020 tasked the MDE with developing guidelines for manufacturers to establish their own takeback and recycling programs which follow an EPR policy structure.[59] None of these bills made it out of committee.

Solar Recycling Fund (2018, 2019, 2020)

The three pieces of proposed legislation that would have established a Solar Recycling Fund include HB 1242 (2018)[58], HB 125 (2019)[57], and HB 165 (2020)[56]. To bring in revenue for the fund, the legislation would create two primary sources.[58] A 10% fee on installation costs would be established for any new solar generating facilities, and a 20% charge on the first sale price of a Renewable Energy Credit would go toward the fund.[58] Local governments would not be able to administer any other taxes or fees on installation cost.[58] The fund aims "to provide funding for technologies and processes that assist with the recycling of solar PV systems and to pay for MDE's administrative costs."[58] The proposed bill got an unfavorable vote from the committee. The bill was reintroduced in 2019 and 2020. In testimony from 2020, some expressed worry it would hinder solar deployment in Maryland as costs would likely be passed on to consumers.[60,61] Some highlighted existing options like the Solar Energy Industry Association's Solar Recycling Partner Network.[61] The proposed bills of 2019 and 2020 also did not make it out of committee.

Panel Stewardship Program (2020)

Another bill, SB 891, introduced in 2020 would have directed MDE to develop guidelines for a panel stewardship program.[59] The program was similar in design to EPR legislation proposed in other states and the Washington program. The MDE-developed guidelines would provide manufacturers with technical assistance in developing, adopting, and implementing a self-directed takeback and recycling program.[59] In testimony for the bill, some noted the short timelines in the bill, which could make it difficult for government agencies and solar manufacturers to comply.[62] Additionally, there was some concern it could hinder solar deployment in the state.[62]

Stakeholder Perspectives

To understand the current state of EoL treatment and options in Maryland and elsewhere, the authors contacted county recycling coordinators, the Department of Natural Resources, solar recyclers, and residential solar installers.

County Recycling Coordinators[63]

Country Recycling Coordinators were asked if their county landfills would accept solar panels and if they had any specific solar panel EoL policies. Some said they would not accept solar panels or have not yet, and some said they would not accept large amounts of panels from a large solar array. Most said they did not have specific solar EoL policies. Others mentioned they were looking for more guidance from the state on matters of solar panel EoL processes and policies.

Department of Natural Resources—Power Plant Research Program

The DNR PPRP has an important role in conducting assessments and making recommendations to the PSC regarding utility-scale solar power plant applications for a CPCN, which must include a decommissioning plan. In conversations with PPRP, representatives confirmed that though each utility-scale solar array goes through an individual case process with the PSC, some general guidelines for management of EoL solar panels have started to emerge. For example, PPRP recommends that a project's decommissioning plan include an element about how the project will "[maximize] the extent of component recycling and reuse, where practicable."[47] Consequently, it may not be critical for additional policy to address utility-scale solar at this time as it pertains to solar recycling and reuse. The success of this approach should be verified through monitoring and data collection efforts once installations reach EoL in Maryland.

Solar Recyclers

While the number of solar-specific recyclers in the US are growing (e.g., SOLARCYCLE and First Solar), there are currently no solar-specific recyclers within the state of Maryland. Therefore, we interviewed representatives of ERI Direct[65] and EVR[66] (Electronics Value Recovery), who are primarily electronics recyclers that also recycle some solar panels. Maryland electronics recyclers, like EVR and eRevival, could play a role in helping the state manage EoL solar in the near-term, which is discussed further in the recommendations section. One interviewee noted that their solar recycling operation is a net cost overall. If panels received by the recycler are in good structural and functional condition, they may try to resell them. This revenue from reselling panels can help offset the cost of recycling panels. Both interviewees noted that reselling panels is a source of revenue, but recycling is a net cost. Additionally, one interviewee discussed the benefits of a universal waste designation for solar panels. Another interviewee said most modern panels are not toxic and frequently pass TCLP testing; therefore, according to this interviewee, a UW designation is not necessary and could actually be a hindrance for handling panels. Further details on interviews are available in the Technical Appendix.

Residential Solar Installers

As noted above, residential solar has fewer processes in place for EoL handling of panels. Additionally, removal and disposal has not been a major activity yet for many installers, some of whom say they have little-to-no guidance, given the relatively recent deployment of residential solar compared to the lifetime of the panels. If rooftop solar panels are leased, the installer or owner of the panels would decide what is done with panels at the end of their life. For those homeowners who own the panels on their rooftops, it may be up to the homeowner how the panels are handled. It is important to consider the actual options available to homeowners who are looking to remove or upgrade their solar panels. It would be valuable to further engage with residential solar companies and installers to get a more complete picture of the current plans and actions pertaining to EoL solar management.

Current Solar Deployment in Maryland

As of 2023, Maryland has deployed 2,372 MW of operational photovoltaic capacity according to the Energy Information Administration (EIA). The majority of this deployed capacity is small-scale distributed solar, with community solar installations growing rapidly in recent years (Figure 3).[67] The comparatively slow growth of utility-scale solar has been in part due to bottlenecks in the PJM interconnection queue, which may ease following the updated interconnection process, which was adopted in July 2023.[68] This could lead to a rapid build-out of large-scale solar installations in the coming years, although other challenges remain such as competition for land use and infrastructure integration.

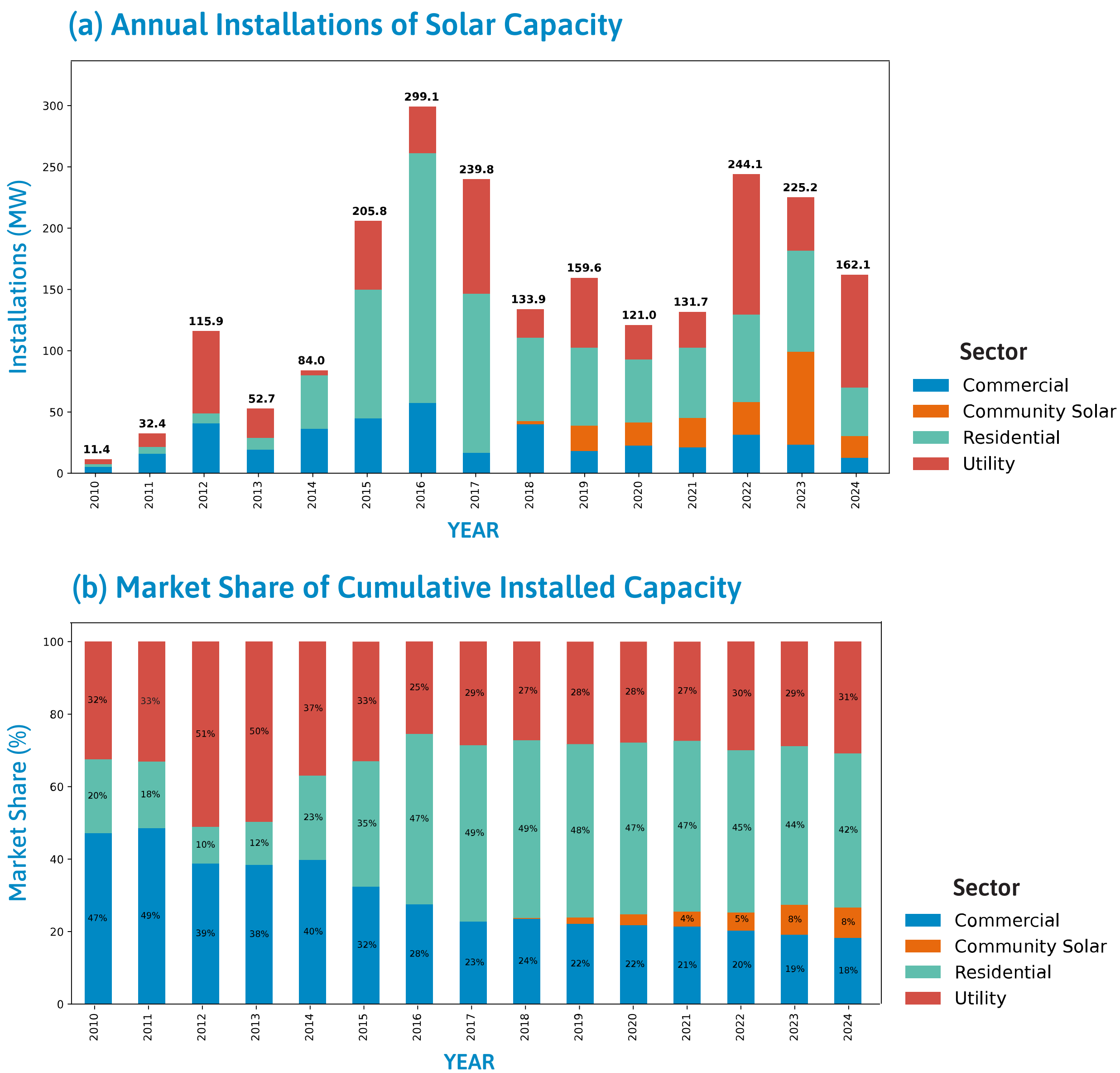


Figure 3. (a) Solar capacity installed each year in Maryland, categorized by the project type: residential, commercial, community solar, or utility. (b) The *cumulative* percentage of installed capacity by project type since 2010. Data provided by SEIA.[69]

The first utility-scale PV installation in Maryland began operation in 2010, and no facilities have been decommissioned as of 2024.[70] The majority of Maryland facilities are small capacity, with only 12 of 147 facilities exceeding 10 MW (Figure 4). Almost all of these installations are on greenfield sites developed solely for solar power. However there are two existing agrivoltaic installations which combine solar with agricultural use of the same site, 6 installations on landfill sites, and 1 installation on a superfund site.[71] It is currently unclear what the use plan is for these greenfield sites after the expected lifetime of the solar panels, which may impact certain options available to the sites at EoL such as extending the operation of the panels in place, repairing the panels for continued operation, or fully repowering the facility.

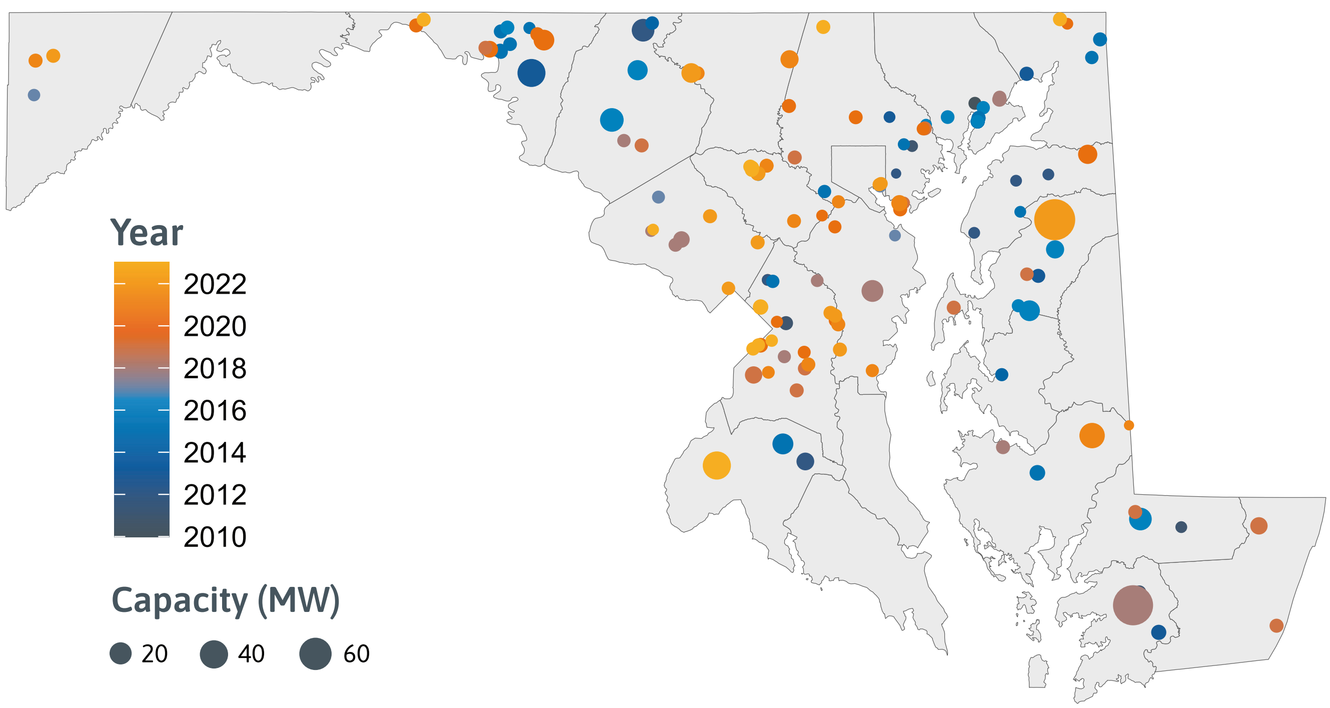


Figure 4. Utility-scale solar installations in Maryland shown by capacity and year of installation. Data: EIA Form 860, 2023.[70]

Materials in Current Panels

The majority of utility-scale solar installations in Maryland use crystalline silicon (c-Si) panels (92.8% of capacity), with two installations using cadmium telluride (CdTe) panels (6.9% of capacity). The remainder of the panels are amorphous silicon (a-Si) (0.4% of capacity), according to the EIA.[70] No new installations of CdTe have occurred since 2013, and First Solar (a company specializing in CdTe solar panel technology headquartered in the United States)[72] has a take-back program in place for end-of-life.[31] Therefore, in this report, we focus primarily on the materials in crystalline silicon panels (c-Si), which account for the bulk of current and expected future installations which will be entering EoL over the next 30 years. As c-Si technology has matured, the relative material composition and the performance of modules have evolved over time. Table 4 outlines the average composition of panels deployed in 2010, per square meter of module area. Recovering the materials from panels requires different processes, which can be categorized into bulk (green), semi-high value (orange), and high value (gray) waste streams. The infrastructure to recover materials at a recycling or waste-management facility is increasingly complex (from bulk to high value), but facilities which recover high-value materials also recover the lower value materials, as shown in Figure 5.

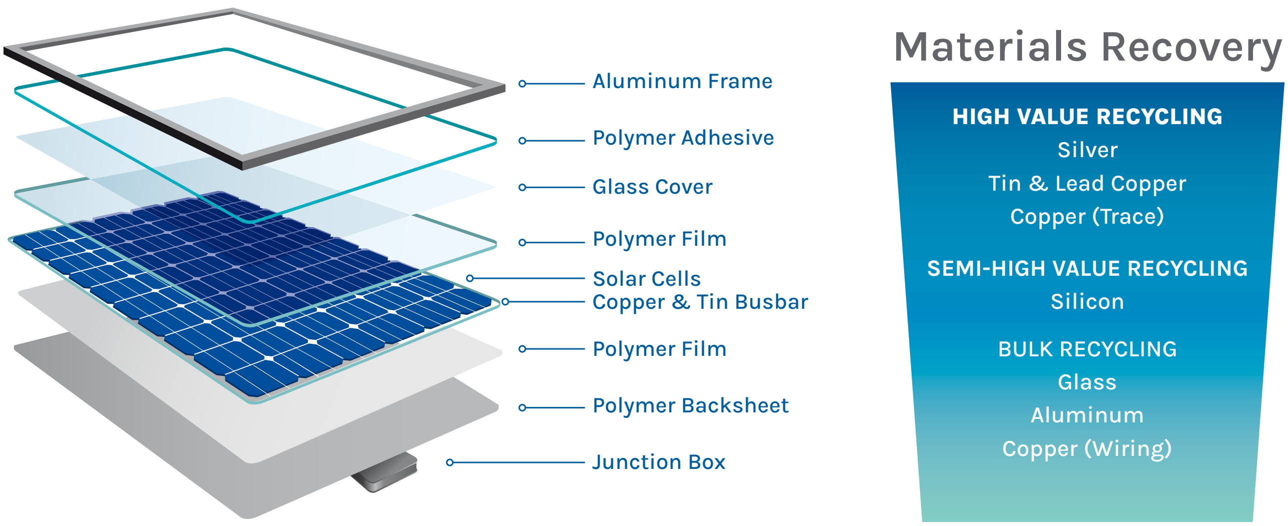


Figure 5. Schematic of solar panel materials and which materials are captured in different types of recycling processes. The materials are divided into categories according to their value after recycling.

Material	Purpose	Composition	Mass (g/m^2 of module)	Volume (cm^3/m^2 of module)
Glass	Panel Surface	79.0%	10000	4000
Aluminum	Frame, Supports	9.6%	1200	450
Polymer	Encapsulant & backsheet foil	9.0%	1100	1100
Silicon	Light Absorber	2.9%	370	160
Copper	Interconnects/Wiring	0.07%	8.5	0.94
Silver	Contacts	0.02%	2.7	0.25
Tin and Lead	Solder	‘trace’	‘trace’	‘trace’

Table 4. Material composition of a generic crystalline silicon photovoltaic panel.[70]

Current Solar Recycling Processes

As a part of the EU's LIFE program, the 'Full Recovery End of Life Photovoltaic' (FRELP) process[73] was developed as one of the first processes meant to maximize the recovery of high-value materials from solar panels. An overview is given below in Table 5:

Process Step	Description	Materials Recovered
Disposition	The module reaches its EoL and its EoL pathway is decided. If the module is no longer functional and recycling is determined to be the appropriate option, the panel proceeds through the next processes.	
Dismount	The module is uninstalled and removed from its place of operation, and transported to a recycling facility.	
Disassembly	The aluminum frames, junction box, and cables are removed from the solar module. The wiring and cables account for most of the copper in a solar module, and are often re-usable with minimal further processing. A sandwich of the solar panels/cells inside glass remains for downstream processing.	Aluminum Copper
Delamination	The glass is separated from the panel. This is done by heating the panel to weaken the encapsulant, and then mechanical removal (i.e. knife cutting) of the glass. This step is often considered the most difficult if the goal is to continue recovering the semi-high and high-value materials, as the internal components of the module must remain intact.	Glass
Cutting Modules	The remaining internal components are cut into small (2-3 square inch) pieces	
Incineration	The solar cell strings (a group of connected cells) inside the panel are cut into pieces and then incinerated to burn off the polymer layers. This process results in recoverable heat as energy from the incinerator. The incineration causes some GHG emissions, but would result in little to no polymer entering landfills. The backsheet polymer often contains chlorine or fluorine, and must be incinerated at a facility that can scrub the halogens from the gas.	
Acid Leaching	The remaining ash from the incineration is sieved and chemically leached with nitric acid or another chemical solution. The silicon pieces are recovered from the sieve after vacuum filtration. Semi-high value recycling ends here, targeting recovery of the silicon for re-melting into metallurgical grade silicon (>98% purity) for use in other markets.	Silicon
Metal Recovery	The leaching solution is then electrolyzed or otherwise processed to recover the trace metals from the panel, including silver and copper. There are many ongoing research efforts to reduce the cost and improve the efficiency of high-value metal recovery in this step.	Copper Silver Trace metals

Table 5. Technical overview of the recycling process for solar modules. The cost associated with recovering the semi-high and high-value materials increases as a function of complexity, while the relative amount of material recovered decreases.

The infrastructure of a recycling facility necessary to reclaim materials beyond the bulk grade is drastically different than what general recycling facilities are equipped with, and very few recyclers in the US focus on high-value recycling processes.[61,73,74] Additionally, the decreasing amounts of high value materials in modern solar cells, for example reduction in silver content (110 mg/cell in 2015 to 75 mg/cell in 2020[75]), has reduced many recyclers' interest in investing in recovering these materials. However, the vast majority of the material in a solar panel is aluminum and glass, which are readily recoverable.

It should be noted that despite most recyclers being unable to process and recover materials beyond the aluminum frames and glass panels, the strings of solar cells are made of many of the same constituents as general electronic waste (e-waste), and can be processed similarly to other e-waste such as cell phones, laptops, and computers.[76–78]

Modeling Maryland's Solar Future

Scenarios and Assumptions

Based on the above data on solar panels in Maryland, we model different potential EoL scenarios for solar panels in Maryland through 2085 using the PV-ICE model, created by NREL.[79] Very few utility-scale solar plants have been retired in the US, with only one retired site having a nameplate capacity >2 MW since 2000.[70] This leaves significant uncertainty around how site retirements will proceed in practice. Also, although Maryland has set high goals for solar deployment, real-world installations have lagged behind these goals, leading to additional uncertainty about the likely rates of deployment in future years. To address this uncertainty, we created a set of scenarios that provide likely upper and lower bounds on what possible waste streams from solar energy generation might occur in Maryland. These scenarios are intended to cover a wide range of potential EoL options ranging from landfilling all panels to implementing best practices for a circular economy.

First, we establish three different potential levels of PV deployment through 2050 which establish these upper and lower bounds for deployment scenarios (Table 6, Figure 6). These deployment levels are based on historical data and prior analysis for Maryland's Climate Pollution Reduction Plan (Climate Plan),[2] which modeled the amount of solar energy generation needed to achieve the emissions reduction goals set forward in the Climate Solutions Now Act. These projections of cumulative installed capacity are

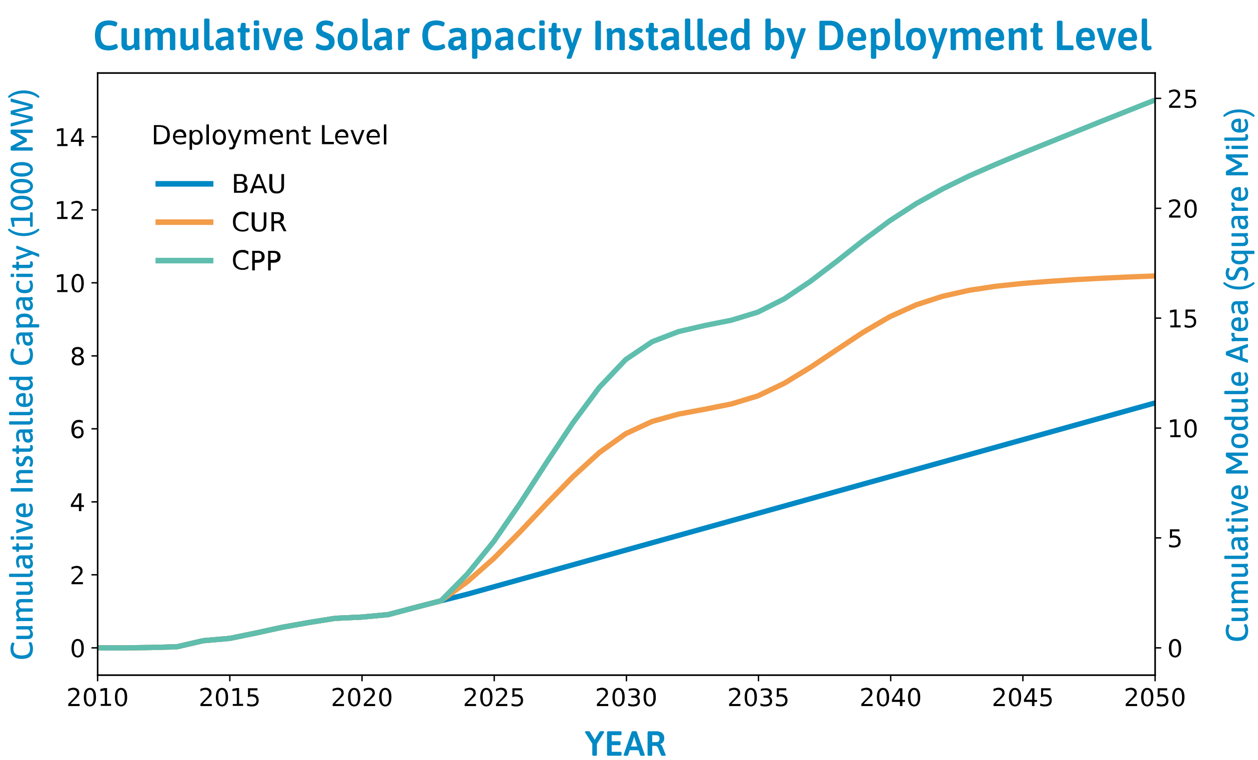


Figure 6. Projected cumulative installed capacity in MW of solar PV through 2050, and associated module area. The Business as Usual (BAU) case is a linear extrapolation of historical trends. The Current Policies (CUR) and Current + Planned Policies (CPP) cases are taken from the modeling used in Maryland's Climate Pollution Reduction Plan.[2] Module area here is not equivalent to land area.

Deployment Levels		EoL Policy Approaches
Business as Usual (BAU): Continuation of current solar deployment trends (Source: EIA State Energy Data System)		**Landfilling**: All panels are landfilled.
Current Policies Scenario (CUR): Renewable Portfolio Standard (RPS) target of 50% by 2030. RPS Solar target: 14.5%. Scaling rates taken from Maryland's Climate Pollution Reduction Plan.	X	**Recycling mandate**: 80% of materials by weight recycled starting in 2030, increasing to 85% in 2035. Similar to EU/South Korea EPR policies.
Current + Planned Policies Scenario (CPP): Proposed Clean Power Standard (CPS) of 100% by 2035. Scaling rates taken from Maryland's Climate Pollution Reduction Plan.		**Circular economy**: Assume 45% waste stream can be repaired or remanufactured, assume 20% reused. Recycling mandate for remainder of panels.

Table 6. Summary of modeled scenarios. The combination of 3 deployment levels and 3 policy approaches yields 9 unique scenarios.

shown in Figure 6, along with an estimate of the module area (in mi^2) needed to achieve this capacity. We note that the module area here is not equivalent to land area, as modules are spaced apart in utility-scale facilities, while community and residential installations on rooftops do not take up any additional land.

The historical installed capacity (2010-2023) was taken from the EIA State Energy Data System (SEDS)[80], which captures utility- and small-scale solar energy generation in the state. In the Business as Usual (BAU) case, we assume linear growth in new solar installations based on trends since 2014, when small-scale installation data began to be reliably included in SEDS. In the Current Policies Scenario (CUR) case, we assume a deployment scenario following the Renewable Portfolio Standard (RPS) target of 50% by 2030, with an RPS solar target of 14.5%. The scaling rates are taken from Maryland's Climate Pollution Reduction Plan. In the Current + Planned Policies Scenario (CPP), we assume a deployment following the Proposed Clean Power Standard (CPS) of 100% by 2035, again with scaling rates taken from Maryland's Climate Pollution Reduction Plan.

Solar technology has advanced rapidly over the past several decades since its market introduction. This means the composition, efficiency, and reliability of panels has been changing since their first deployment, and, consequently, the waste stream will dynamically evolve as each cohort of panels reaches its EoL. For example, solar panels initially had lifetimes in the 10-15 year range in the 1990s, but now typically have economic lifetimes of 25-35 years, depending on the date of manufacturing.[81] This is why we model deployment through 2050 but show waste outcomes through 2085, when panels deployed in 2050 would be reaching their end of life.

For each of the levels of deployment described above, we consider three potential EoL policy approaches that Maryland could adopt (Tables 6 and 7). The "Landfilling" scenario represents a worst-case scenario where all panels are landfilled at EoL. The "Recycling Mandate" scenario is modeled on the EU's waste regulations, and represents a policy focused solely on recycling as the end-of-life option. The "Circular Economy" scenario represents a best-case scenario where circular economy principles are applied to encourage re-use of panels first, then remanufacturing or recycling, with landfilling never the first option for panel disposal.

Assumptions	Landfilling	Recycling Mandate	Circular Economy
% Reused/Resold	0%	0%	20%
% Remanufactured	0%	0%	45%
% Recycled	0%	80% (2030) - 85% (2035)	35%
% Landfilled	100%	20% (2030) - 15% (2035)	0%

Table 7. End-of-life assumptions for modules used in the modeled PV-ICE scenarios. The "Landfilling" scenario represents a worst-case scenario where all panels are landfilled. The "Recycling Mandate" scenario is modeled on the EU's waste regulations, and represents a policy focused solely on recycling as the end-of-life option. The "Circular Economy" scenario represents a best-case scenario, where best practices are applied to encourage re-use of panels first, then remanufacturing or recycling, with landfilling never the first option. We assume a module collection efficiency of 80% for all scenarios, where modules that are not collected for recovery are landfilled.

There are three ways a solar panel reaches its end-of-life:

- **Economic:** The manufacturer or installer's agreement for the operation of the panel ends.
- **Degradation:** The module can no longer produce energy up to specification due to predictable time-dependent performance loss. Typically, this means the panel is producing <80% of the power it was producing when it was first installed.
- **Probabilistic Failure:** The module fails to perform due to manufacturing imperfections. Panels are complex electronic devices, and an individual panel can be faulty earlier than expected.

In the recycling mandate scenario, recycling is defined as the dismantling and destruction of panels into their raw components. While recovery of the aluminum and glass from panels is straightforward using current recycling technologies, we include a goal of attempting to recycle 50% of the copper, found in the bulk wiring and junction boxes of the modules, and a goal of attempting to recycle 20% of the silicon or other semi-high value materials (see Technical Appendix for detailed material assumptions). Even when panels are collected for recycling, there is some waste landfilled due to the finite yields of material that can be successfully recycled.

In the circular economy scenario, there is similarly some landfilled waste due to the finite yield of remanufacturing processes. While currently there is little-to-no emphasis on dispositioning EoL panels for remanufacturing, we use this scenario to highlight the circular economy goal of reusing solar module components to the extent possible. Cleaning and re-using the components as opposed to crushing and reprocessing the materials (as in recycling) preserves the initial energy investment in refining these materials from virgin stock. We further assume there is slightly lower remanufacturing yield than initial manufacturing yield, 90% vs 98%. Any material targeted for remanufacture that does not meet remanufacturing standards is assumed to be recycled, as is standard practice at solar panel manufacturers.

Near Term Outlook (2030-2050)

The earliest installs of large-scale solar arrays, occurring between 2010 and 2019, will reach their economic EoL between 2032 and 2050. This means that EoL policy will determine the amount of landfilled waste from solar modules until 2050, regardless of future deployment levels. Below, we illustrate the cumulative amount of waste and the composition of the waste stream, given different EoL policies in the near term. In this section, for simplicity, we show results only for the CPP (highest) deployment level scenario because the near-term EoL waste stream trajectory is dominated by currently installed capacity. Cumulative waste from lower deployment levels would result in fewer probabilistic failures (i.e., less waste generated from panels before their economic lifetime), but these differences are minimal.

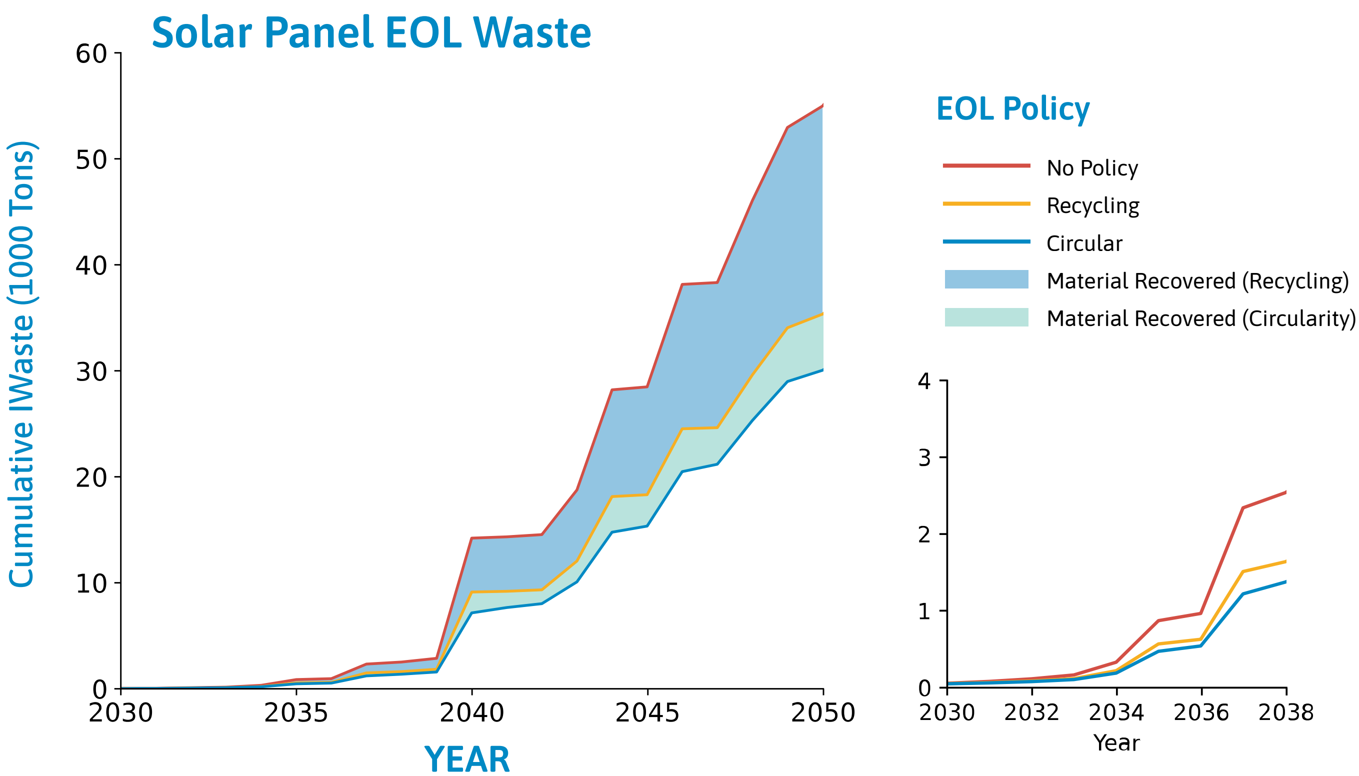
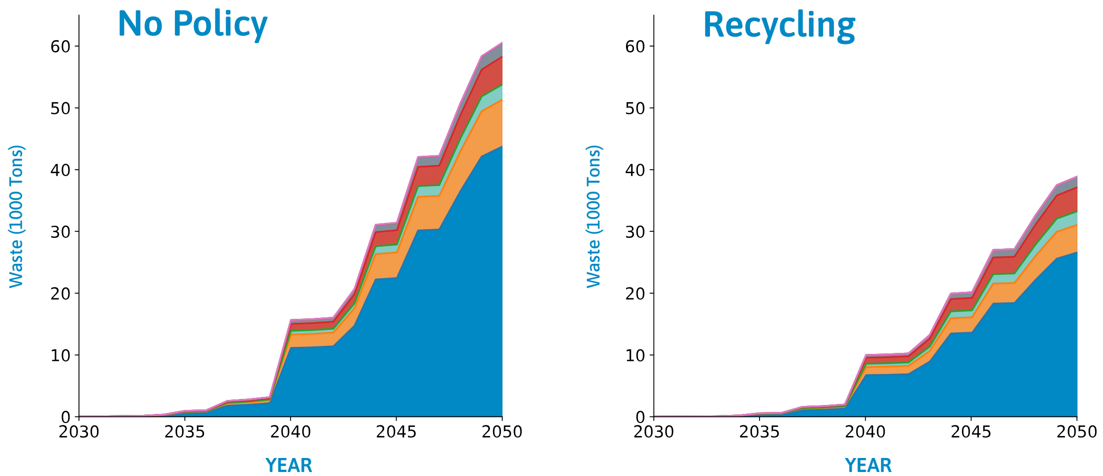


Figure 7. The *cumulative* waste stream representing total module weight reaching EoL from existing installed solar capacity. The shaded areas represent materials that are returned to the supply chain through recycling or remanufacturing processes. The inset shows detail for the 2030 to 2038 timeframe, where waste from the earliest panels are reaching their EoL.

Figure 7 shows model-dependent projections of the total mass of waste (at the module level) that will be entering EoL. By 2050, there is a 35.6% reduction in cumulative landfilled solar waste compared to our 'Landfilling' scenario if our modeled 'Recycling mandate' is adopted, and a 45.3% reduction if our modeled 'Circular Economy' policy is adopted. This is broken down in Figure 8 by the type of material entering the waste stream.

In both the Recycling Mandate and Circular Economy policy scenarios, we see a large reduction in the amount of cumulative total waste due to reductions in landfilled glass and aluminum. The high quality glass and aluminum frames account for the majority of the mass of solar panels, and will account for >80% of the waste generated from the full panel. However, glass and aluminum can be recycled at very high rates, resulting in these materials representing a proportionately smaller share of cumulative waste in the Recycling Mandate and Circular Economy scenarios compared to the Landfilled scenario. Polymer waste (encapsulant and backsheet) cannot be recycled with current technology, and remains constant across EoL policy scenarios. The plastic-like components (backsheet and encapsulant layers) cannot be easily recovered with current recycling technology, and will remain a growing source of waste.

The near-term waste outlook is summarized in Table 8. We find that by 2050, adopting a recycling mandate would add 17,000 tons of glass and 3,100 tons of aluminum back to the supply chain by 2050, with a further 5,000 tons of glass and 800 tons of aluminum returned to the supply chain if the circular economy standards were adopted. The waste that is generated in these cases is due to the assumption that only 80% of EoL modules are being collected, and additional waste is generated from the loss of material in recycling and remanufacturing processes (i.e. less than 100% recycling and manufacturing efficiency), as outlined in the Technical Appendix.



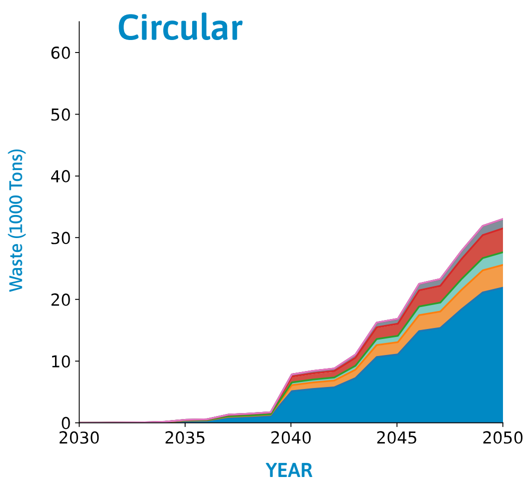


Figure 8. The cumulative mass (in 1000s of tons) of the major materials, such as aluminum and glass, that will enter the waste stream by 2050 due to existing solar installations reaching their economic EoL, separated by EoL policy scenario.

	Cumulative Waste (tons) under different EoL Policies					
	Landfilling		Recycling Mandate		Circular Economy	
	Year 2030	Year 2050	Year 2030	Year 2050	Year 2030	Year 2050
Glass	41	44000	36	27000	34	22000
Aluminum	9.9	7600	8.5	4500	8.2	3700
Polymer	6.5	6900	6.1	6100	6.1	5800
Silicon	2.1	2200	2.0	1700	1.9	1600
Copper	0.03	35	0.02	20	0.02	18
Silver	0.04	24	0.04	21	0.04	20

Table 8. A summary of the cumulative amount of waste (in tons) generated from end-of-life solar modules in 2030 and 2050 under different EoL policy scenarios.

Long Term Outlook (2050 Onward)

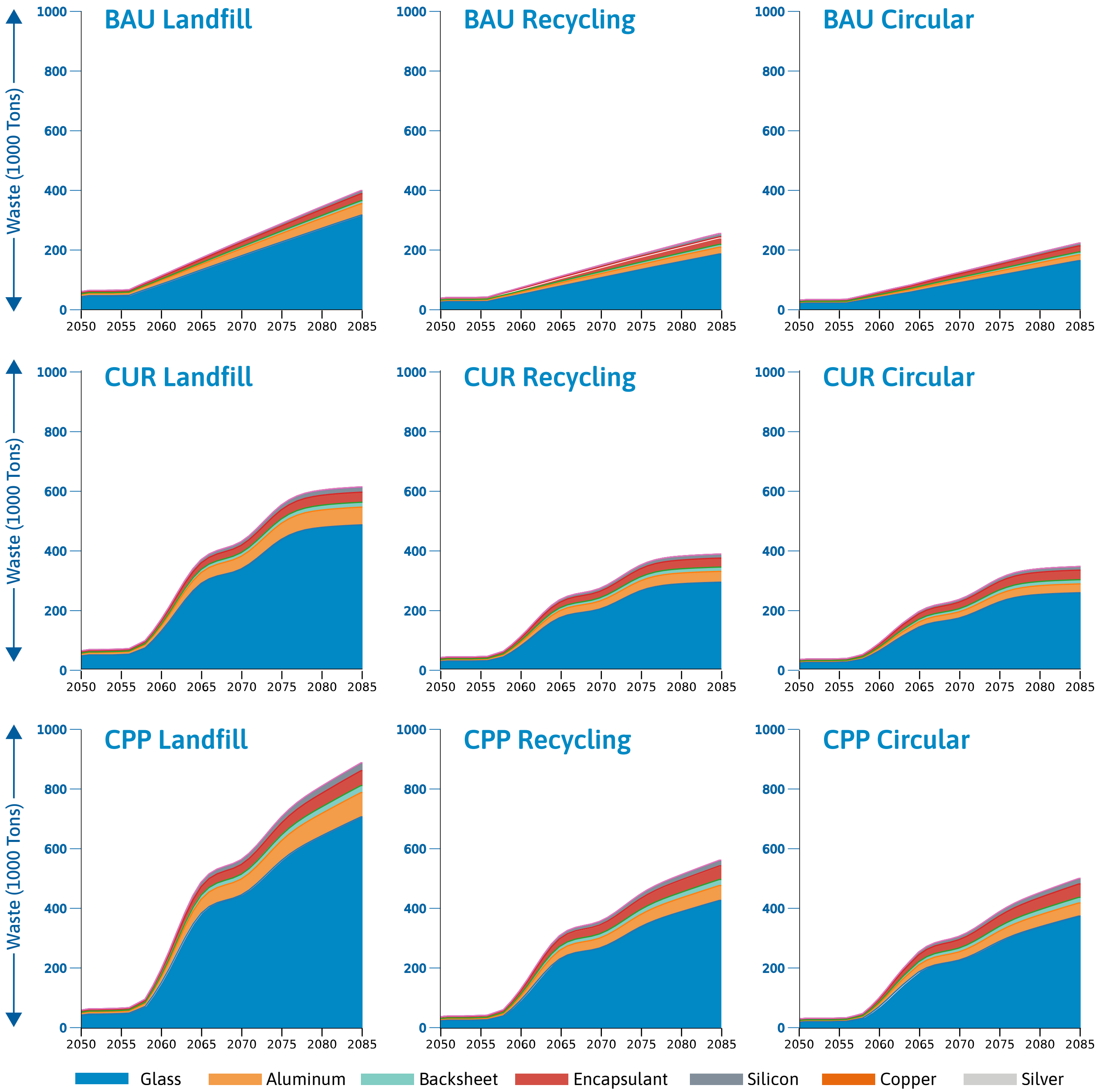


Figure 9. The volume of cumulative waste that will enter landfill, depending on the modeled deployment level and EoL policy.

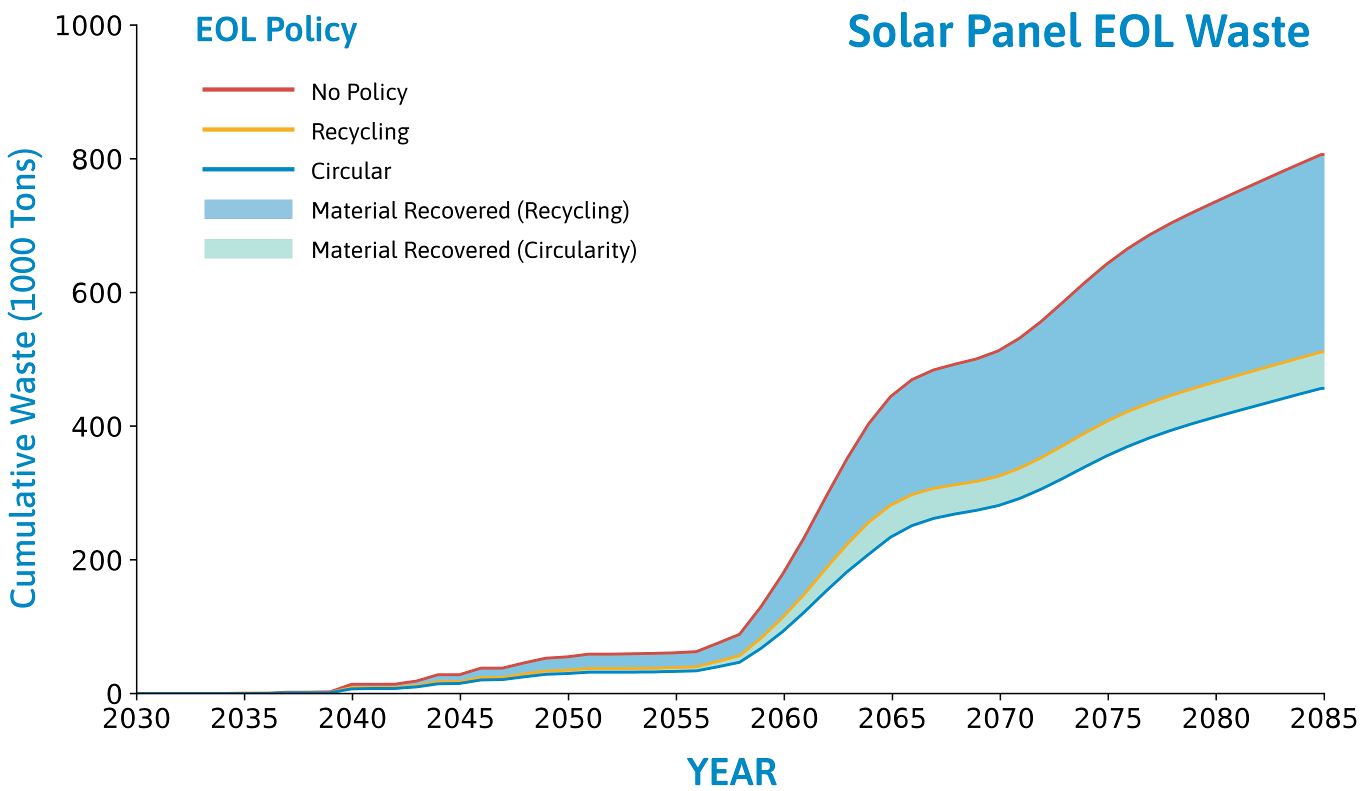


Figure 10. (a) Cumulative waste generated from EoL modules based on deployment levels consistent with the Current and Planned Policy (CPP) climate targets.

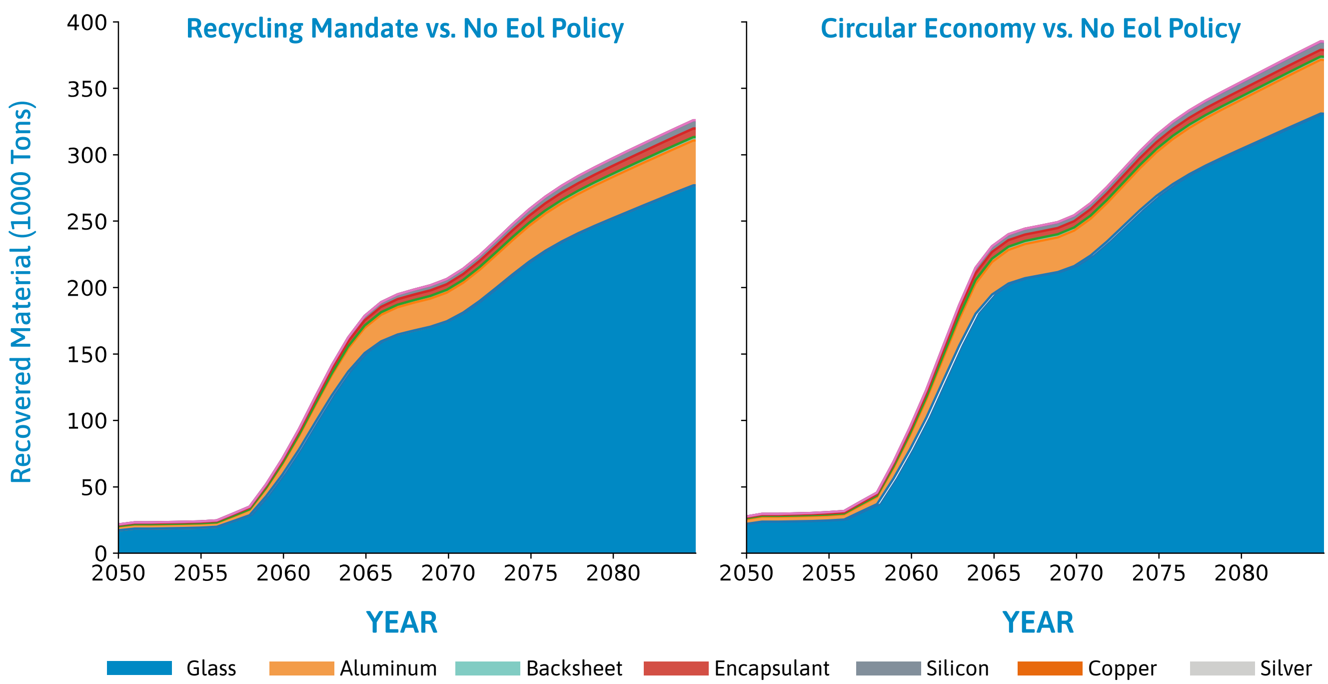


Figure 10. (b) The recovered material that is returned to the supply chain if either a recycling mandate or a circular economy EoL management policy is adopted (as compared to landfilling).

The waste stream of PV modules after 2050 will be generated from panels that were installed between 2020 and 2050. Because of the rapid deployment of solar needed over the next decade to meet the state's Climate Plan targets (as seen in the Current Policies, and Current and Planned Policy deployment levels), we see a large uptick in waste in those scenarios, which grows another 14-15x between 2050 and 2085. As a general trend, we see a roughly 40% reduction in waste with the 'Recycling Mandate', and 45% reduction in landfilled waste in the 'Circular Economy' policy scenarios. The overall waste increases with increased deployment of solar panels. More panels will enter EoL in scenarios where solar is a larger portion of the Renewable Portfolio Standard. The waste stream remains predominantly glass and aluminum; however, the proportion of polymer material being landfilled or otherwise lost in EoL processing will continue to rise, as these materials are not easily recoverable from panels. Additionally, the waste from panels that are not collected is always a factor, so increasing the demand for re-used solar components could prevent even more material from entering landfills. Further waste is generated from imperfect manufacturing, remanufacturing, and recycling processes. Additionally, the relatively small difference in waste between the Recycling Mandate and Circular Economy scenarios does not capture the difference in the energy impact of the material that is not landfilled in those scenarios. Recycling processes are generally much more energy-intensive than re-purposing processes, so the total energy burden of the different scenarios should also be considered.

In the Recycling Mandate and Circular Economy scenarios, there is also a significant volume of material returned to the market, either through recycling or remanufacturing. This difference is shown for the CPP deployment levels in Figure 10, with the highlighted areas indicating the amount of material that is recovered and returned to the supply chain. We see a growth in recovered material from 60 tons in 2030, to 55,000 tons in 2050, to 850,000 tons in 2085 in the scenario with the highest number of modules deployed (CPP). Figure 10(b) shows the amount of material saved from entering landfills in the recycling mandate policy and the circular economy policy, as opposed to the "Landfilling" scenario where all panels are assumed to be landfilled. The waste generated grows with deployment, with the largest uptick occurring between 2055 and 2065.

Implementing EoL policies now will have lasting impacts on how much material can be saved from going to landfills, due to the long lifetime of solar projects. With the deployment levels in the Current + Planned Policy scenarios, we see 295,000 cubic yards of material re-entering the supply stream given the 'Recycling Mandate', and 349,000 cubic yards re-entering the supply stream given the 'Circular Economy' policy scenario. The re-use of material will reduce the total amount of materials needed to be extracted, refined, and processed into solar modules to reach the Climate Plan targets. This 'closes the loop' of the circularity of the economy, as module manufacturers can be encouraged to purchase parts or components from recycled or remanufactured sources. Even though the amount of landfilled material will be a growing issue, reusing and reselling panels is the best way to keep panels productive and offset GHG emissions from fossil fuel sources. The energy, labor, and time spent to initially produce a solar panel from its stock materials are significant. Taking a Circular Economy approach can not only minimize the environmental impact of solar panels over their lifetime, but also maximize the time that the high quality, highly refined materials from solar panels are used towards generating energy before becoming waste.

Solar Waste and State Landfills

Current landfill capacity in Maryland is summarized in Figure 11, along with expected closure years. The modeled scenarios described above demonstrate that panel waste will not greatly increase until 2035 and beyond, which means it is beyond the expected operation of several of the landfills in the state. However, the remaining state landfill capacity should still not be significantly affected, with over 49 million tons (or 90 million cubic yards[82]) of landfill capacity remaining, and an expected growth of 850,000 tons being generated from our highest estimate of deployment (CPP) when all waste is landfilled. As discussed previously, most county recycling coordinators do not have specific policies around solar, and few said they actively accepted solar panel waste. This could impose stricter limits on available capacity to accept solar panels if specific counties decide not to accept them, and many counties stated they would only accept solar waste from within county borders, potentially creating another limitation on landfilling as a EoL option.

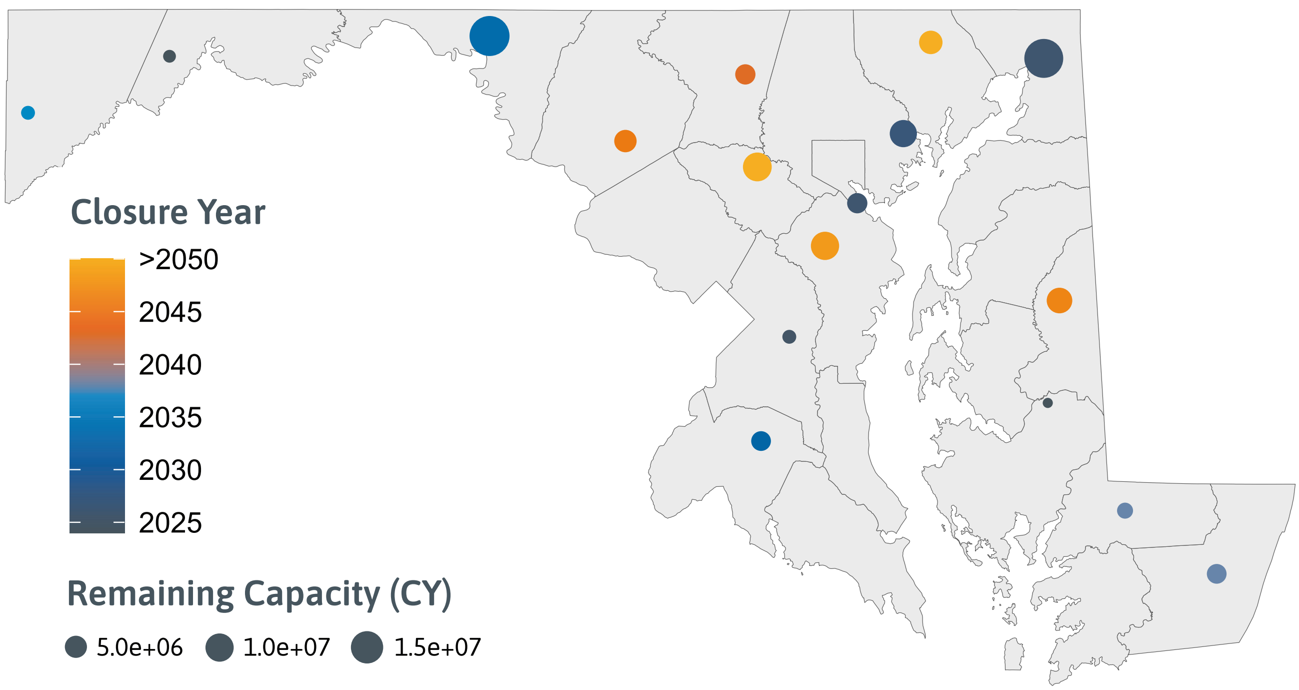


Figure 11. Maryland landfill locations and remaining capacity as of 2022, with colors indicating the year the landfill is expected to close. Two landfills have closure dates later than 2050, which are grouped into a >2050 category for clarity. Data from an EPA Database.[83]

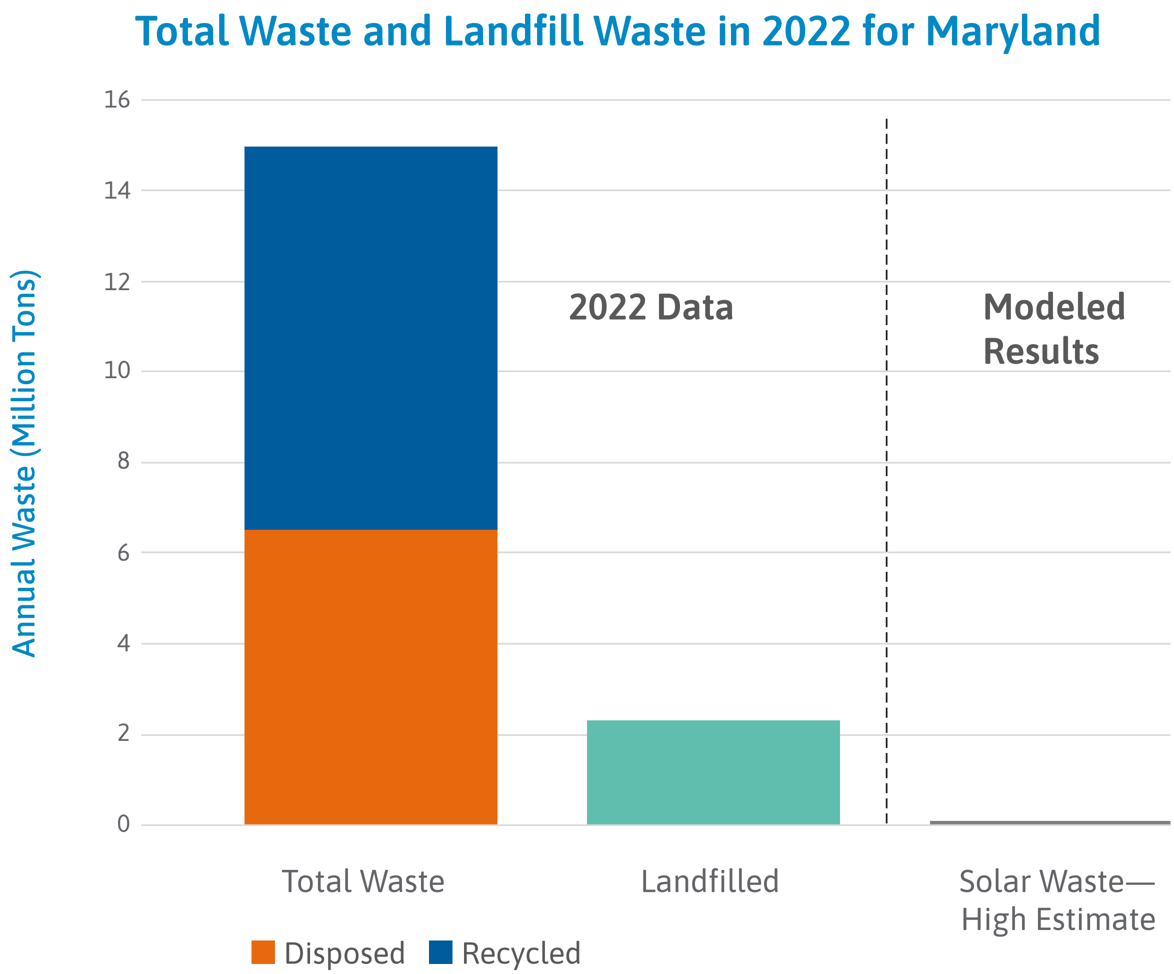


Figure 12. Waste comparison using MDE data from calendar year 2022[82] and maximum annual landfilled waste from any modeled year in the CPP-Landfill scenario, which represents a high estimate for both deployment and disposal in landfills.

Even in the upper bound scenario for deployment and assuming all waste is landfilled, the amount of waste from solar energy does not significantly change the total amount of landfilled space needed on an annual basis (Figure 12). It should also be noted that although there is also a slight concern about the toxicity of the trace (<0.1%) amount of lead contained in the solder, the relative amount of material is a very small portion of the waste stream, and many manufacturers are already pushing to reduce the amount of lead or remove lead from modules entirely.[75] Additionally, as shown in Figure 13, the amount of waste generated annually from solar panels is currently a very small portion of all electronic waste, only rising to be a comparable to the current waste volume after 2040. The total volume of e-waste is also expected to grow over this time period, especially as artificial intelligence and the computational power it requires proliferates.[84]

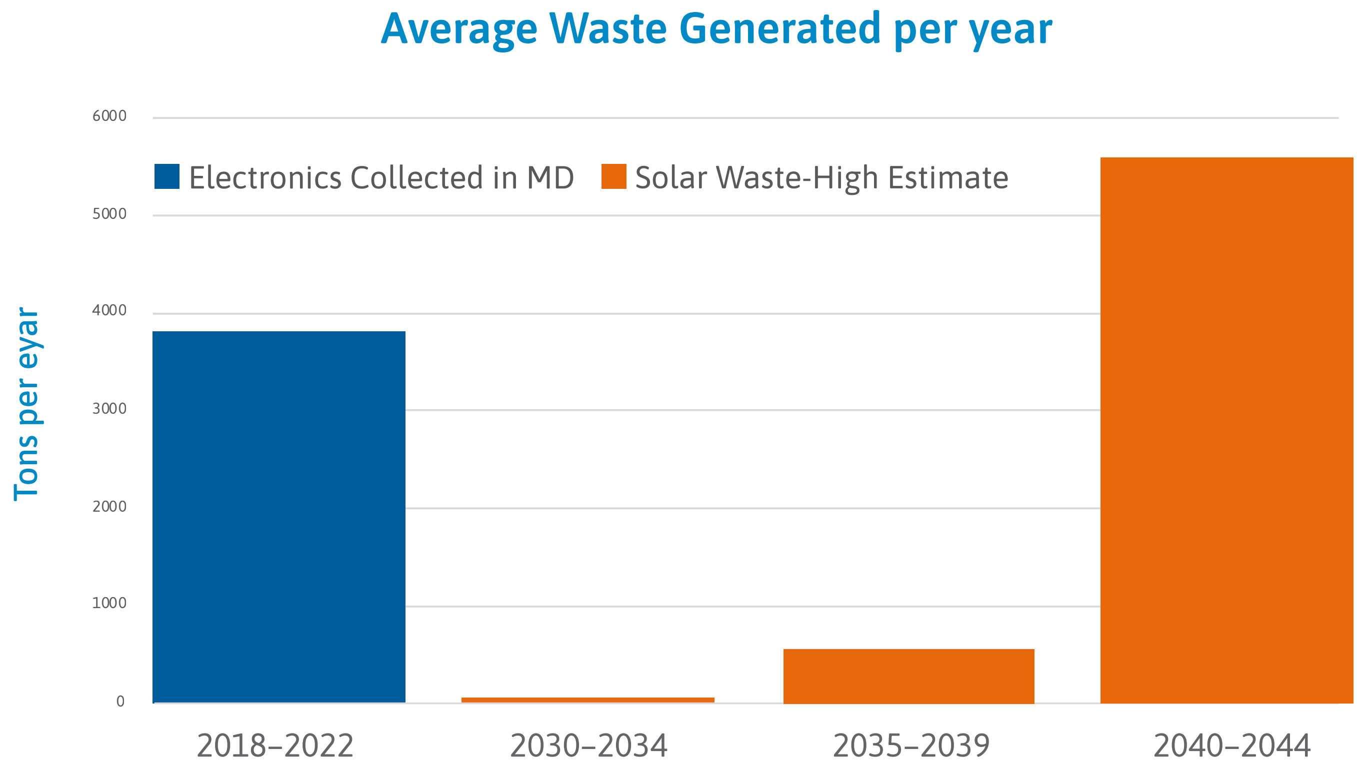


Figure 13. Comparison between annual values of electronic waste handled in Maryland averaged over 5 year periods[82] and potential solar waste (modeled results). The high estimate for solar waste is taken from the CPP-Landfill modeled scenario, which represents a high estimate for both deployment and disposal in landfills.

Impacts of a Circular Economy Approach to End-of-Life

Comparing Generation Technologies

To contextualize the environmental impacts of solar energy, it is important to evaluate key metrics across different technologies to compare how solar performs compared to likely alternatives. Life Cycle Analysis (LCA) metrics are designed to do this by considering the total impact of an energy generating technology's life cycle, from extraction of materials all the way to EoL disposal. Firstly, the energy required to produce a solar system is paid back within about one year for all major solar technologies, so solar provides a net benefit even if non-renewable energy is used for the manufacturing process.[85] On a per kWh basis, while fossil fuel generators may emit up to 1000 g of CO_2 for every kWh of energy produced, LCAs of solar technologies find that they are responsible for only 25 - 40 g of CO_2 per kWh, depending on the technology.[85,86] Solar can also significantly reduce particulate matter pollution compared to fossil fuels, with estimates of per unit lifecycle impact of coal power generation at greater than 100 g PM10eq/MWh compared to only 0.5 g PM10eq/MWh for solar power.[87] Overall, prior research shows that solar on average requires less land and is far less toxic than fossil fuels,[87] with additional data available from the IEA on resource use and acidification.[85] Finally, because the formation of particulate matter pollution is very low for solar compared to fuel-burning generation (coal, gas, biomass), solar can contribute to significant reductions in the negative human health impacts of fossil fuel electricity generation.[87]

Environmental Impacts of Solar

As solar technologies become more efficient, the environmental impacts on a per MWh basis will continue to decrease.[85] However, solar is known to have one of the higher mineral resource requirements compared to many other generation technologies on a per MWh basis.[87] While this may also improve over time as PV technologies continue to develop, it points to even more need to ensure those minerals are captured at EoL either by reusing panels directly, repairing panels, or through high value recycling.[88] Additionally, decarbonization and the energy transition will generally demand large amounts of minerals; therefore, promoting circularity within solar lessens potential competition for minerals between solar and batteries, electric vehicles, and other technologies.[89] The greenhouse gas (GHG) emissions from recycling are also a small fraction of the GHG emissions associated with manufacturing the system.[90] Other research has examined how lifecycle impacts could change as newer solar technologies join the market, showing that more research and studies are needed for emerging thin film photovoltaic technologies (some of which require far less total material but incorporate toxic materials) and their environmental impacts.[91] The impacts of other renewable technologies have also been explored in the literature; solar, wind, hydro, geothermal, and biomass power all have unique environmental benefits and impacts which should be considered carefully in each specific context when choosing which energy system to deploy.[92]

Economic Impacts of Solar Compared to Non-solar Generation

Defining the economic impacts of solar compared to other electricity generation technologies is a complex endeavor. Economic benefits here could include job creation, bringing federal money into the state, increasing business or personal income, growth in state GDP, and other benefits. Economic challenges could include equity concerns around access to solar, daily fluctuations in electricity prices due to the variability of solar generation, siting of solar, and other challenges. While economic impacts have been evaluated for Maryland with respect to reaching its CSNA goals, as shown in the Pathway report[93] and Climate Pollution Reduction Plan,[2] it can be difficult to disaggregate and attribute such impacts to solar specifically without a dedicated study on this topic. Based on the available literature and data, we summarize here some of the key aspects that characterize the economic benefits and challenges of solar compared to other electricity generation technologies.

Employment

The Regional Economic Studies Institute of Towson University analyzed the employment impacts of transitioning the power sector in Maryland when exploring the impacts of the Greenhouse Gas Reduction Act (GGRA) in 2019.[94] They also analyzed job impacts for the Pathway report as well as the Climate Pollution Reduction Plan released by MDE late last year.[2,93] Previous work in Maryland shows clean energy jobs having higher wages than the state average.[95] Solar workers in particular comprise a large portion of clean electricity generation jobs in Maryland,[95] with SEIA reporting 4,973 solar jobs across 208 companies in 2023.[96] Although Maryland saw a loss of solar workers from 2016 to 2020[95], one could expect the growth in solar demand (Figure 6) to also drive growth in the solar workforce in future years. As of 2021, entry-level solar installer positions earned more than the state average entry-level position.[95] At nearly two-thirds, the largest segment of solar jobs is in installation and project development.[97] Taken together, growth in the solar industry could see growth in entry-level installation positions[98] that pay on average more than other entry level positions. Many of these solar jobs, which often require a high school diploma,[99] will be needed for construction and installation, and there will be less need for operations and maintenance (O&M) jobs.[100] This contrasts with wind turbines which have comparatively higher needs for O&M workforce.[100] Solar jobs in Maryland will also likely increase due to the Solar-for-All grant administered by Maryland Clean Energy Center.[101] Nationally, solar has seen some of the strongest growth compared to other generation technologies; furthermore, the fraction of solar jobs which were union jobs was double the national average.[102] Additionally, women and Hispanic or Latino workers were more represented in the solar industry as opposed to the average for energy jobs.[102]

Leveraging Federal Funds

There may be opportunities for recyclers and others to leverage federal money for EoL solar management. For example, capturing some of the key materials and minerals from reclaimed solar panels, or selling used panels which might be considered an “eligible component”, may qualify for the advanced manufacturing production credit in the Inflation Reduction Act (IRA),[103] but applicability is not fully clear from existing guidance.[104] Undoubtedly, the state can encourage investors and developers to leverage the Investment Tax Credit (ITC) or Production Tax Credit (PTC), both updated with the passage of the IRA, which can drive more investment in the state for solar energy.[105] With the prevailing wage and apprenticeship requirements associated with these tax credits, as well as the opportunities for bonus credit for domestic content and siting projects in energy communities, there are numerous opportunities for solar projects utilizing federal incentives to contribute to just transition goals such as workforce development and environmental justice.[105] While wind and other renewable technologies will benefit from the same tax credits, many fossil fuel power plants will not.

Secondary Economic Impacts—Land, Electricity Grid, Air Quality

As more utility-scale solar plants are built, the land needed for solar deployment will increase. However, there is significant potential for Maryland to leverage available rooftop area to deploy solar to mitigate the need for greenfield deployment.[106] Researchers estimate, as of 2016, suitable Maryland rooftops have the potential to provide 19.3 GW of installed capacity and 23.9 TWh of annual generation.[106] With this potential for rooftop solar, including medium (5,000 ft^2 - 25000 ft^2) and large buildings (>25000 ft^2),[106] the amount of land used for solar can be minimized as rooftop solar is maximized through concerted state and local efforts. Nonetheless, with limited land in Maryland, deployment of solar can still compete with other land uses. Of particular concern is the small risk of soil contamination from some of the potentially hazardous materials in panels that could make the land unsuitable for agriculture in the future, although studies have shown this to be unlikely and the risk is mainly from damaged panels.[47] This is also a risk that seems likely to decrease over time as manufacturers are reducing the use of hazardous materials. For large ground-mounted solar installations, clearing vegetation may be necessary, but decommissioning usually seeks to return the area to its original condition.[47] The agricultural sector could also benefit from synergies with the solar industry such as agrivoltaic installations,[107] a couple of which already exist in Maryland, provided there is a robust stakeholder engagement process to address community concerns.

Another secondary economic impact of solar stems from its variability and value to the electricity grid. As more of the state's electricity is sourced from variabile sources like solar, there will likely be a greater need for energy storage capacity. Managing more distributed energy resources will have implications for grid operators and utilities; rates may fluctuate more each day due to variability, depending on the deployment of complementary technologies such as energy storage and demand-side management, but overall solar has a lower levelized cost of electricity than many other renewable electricity generation technologies.[108]

Secondary economic impacts will be realized through health benefits from the broader decarbonization process, as shown in the health impacts modeling for the Pathway report and Climate Pollution Reduction Plan.[2,93] Especially in communities surrounding fossil fuel power plants, pollution will be lower in a decarbonized grid, thereby reducing negative health impacts, (the magnitude of which researchers have estimated at the state level).[109] These health impacts from fossil fuel power plants are also unevenly distributed across communities, leading to serious environmental justice concerns.[110] Over the long term, more solar deployment, in conjunction with greater decarbonization overall, can also contribute to reduced greenhouse gas emissions and associated climate change hazards.[111]

Economic Impacts of Solar Decommissioning on Ratepayers

Estimating the impact of solar decommissioning on ratepayers apart from the impacts of solar generation is a highly complex endeavor subject to many uncertainties. Firstly, at the time of writing no utility-scale solar project has been decommissioned in Maryland, and few utility-scale solar plants have been decommissioned in the US as a whole.[112] This means there is little to no real-world data on these impacts. Secondly, although prior work has found solar deployment to have a particularly complicated relationship with ratepayer impacts, very little research to date has specifically explored the ratepayer impacts of decommissioning.[113–115] Therefore, future studies are needed to address this question, coupled with monitoring of real-world impacts as solar plants are decommissioned in future years.

Conclusions and Recommendations

Maryland has set ambitious goals to reduce GHG emissions 60% by 2031 and reach net-zero emissions by 2045, and solar power will play a critical role in achieving these goals. By supporting the phase-out of harmful fossil fuel use, solar can also contribute to the substantial economic, environmental, and health benefits projected for Maryland's energy transition.[2,3] The required build-out of solar PV generation will generate a predictable waste stream in future years as panels retire, but by adopting a circular economy approach to managing these retirements, Maryland can maximize benefits and minimize harms associated with panel retirements. Long solar PV lifetimes mean that there is time for the state to iteratively develop a best-practices approach to waste management with input from stakeholders, while learning from other jurisdictions that are currently implementing solar PV management policies. Here, we provide recommendations on how Maryland can move towards such a best-practices circular economy approach for solar PV EoL management.

Increase Stakeholder Engagement

The Solar Photovoltaic Systems Recovery, Reuse, and Recycling Working Group should engage further with a broad cross-section of stakeholders. Solar recyclers, installers, homeowners, industry groups, county governments, and others have important perspectives about the current state of managing EoL solar panels. Without these perspectives, it is difficult to develop an optimal policy structure for EoL solar. This report is a first look at the system of stakeholders for EoL management of solar systems in Maryland. Future efforts can engage with stakeholders more robustly, especially with residential solar installers and county sustainability offices, to collect data on the current PV waste stream in Maryland, the fraction of panels recyclers receive that are being resold or recycled, and the relative cost of different EoL options.

Operate at a Multistate, Regional Level

Maryland can partner with surrounding states in a coordinated and regional approach to EoL solar management that could overcome common challenges and pitfalls. Maryland may not generate a significant enough amount of EoL solar in the near term to warrant siting its own solar recycling center. Additionally, Maryland might struggle with compliance for a landfill ban, which could lead to shipping EoL solar panels out of state to other landfills, without sufficient and low cost recycling options within the state. Therefore, a regional approach that builds upon interstate synergies could yield better outcomes for landfill bans, EPR programs, and other policy structures. A UMGC capstone project considered several factors for siting a solar recycling center in the Mid-Atlantic region and found that more optimal locations would be in North Carolina or Virginia; North Carolina already has facilities devoted to solar panel cycling.[116,117]

Consider a Landfill Ban Coupled with Financial Incentives

Maryland could couple a landfill ban with a financial incentive to avoid EoL solar being transported out of state. In a small state like Maryland, under a landfill ban and absent regional coordination, shipping solar panels to out-of-state landfills may be more economical compared to other EoL options, like recycling or remanufacturing. A financial incentive for choosing a circular EoL option could close the gap on the cost difference between landfilling and other options for EoL. The type of incentive appropriate for Maryland can be determined through further stakeholder engagement. For the residential solar sector, installation companies are likely the actors dismounting and transporting panels to landfills or recycling facilities, making them potential partners for implementation of an incentive program. A program partnering with installation companies could also incentivize replacement (along with reuse) as opposed to wholesale dismounting, leveraging existing structures in the residential and commercial solar sector to retain the valuable and finite area already in use for solar power.

Ensuring that circular EoL options are established is the first necessary step to see success in landfill diversion policies. Therefore, in the short-term, supporting in-state e-waste recyclers to expand their operations and promote the recycling, repair, and reselling of solar panels is critical. In the long-term, setting up processes and systems for out-of-state transport to high-value solar recycling facilities can encourage maximum recovery of materials and components.

Address the Current, Near-Term Gaps

Maryland can more immediately address the issue of residential and smaller commercial and community solar with innovative, flexible, ground-up solutions. MDE should provide guidance to landfills, county recyclers, installers, solar panel owners (homeowners, commercial-scale and community solar) about options for EoL panels today. Currently, county landfills and recyclers are already receiving a few requests for how to dispose of solar panels, and while they have been able to manage the requests so far, many are waiting for MDE to provide state-level guidance. This guidance can bridge the gap until the state develops an appropriate, overarching policy structure for solar EoL.

Support Existing Electronics Recyclers

Another way Maryland can address near-term gaps is to support job growth at existing electronics recyclers by providing financial support and technical assistance for their expansion to handle EoL solar panels. Through our interviews with county recycling coordinators, sustainability offices, and e-waste recyclers in Maryland, we know that currently there is a small portion of solar panels reaching their end of life that these stakeholders must handle without clear guidance. County agencies have determined *ad hoc* that some existing Maryland e-waste recyclers can handle solar panel waste streams. Given that EoL solar waste streams will be limited over the next decade, it may be more economical to support existing Maryland electronics recyclers in the near term, as opposed to building new solar recycling facilities. Many recyclers in the state are certified to the common industry standard (R2), and the state could provide assistance in certifying them to Appendix G under the R2 which addresses solar panels.

This expansion of in-state capacity can assist Maryland until it can determine a more robust and concrete plan to handle solar EoL as waste streams increase.

Find and Build Upon In-State Synergies

The state can leverage solar workforce development organizations and programs, like Power52,[118] Civic Works,[119] Hagerstown Community College Renewable Energy training programs,[120] and others[95] to strengthen synergies between building up solar workforce and addressing EoL management. EoL solar panels can be re-used for educational purposes, and curricular scopes can be broadened to include decommissioning practices and circular economy principles. While current programs and training are focused on solar installations, a workforce that is knowledgeable and familiar with EoL solar management will help the sector down the line, as workers integrate their knowledge base and implement best practices. Maryland is investing in and prioritizing the renewable energy workforce, with $9.2 million going towards the Higher Education Clean Energy Grant Pilot Program, which will help fund courses for solar workforce development at institutes of higher education.[121] The state has the opportunity to leverage these efforts and take a long-term approach to ensure these sectors are prepared to manage future EoL solar.

Weave the Waste Hierarchy Into the Above Recommendations

Maryland can actively promote reuse of solar panels above all else, with landfilling being the last course of action. The state can play an active role in pushing for circular economy solutions for EoL solar management. Incentives that support a landfill ban could be prioritized based on the EoL option chosen. Decommissioning plans could be required to adopt the concepts of a waste hierarchy, which could include PPRP recommending utility-scale plants explore stay-in-place options to extend the lifetime of existing installations instead of wholesale decommissioning when appropriate. The state could also support a reuse market to help make solar power more accessible to low-to-moderate income communities. Testing and panel re-certification would be a necessary part of this process to ensure used panels are of high quality and economically advantageous. There may be an opportunity here to partner with the Climate Access Fund, which works to advocate for and finance community solar projects in LMI communities, so that all households can access the benefits of solar power.[122] However, this should be done with great care to ensure reused or refurbished panels are provided when the alternative is not having access to solar at all, and priority is placed on providing LMI households with access to high quality solar with long lifetimes.

As discussed throughout this report, there are many ways to integrate circular economy principles such as the waste hierarchy into the lifecycle of solar modules. However, these principles may be incongruent with the business models of companies who may not prioritize them. Planned obsolescence and decreases in panel life spans are growing concerns as manufacturers and recyclers face higher competition in a more saturated market. Maryland should partner with other states and the federal government to encourage the design and manufacturing of solar modules that are resource-efficient, durable, and integrate the principles of a circular economy by facilitating reuse and recycling at EoL.

Revisit Solar End-of-Life Policy Annually

Solar technology and deployment has changed quickly over the years, and that is true of its EoL management options as well. These changes will continue into the future, and federal and state policies must be able to adapt appropriately to shifting circumstances. Many states are considering a wide array of policies for solar deployment and EoL management. The EPA is developing a rule for a universal waste designation, and the DOE is aggregating data and conducting research and development to decrease the cost of recycling solar modules. The solar recycling industry is growing, and more and more industry standards are being published. Each of these efforts could have notable implications for EoL solar management over the next few years. As the sector continues to evolve and grow, the state should continue to revisit the question of solar EoL, support adaptable and flexible policies, and overall be cognizant of the sector's future evolution.

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