Review Article

Photovoltaic Module Recycling in Urban Solar Energy Systems: Technologies, Economics, Regulation, and Artificial Intelligence

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Abstract

The growth of urban solar installations will increase the demand for decommissioning and recycling. This review examines treatment technologies for end-of-life photovoltaic (PV) modules, recycling costs, and the responsibilities of market participants. It draws on research publications, IRENA and IEA PVPS reports, national statistics, legislation, and company disclosures available through 9 November 2026. Industrial recycling still relies mainly on mechanical treatment. Recovering silver and silicon suitable for use in manufacturing requires delamination and purification. Results from laser and abrasive delamination and aqueous perovskite recycling have yet to be demonstrated in continuous industrial operation. Comparable global recycling statistics are unavailable. In France, 83.9% of the module mass treated in 2025 went to material recycling. The main economic barriers are low plant utilization, dismantling and transport costs, low glass prices, and weak incentives to recover valuable components. A comparison of seven cities identifies three deployment models. The proposed full solar life cycle city model combines an installation registry, pre-decommissioning assessment, batch consolidation, and supplier requirements. It also specifies metrics for tracking where recovered materials go and identifies tasks that artificial intelligence can support.

Keywords: photovoltaic modules; solar panel recycling; delamination; silver recovery; circular economy; urban solar deployment; smart city; extended producer responsibility; artificial intelligence; life cycle

1. Introduction

Solar panels incur recycling costs long after their purchase and installation. According to the U.S. Environmental Protection Agency (EPA), panels typically last more than 25 years. Damage or system upgrades can lead to earlier removal [1]. Testing can identify removed modules that are suitable for repair or reuse before they enter the waste stream [2], [3].

A ground-mounted solar plant usually has one operator and concentrates its modules at a single site. In cities, modules are spread across buildings and may have many owners. Recovering even a small batch can require several site visits and separate arrangements for rooftop access. Studies in Amsterdam link the potential for urban solar generation to the built

environment, property ownership, and the condition of the distribution grid [4], [5]. If contracts leave dismantling and recycling costs unassigned, building owners, property managers, or municipal waste services may ultimately bear them.

Glass and aluminum account for a large share of the mass recovered during recycling. These materials are easier to recover as secondary feedstocks than silver or silicon that meets a downstream buyer's purity requirements [6]. This review distinguishes material extraction from the production of marketable feedstocks and tracks whether those feedstocks enter PV manufacturing or other industries. A closed PV material loop requires recovered materials to re-enter module production [3].

Early recyclers used equipment designed for glass, metals, and electronic waste. Most processes documented in an IEA PVPS study from 2016–2017 were not designed specifically for PV modules [6]. The EU Waste Electrical and Electronic Equipment (WEEE) Directive 2012/19/EU made producers responsible for organizing and financing the management of waste from their products [3], [7]. In 2016, IRENA and IEA PVPS projected 60–78 million tonnes of cumulative panel waste by 2050, depending on the scenario [8]. The 2020s saw the emergence of dedicated processes for delamination, silver recovery, and silicon purification. All seven cases in the 2024 IEA PVPS report involved dedicated PV recycling processes [6].

Previous reviews cover recycling technologies, legislation, and waste projections in detail [9]–[11]. Less attention has been paid to cities. This article examines how cities can manage modules from equipment selection and procurement through dismantling and the sale of recovered materials. It identifies technical, economic, and regulatory barriers and proposes a municipal management model.

The review has six objectives:

- Compare commercial processes and emerging technologies in light of the available evidence.
- Define recycling metrics and identify when they can be compared.
- Examine solar deployment models in leading cities.
- Identify economic and regulatory barriers and describe manufacturers' strategies.
- Assess potential applications of artificial intelligence (AI).
- Propose a municipal model for the full solar life cycle and define metrics for evaluating it.

2. Methods

2.1. Review design and scope

This study is a narrative review. It did not use a PRISMA protocol, an exhaustive database search, a formal risk-of-bias assessment, or a meta-analysis. The review prioritized publicly available IRENA and IEA PVPS reports and primary peer-reviewed studies, followed by

review articles, legislation, and publications from governments and companies. Trade publications helped establish facility start-up dates and when results were released. The review covers information available through 9 November 2026.

The scope is limited to PV modules and excludes inverters, batteries, and mounting structures. The main focus is on crystalline silicon (c-Si). Thin-film modules (CdTe and CIGS) and perovskite devices are examined separately because their composition and treatment requirements differ [2], [10]. The cities were selected to illustrate different deployment models.

2.2. Evidence categories

The review uses four evidence categories (Table 1). Laboratory delamination tests characterize an individual operation. Establishing the profitability of an entire line requires additional evidence. Material yield and product purity also measure distinct aspects of process performance. IEA PVPS reports discuss limits on the comparability of industrial data [6], [57].

Table 1. Evidence categories used in this review

Category	Definition
Industrial experience	The process operates at a commercial facility. Operating scale and reporting detail vary.
Experimental result	The authors measured the result on specified samples in a laboratory or pilot facility.
Model estimate	The value was calculated under stated assumptions.
Proposed approach	The approach has been proposed or anticipated. Its performance across the full industrial process remains unverified.

2.3. Data verification and limitations

The review examined how each reported indicator was defined. In 2025, the French organization SOREN collected 13,760 tonnes of end-of-life PV modules and treated 12,736 tonnes. Of the mass treated, 10,684 tonnes went to material recycling, equivalent to 83.9%. Using the total mass collected as the denominator gives 77.6%. This difference in reporting basis can distort comparisons across facilities and national recycling systems.

The review also distinguished between design capacity and actual throughput. Design capacity indicates how much waste a facility can accept under its design assumptions. Actual throughput records how much it processes over a given period. The two figures are reported separately. Manufacturer-reported figures were interpreted with caution, particularly where independent audit results were unavailable.

Bibliographic details and digital object identifiers (DOIs) were checked against publisher pages and the publications themselves. The study relied on available sources. No laboratory experiments, facility visits, or independent measurements were undertaken.

The municipal management model proposed in Section 4 draws on experience from several countries. Its practical applicability could be assessed through a pilot study in a city

with a registry of PV installations and data on equipment condition, dismantling costs, and module transport costs.

3. Results

3.1. Projected waste volumes and available statistics

Under IRENA's 2026 scenario for limiting warming to 1.5 °C, cumulative end-of-life panel mass could exceed 200 million tonnes by 2050, with annual waste exceeding 25 million tonnes [2]. The estimate depends on deployment rates and module lifetimes. Comparing the figure directly with the 2016 projection would confound projected waste growth with differences in scenario assumptions.

Current collection volumes remain far below these projections. IEA PVPS reported 48,395 tonnes across 18 European countries in 2022. Data for the 2025 report were collected mainly in 2024 [3]. Investors must time capacity expansions carefully to avoid maintaining underused lines while waiting for waste volumes to rise.

France publishes detailed national data (Table 2). SOREN collected 13,760 tonnes of modules in 2025 and 9,477 tonnes in 2024. Of the 12,736 tonnes treated, 10,684 tonnes went to material recycling, 1,298 tonnes to energy recovery, and 754 tonnes to disposal [12], [13], [55], [56]. These streams accounted for 83.9%, 10.2%, and 5.9% of the treated mass, respectively. Material and energy recovery together accounted for (10,684 + 1,298) / 12,736 × 100% ≈ 94.1%. The material recycling share alone was 83.9%. The reported tonnages give a year-on-year increase in collection of (13,760 − 9,477) / 9,477 × 100% ≈ 45.2%, whereas SOREN's 2025 report and the trade press report 40% [13], [55]. Both calculations use the published rounded masses.

Table 2. Verified recycling indicators and their interpretation

Entity and period	Indicator	Interpretation
France, SOREN, 2025	13,760 t collected, 12,736 t treated, and 10,684 t sent to material recycling (83.9% of treated mass)	Three distinct indicators. The percentage uses treated mass as its denominator.
First Solar, 2025	59,522 t of PV materials collected, with an approximately 95% recycling rate	The input stream includes manufacturing scrap. The company-reported figure has an uncertainty of approximately ±2%.
First Solar, 2026 report	Network design capacity of 136,000 t/year. Cumulative total of approximately 500,000 t.	Neither figure measures actual annual throughput.
SOLARCYCLE, 2024	480,406 panels recycled	Actual throughput as reported by the company
SOLARCYCLE, Cedartown, January 2026	Thousands of panels per week. Target of 1 million panels/year by the end of 2026. Design capacity of up to 5 GW of panels per year.	Current throughput, target throughput, and design capacity are distinct measures.

Entity and period	Indicator	Interpretation
18 European countries, 2022	48,395 t of module waste collected	Historical collection figure. It does not measure recycling in Europe in 2025–2026.

For 2025, First Solar reported the following shares of collected mass: glass, 92%; metals other than semiconductor materials, 1.9%; semiconductor materials, 1.3%; and other materials, 0.3% [14]. The previously published figure of 41,921 t/year comes from the 2024 IEA PVPS dataset [6]. SOLARCYCLE reports two different indicators: recovery of 96% of material value and diversion of 100% of waste from landfill [15], [16]. Neither measures the share of mass sent to material recycling.

Available data provide no reliable denominator for calculating a global recycling rate for 2025–2026. National reports often give collected waste mass, while company reports give incoming equipment mass or the mass of recovered materials. Reporting practices for manufacturing scrap, reuse, and energy recovery also vary. The same waste may appear in two reports. For example, First Solar is a partner of France's SOREN [13]. Adding their figures could result in double counting.

3.2. Module composition and established recycling processes

A silicon module contains glass, solar cells, a polymer encapsulant (typically EVA), electrical interconnects, and a junction box. Many designs also incorporate an aluminum frame and a polymer backsheet. Glass–glass modules use a second glass sheet in place of the backsheet [2], [17]. Recycling must separate strongly bonded layers while limiting cross-contamination. CdTe modules require controlled recovery of cadmium and tellurium. For CIGS modules, the target elements are copper, indium, gallium, and selenium. Treatment of lead-containing perovskites must recover functional materials and prevent lead losses [6], [10], [18]. Module type should therefore be identified before processing.

Table 3. Main PV module recycling methods (based on [6], [9], [19])

Method	Operating principle	Advantages	Limitations
Mechanical size reduction and sorting	Crushing and separation by particle size and density	Industrial maturity, high throughput, and low energy demand	Material mixing, dust, and lower value for some outputs
Thermomechanical delamination	Separation of layers with a heated tool	Can preserve intact glass	Performance depends on panel design and condition
Thermal treatment	Polymer decomposition or removal	Liberates glass and cells	Energy demand, off-gas treatment, and loss of polymers
Chemical delamination	Treatment with solvents and other reagents	Selective breaking of bonds	Reagent consumption, treatment time, and solution regeneration

Method	Operating principle	Advantages	Limitations
Hydrometallurgy	Leaching and metal recovery	Selective recovery of valuable components	Wastewater, chemical hazards, and additional purification
Pulsed-light and laser treatment	Localized treatment at layer interfaces	May reduce material mixing	Scale-up and economic viability remain to be demonstrated

A mechanical line removes the frame, cables, and junction box before shredding the rest of the panel and sorting the material. The method is established commercially and requires relatively little energy. It does not typically produce separate, high-purity silicon and silver fractions [6], [57]. Mixed mineral fractions and contaminated glass can find uses outside PV manufacturing.

In equipment made by Japan's NPC, a hot knife at approximately 300 °C softens the EVA and separates the glass from the laminate. For one model, the company reports a processing time of about 60 s per panel when the glass is intact [20]. The figure covers delamination alone. It excludes metal extraction and material purification.

Thermal delamination removes polymers by heating. T. Dobra and colleagues obtained solid products of comparable quality after 65 min at 500 °C and 33 min at 600 °C [21]. Raising the temperature by 100 °C reduced the treatment time by about 49%. Estimating energy savings would also require data on heating power and heat losses. Panels with fluorinated backsheets require prior separation and emissions control. Polymer combustion with energy recovery is counted separately from material recycling [3], [17].

Chemical treatment can remove polymers or treat a separated metal-bearing fraction. Leaching brings silver into solution. The metal is then recovered by precipitation or electrochemical methods. The fraction dissolved during leaching and the yield of the final product are separate measures [17], [22]. Researchers are studying solution regeneration and the treatment of enriched fractions to reduce reagent consumption. Assessing environmental performance requires material and energy balances for the process [22].

3.3. Research advances in 2025–2026

Laser delamination of aged silicon modules. In a manuscript accepted for publication in November 2026, B. N. Alsulami, J. Kettle, and colleagues applied a laser at the EVA–silicon interface [19]. The process produced three fractions: a largely intact EVA film with residual metal, busbars, and a silicon-rich powder. Aluminum was removed, and silver was extracted in a medium containing iron(III) chloride and choline chloride. Selectivity exceeded 99% for the REC240PE and 95% for the CS6P-245P. These values describe extraction selectivity. Whole-module silver recovery and product purity are separate measures. Localized heating may use less energy than bulk heating, but industrial energy data are not yet available.

Layer-by-layer abrasive separation. In the EVERPV project, F. Coustier and colleagues at CEA used abrasive belts to remove the rear layers while keeping the glass intact [17]. They collected the backsheet separately from the encapsulant, cells, and interconnects. Tests covered more than 400 end-of-life modules from four manufacturers. At a belt speed of 2.3 m/min, the pilot line processed about one panel per minute, excluding subsequent powder treatment. The method was described for intact glass–backsheet modules less than 1,300 mm wide. Laboratory tests yielded silicon at 99.9% purity and a silver-bearing product containing about 90% silver. Recovery yields were around 98% for both materials. The industrial silver recovery estimate of 99.9% remains a projection. Polymer fractions also require further preparation before shipment to a recycler.

Aqueous perovskite recycling. X. Xiao and colleagues dissolved the perovskite layer in a heated aqueous medium with additives. Crystals precipitated as the solution cooled [18]. The process recovered 99.0 ± 0.4% of the perovskite material by mass. Devices made from recovered material achieved a mean power conversion efficiency of 21.9 ± 1.1%, compared with 21.8 ± 0.8% after five degradation and recycling cycles. The means differ by 0.1 percentage points. Further statistical information would be needed to assess the significance of that difference. The tests used research devices, including devices subjected to accelerated degradation. Commercial readiness for full-size perovskite and tandem modules remains unproven.

Use of recovered silicon in batteries. Y. Zhao and colleagues (3 November 2026) blended recovered silicon with graphite to make lithium-ion battery anodes. The mixture was heat-treated at 800 °C in nitrogen [23]. After 100 cycles at 0.5 A/g, the composite with a Si:C mass ratio of 2:8 retained 47.5% of its capacity, compared with 12.8% for the untreated waste silicon. The difference was 34.7 percentage points. Even the best sample lost 52.5% of its capacity. The composite outperformed the control, but the test did not establish durability for commercial use.

3.4. Industry participants and manufacturer strategies

Table 4 summarizes the operations in which industry participants specialize. Incomplete reporting precludes comparison by actual recycling throughput. Equipment suppliers, collection organizations, and recycling plants serve different functions.

Table 4. Selected participants in the recycling industry (based on [3], [6], [15], [24]–[28])

Participant	Country	Role	Interpretive limitation
First Solar	United States, international network	CdTe module manufacturer with in-house recycling	Figures apply to the company's technology.
SOLARCYCLE	United States	c-Si recycling and material recovery	Opening a plant does not establish that it is operating at design capacity.

Participant	Country	Role	Interpretive limitation
ROSI	France, expanding in Europe	Recovery of valuable silicon and metal fractions	The announced figures of 3,000 t/year (France, 2022) and 10,000 t/year (planned plant in Spain) are capacities.
Reiling	Germany	Industrial mechanical recycling	The process does not necessarily yield high-grade Ag and Si.
NPC	Japan	Hot-knife equipment	Equipment supplier for the separation step
LONGi	China, international markets	PV CYCLE participation and partnerships with regional operators	Membership does not disclose actual recycling throughput.
Trinasolar	China	Demonstration module using recovered materials	Demonstration unit only
PV CYCLE, SOREN	Europe	Collection, compliance, and coordination	Scheme administrators; no plant operation

Manufacturers use four approaches to managing end-of-life modules. The first is in-house recycling. First Solar operates facilities in the United States, Malaysia, Vietnam, Germany, and India. A third party separates and refines cadmium and tellurium [24]. For sales before 2013, the company used a prefunded program. Current contracts use pay-as-you-go pricing. Owners are responsible for removal, packaging, and delivery, and prices vary by region. The program does not include free rooftop pickup.

The second approach uses collective collection schemes and partnerships. LONGi reports participating in PV CYCLE and working with Soren, Open, and 3Drivers. In Brazil, it works with PV CYCLE and SunR [27], [29]. In 2025, LONGi declared equipment with a combined rated capacity of 4,589.27 MW under the European WEEE system [30]. The figure records producer obligations and does not measure waste treated.

The third approach uses recovered materials in new modules. In October 2024, Trinasolar announced a TOPCon module made using recovered silicon, glass, aluminum, and silver. The company reported an efficiency of 20.7% and an output above 645 W [28]. It described the prototype as the first “fully recycled” c-Si module. The announcement gives insufficient detail on how much of the component mass came from secondary sources, whether the module could be mass-produced, or what it would cost. It remains a demonstration using recovered materials.

The fourth approach is to design modules for recycling. Manufacturers are reducing the use of materials that are difficult to separate, using fluorine-free backsheets, increasing recycled content, and extending product life. LONGi reported that rear glass used in its modules contained 10–30% recycled glass in 2023 [27]. Manufacturing waste also needs to be tracked separately. For example, the more than 2,200 t of packaging material recycled by Trinasolar did not come from the modules themselves [31].

3.5. Leading cities and models of urban solar deployment

A city with the highest installed capacity may rank lower in capacity per capita or in the share of buildings equipped with PV. Table 5 compares deployment models across cities using metrics relevant to each.

Table 5. Cities illustrating different models of urban solar deployment

City	Deployment model or strength	Indicator or benchmark	Implications for recycling
Honolulu, United States	Capacity per capita	Highest among surveyed cities in the U.S. Pacific region, 2022 [32]	Per-capita metrics do not capture equipment age or condition.
Las Vegas, United States	Capacity per capita	Highest among surveyed cities in the U.S. Mountain region, 2022 [32]	Continuous supply requires grid integration. Installed capacity alone does not measure it.
Tokyo, Japan	New construction requirements	Requirements for large housing suppliers since April 2025. Target of about 1 GW on residential buildings by 2030 [33], [34]	Procurement can require disclosure of material composition and specify take-back terms.
Singapore	Centralized deployment on public housing	Panels on more than 4,300 HDB blocks (January 2025) [35]	A single procuring agency simplifies condition assessment and take-back contracts.
Rotterdam, Netherlands	Size of urban PV fleet	More than 1 million panels (December 2024) [36]	The installed fleet needs portfolio-level management.
Amsterdam, Netherlands	Rooftop PV in a historic city	315 MW installed, with a target of 550 MW by 2030 (TU Delft study) [4]	Deployment is shaped by shared ownership and heritage protection.
Dubai, United Arab Emirates	Utility-scale solar park	Mohammed bin Rashid Al Maktoum Solar Park capacity of 3,860 MW in 2026, with a target above 8,000 MW by 2030 [37]	Dismantling can be planned by phase. Part of the capacity is concentrating solar power.

Tokyo has applied, since April 2025, requirements to large housing suppliers that deliver at least 20,000 m² of floor area annually. Solar exposure and roof geometry affect panel placement. The requirements do not apply to all existing homes [33]. The Tokyo Metropolitan Government projects about 1 GW of new residential capacity by 2030, including around 700 MW attributable to the new requirements. It expects annual emissions to fall by approximately 430,000 t CO_2 [34]. These figures are projections.

Amsterdam could generate more than 6.9 PJ of electricity per year (about 1.92 TWh), according to TU Delft. This is roughly half of city electricity use under the study's comparison baseline. Installations are less common on historic buildings and multifamily buildings with shared ownership [4]. In 2026, Amsterdam extended support for panels that meet composition and carbon footprint requirements. It also developed a module reuse program for households with limited means [38]. These measures support reuse. Closing the material loop also requires a route into manufacturing.

Rotterdam reported in December 2024 more than one million installed panels and the largest solar capacity among the four largest Dutch cities [36]. Managing an installed base of that size requires data on module age and condition as well as scheduled roof repairs.

Singapore installs panels on public housing through the Housing & Development Board (HDB). As of 31 March 2024, 325 MWp was in operation. Eight tenders awarded about 455 MWp, and the 2030 target is 540 MWp [39], [40]. The electricity powers lifts, lighting, pumps, and other common services. Surplus electricity is exported to the grid. Individual apartments still rely on the grid [41]. Solar-ready designs reserve space for panels, supports, and electrical infrastructure from the outset [40].

Dubai illustrates the utility-scale solar park model. The 950 MW fourth phase of the park includes 700 MW of concentrating solar power and 250 MW of PV [37]. PV accounts for 250 / 950 × 100% ≈ 26.3% of capacity in this phase. Waste projections for PV modules should therefore use the 250 MW PV capacity.

For future dismantling, the cases illustrate three organizational models. In distributed rooftop systems, the priorities are identifying owners, arranging building access, and consolidating small batches. Centrally managed installation programs can standardize service and take-back terms. Large parks require phase-by-phase replacement schedules and separate collection for different module technologies. The classification was developed for this review and is not an industry standard.

3.6. Economic barriers

IEA PVPS reports that recycling costs are high relative to revenues from recovered materials [42]. Seven factors affect the balance.

Low and variable utilization. Over a given operating range, a plant's annual fixed costs can be treated as constant. As actual throughput falls, fixed cost per tonne increases:

$$c_{fixed} = C_{fixed} / M_{actual} \quad (1)$$

Here, c_{fixed} is the fixed cost per tonne (currency units/t), C_{fixed} is annual fixed cost (currency units), and M_{actual} is annual treated mass (t). With annual fixed costs held constant, a plant operating at 50% of design capacity has twice the fixed cost per tonne of a fully utilized plant. The illustration excludes changes in variable costs. Design capacity alone says little about profitability [42].

Logistics. Urban cost estimates should separate dismantling, consolidation of small batches, and transport. Recycling fees may exclude rooftop work and lifting equipment [42]. A larger plant increases throughput and requires a larger collection area. The optimal service radius depends on where waste arises and what it costs to transport.

Low value of bulk materials. In a silicon module, inexpensive glass accounts for a large share of the mass. Valuable metals are present in small quantities and take several steps to recover [3]. A high mass yield can therefore generate modest revenue.

Advanced treatment costs. Chemical purification improves product quality and adds cost [43]. The step pays for itself when incremental revenue exceeds incremental cost. Otherwise, it requires separate funding.

Markets and impurities. Even a high silicon content may fall short of the specifications for new solar cells [42]. Before purchasing equipment, recyclers need to establish prospective customers' requirements for composition and purity.

Weak incentives to recover valuable components. Heavy fractions can contribute most of the mass needed to meet WEEE targets. IEA PVPS notes that such targets provide limited incentive to invest in costly recovery steps for minor fractions [43].

Changes in module composition. Using less silver in manufacturing reduces the potential recycling revenue per module [2], [43]. Long-term financial assessments should account for future feedstock composition as well as metal prices.

A recycler's financial result over a given period can be represented by the following illustrative equation:

$$\Pi = P_{gate} + R_{material} - C_{logistics} - C_{processing} - C_{residue} - C_{fixed} \quad (2)$$

Here, P_{gate} is gate-fee revenue, $R_{material}$ is revenue from the sale of recovered materials, and $C_{logistics}$, $C_{processing}$, $C_{residue}$, and C_{fixed} are logistics, processing, residue management, and fixed costs over the same period. All terms are expressed in the same currency. At break-even ($\Pi = 0$), the minimum gate-fee revenue equals total costs less material sales revenue. When material sales fall short, the owner, a producer responsibility scheme, or another contractual arrangement covers the difference. Process improvements may still leave a need for gate fees.

3.7. Regulation

Extended producer responsibility (EPR) determines who organizes and pays for the management of product waste. Producers may meet their obligations independently or through a collective scheme [44]. For solar panels, the financing arrangement must have a long time horizon, as decades can elapse between sale and decommissioning.

In the EU, PV panels have been within the scope of WEEE since 13 August 2012. Directive (EU) 2024/884 clarified producer obligations after the Court of Justice of the European Union ruled against retroactive application. Financial responsibility applies to products placed on the market from that date [44]. The amendments call for assessing whether panels should have their own category, whether collection targets should reflect service life, and how to cover costs if a producer becomes insolvent. These matters remain subject to further review [44].

In the United States, federal requirements differ from state rules. The EPA describes the inclusion of solar panels under the universal waste regime as a proposed change. California and Hawaii already classify qualifying panels as universal waste [45]. This approach simplifies certain hazardous-waste procedures and does not require producers to fund recycling. Panels

are safe in normal use. Whether a discarded panel is classified as hazardous waste depends on its composition and the leaching of metals such as lead and cadmium [1].

Washington State's program, adopted in 2017, requires manufacturers to fund take-back and recycling without charging panel owners [46]. Under the 2025 amendments, plans are due by 31 January 2030, and the ban on selling panels without an approved plan takes effect on 31 January 2031 [47]. The timeline illustrates the interval that can separate enactment from implementation.

Table 6. Scope and limits of regulation

Regulation can	Regulation alone cannot guarantee
Assign responsibility and identify a funding source	Plant profitability
Set collection and treatment requirements	High-purity silicon or glass
Mandate reporting	Reliable reporting without oversight
Restrict improper handling	Buyers for recovered materials
Create demand for recycling services	Commercial readiness of new technologies

3.8. Artificial intelligence in module life cycle management

AI in PV recycling is most useful for decisions involving heterogeneous inputs, such as selecting modules for reuse, identifying materials, and forecasting waste volumes [11], [48], [49]. Delamination and metal recovery are still physical and chemical processes. The evidence for AI varies by application (Table 7).

Table 7. AI applications across the module life cycle and strength of evidence

Stage	Task	Role of AI	Evidence
Intake	Select modules for reuse, repair, or recycling	Condition classification	Company-reported
Planning	Forecast where and when waste will arise	Deployment forecasts combined with lifetime models	Peer-reviewed studies
Treatment	Detect incomplete separation	Analysis of process deviations	Company-reported
Sorting	Distinguish materials and contaminants	Recognition and classification of material streams	Company-reported
Robotic disassembly	Adapt to heterogeneous panels	Machine vision	Potential application
Process development	Select treatment conditions	Models fitted to experimental data	Research application

SOLARCYCLE reported that its AI model helped select more than 1,000 previously operated modules for a 500 kW power plant in Texas [48]. The company also reports using AI to monitor separation and identify materials. It has not published classification error rates, the

subsequent service life of the modules, or results from a control process without AI. The available information does not support a quantitative estimate of the algorithm's effect.

A. Franzoni and colleagues used installation data for 2008–2024 and socioeconomic indicators from 20 Italian regions [49]. They compared linear regression, ARIMA, a backpropagation neural network (BPNN), and a long short-term memory network (LSTM). The BPNN performed best. It forecast installed capacity, which the authors then converted to estimated waste volumes using a Weibull distribution. Four coauthors work for the energy company A2A S.p.A., an affiliation relevant to assessing the study's independence.

4. Discussion

4.1. Why high recycling rates do not establish a closed material loop

Four metrics are needed to compare technologies: the fraction of mass sent to material recycling, the recovery yield for each target element, product purity, and the fraction of product that actually re-enters the intended manufacturing process. For silver, recovery yield is the mass of silver in the final product divided by the mass of silver in the original module. Purity is the silver mass divided by the total mass of the product. Both are percentages with different denominators. Even silicon at 99.9% purity may fail to meet solar cell specifications because of the impurities present. Silver recovered from powder also tells us little about losses upstream [6], [17]. The 2024 IEA PVPS report compared some technologies only at the stage of separating cells from glass and polymers [6]. Those data cannot establish which process performs best across the full recycling chain.

4.2. Consequences of limited progress in technology and organization

Basic PV module recycling is already available [6], [50]. The risks examined here arise from continued reliance on current practices, which leave some valuable materials unrecovered and limit the quality and traceability of recovered fractions.

- Plants are likely to continue recovering mainly aluminum frames and glass. High mass-based recovery can coexist with losses of silver and silicon [6]. Even advanced recycling cannot quickly replace virgin feedstocks. In a growing market, new modules require more material than retired modules supply [51].
- When recycling costs exceed recovered material value, panels may remain in storage for extended periods. Without records of condition and intended use, it is difficult to distinguish modules held for reuse from waste awaiting disposal. The risk depends on storage rules and contract terms [2], [3].
- If processes are developed only after modules reach end of life, plants may be unprepared for large volumes of retired glass–glass, multilayer, perovskite, or tandem modules [10], [18].

– Improper treatment can cause losses of recoverable materials, generate fine mixed fractions, release hazardous constituents, and contaminate process solutions [1], [6].
– Public confidence in municipal environmental programs may decline if they lack provisions for end-of-life modules.
– Distribution grids must accommodate bidirectional flows from rooftop installations, storage, and electric vehicles. Grid investment is lagging behind generation growth [52], [53]. Without upgrades, some generation may be curtailed or go unused.

The risks point to gradual losses of materials and money, idle recycling capacity, and limits on usable solar generation.

4.3. Implications for urban development

The studies reviewed do not establish an effect of solar energy on urbanization rates or the share of the population living in cities. The main change is in how buildings interact with the energy system. They generate electricity as well as consuming it [52]. This affects roof use, grid operation, how benefits are shared among residents, and how equipment is maintained.

Rooftops serve several functions. Design must account for heritage constraints, maintenance access, building services, vegetation, and stormwater retention [4], [40]. Preliminary results from the Mannoury project in Amsterdam showed that panels over an irrigated blue-green roof generated about 4.5% more electricity than those over a bitumen roof [54]. The result applies to this site. The vegetation and roof assembly provide cooling and water retention.

In multistory buildings, roof area per unit of gross floor area falls as the number of stories increases. With identical floor plates, the ratio is approximately 0.1 for a 10-story building and 0.05 for a 20-story building. This geometric illustration excludes mechanical floors and installation constraints. In Singapore, rooftop panels primarily serve common building loads [41]. The example provides no basis for recommending a shift to low-rise construction.

Generation and demand do not always coincide. At the district scale, this calls for load management, storage, and shared resources [4], [52]. Even an annual electricity surplus cannot guarantee self-sufficiency in every hour.

Residents' access to solar generation depends on ownership, roof access, and the ability to pay for installation. Multifamily buildings and public housing therefore require specific arrangements [4], [38].

Wider deployment creates demand for testing, repair, dismantling, sorting, and recycling [50]. Sustaining these services depends on plant utilization, workforce skills, and markets for recovered materials.

4.4. The full solar life cycle city model

The proposed full solar life cycle city model is a municipal framework for recording and servicing solar installations and deciding in advance where the equipment will go after dismantling. It draws on published approaches [2], [3], [6] and requires testing in a specific city.

Table 8. Stages of the proposed module life cycle management model

Stage	Actions	Verifiable outcome
1. Design and procurement	Select materials with future separation in mind, document their composition, and include take-back terms in the supply contract.	Defined disassembly route without reduced durability
2. Commissioning	Enter the installation in the municipal registry, assign responsibility, and confirm the supplier's participation in an EPR scheme.	Traceability of each installation
3. Operation	Record defects, repairs, and replacements. Coordinate with roof maintenance.	Records that support decisions about continued use
4. Pre-decommissioning assessment	Check performance, electrical safety, and repairability.	Allocation to reuse, repair, or recycling
5. Dismantling and consolidation	Use qualified contractors and local consolidation points.	Module identification and condition preserved
6. Intake and sorting	Identify technology, design, damage, and hazardous components.	Separate streams for c-Si, CdTe, and other technologies
7. Recycling	Carry out preliminary disassembly, delamination, recovery, and purification at a regional facility.	Products with verified specifications
8. Material recovery and reporting	Send recovered materials to users according to their specifications, manage residues, and reconcile the mass balance.	Verified end uses and a documented route for the entire batch mass

Five measures support implementation of the stages in Table 8.

– Equipment registry. The registry records the installation address, owner, module models and quantities, commissioning date, composition, repair history, and take-back terms. It supports forecasting and planning. A fixed retirement date 25 years after installation would ignore variation in actual service life. In a simple model for a cohort of mass M installed in the same year, the expected mass retired between ages a and b is $M \times [F(b) - F(a)]$, where F is the cumulative probability of retirement. A numerical forecast requires distribution parameters for different module types and ages. This review did not estimate those parameters.

– Pre-decommissioning assessment. Higher efficiency in a new panel is insufficient to establish the life cycle benefits of replacing a functioning installation. Removed modules should be reused only after they pass safety and performance checks [2].

– Regional recycling. Cities can host collection and assessment points. Large specialized facilities can serve a wider region, with location and capacity chosen in light of expected waste volumes and transport requirements [3].
– Procurement requirements. Supply contracts should specify the technical documents the supplier must provide and the method of identifying individual modules. They should itemize the services covered, including removal, packaging, transport, and treatment. Contracts should also define what happens if a building changes hands or the supplier ceases trading. Reports should distinguish accepted module mass, material recycling, energy recovery, and residues. These terms supplement EPR obligations [44].
– Digital tools and AI. Algorithms can read labels and documents. Where composition data are missing, the registry should record the composition as "unknown." A generative model should not infer the missing composition. AI can support condition assessment, but safety clearance requires a separate decision. Uncertain cases go to manual review. Waste forecasts should report scenario ranges and may use hybrid models [49]. Conventional optimization methods are sufficient for routing. Process control should retain independent safety interlocks.

Installed PV capacity is one measure of program performance. Table 9 also covers operational, social, and material outcomes.

Table 9. Proposed performance indicators for a full solar life cycle city

Area	Indicators
Energy	Actual generation, curtailment, and self-consumption
Reliability	Failures, repair time, and verified service life
Equitable access	Participation of public housing and lower-income households
Reuse	Number of modules that passed testing and were reinstalled
Collection	Share of end-of-life equipment entering a controlled system
Recycling	Recovery of individual materials, their purity, and their end uses
Residual waste	Mass and verified management route
Economics	Total life cycle cost and cost of meeting obligations

Evaluating AI requires comparing the same process with and without the algorithm. Relevant measures include treatment cost per tonne, including digital system operation, as well as target material yield and purity and consumption of energy, water, and reagents. For condition assessment, additional measures include the number of modules safely reinstalled, the false clearance rate, and the share of cases requiring manual review. The false clearance rate can be defined as the number of unsafe modules incorrectly cleared for operation divided by the total number of unsafe modules in the validation sample. Calculating it requires an independent reference assessment, the sample size, and the error count. Comparisons should use similar batches to avoid attributing differences in feedstock quality to AI.

4.5. Study limitations and future work

This narrative review did not attempt an exhaustive systematic search. Some industrial data come from company disclosures without independent audits. City indicators differ in dates, geographic boundaries, and methods of calculation. The municipal model is conceptual. Further technology assessment requires prolonged operating trials with mixed batches, material balances, life cycle assessment, and cost analysis [6]. The registry should be piloted in a municipality, and digital algorithms should be evaluated against a baseline process without AI.

5. Conclusions

1. Mechanical recycling lines can recover the bulk of the material in silicon modules. Retaining silver and returning silicon to manufacturing require dedicated delamination and purification steps.
2. Laboratory and pilot results for laser and abrasive delamination and aqueous perovskite recycling are promising. Stable operation across a full industrial process has yet to be demonstrated.
3. The available statistics do not support a global material recycling rate for 2025–2026. Collection, treated mass, material recovery, energy recovery, design capacity, and recovered material value should be reported separately.
4. Financial assessments should account for actual plant utilization, dismantling and transport costs, glass prices, and the cost of producing marketable silver and silicon. Improving one operation leaves constraints elsewhere in the process.
5. Regulation assigns responsibility and determines who pays. Washington State's revised compliance deadlines illustrate the distinction between enactment and implementation.
6. Distributed rooftop systems need consolidation of small batches, centralized programs benefit from common contract terms, and utility-scale parks require phase-by-phase replacement schedules. Deployment alone provides no assurance of energy self-sufficiency or that recovered materials will return to manufacturing.
7. The most substantiated applications of AI are condition assessment, waste flow forecasting, and separation monitoring. Economic evaluation requires comparable line data with and without the algorithms.
8. The proposed municipal model includes module registration from procurement onward, pre-decommissioning assessment, regional collection, contractual requirements, and reporting. A pilot is needed to establish its practical value. Evaluation should cover installed capacity, actual service life, waste management costs, and the end uses of recovered materials.

Declarations

Author contributions (CRediT). S. Y. Shipulin: conceptualization, methodology, source analysis, writing and editing. The author approved the final manuscript and takes responsibility for its content.

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Data availability. This review generated no experimental data. The information used is available in the sources listed in the references. The review covers information available through 9 November 2026.

Ethics approval. The study involved no human participants, personal data, or animal experiments and did not require ethics committee approval.

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