SOLAR PANEL RECYCLING
A Review of Existing Markets and Practices
Discussion Draft
August 2023

Introduction

This report was developed by the Massachusetts Department of Environmental Protection (MassDEP) with assistance from the Massachusetts Clean Energy Center, Massachusetts Department of Energy Resources, and the RecyclingWorks in Massachusetts program. This report does not constitute policy recommendations by MassDEP, but rather is intended to inform future policy and program development.

Background on Solar Panel Recycling

Climate change concerns continue to fuel widespread solar installations in the United States. According to the U.S. Environmental Protection Agency, solar panels provided about 40 percent of new U.S. electric generation capacity in 2020. In Massachusetts, the Commonwealth's Clean Energy and Climate Plan focuses on electrification of the electrical grid, which will include substantial growth in the portion of our electricity generation that comes from solar panels.

But the industry's future growth and reputation stands to suffer should the sector fail to develop reuse and recycling systems for panels as they are taken offline (Wesoff & Beetz, 2020). "The solar industry cannot claim to be a clean energy source if it leaves a trail of hazardous waste," cautioned a December 2020 article published in *PV Magazine* (Wesoff & Beetz, 2020).

By 2030, the U.S. is expected to see approximately one million tons of solar panel waste and by 2050, the country is expected to have the second-most end-of-life panels in the world, with as many as 10 million tons of panels (U.S. Environmental Protection Agency, 2021). In Massachusetts, it is estimated that, based on an average 25-year panel lifespan, the amount of solar panels retired will reach about 6,500 tons annually by 2030, with a maximum annual tonnage of approximately 40,000 tons by 2050. More detail on these estimates is provided later in the report.

Current options for photovoltaic (PV) recycling in Massachusetts and throughout the United States are limited. Some of the recycling locations across the US include Ohio, Wisconsin, California, Arizona, Texas and Nevada (Salvi, 2022). However, lacking industry innovation, government intervention, or both, disposing of panels as solid waste could often be a likely result.

Most installed PV systems have been deployed within the last decade and have yet to reach end-of-life (SEIA, 2020). While lack of demand is one reason for limited recycling options, another is the low market value of salvageable materials. There is value in aluminum frames, as well as the copper, silver and silicon contained in components. But, as detailed below, glass comprises most of the material by weight for all technology types and this glass has little value. Current recycling costs per panel are many times greater than the value of the reusable and marketable material (Pyzyk, 2021). Professor Meng Tao of Arizona State University has noted that it costs approximately $30 to process a single module, and revenue is roughly $3 per module (Tao & Young, 2021).

"There is a real gap between the cost to recycle solar panels and the value of the materials that you're deriving from that process. It's cheaper to dispose of the products in landfills," environmental consultant Kelly Sarber told *Waste Dive*.

Approaches in Other State and Countries

With little inherent value for solar modules, some states have turned to policy mechanisms to stimulate the PV recycling market. In July 2017, Washington became the first state to pass a solar stewardship bill (ESSB 5939), requiring manufacturers selling solar products in the state to have end-of-life recycling programs for their own products.[1] However, according to the PV Module Stewardship and Takeback Program through the State of Washington Department of Ecology (Ecology), the statewide collection program is not currently operational and there do not appear to be any sites in Washington recycling PV modules. The program collection is expected to begin in July 2025 and Ecology has developed a guidance document for manufacturers to use for development of their plans (Salvi, 2022).

In June of 2021, New York's Niagara County passed the nation's second such law. The program tasks manufacturers with providing collection services and sets aggressive goals for reuse and recovery: 65 percent within five years of implementation and 85 percent after 10 years (The Product Stewardship Institute, Inc., 2021).

California's SB 489 Hazardous Waste: Photovoltaic Modules, passed in 2015, encourages safe disposal of old panels and designates end-of-life solar panels as universal waste. A January 2021 update to the universal waste regulation is a first-in-the-nation measure that relaxes storage requirements and eases transport issues and costs (Heinzman, 2020).

In 2019, North Carolina convened a stakeholder group selected by the state's Department of Environmental Quality to develop decommissioning rules by the end of 2022 (Ouzts, 2019). The New Jersey legislature also authorized a Commission to investigate end-of-life management options and develop similar recommendations.

Other countries also have adopted measures to curb the waste impacts of solar panels.

[1] Note: there are some delays in implementation due to state budget cuts associated with COVID-19. See Governor Inslee's letter here.

The European Union's extended producer responsibility (EPR) model for solar panels was established in 2012 through the Waste Electrical and Electronic Equipment (WEEE) Directive. Across the EU, panel producers are responsible for the costs of collection, treatment, and monitoring. They are also required to report sales, as well as quantities collected and forwarded for recycling and recovery. Additionally, producers are responsible for informing buyers of the end-of-life management scheme (via a sticker placed on all panels).

Japan developed a "decommissioning fund" requirement for solar developers and operators (with funds to be set aside at the discretion of the regulated entity), but a January 2019 survey found that less than five percent of solar power operators had set aside a reserve for this purpose. The rule is expected to be replaced by a mandatory decommissioning fee that has not yet been enacted (Moroi & Bong, 2020).

Meanwhile, farmers, homeowners and businesses in developing nations have turned to secondhand systems to quench power demands unmet by government and utilities. For instance, due to environmental conditions, a used panel installed in Africa will generate far greater power than an aging one in the Northeast U.S.

Online marketplaces have developed for used solar equipment, with one Minnesota-based exchange estimating as many as five million solar parts available on the site at a time. A Hong Kong tech broker "pessimistically" estimated 10 million used panels available on the global market (Minter, 2021). And a Japanese trading house has announced it will establish a blockchain-based market for solar panels (Minter, 2021).

PV Cycle is an environmental nonprofit founded in Europe in 2007 by and for the solar industry. They helped develop the EPR concept before it was policy, and now help companies comply with requirements while promoting and facilitating recycling of PV equipment. According to their website, PV Cycle offers the following services:

- A network of 300 fixed collection points across the EU
- Partnerships with distributors and municipal collection points
- On-site pick-up service
- State-of-the-art recycling and disposal solutions
- Tailor-made company solutions for one or multiple waste products
- Concept development for internal waste management programs
- Dismantling and waste packaging
- Production scrap

Modeled after PV Cycle, the Solar Energy Industries Association (SEIA) in the U.S. started a national recycling program, RecyclePV, to accept mono-crystalline and poly-crystalline panels (no thin film). Operating as a member-based organization, whereby solar manufacturers paying membership fees for access to the take-back recycling model at preferential prices, RecyclePV developed partnerships with recyclers across the nation (SEIA, 2020). However, their facility in Nevada closed, citing a failure to attract sufficient funds given insufficient federal or state regulations requiring recycling.

We Recycle Solar has a facility in Yuma, AZ. Currently, the three-year old company is recycling manually, waiting on equipment to scale up. Once the facility is functional, the facility is expected to have the capacity to recycle nearly 2,500 panels a day, compared with the 600 it can currently recycle manually. We Recycle Solar focuses on aluminum and glass recycling from the solar panels, but it also has been working to strip traces of copper, silver and other metals away from the glass and plastics through chemical reduction (O'Brien, 2022).

One particular U.S. manufacturer, First Solar, has in-house solar panel recycling capability and says it recovers up to 90 percent of materials. It notes that cadmium and tellurium separation and refining are conducted by a third party (First Solar, n.d.). Domestic recovery of solar panel components could help reduce U.S. dependence on foreign imports (Curtis et al., 2021).

Solar panel recycling is complex, which contributes to the high cost of recycling when compared to landfill disposal. Adhesives and sealants make it difficult to break panels apart (Berg, 2018). Recovering the more valuable materials - like silver, copper, indium, tellurium, cadmium, and lead - requires chemical, thermal, or metallurgic processes (Lunardi et al., 2018). For instance, panels can be torn apart mechanically and broken down with acids to separate out crystalline silicon. Heat systems are used to burn up adhesive that bind panels to their armatures. And acidic hydo-metallurgical systems are used to capture the precious metals (Berg, 2018).

When solar panels are processed at mixed recycling plants, they usually undergo mechanical separation processes, which can lead to higher rates of impurities in the recovered materials, and lower market prices (SEIA, 2020). Researchers are working on improving the efficiency, cost-effectiveness, and environmental impacts of these techniques (Lunardi et al., 2018). Garvin Heath, senior scientist at the National Renewable Energy Laboratory, suggests researchers focus on the recovery of solar-grade silicon to improve the economics of panel recycling (Wesoff & Beetz, 2020). The Solar Energy Industries Association contends that aggregating solar manufacturers and recycling services will lead to more cost-effective and environmentally responsible end-of-life management (Pyzyk, 2021).

"Consumer awareness and attitude are an important piece of the puzzle that must be considered in PV circular economy research and solutions," said researcher Julien Walzberg. "A solution may be technically feasible, but if there's no incentive for consumers to do it, it won't work." (NREL, 2021).

There are currently two accredited certification standards for electronics recyclers: the Responsible Recycling (R2) Standard and the e-Stewards© (US EPA, 2022). In spring 2022, Sustainable Electronics Recycling International (SERI), voted to begin the process of adding solar panels to the R2 certification standard; a first draft of solar panel recycling certification requirements is expected in 2024 (Pyzyk, 2021).

Components of a Solar System

- **PV Module**. glass, aluminum, copper, silver and semiconductor materials that can be successfully recovered and reused. By weight, most PV panels are over 80 percent glass and aluminum.
- **Inverter**. Recycled as e-waste.

- **Racking System**. Reused with newer technology or recycled like other metals.

PV Technology Types and Composition

The vast majority of installed photovoltaic systems are the silicon based (c-Si) technology type, usually mono- or polycrystalline (Table 1). Thin-film technology is expected to have an increasing market share over the next two decades but is likely to remain significantly smaller than c-Si (Table 1).

Table 1. Market share of photovoltaic panels (2014-2030). Source: IRENA and IEA-PVPS (2016).

Technology		2014	2020	2030
Silicon-based (c-Si)	Monocrystalline	92%	73.3%	44.8%
	Poly- or multicrystalline			
	Ribbon			
	a-Si (amorph/micromorph)			
Thin-film based	Copper indium gallium (di)selenide (CIGS)	2%	5.2%	6.4%
	Cadmium telluride (CdTe)	5%	5.2%	4.7%
Other	Concentrating solar PV (CPV)	1%	1.2%	0.6%
	Organic PV/dye-sensitised cells (OPV)		5.8%	8.7%
	Crystalline silicon (advanced c-Si)		8.7%	25.6%
	CIGS alternatives, heavy metals (e.g. perovskite), advanced III-V		0.6%	9.3%

- **c-Si:** The dominant materials are glass, polymer and aluminum: 76 percent glass, 10 percent polymer (encapsulant and back-sheet), eight percent aluminum (mostly the frame). Other materials include silicon (five percent), copper (one percent) and less than 0.1 percent silver, tin, and lead. As new technologies are adopted, the percentage of glass is expected to increase while aluminum and polymers will decrease, as a result of dual-glass bifacial designs and frameless models (IRENA & IEA-PVPS, 2016).

- **Thin-film** technologies are 98 percent glass, polymer, and aluminum, and two percent copper and zinc. They also contain trace amounts of semiconductor or hazardous materials such as indium, gallium, selenium, cadmium, tellurium, and lead.

Estimated Solar Panel Generation in Massachusetts

The Massachusetts Clean Energy Center (MassCEC) and Massachusetts Department of Energy Resources (MADOER) developed estimated projections for future installations of solar panels based on historical growth, policy targets, and power-to-weight ratios to inform potential timelines for decommissioning. Please note that these projections are extremely sensitive to assumptions such as panel lifetime, panel weights, retirement curve, and particularly installation forecasts. As such, the forecasts below should be treated as analyses specific to a particular industry growth scenario, in this case intended to align with the Commonwealth's 2050 emissions targets. However, technology or market developments could result in significantly different scenarios for Massachusetts based solar deployment. As shown, all scenarios point to increased retirement of solar panels over time. MassCEC and MADOER completed projections using a 20-year panel lifespan, a 30-year lifespan, and a reduced growth model as described below.

Based on the linear model for the 20-year lifespan (as shown by the orange line in Figure 1 below), Massachusetts is expected to retire approximately 10,000 tons of panels annually by 2030, with a maximum annual tonnage of 40,000 tons by 2050, followed by a plateau until about 2065. Subsequently, there will be a projected decrease of solar panel tonnage down to 20,000 tons annually, which is expected to be a relatively constant rate after 2075. Please note that this decrease and plateau in the long term is driven by the simplistic assumption that after 2050 emissions targets are met, solar deployment will match annual retirements in order to maintain the overall solar capacity available to the market. This does not consider long-term economic or energy consumption changes beyond what is considered in the Commonwealth's 2050 modeling.

Based on the linear model for the 30-year lifespan (as shown by the blue line in Figure 1 below), Massachusetts is expected to retire over 2,000 tons of panels annually by 2030, with a maximum annual tonnage of 40,000 tons by 2060, followed by a plateau until about 2070. Subsequently, there will be a projected decrease of solar panel tonnage down to 20,000 tons annually, which is expected to be a relatively constant rate after 2090.

Based on the linear model for the reduced growth forecast (as shown by the gray line in Figure 1 below), Massachusetts is expected to retire over 2,000 tons of panels annually by 2030, with a maximum annual tonnage of 25,000 tons by 2045, followed by a plateau until about 2060. Subsequently, there will be a projected decrease of solar panel tonnage down to 15,000 tons annually, which is expected to be a relatively constant rate after 2080.

For planning purposes, we have estimated that, based on an average 25-year panel lifespan, the solar panels retired in MA will reach an approximate annual 6,500 tons by 2030, with a maximum annual tonnage of approximately 40,000 tons by 2050.

Fig. 1: Projection of the Weight of Solar Panels Retired Annually in Massachusetts

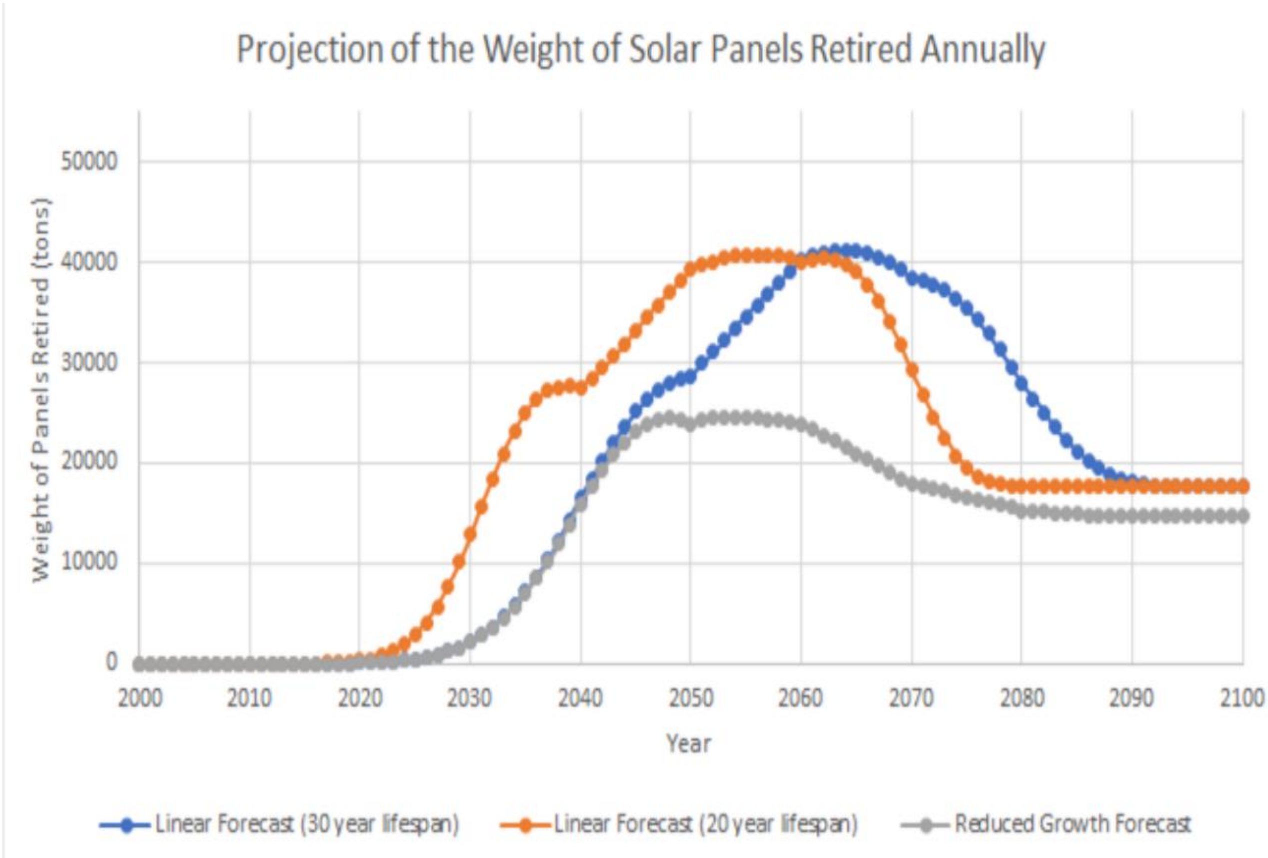


Fig. 2: Weight of Panels Retired by Decade in Massachusetts (20 Year Lifespan)

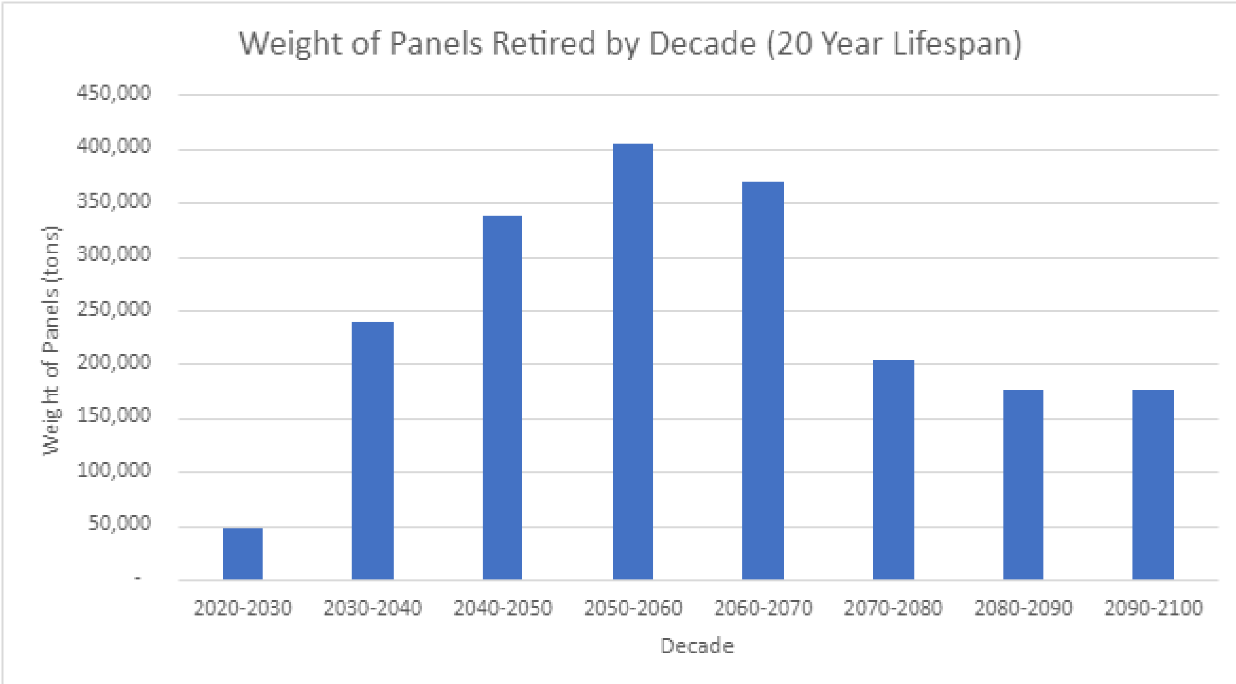
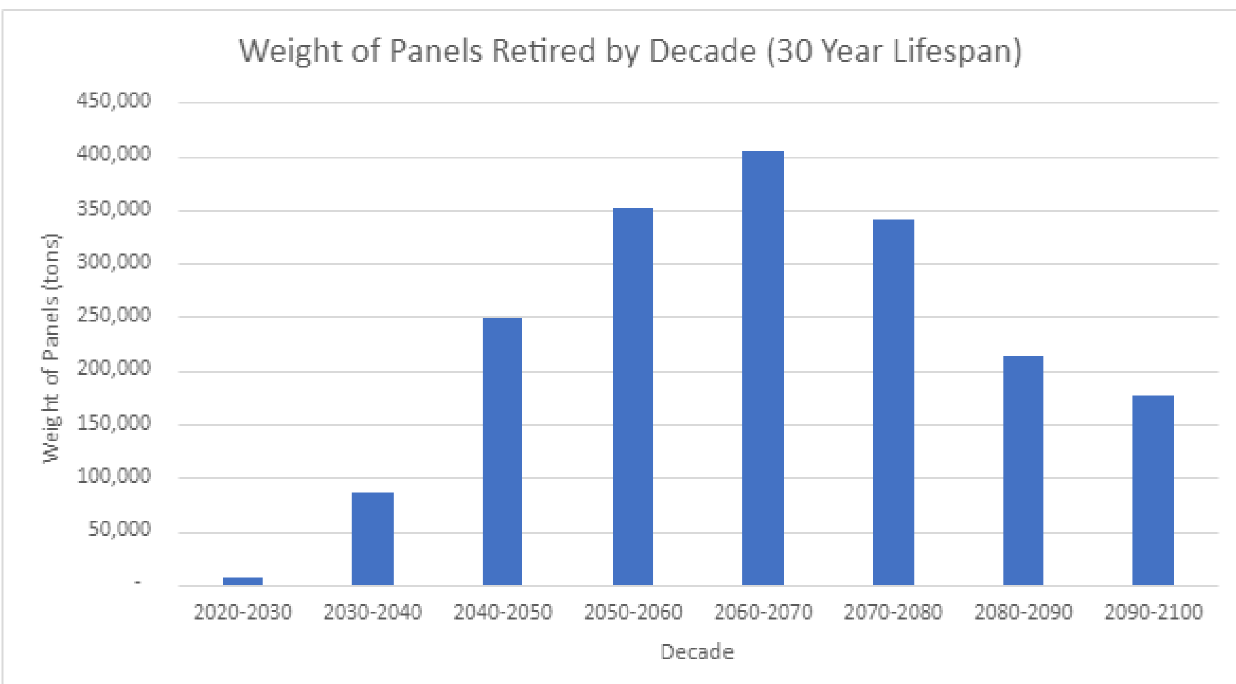


Fig. 3: Weight of Panels Retired by Decade in Massachusetts (30 Year Lifespan)



As shown above in Figure 2, for the 20-year lifespan scenario, there will be an estimated cumulative 50,000 tons of solar panels in MA retired within the 2020-2030 decade, nearly 240,000 tons within the 2030-2040 decade, and nearly 340,000 tons within the 2040-2050 decade. This equates to a cumulative total of 630,000 tons in MA by 2050.

As shown above in Figure 3, for the 30-year lifespan scenario, there will be a cumulative 7,500 tons of solar panels in MA retired within the 2020-2030 decade, over 85,000 tons within the 2030-2040 decade, and nearly 250,000 tons within the 2040-2050 decade. This equates to a cumulative total of 342,500 tons in MA by 2050.

For planning purposes, based on an average 25-year panel lifespan, the cumulative total retired panel tonnage by 2030 in MA equates to approximately 28,750 tons and 486,000 tons by 2050.

PV System Recycling in Massachusetts

MassDEP and RecyclingWorks in Massachusetts (RecyclingWorks) interviewed Massachusetts PV system installers and recyclers to learn more about local practices. The range of responses speaks to the nascency of the marketplace and evolving best practices. Vendors confirmed that, to date, they have very limited demand for solar panel recycling. Deinstallations are rare, and if a panel is damaged, many manufacturers want them back in exchange for a replacement.

Here is a summary of disposal and recycling practices identified in this effort:

- *Disposal of panels in the trash*. At least one vendor disposes of panels in their trash dumpster. They would prefer to recycle them; however, the options they have identified are cost prohibitive.
- *Using the manufacturer's take-back program*. One installer uses SunPower panels (founding member of PV Cycle and RecyclePV described above), which has a cradle-to-grave model. The costs of shipping the panels back to SunPower's partner recycling facility are built into the original purchase price. Therefore, the installer exercises this option at no cost.
- *Hiring a local electronics recycler* to collect the panels. The same installer that uses SunPower panels has identified a local recycler that collects non-SunPower panels for a fee of $10/panel. See more on recycling practices below.
- *Reselling or giving away panels* for reuse. According to installers, there is a market among local hobbyists and DIYers to repair and install small-scale systems. At least one installer has been able to unload used and even damaged panels through this market.
- *Sending panels to a local scrapyard*. Metal recyclers can use the aluminum, but this fails to address the remaining components.
- *Sending panels to C&D processing sites* with roofing materials when a homeowner replaces their roof.
- One recycler noted that some solar installation companies instruct crews to smash solar panels they replace to avoid lost sales in the secondary market.

The recyclers reached for this exercise are for the most part still learning about recycling practices and options. The following is a list of companies known to accept solar panels for recycling (Note: MassDEP does not promote or endorse any specific recycling business and the information reported in this document is self-reported by these companies):

- *Complete Recycling Solutions*, Fall River. Confirmed that they pick up solar panels of any condition from across the state for reuse and/or recycling. Further information is needed about the recycling process.
- *EarthWorm Recycling*, Somerville. This multi-purpose recycler currently accepts panels for pick up or drop off. However, they do not process them. Earthworm ships the panels to their partner, Good Point Recycling.
- *Environmental Integrity Company, LLC*, South Hadley. The electronics recycler provides a pick-up service for one solar installer. They are currently warehousing the panels while they learn about efficient and effective processes to salvage material and explore viable end markets.
- *Good Point Recycling*, Middlebury, VT. Division of American Retroworks, Inc. Accepts used solar panels for reuse and damaged solar panels for recycling. They have a pick-up fee, as well as a fee per panel depending on the size. Further information is needed about the recycling process.
- *Solar Energy industries Association* (SEIA) has a national recycling program.
- *SMR Worldwide/Sprout* accepts panels for a fee and recycles through existing downstream markets.

Massachusetts Hazardous Waste Regulations

There are many different types of panels used in ground-mounted or roof mounted solar PV systems; some have components that may require special hazardous waste disposal or recycling. Solar module manufacturers typically provide a list of materials used in the manufacturing of their product, which may be used to determine the proper disposal requirements at the time of decommissioning.

When solar panels are decommissioned and discarded, state rules require panel disposal be properly managed pursuant to the Massachusetts Hazardous Waste Regulations, 310 CMR 30.000 (Massachusetts Department of Energy Resources [MA DOER] et al., 2015).

Unlike California, where panels are automatically assumed to be universal waste, the burden is on the generator of the panels to determine if the waste being generated (the solar panels) is hazardous or not. This determination can be made using "knowledge" (i.e., an MSDS sheet listing the materials used in manufacture of the panels) or testing (i.e., the Toxicity Characteristic Leaching Procedure – TCLP). If a panel is tested and passes TCLP then it is regulated as a solid waste; if it fails TCLP, then it is regulated as a hazardous waste (MA DOER et al., 2015).

However, if the solar panel is determined to be hazardous solely due to the presence of metal-bearing circuit boards, or if the panels or components meet the definition of a scrap metal (see 310 CMR 30.010), the panels may be conditionally exempt from hazardous waste regulations if destined for recycling (Massachusetts Department of Environmental Protection, 2019). See 310 CMR 30.202(5)(d)-(f) in the Mass. Hazardous Waste Regulations:

The following materials are not subject to 310 CMR 30.200, or any other provision of 310 CMR 30.000: (d) Whole used circuit boards being recycled provided they are free of mercury switches, mercury relays, nickel-cadmium batteries, or lithium batteries. (e) Shredded circuit boards being recycled provided that they are: 1. managed in containers sufficient to prevent a release to the environment prior to recovery; and, 2. free of *mercury switches, mercury relays and nickel-cadmium batteries and lithium batteries. (f) All scrap metal items being recycled.*

Using the conditional exemption, a generator could transport material to an electronics recycler without a manifest or licensed transporter. If the recycling facility receiving the used solar panels generates hazardous waste (e.g., residual metals), it would need to notify as a hazardous waste generator.

Potential Next Steps

Through our limited discussions to date, stakeholders have identified potential action items MassDEP or others may implement to advance the recycling infrastructure for solar panels in Massachusetts. These initial strategies should be discussed further both internally and with external stakeholders to develop an integrated strategy to advance this infrastructure in Massachusetts. Potential strategies proposed by external stakeholders include:

Research and Information

- Gain a better understanding of existing recycling processes in the region to better serve project managers seeking end-of-life options for solar panels.
- Utilize Massachusetts' standing as a college and university hub to kickstart research and development on processes to make solar panel recycling more efficient and economically viable. Research solutions for recyclability of "thin film" silicon systems (Coyne, 2021) and evaluation of thin film weights/volume, including exploration of whether thin film utilizes significantly less material than existing c-Si solar panel systems.
- Consider strategies to stimulate reuse of solar panels, particularly in developing nations with stronger sunlight than the Northeast U.S.
- Work with leaders in the field of corporate environmental responsibility to foster sustainability throughout the supply chain, perhaps through the creation of Best Management Practices for panel installation and retirement.
- Conduct outreach to solar project developers and installers to ensure that they are aware of recycling outlets and applicable regulatory requirements.
- Conduct analysis of the wastes solar panels are displacing by eliminating the use of other power generating sources.

Public Facilities

- Modify the state contract for suppliers to include language that addresses end-of-life needs.
- Establish a state contract for solar panel recycling to give entities access to appropriate options.
- Require vendors to have appropriate third-party certification when applicable (e.g., e-Steward© or R2 certified).
- Work with state agencies to implement pilot solar panel recycling projects and develop approaches to solar panel recycling.

Market Development

- Stimulate solar panel reuse and recycling market development via the Recycling Loan Fund or Recycling & Reuse Business Development Grant for commercial entities.
- Award Sustainable Materials Recovery Program grants to municipalities and non-profits to implement solar panel recycling projects.

Policy and Legislation

- Assess EPR legislation for solar panels, taking into consideration proposed EPR legislation in Massachusetts for other electronics (Commonwealth of Massachusetts H.979, 2021).
- Institute a carbon offset model, or "Fair Trade Recycling Offset," to address concerns about waste externalization. For example, for every ton of panels shipped to Africa for reuse, x tons of e-waste will be recycled in Massachusetts.
- Institute mandates or incentives for manufacturers to label PV modules with concentrations of hazardous material (such as lead) to clarify whether panels need to be managed as hazardous waste.

Regulatory Approaches

- Implement a Waste Ban for solar panels - in conjunction with market development initiatives. Arizona recently implemented one. This would require adequate recycling infrastructure to support a waste ban.
- Develop model regulatory language for new solar installations, for example at closed landfills, potentially including language regarding a Financial Assurance Mechanism or factoring end-of-life into Power Purchase Agreements.

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