ELECTRIC POWER RESEARCH INSTITUTE

Program on Technology Innovation: Feasibility Study on Photovoltaic Module Recycling in the United States

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ABSTRACT

This report examines the feasibility of photovoltaic (PV) module recycling in the United States through a review of available literature. The review includes known module recycling technologies and practices, PV recycling regulations in other countries, and collection systems for transporting module waste to recycling facilities. The study's findings show that module recycling is technically feasible and is being improved through technology and process advancements, though it is not yet economical. Implementing PV module recycling in the United States would likely require a robust collection system and could be accelerated through regulations. The geographic distribution of PV module waste sources and currently low module waste volumes are some of the factors that would need to be addressed in the creation of an efficient collection system. The concept of PV take-back centers that offer consolidation, disassembly, and transportation services—as an intermediary between sources of PV waste and recycling facilities—is one potential option to mitigate these challenges. Based on lessons learned from existing regulations in the European Union and Japan, a few concepts are discussed that warrant consideration for potential inclusion in future U.S. PV module recycling programs.

Keywords

Collection systems
Decommissioning
Life cycle analysis
Photovoltaic (PV) recycling
PV take-back centers (PVTBC)
Regulations

ACRONYMS

a-Si	Amorphous Silicon
c-Si	Crystalline Silicon
CdTe	Cadmium Telluride
CFR	Code of Federal Regulations
CIS	Copper Indium Selenide
CIGS	Copper Indium Gallium Di-Selenide
DTSC	Department of Toxic Substances Control (California)
EPA	Environmental Protection Agency, United States
EPC	Engineering, Procurement and Construction
EPBT	Energy Pay Back Time
EPR	Extended Producer Responsibility
EPRI	Electric Power Research Institute
ER	Exhaustive Recycling
EROI	Energy Return on Investment
EU	European Union
EU-PVSEC	European PV Solar Energy Conference
EVA	Ethylene-Vinyl-Acetate
GPI	Glass Packaging Institute
HWCL	Hazardous Waste Control Law, California
IEA-PVPS	International Energy Agency Photovoltaic Power Systems
IEEE	Institute of Electrical and Electronics Engineers
IRENA	International Renewable Energy
JCC	Junction Box, Cables, Connectors
LCA	Life Cycle Analysis
LCI	Life Cycle Inventory
MSW	Municipal Solid Waste
NEDO	New Energy and Industrial Technology Development Organization

NR	No Recycling
NREL	National Renewable Energy Laboratory
PBDE	Poly Brominated Diphenyl Ethers
p-Si	Polycrystalline Silicon
PV	Photovoltaics
PVB	Poly-Vinyl-Butyral
PVSC	Photovoltaics Specialist Conference
PVTBC	Photovoltaics Take-Back Center
R&D	Research and Development
RCRA	Resource Conservation and Recovery Act
RLC	Reverse Logistics Companies
ROHS	Reduction of Hazardous Substances
SEIA	Solar Energy Industries Association
SERI	Sustainable Electronics Recycling International
SVTC	Silicon Valley Toxics Coalition
TCLP	Toxicity Characteristic Leaching Procedure
U.S.	United States
WEEE	Waste Electrical and Electronic Equipment

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INTRODUCTION

Background

Utility scale photovoltaic (PV) power plants are typically expected to have 25-year life spans. As PV plants reach the end of their useful life, plant owners in the U.S. will face the challenge of how to dispose of massive quantities of PV modules in an economic, but environmentally responsible way [1]. Disposal options include landfills, incineration, source reduction, and recycling [13]. Specific potential end-of-life options for PV modules include repair and reuse, disposal in regular or hazardous waste landfills, recycling, or long-term storage. PV module age, condition, composition, and other factors may influence disposal options. Some PV modules may contain hazardous materials like lead, polybrominated diphenyl ethers (PBDE), chromium (Cr), and cadmium (Cd) [2], [3], [4]. The main environmental concerns associated with disposal of PV modules in landfills are leaching lead (Pb) and Cd, loss of conventional resources, such as aluminum (Al) and glass, and loss of rare materials such as silver (Ag), indium (In), gallium (Ga), and germanium (Ge) [5]. Installed PV modules typically pose no health risks unless they break and leach toxic materials [3]. Recycling PV modules is an alternative to landfill disposal that may reduce health and environmental issues. PV modules have been recycled in mature markets, such as Europe, for several years, and recycling technologies and process improvements have gradually improved the recycling rate, defined as the percent of materials recovered from PV modules [6]. Currently, an estimated 96% recycling rate can be achieved for crystalline silicon based PV modules [6]. In the U.S., there are currently no federal, state, or local regulations mandating PV module recycling, though some efforts to study the issue and develop regulations have been initiated. Research into PV module recycling has been slow due to low volumes of modules reaching end-of-life. However, with the rise in PV deployment in the past decade, and examples of economically and technically feasible recycling models that have been implemented overseas [6], interest in understanding the technical, economic and environmental potential and challenges of PV recycling has been increasing in the U.S.

Motivation for Feasibility Study

As PV modules reach end-of-life, utility-scale system owners and operators who need to manage modules may have to determine whether modules would be considered hazardous materials and if there are recycling or disposal regulations that apply to the modules.

Module Toxicity

Broken PV modules could pose environmental and health risks through leaching of toxic materials. It is possible that leaching could occur while broken modules are in service; disposal in landfills is also a concern. There is disagreement on the concentration of leached chemicals due to PV module disposal in landfills [2], [7]. Leached chemicals have the potential to contaminate ground and surface water. For cadmium telluride (CdTe) and copper indium selenide (CIS) modules, cadmium is of primary concern. For crystalline silicon PV modules, lead is of primary concern [3]. Other materials of concern include PBDE and chromium. As PV module technology has evolved, the composition and relative content of materials used in commercial module construction has varied. Hence, modules currently installed in the field comprise a wide variety of module compositions depending on the cell technology, manufacturer, and supply chain contributors [3]. As most PV modules have not reached end-of-life, there is very limited public data available on the leaching of chemicals in landfills.

Waste Disposal Regulations

Existing regulations in the U.S. apply to all types of waste, including PV modules. The Resource Conservation and Recovery Act (RCRA) [8] regulates hazardous and non-hazardous waste and is enforced by the Environmental Protection Agency (EPA). The RCRA governs the generation, transportation, treatment, storage, and disposal of hazardous waste [8]. A material is considered hazardous waste if it does not meet concentration limits when tested using EPA's method 1311 Toxicity Characteristic Leaching Procedure (TCLP) [2], [8], [9]. In California, materials must additionally meet the more stringent Hazardous Waste Control Law (HWCL), which is like the Reduction of Hazardous Substances (ROHS) directive, adopted in February 2003 by the European Union (EU) [2]. ROHS restricts the use of certain hazardous elements in electrical and electronic equipment, including Pb, Cd, hexavalent chromium (Cr^{6+}), and PBDE. International standards similar to the TCLP include landfill directive EN 12457 in Europe, standard domestic waste process test method in Korea, and Ministry of Environment Notice 13/JIS K 0102:2013 method in Japan [10].

Toxicity Testing

TCLP testing can be used to determine whether specific PV modules qualify as universal waste and can be disposed in regular landfills, or if they qualify as hazardous waste and must receive special handling. TCLP testing was designed to safeguard against potentially toxic materials leaching into ground water. The TCLP determines the mobility of organic and inorganic materials in liquid, solid, and multiphasic waste [8]. There are 40 contaminants outlined in the TCLP. If a PV module fails the TCLP test for any one contaminant, then it is deemed hazardous. California passed SB-489 directing the CA DTSC (Department of Toxic Substances Control) to write rules to reclassify PV modules as universal waste, even if they fail TCLP [42]. These rules exclude physically damaged, fractured or fragmented PV modules, that are no longer recognizable as PV modules. The CA DTSC is in the process of rulemaking, and these rules are not yet in effect. Literature on TCLP or other leachate test results for PV modules is not widely available to the public. Experimental efforts in a recent study [11] compared PV module leachate concentrations with the current European and Italian law limits for drinking water, discharge on soil, and landfill inert (chemically and biologically non-reactive) disposal. Less than 3% of module samples met all law limits. Recent TCLP evaluations [12] of a few crystalline silicon PV modules found lead concentrations more than 5 times the allowable limit, which would lead to these PV modules being classified as hazardous waste. However, these observations need to be independently and thoroughly evaluated through an in-depth particle size and TCLP study, which is the focus of a forthcoming EPRI report.

PV Module Recycling Feasibility Study

This report focuses on the feasibility of PV module recycling in the U.S., including known module recycling technologies and practices, regulations for PV recycling in other countries, and collection systems for transporting module waste to recycling facilities. A review of PV module recycling literature was undertaken to study the feasibility of module recycling in the U.S. This analysis focused on recycling of crystalline silicon (c-Si) modules in utility-scale applications. Information was largely drawn from the 2016 IEA-PVPS (International Energy Agency Photovoltaic Power Systems) report on module end-of-life management [1]. In Section 2, **PV Recycling Technology**, the two major objectives are:

1. Determine technical feasibility of crystalline silicon PV module recycling based on a literature survey of recycling technologies and processes, and
2. Determine economic feasibility of crystalline silicon PV module recycling.

The results of the review show that module recycling is technically feasible and is being improved through technology and process advancements. However, the review also shows that recycling is not yet economical. In this situation, environmental or other societal reasons, may need to drive decisions to recycle. For PV recycling to be adopted in the U.S., regulations will likely be needed, along with a robust collection system. Both PV recycling collection systems and regulations for PV recycling were investigated through a literature review.

Based on experiences in Europe and Japan, a regulated recycling program will likely entail a robust collection system that gathers PV modules from sites of waste generation and transports them to a cost-effective recycling plant [1]. Section 3, **PV Recycling Collection Systems,** presents the results of the literature survey.

While voluntary take-back and recycling initiatives have had success [1], [2], [3], an enabling regulatory framework typically allows multiple stakeholders (producers, consumers, and society) to obtain benefit from recycling PV modules. Section 4, **PV Recycling Regulations,** presents the results of a literature survey of PV module recycling regulations in mature PV markets, as well as U.S. regulations related to waste disposal.

A separate EPRI study co-funded by the National Renewable Energy Laboratory (NREL) reviewed processes at several European PV module recycling plants. These results have been documented in EPRI report 3002008846 [52], and they will also be described in an IEA PVPS Task 12 report expected to be published in early 2018 [53].

2
PV RECYCLING TECHNOLOGY

Introduction

When PV modules reach end of life, they need to be disposed of safely, considering environmental and economic factors. End-of-life PV modules are classified as solid waste [1], which is generally defined as solid objects or particles that are no longer useful [3]. Industrial solid waste in the U.S. is categorized by the sector that produces them, like mining, manufacturing, or agriculture. RCRA [8] and TCLP tests can determine if modules should be classified as hazardous or non-hazardous.

PV Sustainability

As PV deployment increases, it is important that the life cycle of PV modules, from cradle-to-grave is safe and sustainable [2]. Sustainability is commonly defined by the 3R's [14] of waste hierarchy: Reduce, Reuse, and Recycle. Analysis of the PV module life cycle is important to determining if solar PV energy is on a path to sustainability.

Reduce

"Source reduction is the practice of designing, manufacturing, purchasing, using and reusing materials so that the amount of waste or its toxicity is reduced [13]". Research and development into the life cycle of PV modules, particularly the manufacturing phase, will help to reduce the amount of raw materials used per watt of power generated. For example, average silicon consumption has fallen from 5.3 grams per watt (g/W) in 2014 to 4.8 g/W in 2016 [54]. Also, research efforts exist that are aimed at reducing, and eventually eliminating where possible, hazardous materials used in the PV module lifecycle [1], [2].

Reuse

The existence of robust secondary markets may be one way to make PV more sustainable. At the end-of-life, PV modules may be repairable and reusable. If the module glass-cell laminate is not physically damaged, it can be used in lower voltage systems like off-grid or remote power systems. Certain types of damage to the back-skin, junction box, and wires can be repaired or replaced. Modules performing at less than 80% of their original power rating after 25 years of operation can be reused, or the glass and frames from the degraded modules can be reused after separating them from the laminate using physical/thermal/chemical methods. These practices may be most practical for utility-scale systems where large batches of similar modules can be processed and prepared for reuse.

Recycle

The U.S. EPA [14] defines recycling as the process of collecting and processing waste materials and turning them into new products. Recycling has obvious benefits of reducing landfill waste, conserving virgin resources, and preventing some pollution. It is also a source of "green" jobs in the U.S. Expanding existing U.S. recycling capabilities to accommodate current and future PV waste volumes, including the collection systems and recycling technologies and infrastructure, may increase the sustainability of PV. There may be opportunities for module manufacturers to design modules that are easier to recycle. It may also be possible for modules to be made from recycled materials [2]. For example, the silicon wafers from silicon cells can be extracted and recycled by removing the interconnects and metallization, allowing them to be used in new modules.

PV Recycling Technology

The typical crystalline silicon PV module [15] consists of a sandwich of four main components: the front cover, encapsulant, solar cells, and the backsheet as shown in Figure 2-1. The front cover is primarily made of glass, though a polymer film is used in some instances. The encapsulant acts as an adhesive and connects the front and back covers of the solar cells. Typically, the encapsulant is ethylene-vinyl acetate (EVA), but polyvinyl butyral (PVB) has also been used in the past. The solar cells in a silicon-based PV module are either made from monocrystalline or polycrystalline technology. The solar cells are electrically connected in series and/or parallel using ribbons that are soldered to the front and back of the cells. The solder and paste often contain lead. The back cover is typically Tedlar® film, which is made from polyvinyl fluoride, providing a durable, weather-resistant backsheet for PV modules. An aluminum frame seals the perimeter of the module. The junction box is attached on the backside of the module and is used to electrically connect to the solar cells. Solder and paste used in junction boxes can also be a source of lead and other chemicals.

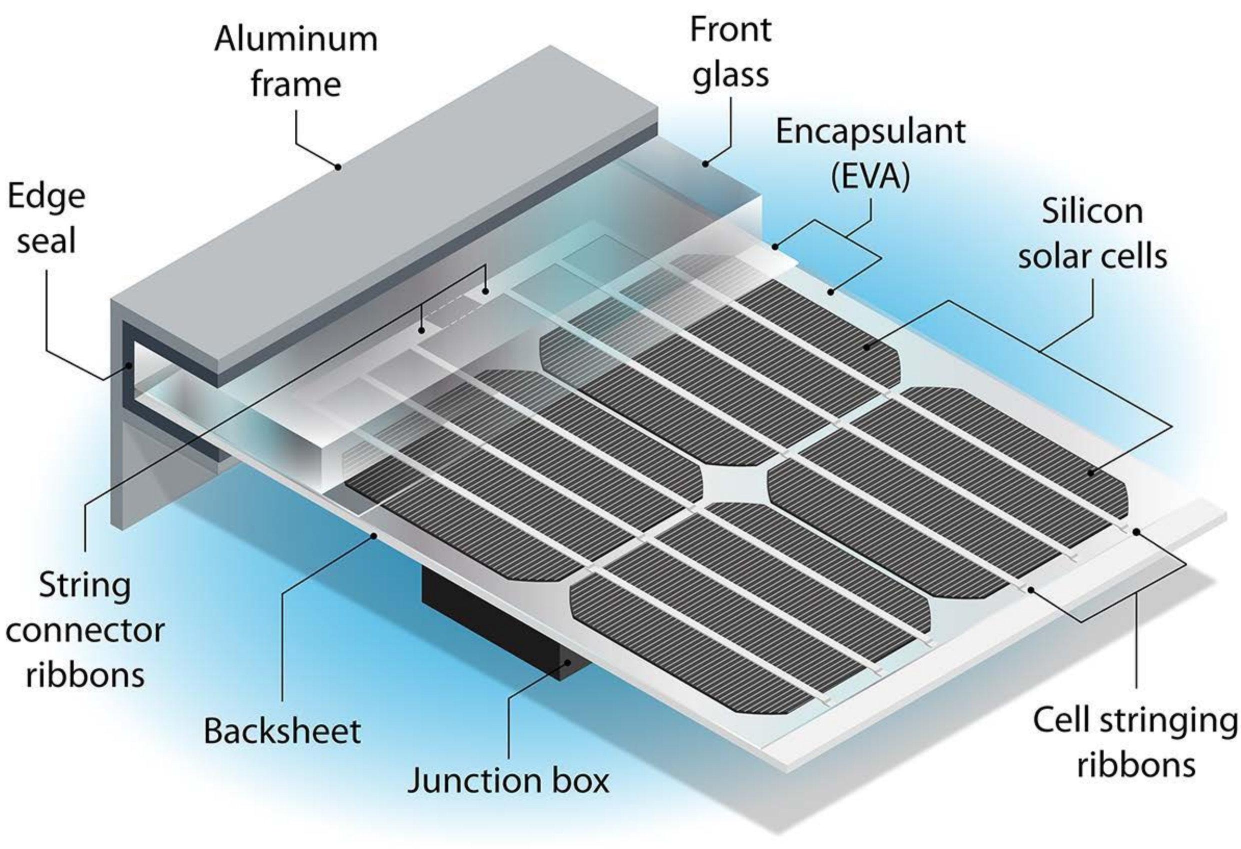

Figure 2-1
Cross-section of typical monocrystalline silicon (c-Si) module [15]

A set of generic steps in PV recycling [1], [16] is shown in Figure 2-2. The disassembly process consists of removing the frame, wires, and junction box, sometimes after coarse-crushing of the modules. Then the sandwich is delaminated to recover glass, silicon (Si), EVA, and other metals. Any hazardous materials can be contained, and non-hazardous waste can be disposed of in a landfill or incinerated.

The primary product of disassembly is aluminum, which is easy to recycle [14]. Waste aluminum is shredded and melted. Melted aluminum is collected into ingot blocks, then cut into sheets to make new products. Copper from the wires and connectors can also be recycled. The junction box consists of copper and plastic, in addition to e-waste. Hazardous materials, like lead, in the junction box can be contained (through recycling or hazardous waste disposal) at the end of the disassembly stage, and useful materials like Si and Ag can be recovered.

The delamination process consists of breaking the sandwich into its components. The process most often involves a mechanical separation like crushing. Thermal processes like a muffle furnace (which separates the module from the combustion fuel, ash, and other contaminants), or chemical processes involving solvents, can also be used to separate the polymer from the glass. Glass, which makes up over 75% of typical c-Si modules by weight, is the primary material recovered in this stage. Glass is made of sand, soda ash, and limestone and is easy to recycle [14], [17]. Waste glass is cleaned and crushed into cullets, which are then mixed with more sand, soda ash, and limestone. The mixture is melted and then molded into new glass products. Glass is also infinitely recyclable. Up to 95% of glass in new products can be recycled content. Members of the Glass Packaging Institute (GPI) are trying to achieve a goal of 50% recycled content [17] in all new glass products. Use of recycled glass has been shown to reduce carbon dioxide emissions and energy use as compared to use of virgin materials. Silicon, EVA, and other rare metals like Ag may also be recovered during the delamination process. Materials that are not recoverable may be contained (stored) if they are hazardous or disposed of in a landfill.

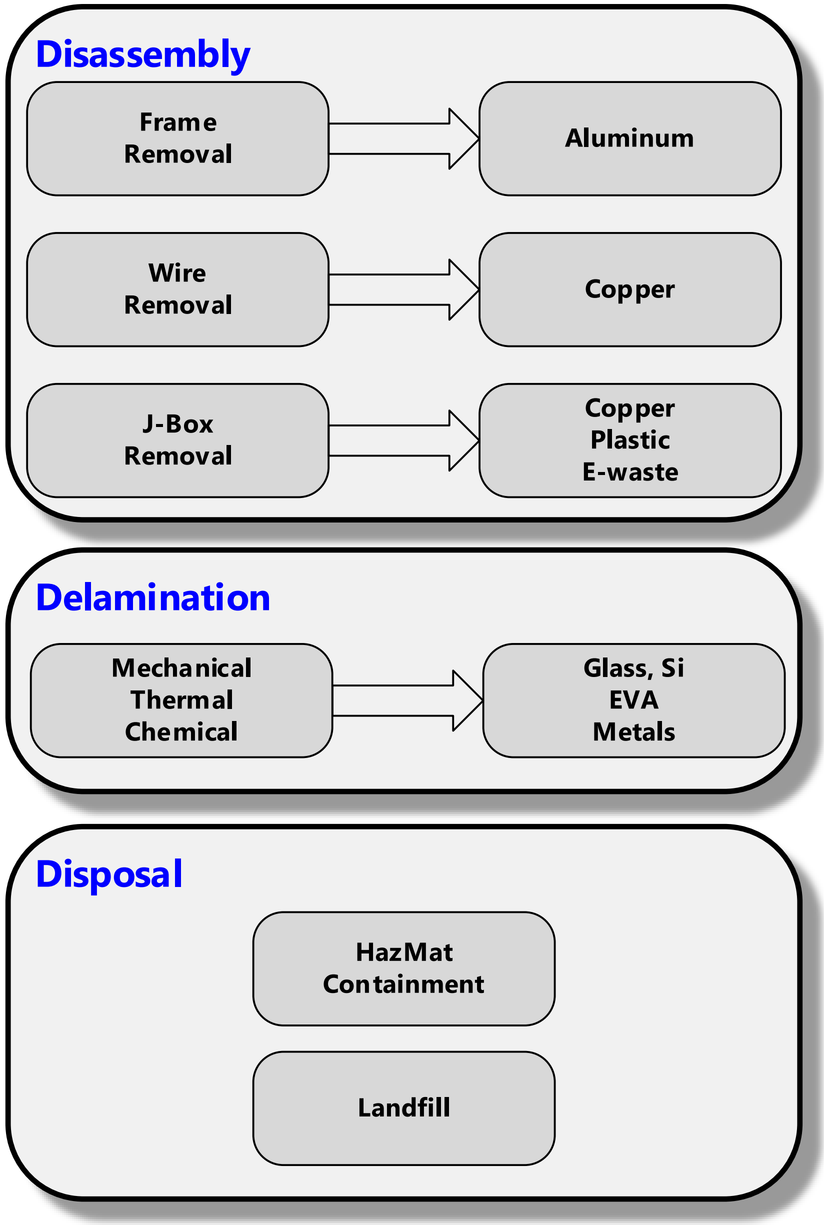

Figure 2-2
Generic steps in PV recycling

Current recycling technologies mainly involve mechanical separation using crushing or shredding and are centered around glass recycling [19], [5]. This makes sense because (1) glass composes the highest weight percentage of material in a PV module, (2) existing glass recycling facilities operate at high capacities and can often accommodate current waste volumes of PV glass, and (3) the costs of universal glass recycling processes are well understood. Commercial processes to recover or recycle high-value by-products like Si and Ag in near pure form are not yet available. These processes are highly dependent on module construction and material use, which varies widely. Because the volume of waste from manufacturing and end-of-life is currently very small, module recycling is typically carried out in batches (volume or time) using excess capacities in existing glass recycling plants.

Commercial PV Recycling

Some recycling facilities now process PV modules in batches using existing facilities designed for laminated glass, metal, and e-waste. The quality and yield of the outputs is typically optimized for both compliance with laws and economics, frequently resulting in the loss of Si and Ag, which would require additional processing steps to recover.

While mechanical recycling processes (laminated glass, metal and e-waste recyclers) dominate the current market, chemical, thermal, and other processes may also be employed. Electricity is the major consumable, and diesel fuel or oil is often used for internal transport of materials.

ENF Solar's website [23] lists ten companies in the U.S. that offer module recycling services, but not all the links specify PV module recycling. Anecdotally, other recyclers not on the ENF list may be willing to accept small volumes of PV modules.

Experimental PV Recycling Methods

Achieving higher recycling quality and yields will likely require more process steps and the associated increase in energy consumption. New technologies specifically designed for PV modules are combining several methods (mechanical, thermal, chemical) in research and pilot-scale demonstrations to recover high-value materials like silver. Several experimental methods described in recent literature are summarized, with references, in Table 2-1.

Table 2-1
Experimental PV Recycling Methods

Reference	Method Description
[24]	This method is a thermal separation process which involves pyrolysis in a fluidized bed reactor. While an alternate chemical separation process may be feasible, disposal of chemical waste would need to be considered. The recovered silicon wafers have relatively high value and energy content. Reuse would avoid the high energy consumption associated with using virgin materials, as recycled silicon wafers have shown a significantly lower energy payback time.
[25]	A life cycle analysis (LCA) of PV module recycling at a commercial glass recycler – Maltha Recycling in Belgium – is presented. The Maltha plant is also powered by its own PV plant, which provides about 50% of its power needs. A screening LCA using a commercial LCA software (http://www.gabi-software.com) is used to perform an environmental assessment of the PV module recycling process applied at the plant.
[26]	The study addresses the recovery of high value content like Si, Ag, and Cu, in addition to Al and glass from PV modules, using pyrolysis. Si is the most important by-product recovered due to its cost and scarcity. Ag improves the economic viability of the recycling process.
[27]	The study evaluates the possibility of using a common recycling process for different module types including Si and CdTe. The process involves two steps: physical (triple crushing and thermal treatment) and chemical treatment. Triple crushing results in 1 mm pieces of directly recoverable glass, coarse (>1 mm) pieces that need thermal treatment to separate cells and other material from the EVA, and fine < 0.4 mm pieces that are sieved into two sub-fractions and chemically treated to dissolve metals and obtain glass. An overall recycling rate of 91% is achieved using this common process for both CdTe and Si modules.

Reference	Method Description
[28]	This approach would recycle both Si and CdTe modules using a crushing method involving two-blade rotors followed by hammer crushing. This is followed by a thermal process. These processes are geared towards recovering the highest glass fraction feasible and discarding the rest of the materials.
[29]	The authors present a detailed review of various methods and feasibility of recycling technologies for PV modules. While a lot of attention in literature has been focused on module recycling, the authors also evaluate waste management techniques at the manufacturing stage.
[30]	This study presents an environmental LCA of an experimental recycling method. This method involves sequential physical and chemical techniques. The analysis shows that the biggest environmental impact is from the incineration of the encapsulant layers and recovery of silicon, silver, copper, and aluminum.
[31]	The authors present a recycling process that recovers silicon using a chemical (acid-based) etching process, followed by a thermal process. The recovered silicon was then used to manufacture solar cells, which showed similar spectral response and efficiency compared with virgin silicon solar cells.
[32]	The module glass is recovered using a chemical method (organic solvents) in this experimental recycling technique. Silicon is also recovered using a chemical method (etching). This method claims to produce a high yield of pure silicon (99.999% purity cited).
[33]	Unlike experimental methods, the authors present field experience from tear-down and recycling of a 23-year old, 300 kW, plant on Pellworm Island (Germany). The paper describes the physical, thermal, and chemical process used in the recycling of more than 15,000 modules. A recycling recovery rate of 94% was achieved.
[35]	The authors use a combination of physical, thermal, and chemical process to recycle the modules. Primarily thin-film modules are considered, but this process could be extended to silicon modules for an inexpensive recovery of glass.
[36]	This study disposes (not recycles) silicon modules by including them in cement (calcium aluminate) matrices. The hydration process of the resulting cement mixture is studied for leaching susceptibility.

Figure 2-3 shows an existing experimental plant in Japan that is designed to recycle different module types in a common process [34]. Details of the process and the degree of success achieved are not available in the reference and could not be included in the above table.

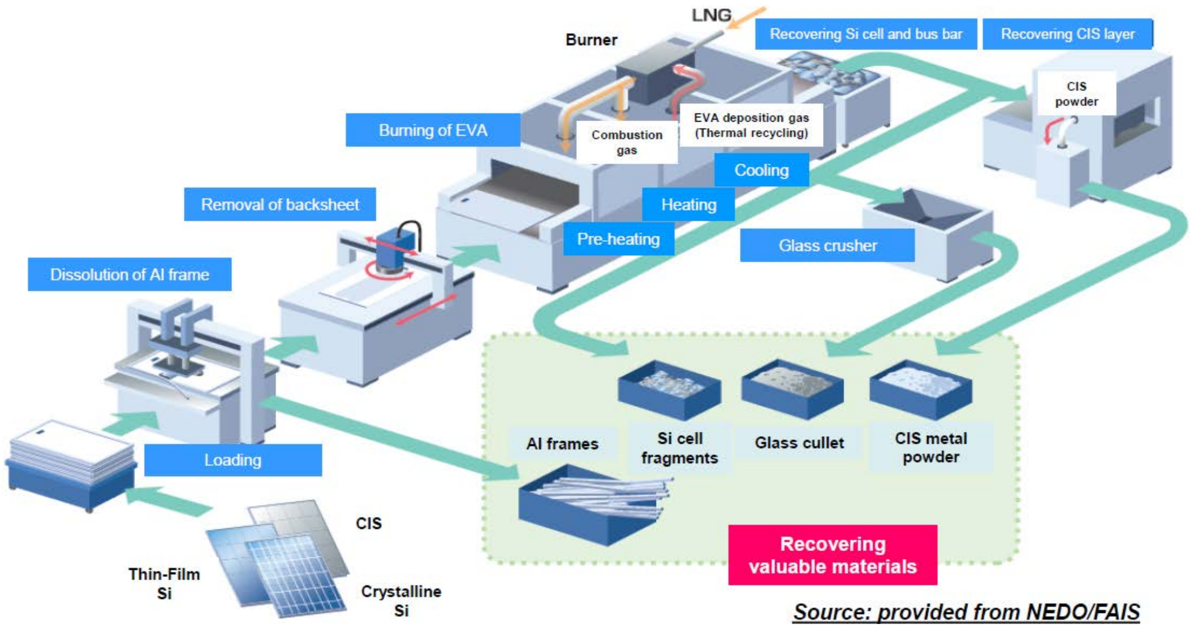

Figure 2-3
Recycling process in Japan [34]

Economics of PV Recycling

The preceding literature survey of PV recycling technologies, based on experimental and pilot projects in Europe, Japan, and elsewhere, indicates that PV module recycling could be a technically viable option for end-of-life management in the U.S. Under the assumption that PV module recycling technology is viable, the economic value proposition for recycling was explored through a literature survey.

The economics of recycling are dependent on three main factors [18]:

1. Regulatory costs and financial incentives for recycling
2. Value of materials reclaimed
3. Costs associated with collecting, transporting, and recycling materials

As discussed in Section 1, in the U.S., the RCRA determines when objects (solid objects in the case of PV modules) are classified as waste. PV modules are classified as waste and regulated by RCRA (and TCLP) when the modules are no longer useful as intended. If the modules are classified as hazardous, and consequently subject to RCRA, then they have to be handled using special procedures. They cannot be sent to municipal landfills. Storage requirements for hazardous waste are more stringent than universal waste. Specifically, hazardous waste is subject to Title 40 of the Code of Federal Regulations (CFR) in Part 262, which is the standard applicable to generators of hazardous waste in the RCRA. Hence, waste subject to RCRA is generally more expensive to collect, consolidate, transport, and recycle compared to non-hazardous waste. Recycling could avoid costs associated with storage and disposal if the modules are classified as "hazardous" under RCRA. Recycling facilities can have the infrastructure, equipment, and trained personnel to meet hazardous waste regulations more efficiently than PV system owners and operators. Recycling facilities could separate and capture hazardous materials from PV modules during and after the recycling process. This hazardous waste, from various PV plants and different module technologies, can be consolidated, stored, or disposed at hazardous waste disposal facilities. Post-recycling, non-hazardous waste can also be consolidated and disposed in landfills.

Regulatory costs and financial incentives can motivate recycling when otherwise not economical. If financial incentives to recycle are created, these could include utility credits, local, state, and federal tax credits, and accelerated depreciation schedules. Incentives can also include cost and penalty avoidance from regulations such as landfill conservation laws, anti-litter campaigns, environmental "green" standing, and hazardous substance control. As PV module recycling infrastructure becomes established in the U.S., improvements to recycling processes will likely be implemented over time to improve efficiencies and reduce the cost of recycling. Reduced cost and improved benefits may result in a favorable cost-benefit analysis, which could lead to PV recycling sustaining itself economically, without incentives, though there is not yet evidence of this.

The value of materials reclaimed depends on the yield and purity of the output streams from the recycling process. Recovered materials like Al and glass have inherent value. PV modules also contain high value materials like Si and Ag, which can make recycling more economical if these elements can be recovered in enough volume to be reused [19].

The economics of recycling also involve the cost of collecting, transporting, and processing the modules [18]. There are several challenges in reducing the cost. One is the logistics of gathering waste from large geographically distributed locations of end-of-life modules. Additionally, as module technologies have evolved, manufacturers have constantly changed the type of materials, construction process, packaging, and form factors to reduce cost and increase efficiency. As a result, the wide variety of manufactured technologies also presents a challenge to processing modules. Experience with recycling programs for other waste streams has shown that cooperation between manufacturers, distributors, users, and other stakeholders is critical to making recycling cost effective. Recycling is more likely to succeed if undertaken through the collective effort of the PV community.

Additionally, PV recycling options will likely increase as the volume of end-of-life modules increases, becomes more steady, and the yield and purity of recoverable valuables improves. Currently, these conditions are absent. Hence, initially module recycling will likely not be feasible by market forces alone but will need to rely on regulations and/or incentives, as is the case in more mature PV markets.

In 2010, McDonald et al. [20] examined the profit potential of five types of PV technologies for CIGS, CdTe, mono-Si, poly-Si, and amorphous-Si (a-Si). The value of all recyclable materials in each of the technologies were considered. The cost of recovering the materials and the profit from reselling the materials was considered. The study determined that only CIGS recycling would be profitable, and a-Si would break even.

In addition to economic payback, another method of technically evaluating different recycling technologies is presented in Goe et al. [21]. The energy payback time (EPBT) defined in equation (2-1) is the time needed to recover the energy consumed in producing modules. The EPBT is reduced by considering the embodied energy, which is the energy required to manufacture new and recycled modules. The energy return on investment (EROI) defined in equation (2-2) is the ratio of lifetime energy output to embodied energy.

$$EPBT = \frac{Embodied\ Energy\ \left(\frac{MJ}{m^2}\right)}{Annual\ Generated\ Energy\ \left(\frac{MJ}{m^2 \cdot year}\right)} = \frac{\sum_n c(1-r)(E_p) + r(E_s)}{PR \cdot \eta \cdot I} \tag{2-1}$$

where,

c = number of new modules manufactured (annually)
r = recycling rate (% of modules recycled per year)
Ep = primary energy required to manufacture a new module
Es = secondary (recycled) energy, which includes energy for recycling a waste module and manufacturing a new module from the recycled materials
PR = performance ratio (fixed in this study for each technology, and typically 0.8)
η = module efficiency
I = total insolation per year

$$EROI = \frac{Lifetime\ Energy\ Output\ \left(\frac{MJ}{m^2}\right)}{Embodied\ Energy\ \left(\frac{MJ}{m^2}\right)} \tag{2-2}$$

As the recycling rate increases or the secondary energy decreases, the EPBT reduces and EROI increases. The estimated primary energy of various technologies is shown in Figure 2-4. The EPBT of various technologies is calculated using three scenarios below. The hazardous properties of individual materials are not a factor in the rates.

1. NR = No recycling. Here the recycling rate is set to zero.
2. MSW = Municipal solid waste. The recycling rates for various materials for example, glass, aluminum, silicon, copper, and plastic, are set equal to EPA published rates.
3. ER = Exhaustive recovery rate with recycling of all materials.

As shown in Figure 2-5, EPBT for Si modules can be reduced by 1.1 years relative to NR for exhaustive recovery of materials, while MSW rates only reduce EPBT by 0.2 years. EPBT and EROI can be used to evaluate different recycling technologies.

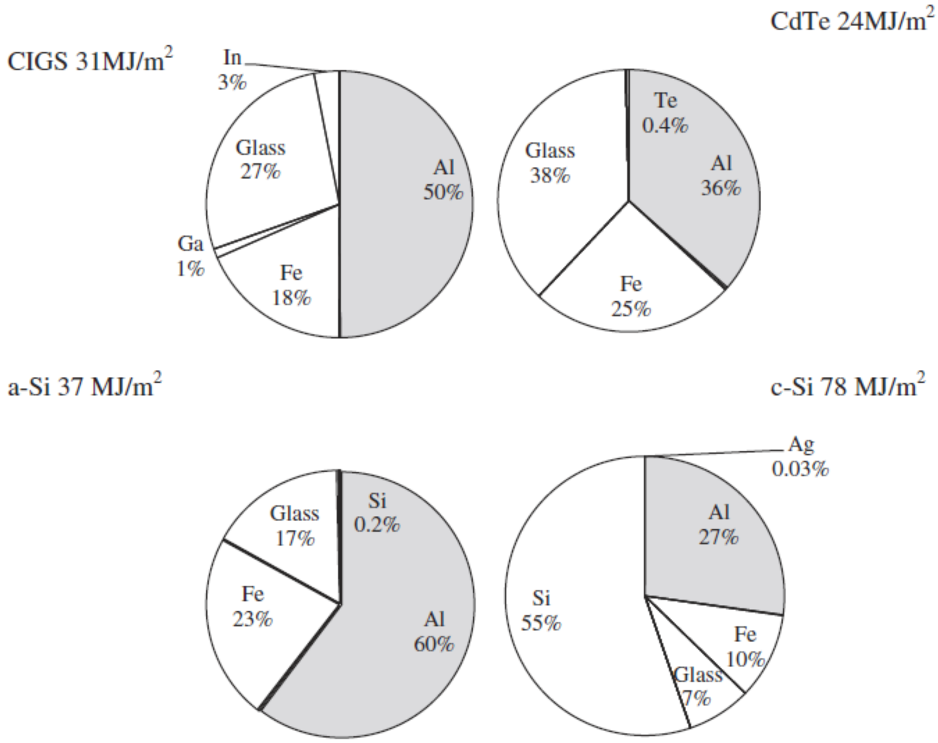

Figure 2-4
Primary embodied energy of 1 kg of material for each PV technology [21]

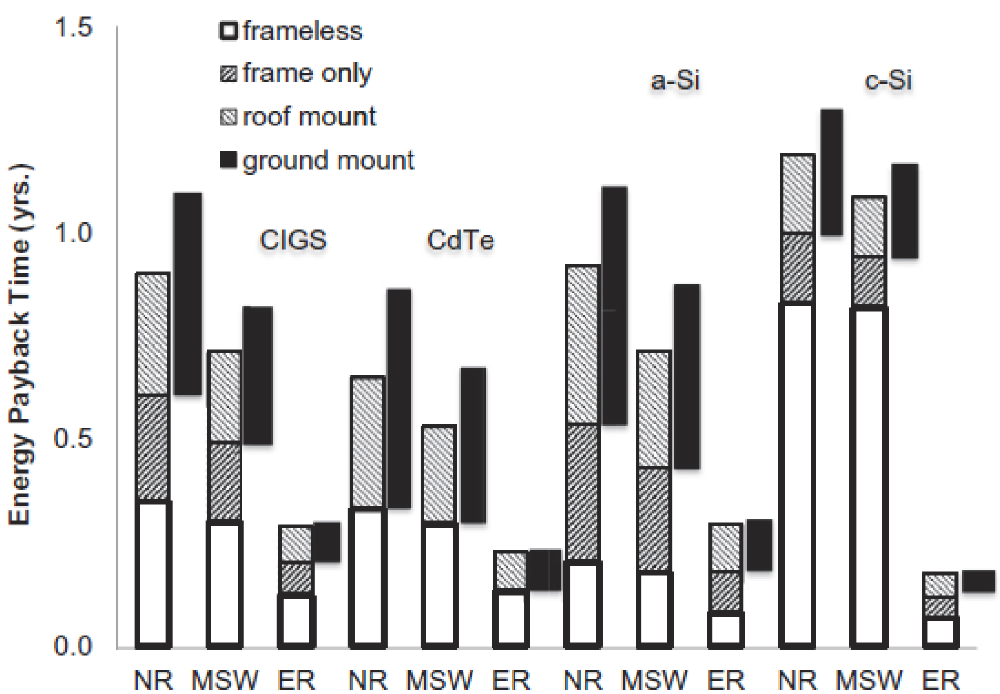

Figure 2-5
EPBT for roof and ground mount with NR = No Recycling, MSW = Municipal Solid Waste, and ER = Extensive Recycling [21]

Another technique to evaluate recycling methods is a life cycle assessment (LCA), which uses a life cycle inventory (LCI), to quantify inputs and outputs of a product or system from resource extraction to end-of-life [22]. LCI can quantify the total energy, sources of energy, pollution, solid waste, and disposal of the life-cycle for a given system. NREL's LCI database protocol requires the definition of clear study boundaries. Data are collected using a unit process approach, which is transparent and documented, so it can be compared, combined, aggregated, or otherwise used for critical analysis with other products and systems. LCI analysis can be used as one metric to evaluate the effectiveness of PV module recycling technology.

Summary of Literature Survey on PV Recycling Technology

Recycling of PV modules as currently performed can recover most useful materials. Recycling, if it proves to be cost effective, is a viable alternative to long-term containment of any hazardous materials. Currently, recycling is not economically feasible in the U.S. due to the low volume of PV module waste, except possibly for CIGS modules. Recycling technology has been proven to be technically feasible in commercial operations and pilot plants, and research demonstrates the potential to lower EPBT and increase EROI. High value recycling with recovery of high-energy content, high-value materials like Si and Ag would further improve the profitability of recycling and reduce EPBT.

3
PV RECYCLING COLLECTION SYSTEMS

Introduction

PV power plants (utility, commercial, and residential) and their module waste are geographically distributed. Currently, most PV plants in the U.S. have not reached end of life [1] and most of the generated PV module waste is from damage sustained during manufacturing, transportation, installation, or operation. Due to current low PV waste volumes [52], recycling facilities in the EU only process PV modules on a periodic basis in batches. It is not currently feasible to build and run dedicated PV recycling facilities in close proximity to sources of PV waste.

Cost-effective recycling requires an efficient module collection system to transport PV module waste from sources of waste generation to recycling facilities. Today's low PV waste volumes present challenges to developing an efficient national collection system in terms of cost, scheduling, storage, and capacity usage. One method to alleviate this problem is the concept of intermediary PV take-back centers (PVTBC), which could act as an intermediary between the source of PV waste and the recycling facility by offering consolidation, disassembly, and transportation services. There are no known examples of PVTBCs currently in the U.S.

This section summarizes findings from a literature review of c-Si PV module end-of-life collection systems around the world. Information is largely drawn from the 2016 IEA-PVPS report on module end-of-life management [1]. The European PV-CYCLE model of collection is briefly described [1] and suggestions for a collection system for utility scale PV recycling in the U.S. are presented.

PV-CYCLE Collection System

In Europe, PV module recycling started as a voluntary take-back and recycling program involving manufacturers, consumers, and other stakeholders. Take-back refers to the process where manufacturers collect their end-of-life products from consumers, so they can be properly disposed of or recycled. Other examples of common products with take-back programs include batteries, compact fluorescent lamps, and printer cartridges.

The PV-CYCLE [1] organization was formed as a non-profit association in 2007. Its function was to implement a take-back and recycling program for end-of-life PV modules. In addition, it now provides dedicated compliance and waste management services under the Waste Electrical and Electronic Equipment (WEEE) regulations. See Section 4 for more information on WEEE. PV-CYCLE continues to be funded with fees paid by manufacturers and project developers. Fees are not fixed but vary on a case-by-case basis depending on country of import, location of PV plant, and local regulations that modify the WEEE directive. PV-CYCLE is headquartered in Brussels and operates in all EU countries.

The PV-CYCLE collection system, shown in Figure 3-1, consists of a sub-contracted network of collection points, certified waste transporters, and recycling centers. The PV industry identified a need to incentivize recycling in residential and distributed plants which have lower volumes of waste and are more geographically dispersed from each other. As such, PV-CYCLE mainly focuses on these sources due to higher collection costs. For utility scale power plants, PV-CYCLE provides a free service to schedule and pick up modules at plant sites and transport them to recycling plants.

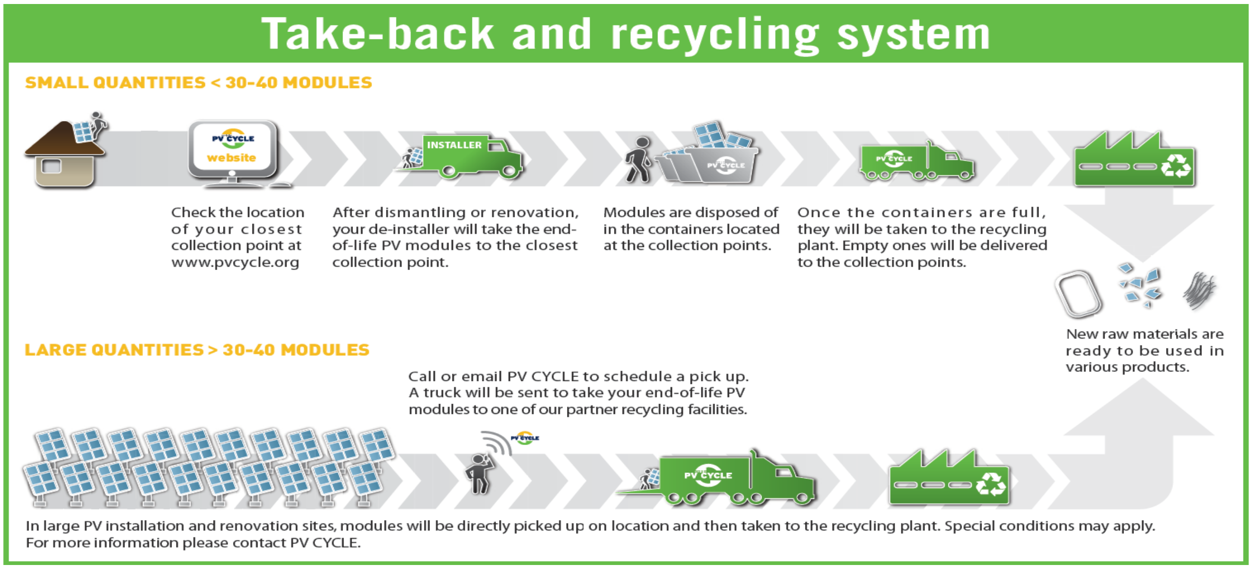

Figure 3-1
PV CYCLE take-back and recycling system [1]

PV Module Collection Systems in the U.S.

This study considers collection systems for utility-scale, crystalline silicon PV plants, though some considerations may also apply to residential or distributed PV plants. Due to current low waste volumes, utility-scale plants will need to handle and provide on-site storage for end-of-life PV modules, so they can be consolidated prior to shipping to recycling plants. This process will likely involve the system owner (e.g., utility), an engineering, procurement, and construction (EPC) company, the manufacturer, or a combination of these entities to properly dismantle the modules, handle them, package them, and store them in a manner that prevents leaching of toxic materials into the ground. Aggregating many modules before transporting them to recycling facilities reduces transportation costs.

Currently, there are no dedicated c-Si PV module recycling facilities in the U.S. ENF Solar's website [23] lists ten companies in the U.S. that offer module recycling services, but none of them operate a dedicated facility to recycle crystalline silicon modules. Based on information available on their web sites, it appears that a few e-waste recyclers on the list can potentially process crystalline silicon modules. As it is not currently feasible to build and operate dedicated PV module recycling facilities close to sources of waste (due to low volume), future PV recycling centers will likely be sparse and geographically distributed.

According to Choi and Fthenakis [38], [39], future PV module collection systems for utility-scale, end-of-life modules will likely involve two parts:

1. Pickup and transportation
2. PV take-back centers (PVTBC)

Pickup and Transportation

Pickup and transportation can be handled by reverse logistics companies, modeled after the municipal solid waste (MSW) industry. Current collection infrastructure paradigms [16] for MSW are a combination of one or more of the following:

1. Large User (e.g., utilities): The user is responsible for collection and transport to the recycler. Typically, recycling is done at dedicated facilities. The costs are ultimately borne by the utility customer as the charges are embedded in utility rates.
2. Manufacturer: In voluntary or regulated take-back programs, the manufacturer handles both collection and take-back. Manufacturers typically employ reverse logistics companies or reverse retail chains for collection and transport of materials. Manufacturers also recycle the materials in-house or at dedicated facilities. The costs are borne by the manufacturer or charged to the end user as a fee.
3. Industry Collective: Manufacturer or trade-group collectives are responsible for collection and recycling. Reverse logistics companies or reverse retail chains provide transportation. Costs are typically paid by industry dues to the industry collective.

Reverse logistics companies (RLC) could provide services for collecting, consolidating, and transporting end-of-life modules [18]. These RLCs could be contracted by manufacturers, utilities, municipalities and recyclers. Similar to RLC is the concept of "reverse retail chain". In this scheme module distributors and dealers function as front-line (customer-facing) drop-off points. The costs of these services will vary with services provided (such as pre-processing), geographic location, and distance from front-line locations to recycling facilities. The experience of recycling programs in other e-waste streams on issues such as cost, best-practices, scheduling and planning, resources needed, regulations, training, and other metrics should be taken into account when designing these systems. In designing an efficient transportation system, overhead for facilities and personnel to manage the process should be considered. Scheduling frequencies for transporting modules should be determined – either on a fixed schedule or based on specific threshold volumes. As PV recycling volumes grow, the necessary transportation infrastructure is expected to develop.

While pickup and transportation systems aid in PV module recycling, they have an environmental impact above the no-recycling option. Goe and Gaustad [37] consider the environmental impacts of collection systems and handling modules through geo-spatial modeling, LCA, and the pickup and transport process optimization. The evaluation model considers energy consumption during transportation, landfill processing, and recycling. As expected, distance traveled from the source of waste to the collection center impacts the environmental costs. For example, collection systems add 7 g to 252 g of CO_2 equivalent per kWh of module lifetime energy, compared to the no-recycling scenario where no transportation due to recycling was required. These environmental costs are determined using a LCA process to examine transportation, energy required for recycling, and the recycling rate. Goe and Gaustad stated this environmental cost may be offset by the environmental benefits of recycling, including prevention of toxic leaching in landfills, although these benefits are not quantified in this study. Processing and recycling sites located close to large solar PV installations would reduce this footprint.

PVTBC

A pickup and transportation system could deliver module waste directly to PV recycling facilities. However, in the near-term this is not a feasible option, as waste volumes are low, recycling facilities are expected to be sparsely located, and it is likely that one facility cannot recycle all parts of a crystalline silicon module. A PVTBC could act as a collection point, an intermediary between the source of module waste and the recycling facility.

The primary function of PVTBCs developed in the near-term would be to aggregate waste from several power plants for later recycling or disposal. In addition, PVTBCs could offer synergistic waste management services, so batch processing at recyclers can be optimized. Modules can be sorted by type, size, or manufacturer. As described in Section 2, experience in the EU [52] shows that PV module recycling is mainly handled by glass recyclers using excess plant capacities. The PVTBC could handle the disassembly stage by separating the frame, junction box, and wires. These components can then be sorted and shipped to the respective recyclers. RLCs may also be capable of offering these dismantling services. Hazardous waste either from the plant site or as by-products from the recyclers could be sent back to PVTBCs for containment or disposal. Once recycled, recovered, useful materials from the PV modules could be aggregated and sold by the PVTBC.

PVTBCs could potentially also participate in the regulatory process, by managing the overall recycling process, including regulatory enforcement. It may be practical for PVTBCs to also handle all the financial processing associated with collecting fees from and making payments to the various stakeholders in the module recycling chain.

Determination of the optimal locations for PVTBCs [38] should involve careful consideration of PV plant density, potential for large PV waste streams (e.g., due to age of plant, environmentally-driven module degradation), availability of third party reverse logistics companies nearby, opportunities to reuse existing recycling infrastructure, maximization of revenue, and minimization of cost. The type of PV module and market value of reclaimed materials also play a role. Other considerations include waste management costs like tipping fees (a common fee collected by landfills), shipping methods and costs, processing costs, inventory, capital costs, and labor costs.

In a direct waste generator-to-recycler situation, utility-scale power plants could have on-site secure storage, eliminating the need for PVTBCs.

Economic Impact of Collection Systems

PVTBCs would face tradeoffs on the cost versus the revenue structure of services offered to the PV recycling industry. Mathematical cost-benefit models [38] could be used as quantitative tools to evaluate services offered, perform sensitivity analysis, and encourage research, design, and process controls. Such models may use revenue from the recycled materials, cost of incoming modules, processing costs, and inventory costs as input values.

For example, Choi and Fthenakis [39] use macro and micro mathematical models to evaluate the economic impact of recycling collection systems. The macro model considers the marginal capital cost of each PVTBC, cost of reverse logistics, distance traveled, and the amount of PV waste collected from various locations [39]. The model results show that the cost of PV recycling is highly sensitive to the location of the PVTBC, due to the cost of reverse logistics and dependence of transportation cost on distance traveled. So optimally locating the PVTBC is of primary importance for recycling to be profitable. The micro model examines the cost of recycling and concludes that recycling process automation systems need to be developed to significantly reduce the cost of recycling modules. Module recycling processes are based on other e-waste products like flat-glass. Using improved automation techniques throughout the recycling process will increase energy efficiency and the cost effectiveness of recycling, more effectively handle diverse module types, recover more materials, as well as scale to larger volumes of expected waste when modules reach end-of-life. The model considers the market price of recycled materials, which could change when PV recycling reaches scale and more waste PV materials are available.

This model uses fuel cost, mileage, labor, and materials to model the PVTBC reverse logistics costs. Other financial assumptions include the cost of material pre-processing, revenue structures, volatility of material market prices, macro logistics costs, and external environment costs like landfill tipping fees and avoidance of waste management risks. The total capital cost for a region is the average of the capital costs for each individual PVTBC. The capital cost of each individual PVTBC varies with location. This type of model can be adapted to various geographic regions in the U.S. to evaluate proposed PVTBCs or to optimally locate new ones based on expected waste volumes. For example, Figure 3-2 shows the reduction in reverse logistics costs as the number of PVTBCs increases and the distance traveled decreases within a specific geographic region.

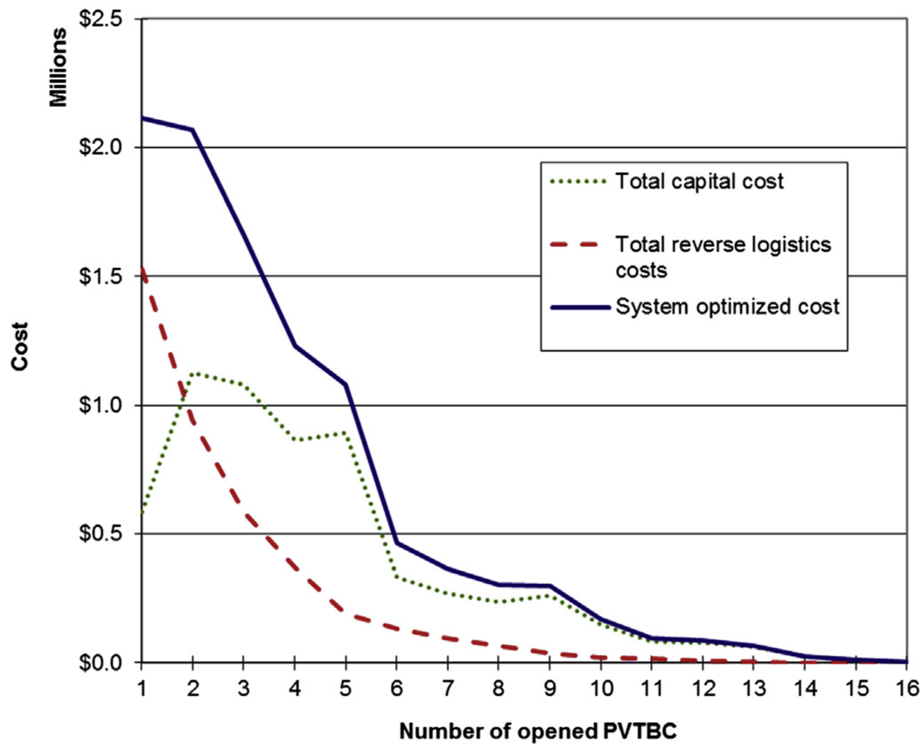

Figure 3-2
Change in total reverse logistics cost with increase in PVTBC [39]

Summary of Literature Survey on PV Recycling Collection Systems

PV waste volumes are currently low. As a result, dedicated silicon module recycling facilities do not exist in the U.S., though some e-waste recyclers may offer PV module recycling services. PV waste volumes are expected to increase, likely requiring future module recycling facilities to be developed in the U.S. The collection of waste is an integral part of any potential module recycling system. The European PV-CYCLE collection system, likely the most mature PV module collection system, is briefly examined. The concept of PVTBCs is one potential option for the U.S. that could be used to reduce recycling costs, given initial low waste volumes, geographic dispersion of waste sources, and special processing requirements of PV modules. PVTBCs and the collection process add financial and environmental costs which are potentially offset by the benefits of recycling. The location of PVTBCs can be optimized to reduce total system costs.

4
PV RECYCLING REGULATIONS

Introduction

Currently, there are no dedicated crystalline-silicon PV module recycling facilities in the U.S. ENF Solar's website [23] lists ten companies in the U.S. that offer recycling services, but none of them operate a dedicated facility to recycle crystalline silicon modules. A few e-waste recyclers in the list mention recycling of "solar panels". Only one of them, ECS Refining (https://www.ecsrefining.com/industries-served/solar-and-pv-systems) mentions "solar & PV systems" and states that the company has mostly worked with OEMs to recycle manufacturing waste. They, however, claim to be ready for end-of-life recycling if needed. None of the other "solar panel" recyclers mention PV on their websites. First Solar recycles their own CdTe modules only. The Solar Energy Industries Association (SEIA) and other organizations like NREL and SVTC (Silicon Valley Toxicity Coalition) have efforts underway to encourage PV recycling [23], [40], [41]. SEIA has a program to connect members to pre-approved PV recyclers, facilitate a single point of contact, offer discounts, provide industry-wide module aggregation services, and collect data on industry level recycling. The only PV recycler currently listed is ECS Refining. Currently, there are no regulatory frameworks for PV recycling in the U.S. at the state or federal levels. State-level legislation and initiatives are under consideration in the U.S. For example, California may require non-U.S. manufacturers to perform TCLP testing before modules are sold in U.S. markets [42].

In the EU, PV module recycling is a legal requirement and is addressed through WEEE. Japan has established a recycling program that includes PV modules. This section contains a literature survey of existing international PV recycling regulations in the EU and Japan. Considerations for development of a broad regulatory framework for PV recycling in the U.S. is presented. Information is largely drawn from the 2016 IEA-PVPS report on module end-of-life management [1].

PV Recycling Regulations in the EU

In the EU, recycling PV modules is a legal obligation under the WEEE directive [43], [1], [2], [4]. WEEE was initially adopted in 2003 and revised in 2012. The 2012 revision has been adopted by all member states in the EU. The 2012 revision classified end-of-life PV modules as electronics and electrical appliance waste (e-waste). The WEEE directive is based on the extended-producer-responsibility principle [1]. In accordance with this principle, the producer (manufacturer) is financially responsible for collecting and recycling PV modules. In addition, the producer is also responsible for reporting on collection and recycling efforts, labeling PV modules with recycling information, and to inform the buyer that collection and recycling are available free of charge. The WEEE directive sets minimum standards for collection, recycling, and recovery targets as a percentage of modules sold. Individual member states may add to these requirements.

The PV-CYCLE organization [1], [2], headquartered in Brussels, was developed to implement the WEEE directive for PV module recycling. Member countries include UK, Netherlands, France, Czech Republic, Germany, Spain, Switzerland, Belgium, and Bulgaria. WEEE and Restriction of Hazardous Substances (ROHS) directives seek to decrease the amount of e-waste sent to landfills [2]. While the WEEE deals with waste, ROHS restricts the amount of hazardous materials that may be used in the manufacture of PV modules.

In 2011, the BIO intelligence service [5] studied the impact of including PV module recycling in WEEE. Assessment of different scenarios led to the conclusion that including PV modules would reduce the potential negative environmental impacts of improper disposal and generate economic benefits [5]. Additionally, it avoids potential resource loss due to non-recovery of valuable conventional resources and rare metals in photovoltaic panels which are otherwise disposed of [5].

The long-term success of recycling programs is tied to other economic incentives, such as relevant taxes (container laws, government subsidies for raw materials, curbside recycling), and the development of and demand for products manufactured from recycled materials [13]. Recycling PV modules is a cost, and it increases the levelized cost of electricity (LCOE) by affecting operating costs at end-of-life, or capital costs if a fee is collected at time of sale. Francia [44] found that recycling only slightly affects the LCOE and that, if processes for reusing the solar silicon are developed, recycling could even favorably affect the cost. Job creation potentially increases with the quantity of end-of-life panels generated and the quality of recycling applied to waste panels [5].

PV Recycling Regulations in Japan

Japan's Ministry of the Environment has jurisdiction over the National Waste Management law, for which enforcement began in 2001 [45]. The law's framework includes permits, regulations, prohibited activities, clean-up and compensation, penalties, public and private registers, environmental auditing, reporting requirements, insurance, risk assessment, and environmental taxation associated with general waste management.

E-waste management in Japan was originally developed to handle televisions, refrigerators, washing machines, and air conditioners [46]. Certain types of e-waste, such as computers and other electronic products, are not specifically mentioned [2]. The home appliances above are specifically mentioned in this law as there are limits to their treatment prior to recycling, size of these appliances is increasing, and there is a high value for materials recovered from end-of-life waste. The e-waste law includes emissions control, waste treatment, installation of recycling and waste treatment plants, waste treatment contractor management, and other waste treatment standards. The "Law for the Promotion of Effective Utilization of Resources" is a separate law that controls recycling, including resources, incentives, structure, innovation, recovery, and utilization of by-products. In addition, the "Green Purchasing Law" is another separate law that requires local and national governments to purchase recycled products. Manufacturers and retailers are responsible for take-back, recycling, and documentation/reporting. Customers are responsible for proper disposal of these appliances and bearing some of the cost of collection and recycling. The government is responsible for the collection system, as well as some of the recycling, especially in rural areas. The e-waste law (also known as the "Home Appliance Recycling Law"), the "Law for the Promotion of Effective Utilization of Resources," and the

"Green Purchasing Law" classify PV modules as e-waste and require the collection and recycling of end-of-life modules.

Experiences with e-waste recycling systems in Japan and China [47] showed that pre-treatment of e-waste and recycling were labor intensive, leading to outsourcing e-waste treatment from Japan to China. It was relatively easy to monitor compliance with regulations for each of the different stages in the recycling process in Japan, but illegal dumping and export of e-waste to China were issues. In China, a high reuse rate of the separated materials was observed, but collection of data, illegal import of e-waste, and excess pollution in landfills due to dumping, continue to prove challenging.

According to [48], when producers are billed at the time-of-sale for the cost of recycling, incentives encourage them to make an investment in plants and equipment, leading to designs that are easier to recycle. Consumers can be billed to avoid illegal dumping aimed at avoidance of disposal fees.

Japan's e-waste management system was developed to address concerns such as difficulty in properly treating e-waste, the volume and size of e-waste generated, landfill and emissions costs, and loss of useful resources in e-waste. This e-waste management system consisted of several regulatory mechanisms as explained above. Lessons learned from Japan's e-waste management system include [46]:

- It is important for regulations to be clear and specifically identify the law's scope. The exact types of waste should be identified.
- Once laws classify waste and mandate recycling, market forces should inform specifics of take-back and recycling. Regulations should be designed so as not to impede market mechanisms related to take-back and recycling.
- There should be clear descriptions of roles and responsibilities for all stakeholders.
- Mechanisms are needed to prevent free-riders. Free-riders can include producers and consumers responsible for illegal export of waste and landfill dumping.
- Improvements in collection efficiency are needed.
- Reporting mechanisms are needed to determine exact recycling cost.

Considerations for U.S. Regulations

Since most utility scale PV power plants are relatively new, there is currently a small volume of scrap from the field and manufacturers. The 25-year life span also provides time to develop robust disposal or recycling mechanisms. One study reviewed in Section 2 suggests there is apparently little to no profit [20] in recovered materials. Although SEIA and other organizations have current efforts to promote recycling, these efforts are not geared towards regulation, and PV industry stakeholders in the U.S. are generally not working towards development of viable PV recycling regulations. Regulations for universal PV module recycling may accelerate recycling in the U.S. This section examines a broad set of issues that could be considered for PV recycling systems in the U.S.

Goals of Recycling Regulations

Initial U.S. regulations around PV recycling would benefit from being broadly based on what has been found to be successful in both the WEEE and Japan's waste management law. Another source that could inform U.S. regulations are the current e-waste laws included in the RCRA. Coyle [49] lays out a detailed framework for environmental law based on e-waste. According to [49], many types of e-waste have a similar toxic leachate content to crystalline silicon PV modules. Lessons learned from e-waste management [50] indicate that initial and ongoing regulations have led to a significant strain on U.S. environmental resources. E-waste generated in the U.S. is shipped to developing countries, where it is often handled without environmental and human health standards and enforcement. To avoid this, the U.S. EPA is expending resources (primarily funds) to coordinate e-waste management with other countries. According to the U.S. EPA, cleaning up e-waste before export to reduce harm from U.S. exports, is now one of its top six global priorities [50]. This is one of the main lessons from e-waste management: though waste volumes for end-of-life modules are currently small, adequate and effective PV recycling regulations could be developed early to prevent PV end-of-life modules ending up in landfills in the U.S or other countries where they could cause harm.

Based on the IEA-PVPS report [1], regulations in the EU and Japan presented in this section, and the literature review presented in this study, potential regulations could consider the following concepts, which are explained in further detail below:

- Mandate PV take-back and recycling
- Arrange for payment
- Streamline classifications
- Determine processes
- Implement, verify, and enforce

Mandate PV Take-Back and Recycling

The WEEE directive includes the concept of EPR (Extended Producer Responsibility). Manufacturers are required to take responsibility for the technical and financial impacts of their products [2] from cradle (manufacturing) to grave (recycling or disposal). One form of EPR is manufacturer take-back of PV modules at end-of-life so they can be properly disposed of or recycled. EPR incentivizes companies to design modules for easier and more cost-effective dismantling and reuse of waste materials.

Recycling companies can be certified for PV module recycling. "Responsible Recycling" (R2) practices are a set of standards promoted by Sustainable Electronics Recycling International (SERI) for use in certifying electronics recyclers [51]. The standards provide a means for end users to verify a recycler's environmental, health, safety, security, values, and performance. The standard also lays out best practices in electronics recycling. This standard is only a recommended guideline, but it is gaining popularity amongst e-waste and other recyclers as an industry best-practice. It may be applicable to PV modules, or used as a basis for PV-specific guidelines in the future.

Identifying stakeholders and assigning responsibility is one of the prerequisites of PV recycling regulation [19]. Regulations could mandate recycling and take-back with provisions for incentives and penalties.

Arrange for Payment

The cost of recycling must be paid for regulation to succeed. Currently, there is very low commercial interest in recycling as the economic payback is low or negative. One way to finance recycling is to make the owner of the technology pay for the costs. However, as in any industry, the costs and benefits of recycling accrue to different stakeholders including society. Hence, if the playing field is somewhat leveled by identifying all the stakeholders and spreading the costs and benefits, regulations and associated costs might be more readily acceptable. Several potential sources of funds to pay for the costs of recycling are presented below.

Most manufacturers meet WEEE in order to allow their operation in the EU. If U.S. laws are modeled after WEEE, manufacturers would not have to devise processes or products to meet an entirely new set of standards. Manufacturers already pay fees, meet reporting requirements, label products with recycling data, disseminate information, and meet audit requirements.

Alternatively, the government (local, state, federal) can generate funds for a recycling program through taxation. Consumers can pay direct and/or indirect fees to support research and take-back programs.

Funds could also be used to develop PVTBCs. A portion of the funds would be allocated for overhead and processing, in addition to PVTBC management. For efficient use of funds, the PVTBC locations should be optimized based on sources of projected waste, travel distance and other factors. Another option is to recoup funds on recycling indirectly through increased tax revenue from job creation in the public sector, or offset spending through industry funding for research institutes. Additionally, any funds spent on PVTBCs will assist overall waste management infrastructure development.

Streamline Classifications

PV module waste is currently not classified *a priori* as hazardous waste under RCRA. Hence, it may be classified as hazardous waste if it is destined for disposal and fails the TCLP test. One approach to facilitate PV take-back and recycling may be to create a regulatory determination of PV with a categorical classification that reduces the regulatory burden associated with waste management for PV modules that are destined for recycling. For example, US EPA determined that all coal combustion wastes (CCPs) should be regulated only under the non-hazardous provisions of RCRA Subtitle D (40 CFR Parts 257 and 261); they are also not subject to any hazardous waste testing or management requirements under Subtitle C. Further, CCPs managed in approved beneficial use applications, such as component of concrete and wallboard, are exempt from the RCRA Subtitle D requirements (**§** 257.50a and g). Approved uses are based on an assessment of the potential environmental risks associated with a specific application.

Modules that will be landfilled may pose different safety and environmental risks than modules destined for recycling facilities. Some considerations for risk evaluation may include module condition and the risk to personnel involved with handling, storing, and transporting waste. Similar to the EPA's classification of CCPs, an e-waste classification allows electronic products to be handled, transported, stored, and used as non-hazardous materials until the end-of-life. One option is for PV modules to be classified as e-waste or another unique designation that would regulate them as non-hazardous during their operating life.

Currently, very little public information is available regarding module toxicity and whether individual module products would be classified as hazardous at any step in the process from demobilization to a landfill or recycling center. For this reason, independent evaluation and understanding of environmental impacts of past, current, and emerging PV technologies by stakeholders is a critical need.

Determine Processes

A streamlined, centralized organization, like PV-CYCLE, will be needed to manage processes related to PV recycling. Logistics of PV recycling like collection systems, transportation to recycling centers, and hazardous waste storage/disposal, should be included in the process. This organization could be responsible for driving research, education, training, and certification for various stakeholders in the PV recycling chain. Safety standards like NEC and UL can also play a role in PV module recycling by determining safe operating procedures for the dismantling.

Classifying modules as e-waste offers several benefits. Modules can be stored onsite at end-of-life before transport to a PVTBC or recycling facility. PV modules can be allowed to be transported as universal waste, instead of requiring hazardous material transport criteria. PVTBC can act as temporary storage of universal-waste classified modules, so batch processes can be carried out at recycling centers.

Implement, Verify, and Enforce

To evaluate the impacts of recycling regulations, accurate assessments of the waste streams are needed. Manufacturers and other stakeholders could be encouraged to maintain statistical data on the amount, type, and frequency of waste, in addition to the causes of module failure. Prediction models can then use this statistical data to predict regular and early performance loss rates. Coordinated research between the energy and waste management sectors is potentially valuable, as is communication, information dissemination, and education of the recycling process. These types of activities could be encouraged and incentivized.

Transparency of the institutions involved in implementing recycling is important, and a robust infrastructure for verification is needed. External audits, including LCA, of the entire PV recycling value chain could be conducted regularly. Enforcement could include both penalties and incentives, in addition to assignment of liability and contractual/regulatory compliance. The split of implementation burden between the federal, state, and local authorities will have to be determined, though most of the burden for implementation will likely fall to the states, as the federal government currently delegates this authority for e-waste and other similar waste management functions. These processes could change as waste volumes increase, where PV recycling is incrementally added to existing waste management enforcement procedures to reduce cost and improve efficiency.

Summary of Literature Survey on PV Recycling Regulations

As PV recycling is not currently economically feasible, and waste volumes are low, regulations would likely accelerate large-scale PV recycling in the U.S. Recycling regulations in the EU and Japan have led to the implementation of recycling programs for PV module waste at end-of-life.

Based on a literature survey of PV recycling regulations, and using lessons learned from existing regulations, the following five concepts are recommended for inclusion in future U.S. regulations:

- Mandate PV take-back and recycling
- Arrange for payment
- Streamline classifications
- Determine processes
- Implement, verify, and enforce

5
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