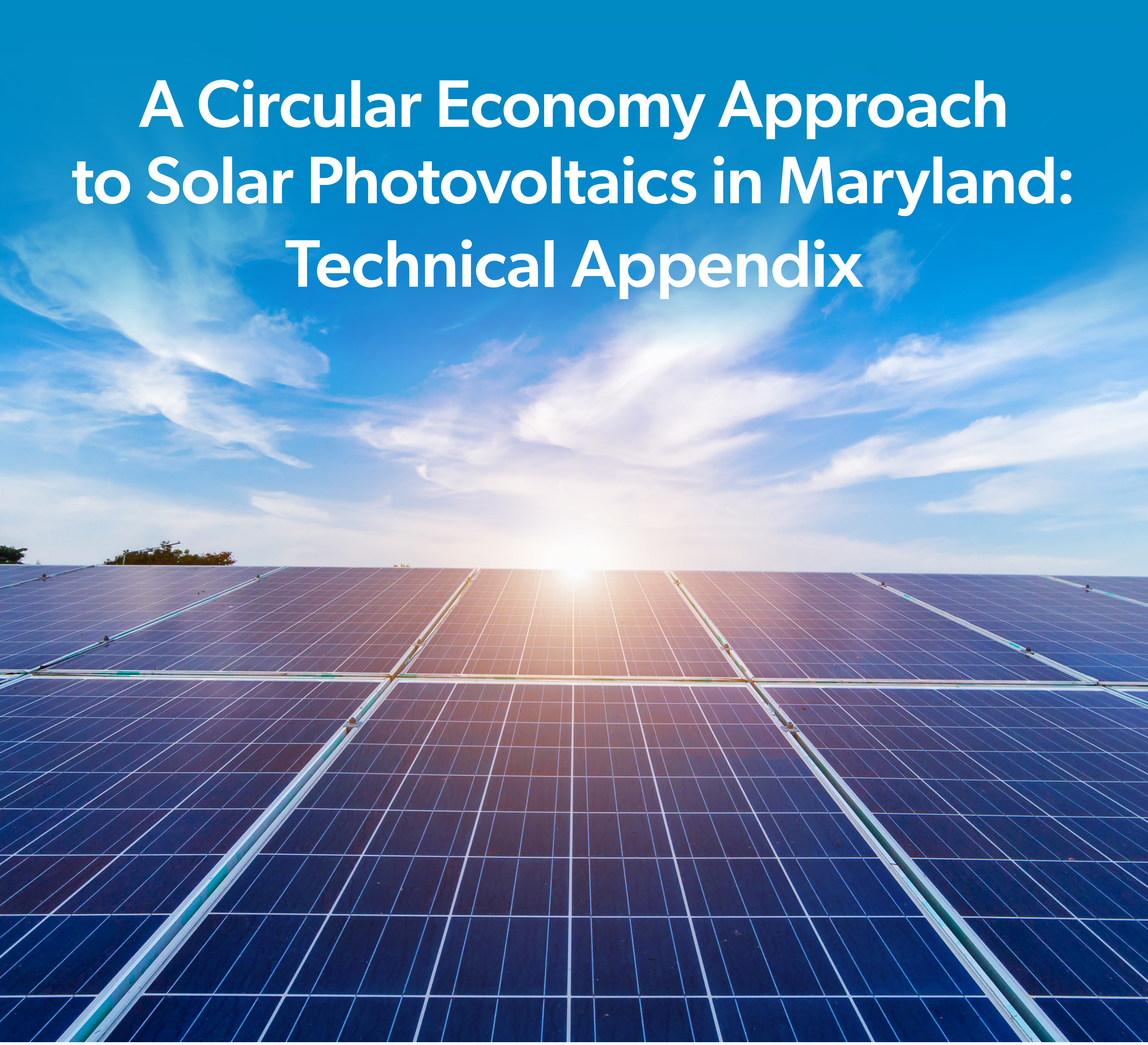
A Circular Economy Approach to Solar Photovoltaics in Maryland: Technical Appendix



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Supplementary Information on Policies and Financing

Figure 2 of this report shows a simplified cash flow diagram of an idealized utility-scale solar power plant, which is drawn from a National Renewable Energy Laboratory (NREL) report[1] that discusses different end-of-life (EoL) scenarios. The authors of the report provided the latest version of the financial scenarios that reflect changes in labor rates and other costs and revenues since the original release of the report. The report notes that increasing operations and maintenance costs as the power plant ages often factor into decisions to repower, decommission, or refurbish a PV system.[1] The Decommission case represents the baseline case — demonstrating the decommissioning of a solar power plant after its intended 25 year lifetime.[1] The Decommission case and Extend Case assume a degradation rate of 1% per year (0.6% is nonrecoverable degradation and 0.4% is recoverable degradation).[1] The Repower case resets the entire degradation rate at 25 years because it represents a scenario in which the panels are replaced in that year, thus incurring a capital cost and immediate increase in power output.[1] The Refurbish case resets the recoverable degradation rate because it represents a situation in which some panels, whose damage is repairable to some extent, are repaired or refurbished.[1] The figures represent an idealized solar power plant, and many other factors influence decisions as solar power plants age. More detail about the scenarios and assumptions can be found in the report or through contacting the authors of the report; the core assumptions are detailed below in Table 1.[1]

RE System Capacity (kW)	1	Discount Rate (%/year)	3%
Annual energy delivery (kWh/year)	1,400	Federal Investment Tax Credit	10%
Initial Cost of System	$1,600,000	Developer Income Tax Rate (%)	30%
Decommissioning ($/kW)	$300	State Sales Tax	3%
Refurbish ($/kW)	$400	Non-recoverable PV degradation Rate (%/year)	0.4%
RePower ($/kW)	$750	Recoverable PV degradation Rate (%/year)	0.6%
Federal Investment Tax Credit	$160,000	Inflation rate	2%
Tax Depreciation Basis ($)	$1,520,000	Analysis Period (years)	40

Table T1. Core assumptions for solar EoL financial scenarios in Figure 2.1

Additional Information on Industry Standards

Another industry standard that may be of relevance for this report is EPEAT,[2] an ecolabel from the Global Electronics Council.[3] The EPEAT label is used by the EPA when considering solar panel purchasing.[4] The label is contingent on criteria that address the whole product lifecycle; additionally, considerations for labor and embodied carbon are part of EPEAT criteria.[3] The label is designed to help purchasers and manufacturers of solar panels.[3]

Details on Stakeholder Perspectives

County Recycling Coordinators were contacted via email. Their responses were collected and analyzed systematically for common themes. The authors also interviewed representatives of the Department of Natural Resources Power Plant Research Program (PPRP) about the Certificate of Public Convenience and Necessity (CPCN) process. Additionally, the authors interviewed representatives of solar companies and installers, many of whom noted a lack of guidance for end of life management. The installers also mentioned there is limited practical experience of residential solar panel removal and EoL management to draw on to inform policy; few installations have been retired or reached EoL.

Lastly, two recyclers, one working inside Maryland the other not located in Maryland, discussed the process, economics, and policy surrounding solar EoL and solar recycling with the authors. They provided information on what the current waste stream looks like outside of Maryland, general information on the economics of recycling, and some initial thoughts on policy. The recycler working in Maryland also provided information on recycling in Maryland specifically. The perspective of solar panel recyclers is very valuable, and more conversations with solar recyclers would greatly benefit the working group and state as it considers EoL policy for solar waste.

Supplementary Information on Maryland's Current Solar Installations

State Energy Data System (SEDS)

The State Energy Data System[5] and Form EIA-8606 data are both publicly available from the Energy Information Administration (EIA), a Department of Energy group that provides detailed data on energy systems in the US and beyond. This data was used to map utility-scale solar arrays in Maryland in Figure 4.

U.S. Large-Scale Solar Photovoltaic Database

The U.S. Large-Scale Solar Photovoltaic Database[7] was used to describe the type of installation sites for large-scale solar installations in Maryland (Figure T1). The data comes from a joint project between USGIS and Lawrence Berkeley National Laboratory (LBNL). Much of their data is also derived from EIA data, which provides capacity, location, technology type, age, and other valuable information for utility-scale solar arrays in the state. Map services and data are available from the Large-Scale Solar Photovoltaic Database, provided by the U.S. Geological Survey and Lawrence Berkeley National Laboratory via https://eerscmap.usgs.gov/uspvdb.

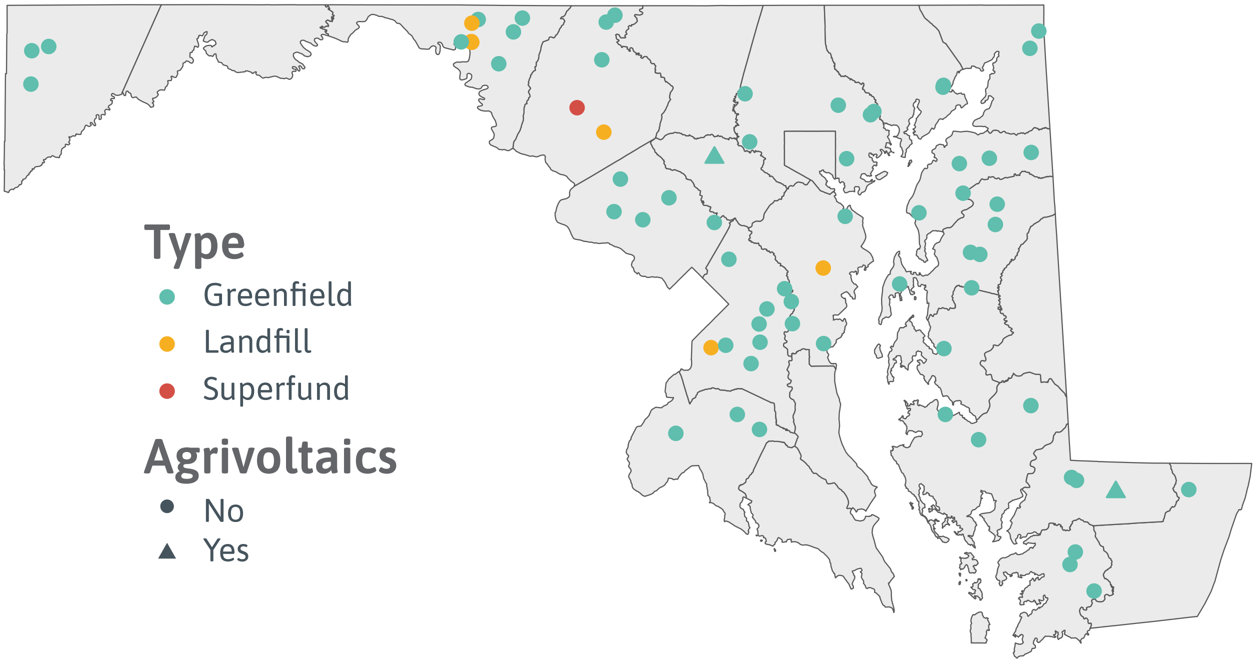

Figure T1. Utility-scale solar installations in Maryland by type. Data source: USGS[7]

Solar Energy Industry Association (SEIA) Data

The SEIA data originates from a report done by Wood Mackenzie in conjunction with SEIA.[8] The data are proprietary, and were provided to the authors upon request. The definitions established below which accompany the data were also provided directly by SEIA.

SEIA Category Definitions

Residential

A residential PV installation is defined as a project in which the offtaker of the power is a single-family household. Any PV system installed on a homeowner's property that participates in a feed-in tariff program is considered residential even if the offtaker of the power is a utility.

Commercial

Rather than using a capacity cutoff to differentiate between residential, commercial and utility systems, Wood Mackenzie defines a system according to its contracted power offtaker. A commercial PV installation is defined as a project in which the offtaker of the power is a "non-residential" customer — neither a homeowner nor a utility. The spectrum of offtakers typically includes commercial, industrial, agricultural, school, government and nonprofit customers. Importantly, we exclude customer-sited projects that sell power to a utility through a feed-in tariff or power purchase agreement, as the ultimate power offtaker is the utility and not the onsite customer. Examples of excluded projects include the Qualifying Facilities projects in the Massachusetts SMART program and the REDI program projects in Georgia. These are included in the utility-scale segment. While most commercial solar projects under this definition will be connected behind-the-meter on the customer's property, there are clearly exceptions such as remotely net-metered projects with non-residential offtakers.

Community Solar

Community solar projects are those where multiple customers can subscribe to power offtake from a project installed in their community and receive credits on their utility bills. These projects are further subdivided into "third-party-led" community solar, where projects are built and operated by third parties, and "utility-led" community solar, where projects are procured or built by utilities. (See community solar publications[9] from SEIA for more details on this distinction). In either case, community solar projects are typically "anchored" by commercial customers, but this can vary depending on the program structure.

Utility Scale

A utility PV installation is a project in which the offtaker of the power is a utility, a third-party power supplier, or a commercial/industrial entity. Projects with commercial/industrial entities as the power offtakers are only considered utility-scale if the projects are front-of-the-meter and connected to the transmission system. These projects are also referred to as "corporate offsite" projects. Utility PV projects also include any PV systems installed on a non-residential customer's property that participates in a feed-in tariff program, in which the system's power is sold to a utility.

Supplementary Modeling Information

Description of PV-ICE Model

Photovoltaics in Circular Economy (PV-ICE)[10] is a software package developed by the National Renewable Energy Lab (NREL) which is built to calculate the net mass and energy flows associated with the entire lifecycle of photovoltaics. The model takes into account material extraction, manufacturing, and performance parameters during a module's operation. After a module is deemed to have reached EoL through one of the three modes of failure (economic/warranty, performance degradation, or probabilistic), then an EoL policy is applied to the module. In the context of circularity, the module (or its constituent materials) can re-enter its lifecycle as described in Figure T2.

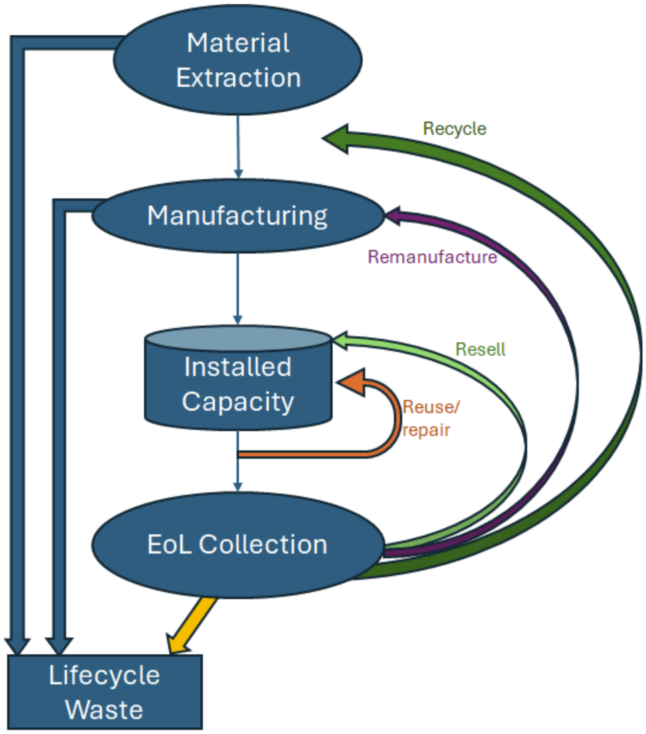

Figure T2. Simplified schematic of PV-ICE model. Solar modules, or their components, can re-enter the supply chain at various phases of production.

Additionally, PV-ICE takes into account the annual installed nameplate capacity (in MW) of solar power generation being added per year (deployment). The deployment schedule and module efficiency are used to calculate the area required for newly deployed capacity. Material demand is then derived based on this deployment area, as materials are tracked per unit area of PV modules. Annual cohorts of installed modules (and their associated materials) are monitored for key factors, including power degradation (e.g., 0.5% power loss per year), failure probability (modeled using a Weibull distribution), and economic lifetime (e.g., 25-year warranty). When modules reach EoL through any of three possible criteria, a collection rate is applied. In all scenarios, we assume a module collection efficiency of 80%, similar to the EU WEEE directive.[11]

At this stage, modules are assessed as being in "good" or "bad" condition. This classification determines their eligibility for different EoL pathways, such as landfill, reuse, remanufacturing, or recycling. Inputs specify the fraction of modules directed to circular EoL pathways, which can reduce the need for virgin materials in future deployment cycles. In all scenarios, we assume the same definition of EoL regardless of the panel condition which can serve as an upper bound. In other words, all modules not being collected for recovery are assumed to be landfilled, in order to avoid assumptions on the decommissioning criteria of a module itself. After dispositioning of a panel at its EoL for reuse/resale, remanufacturing, recycling, or landfilling, each material is then assigned a different remanufacturing or recycling yield.

Detailed Modeling Assumptions

Module Performance

As described above, PV-ICE can take into account the historical values of manufacturing process efficiencies and module performance, and give a projection of continued, incremental technological improvement, as well as various EoL policies. The historical module level performance parameters are given in Figure T3, by module year of installation. These values were taken from historical aggregate industry data from the International Technology Roadmap for Photovoltaics (ITRPV),[12,13] with incremental improvements to module efficiency projected to reach 25% in 2050. After 2030, we assume a fixed value for all technological parameters, such as energies required to manufacture a panel, or further improvements outside of EoL pathway variables, to provide a conservative estimate of further technological development and highlight the differences in EoL policy.

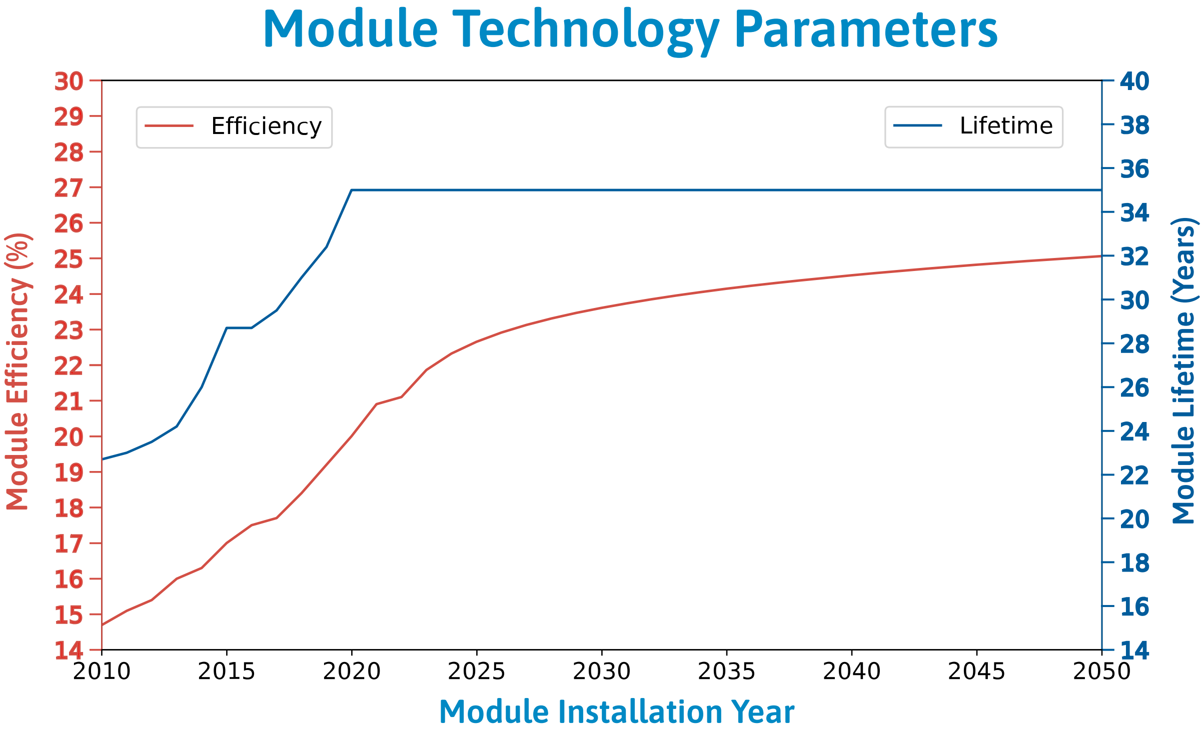

Figure T3. Module properties per cohort of installed panels. The data was collected from the ITPRV[12,14] and historical industry data[15] to develop a limited estimate of the technological development of c-Si panels.

Material Recovery

The next major inputs to the models were the EoL policy: the rates and efficiencies of recovering materials through various pathways. Table 2 shows the assumed rates of recovery broken down by the material in a solar panel. Virgin Material Extraction Efficiencies[16] and Recycling Yields[10] were taken from the existing baselines in the PV-ICE model, which themselves were taken from various industrial reports from each refining industry.

Material Recovery Parameter	**Material**						
	Aluminum Frames	**Backsheet**	**Copper**	**Encapsulant**	**Glass**	**Silicon**	**Silver**
Virgin Material Extraction Efficiency (%)	18.6	99	76	99	60	30	75
Rate of Material Targeted for Recycling (%)	100	0	50	0	100	20	0
Recycling Yield (%)	42	75	95	75	40	80	97
Rate of Material Targeted for Remanufacturing (%)	100	0	50	0	100	20	0
Remanufacturing Yield (%)	50	0	50	0	50	50	0

Table T2. The modeled rates and yields of extraction, recycling, and remanufacturing of the materials in a solar module.

The 'Rate of Material Targeted for Recycling' parameter was chosen to be 100% for aluminum and glass since these are both bulk-recyclable materials, and in the case of a Recycling Mandate, would be recycled. A value of 50% was chosen for copper because the bulk wiring of panels can typically be easily recycled. The rest of the copper in the cells is more difficult to recycle, and is located in the wiring and electronics which require more advanced processing to recover. We chose a value of 20% for Silicon, to model the introduction of some degree of semi-high value recycling, as described in the main text, to the EoL pathway flow. We pessimistically assume that no silver or other high-value solar materials recycling takes place until 2085. We also assume a rate of 0% recycling for the backsheet and encapsulant as these are polymer materials, which are currently either landfilled (in bulk recycling) or incinerated (in high value recycling). Remanufacturing yields of 50% were chosen to represent cases where there is either a mechanical (glass cracking) or electrical (circuitry issue) failure, but dismantling the module could result in a re-manufacturable component.

Deployment Levels

The most critical assumption to modeling the EoL waste in the future is defining how many modules will be needed, i.e. how much power will be coming from solar power based on deployment projections. We use the Marylance Climate Pollution Reduction Plan (MCPRP)[17,18] targets for solar energy generation at 3 different deployment levels:

1. Business-As-Usual (BAU): SEDS data[5] on the amount of solar energy generated in Maryland, linearly extrapolated from 2014 until 2050. The year 2014 was the first year residential scale solar began being reported reliably to the SEDS system.

2. Current Policies (CUR): Scaling rates were taken from Maryland's Climate Pollution Reduction Plan.The Renewable Portfolio Standard (RPS) target of 50% by 2030 and the RPS Solar target of 14.5% are included in this scenario.

3. Current + Planned Policies Scenario (CPP): Scaling rates were taken from Maryland's Climate Pollution Reduction Plan. The proposed Clean Power Standard (CPS) of 100% by 2035 was included in this scenario.

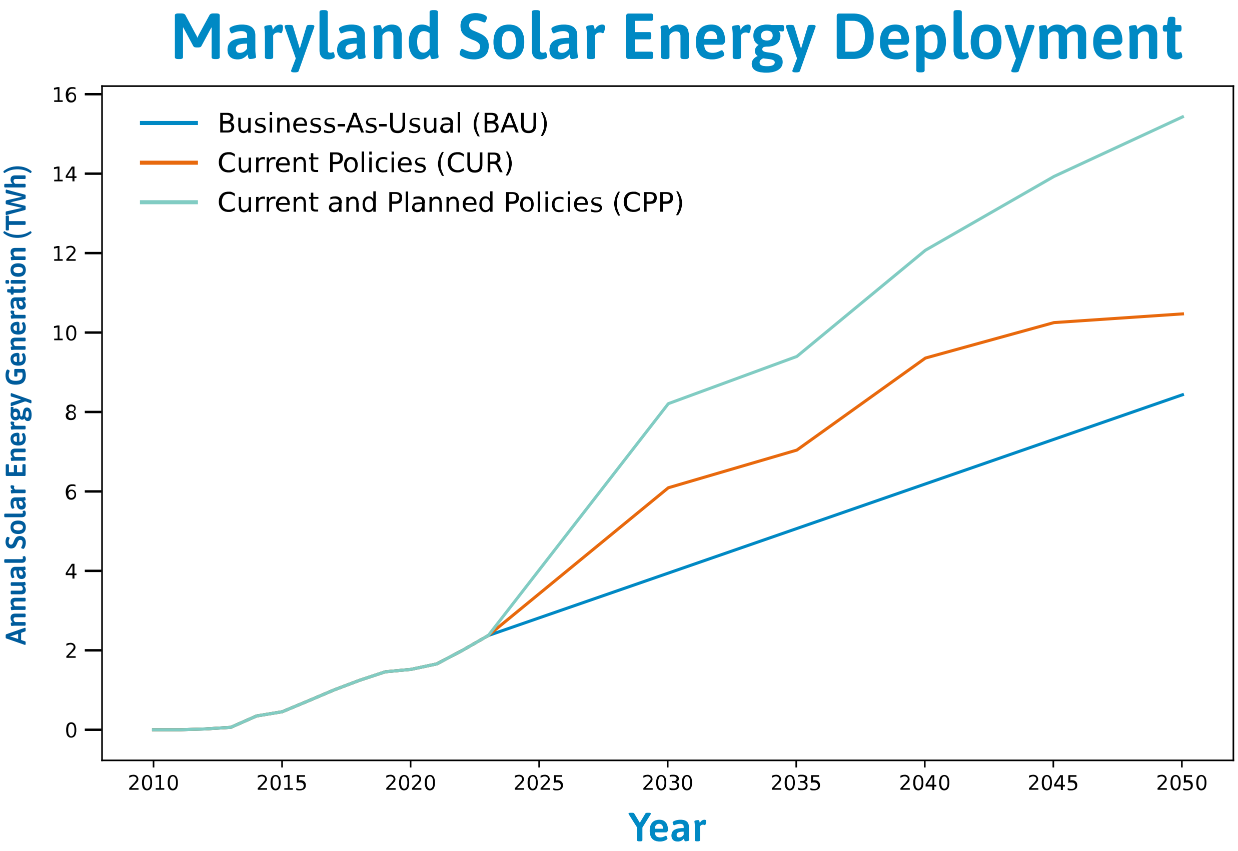

Figure T4. The amount of annual solar energy generation based on three levels of deployment, as outlined in the Maryland Climate Pollution Reduction Plan.

Next we convert the annual solar energy generation to the added nameplate capacity each year through the capacity factor, CF, defined as:

$$\text{CF [\%]} = \frac{\text{(Annual Energy Generation [MWh/year])}}{\text{(365 [days/year])(24 [hours/day])(Nameplate Capacity [MW])}} \ {}^{*}100[\%]$$

Utility-scale solar has a 25% capacity factor in Maryland — the actual amount of energy generated relative to a solar facility's nameplate power capacity - while residential and community solar have a capacity factor of 19%.[19] To conservatively estimate the amount of utility-scale solar that will continue to develop, we assume that the market-share of utility:small-scale solar stays fixed at roughly 30:70%. This implies that there are more panels deployed in the less-efficient residential sector, and more panels overall will have to be deployed to hit the solar RPS target. This gives a projected 'effective capacity factor' of:

$$CF_{eff} = 30\%\ CF_{Utility} + 70\%\ \ CF_{(small\text{-}scale)} \approx 20.8\%$$

We then apply this CF to get the additional required capacity as shown in the main text (Figure 6). The data was smoothed using a smoothing spline to give additional capacity on a yearly basis, as opposed to 5-year basis as set forth in the MCPRP, and to provide more granularity on the waste stream each year.

We also assume there is no additional solar installation after 2050, to see the long term effects of adopting policies without speculating on solar installation levels past the MCPRP targets for the various deployment levels, and thus simulate waste until 2085, when panels installed in 2050 reach their economic end of life.

Scenario Description

Given the three deployment levels and the three modeled EoL policies, Table 3 shows the difference in modeled parameters across each of the 9 scenarios.

	Landfilling	**Recycling Mandate**	**Circular Economy**
BAU (Low Deployment)	Reused/Resold: 0% Remanufactured: 0% Recycled: 0% Landfilled: 100%	Reused/Resold: 0% Remanufactured: 0% Recycled: 80% (2030) - 85% (2035) Landfilled: 20% (2030) - 15% (2035)	Reused/Resold: 20% Remanufactured: 45% Recycled: 35% Landfilled: 0%
CUR (Middle Deployment)	Reused/Resold: 0% Remanufactured: 0% Recycled: 0% Landfilled: 100%	Reused/Resold: 0% Remanufactured: 0% Recycled: 80% (2030) - 85% (2035) Landfilled: 20% (2030) - 15% (2035)	Reused/Resold: 20% Remanufactured: 45% Recycled: 35% Landfilled: 0%
CPP (High Deployment)	Reused/Resold: 0% Remanufactured: 0% Recycled: 0% Landfilled: 100%	Reused/Resold: 0% Remanufactured: 0% Recycled: 80% (2030) - 85% (2035) Landfilled: 20% (2030) - 15% (2035)	Reused/Resold: 20% Remanufactured: 45% Recycled: 35% Landfilled: 0%

Table T3. Each of the 9 scenarios's EOL policy management parameters and the deployment level gives a set of unique conditions used to project solar module waste in Maryland.

The total amount of solar waste will increase proportionally to the deployment level, as more modules will be in place and reaching EoL. At each deployment level, we model the three EoL policies, which take effect in 2030. All modules reaching EoL before 2030 are assumed landfilled.

The ‘Landfilled’ scenario is a worst-case assumption, where every module is assumed to be put into a landfill at its end-of-life. This provides an upper bound for the amount of module waste given a deployment level.

The ‘Recycling Mandate’ EoL policy is based on existing EU[11] and South Korean[20] policies for solar waste management.

The ‘Circular Economy’ EoL policy was chosen to represent and show the added benefits of remanufacturing and reusing panels beyond their economic end of life. In this EoL policy, 20% of panels that reach their economic lifetime which are still performing at >80% of capacity remain in place generating energy (until they degrade to a power output <80% of their initial output). The remainder of modules are decommissioned, and we assume 35% have parts that can be re-manufactured directly into other PV modules, and 45% are recycled. The remaining waste that is sent to landfills is due to imperfections in the recycling and remanufacturing processes, as well as modules failing probabilistically over their lifetime.

Solar Waste and State Landfills

The data for waste handled in Maryland in 2022 is from a Maryland Department of the Environment Resource Management Program report (MDE RMP report) for CY 2022.[21] Figure 11 of this report draws from the MDE RMP report, but it is supplemented by a database of landfills from the EPA.[22] The database is a repository for thousands of municipal solid waste facilities across the US, providing details on location and capacity that are helpful in looking broadly at landfill capacity in Maryland.[22] For Figure 12 of this report, the total waste is from Table 2 of the MDE RMP report, and waste disposed of in Maryland MSW landfills is from Table 4 of the MDE report.[21] The Solar Waste - High Estimate value it taken from the maximum waste in a single modeled year (2062) from the scenario with Current + Planned Policies deployment and Landfill policy. The electronic waste data for Figure 13 of this report is from Figure 9 of the MDE RMP report.[21]

Summary of Related Sources

We provide below a brief summary of related materials that offer further analysis of topics discussed in this report.

1. "*Solar Photovoltaic Module Recycling: A Survey of U.S. Policies and Initiatives*" (NREL)[23]
   Though a couple years out of date, this report provides an overview of policy actions and discussions throughout state and federal governments; it highlights the advantages and challenges with different strategies proposed in various states.

2. "*A Circular Economy for Solar Photovoltaic System Materials: Drivers, Barriers, Enablers, and U.S. Policy Considerations*" (NREL)[24]
   This report highlights important features, conditions, and enablers of a circular economy for solar PV in the US, illuminating how policy could be leveraged to help realize this circular economy.

3. "*Best Practices at the End of Photovoltaic System performance Period*" (NREL)[1]
   This report raises important regulatory and policy considerations for handling solar PV as it nears the end of its useful life, including details on reuse and decommissioning.

4. "*Status of PV Module Recycling in Selected IEA PVPS Task12 Countries*" (IEA PVPS)[25]
   Given the finite amount of federal and state policy governing EoL solar, examining solar PV recycling abroad is useful. This report provides information on the technical and policy aspects of recycling that is happening around the world.

5. "*DRAFT: Review of Decommissioning Considerations for Solar Energy Projects in Maryland*" (Department of Natural Resources — Power Plant Research Program)[26]
   Once released publicly, this report will be valuable in understanding EoL solar for utility-scale projects in Maryland. It could also provide useful information for the commercial and community solar projects that are not large enough to require a CPCN but share commonalities with smaller utility-scale projects.

6. "*Environmental and Circular Economy Implications of Solar Energy in a Decarbonized U.S. Grid*" (NREL)[27]
   Looking more broadly at solar PV in a Circular Economy (CE), this report details CE for manufacturing, operation and EoL phases of solar. This report is useful in understanding holistically that CE for solar requires evaluating the entire lifecycle of panels and the economic, technical, and policy structures foundational to that lifecycle.

References

(1) Curtis, T.; Heath, G.; Walker, A.; Desai, J.; Settle, E.; Barbosa, C. *Best Practices at the End of Photovoltaic System Performance Period*; NREL/TP--5C00-78678, 1765595, MainId:32595; 2021; p NREL/TP--5C00-78678, 1765595, MainId:32595. https://doi.org/10.2172/1765595.

(2) Drozdiak, K. Solar PV Recycling Best Practices, 2024. https://mde.maryland.gov/programs/air/ClimateChange/MCCC/Pages/SPSRRRWG.aspx (accessed 2024-11-06).

(3) Global Electronics Council. *EPEAT FOR SOLAR*. https://globalelectronicscouncil.org/epeat-for-solar/ (accessed 2024-11-06).

(4) Environmental Protection Agency. *Recommendations of Specifications, Standards, and Ecolabels for Federal Purchasing*. https://www.epa.gov/greenerproducts/recommendations-specifications-standards-and-ecolabels-federal-purchasing (accessed 2024-10-28).

(5) US Energy Information Administration. State Energy Data System, 2023. https://www.eia.gov/electricity/data/browser/#/topic/0?agg=2,0,1&fuel=g6db&geo=00000008&sec=g&linechart=ELEC.GEN.ALL-MD-99.A&columnchart=ELEC.GEN.ALL-MD-99.A&map=ELEC.GEN.ALL-MD-99.A&freq=A&ctype=linechart&ltype=pin&rtype=s&pin=&rse=0&maptype=0.

(6) U.S. Energy Information Administration. Form EIA-860 (2023), 2024. https://www.eia.gov/electricity/data/eia860/ (accessed 2024-09-30).

(7) K. Sydny Fujita; Zachary H Ancona; Louisa A Kramer; Mary M Straka; Tandie E. Gautreau; Christopher P Garrity; Dana Robson; James (Jay) E. Diffendorfer; Ben Hoen. United States Large-Scale Solar Photovoltaic Database (Ver. 2.0, August 2024), 2024. https://doi.org/10.5066/P9IA3TUS.

(8) SEIA; Wood Mackenzie. Solar Market Insight Report, Q3 2024, **2024**.

(9) Norris, B.; Gahl, D. *Community Solar Project Siting: A Framework for Producing Zero Carbon Electricity and Serving Ecosystem Enhancement & Conservation*; SEIA Whitepaper; Solar Energy Industries Association, 2022. https://seia.org/wp-content/uploads/2022/02/SEIA20Community20Solar20Project20Siting20-20Land20Use20Framework202.28.22.pdf.

(10) Ovaitt, S.; Mirletz, H.; Seetharaman, S.; Barnes, T. PV in the Circular Economy, a Dynamic Framework Analyzing Technology Evolution and Reliability Impacts. *iScience* **2022**, *25* (1), 103488. https://doi.org/10.1016/j.isci.2021.103488.

(11) European Union. *DIRECTIVE 2012/19/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 4 July 2012 on Waste Electrical and Electronic Equipment (WEEE)*; 2012; pp 38–71. https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2012:197:0038:0071:EN:PDF (accessed 2024-10-21).

(12) International Technology Roadmap for Photovoltaic (ITRPV) 2019 Results, 2020.

(13) Oberbeck, L.; Alvino, K.; Goraya, B.; Jubault, M. IPVF's PV Technology Vision for 2030. *Prog. Photovolt. Res. Appl.* **2020**, *28* (11), 1207–1214. https://doi.org/10.1002/pip.3305.

(14) *International Technology Roadmap for Photovoltaic Results*; VDMA, 2015. https://www.vdma.org/international-technology-roadmap-photovoltaic.

(15) Nemet, G. F. Beyond the Learning Curve: Factors Influencing Cost Reductions in Photovoltaics. *Energy Policy* **2006**, *34* (17), 3218–3232. https://doi.org/10.1016/j.enpol.2005.06.020.

(16) Yue, D.; You, F.; Darling, S. B. Domestic and Overseas Manufacturing Scenarios of Silicon-Based Photovoltaics: Life Cycle Energy and Environmental Comparative Analysis. *Sol. Energy* **2014**, *105*, 669–678. https://doi.org/10.1016/j.solener.2014.04.008.

(17) Maryland Department of the Environment. *Maryland's Climate Pollution Reduction Plan*; Maryland Department of the Environment, 2023. https://mde.maryland.gov/programs/air/ClimateChange/Maryland%20Climate%20Reduction%20Plan/Maryland%27s%20Climate%20Pollution%20Reduction%20Plan%20-%20Final%20-%20Dec%2028%202023.pdf.

(18) Kennedy, K.; Zhao, A.; Steven J. Smith; Kowan O'Keefe; Bradley Phelps; Shannon Kennedy; Ryna Cui; Camryn Dahl; Sarah Dodds; Shawn Edelstein; Eshna Ghosh; Yang Ou; Aishwary Trivedi; Jared Williams; Nathan Hultman. *Maryland's Climate Pathway: An Analysis of Actions the State Can Take to Achieve Maryland's Nation-Leading Greenhouse Gas Emissions Reduction Goals.*; Center for Global Sustainability, University of Maryland, 2023; p 118.

(19) DNR - Power Plant Research Program. Responses to Comments from Alex Pavlak Provided March 3, 2022, 2022. https://dnr.maryland.gov/pprp/Documents/Response-to-Alex-Pavlak_2.pdf (accessed 2024-10-22).

(20) Lee, S.-H.; Jang, Y.-C. Analysis for End-of-Life Solar Panel Generations by Renewable Energy Supply towards Carbon Neutrality in South Korea. *Energies* **2023**, *16* (24), 8039. https://doi.org/10.3390/en16248039.

(21) Maryland Department of the Environment - Resource Management Program. *MARYLAND SOLID WASTE MANAGEMENT and DIVERSION REPORT 2023 (CY 2022 Data)*; Annual Report 2023 (CY 2022 Data); 2023. https://mde.maryland.gov/programs/land/Documents/Maryland%20Solid%20Waste%20Management%20and%20Diversion%20Report.pdf (accessed 2024-10-21).

(22) Environmental Protection Agency. *Project and Landfill Data by State*. https://www.epa.gov/lmop/project-and-landfill-data-state (accessed 2024-11-05).

(23) Curtis, T.; Buchanan, H.; Heath, G.; Smith, L.; Shaw, S. *Solar Photovoltaic Module Recycling: A Survey of U.S. Policies and Initiatives*; NREL/TP-6A20-74124, 1774839, MainId:6273; 2021; p NREL/TP-6A20-74124, 1774839, MainId:6273. https://doi.org/10.2172/1774839.

(24) Curtis, T.; Buchanan, H.; Smith, L.; Heath, G. *A Circular Economy for Solar Photovoltaic System Materials: Drivers, Barriers, Enablers, and U.S. Policy Considerations*; NREL/TP-6A20-74550, 1774574, MainId:6505; 2021; p NREL/TP-6A20-74550, 1774574, MainId:6505. https://doi.org/10.2172/1774574.

(25) Komoto, K.; Held, M.; Agraffeil, C.; et al. *Status of PV Module Recycling in Selected IEA PVPS Task12 Countries*; International Energy Agency - Photovoltaic Power Systems Performance, 2022. https://iea-pvps.org/wp-content/uploads/2022/09/Report-IEA-PVPS-T12-24_2022_Status-of-PV-Module-Recycling.pdf (accessed 2024-10-22).

(26) ERM, Inc.; Exeter Associates; Mondre Energy, Inc.; Versar, Inc. *DRAFT: Review of Decommissioning Considerations for Solar Energy Projects in Maryland*; Technical Memorandum; Maryland Department of Natural Resources - Power Plant Reserach Program, 2024.

(27) Heath, G.; Ravikumar, D.; Ovaitt, S.; Walston, L.; Curtis, T.; Millstein, D.; Mirletz, H.; Hartmann, H.; McCall, J. *Environmental and Circular Economy Implications of Solar Energy in a Decarbonized U.S. Grid*; NREL/TP-6A20-80818, 1844985, MainId:78596; 2022; p NREL/TP-6A20-80818, 1844985, MainId:78596. https://doi.org/10.2172/1844985.

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