

Upcycling strategies for end-of-life photovoltaic modules into advanced ion-battery materials: a comprehensive review

Jun Sun

Faculty of Science in Instrumental Analytical Chemistry, University of Malaya, Kuala Lumpur, Malaysia

Junsunchem@126.com

Abstract. The conventional recycling of end-of-life solar modules typically focuses on bulk materials like glass and aluminum to mitigate landfill pressures, these processes are often energy-intensive, result in material degradation, and yield low value-added products. Therefore, this review paper proposes a fundamental shift in approach: moving beyond 'weight-based' recycling towards a 'battery-oriented' upcycling strategy that prioritizes material quality. We explore in detail how components from first-generation crystalline silicon (c-Si) modules can be transformed into effective precursors for lithium-ion and sodium-ion battery technologies. Our analysis highlights the potential to engineer recovered silicon into advanced anode materials, to utilize low-iron PV glass as structural additives or inorganic fillers in solid polymer electrolytes, and to incorporate salvaged metals (Ag, Cu, Al) into current collectors or lithiophilic interlayers. Additionally, the key technical hurdles, such as interfacial delamination, managing impurity migration, and preventing secondary contamination, are identified and discussed in this review. To facilitate the integration of these recycled materials into energy storage manufacturing, we introduce a set of quality descriptors and outline a robust techno-economic and environmental assessment framework.

Keywords: photovoltaic recycling, upcycling, crystalline silicon modules, lithium/sodium-ion batteries, quality descriptors

1. Introduction

Photovoltaic (PV) power generation has emerged as a major component of the global low-carbon energy transition. With the continuous increase in cumulative installed capacity, a large number of early-deployed PV modules are gradually approaching their end-of-life stage [1]. The resulting waste stream is not only just a disposal issue, but rather than a comprehensive resource-management and materials-recovery challenge encompassing glass, aluminum, silicon, copper, silver, and polymeric encapsulants [2].

A key feature of end-of-life PV modules is the mismatch between mass distribution and value distribution. Glass and aluminum represent the largest mass fractions in crystalline silicon (c-Si) modules, whereas silicon wafers, silver gridlines, copper ribbons, and aluminum contacts are more directly related to functional value

and downstream reuse potential [3]. Consequently, an evaluation based only on recovery mass fails to adequately capture the full potential for high-value material utilization [4].

This review considers PV recycling from a battery-oriented upcycling perspective. Instead of treating retired modules merely as solid waste, the discussion focuses on whether recovered silicon, glass, and metals can be converted into battery-relevant precursors through controlled separation, precise impurity regulation, surface modification, and structural reconstruction [5]. The key point of this article aims to first-generation c-Si modules, while thin-film and emerging PV systems are discussed as boundary cases where critical-metal recovery and environmental control are particularly important [4].

Conventional PV module recycling has mainly focused on the separation of bulk components, particularly glass and aluminum frames. While this strategy proves effective in mitigating landfill pressure, it often yields limited value addition when high-value functional components are not recovered in a controlled state [5]. Notably, recovered silicon, silver, and copper often require further purification or reconstruction before they can enter advanced material systems.

A significant technical impediment arises from the robust interfacial adhesion among glass, encapsulants, cells, ribbons, and backsheets. While mechanical comminution offers simplicity and scalability, it frequently leads to severe cross-contamination among glass fines, metal fragments, and polymer residues [6]. Thermal delamination effectively removes encapsulants, however, it often needs substantial energy input and may also generate carbon residues, metal oxidation, or emission-control burdens. Solvent-assisted routes are gentler, but their industrial feasibility depends strongly on solvent recovery, process time, safety, and cost [5-7].

Indeed, the limitation of traditional recycling is attributed to low recovery efficiency, and the lack of a quality-oriented connection between recovered outputs and their next-stage applications [5]. Thus, A battery-oriented upcycling route should be evaluated by purity, surface chemistry, particle morphology, manufacturing compatibility, energy consumption, and environmental burden, rather than by recovery rate alone [8].

Based on this background, upcycling offers a more application-centric route for end-of-life PV modules. In contrast to conventional recycling, which primarily seeks to reintroduce materials into low-value recycling streams, upcycling emphasizes functional reconstruction and value creation. For PV-derived materials, this means converting recovered fractions into battery precursors or battery auxiliary components with controlled composition, structure, and interfacial properties [9].

PV-derived silicon represents a prime target, owing to its high theoretical capacity as an anode material for both lithium-ion and sodium-ion batteries [8, 10]. However, recovered silicon cannot be regarded as a direct substitute for commercial battery-grade silicon powder. Its residual metals, surface oxide layers, carbonaceous residues, particle-size distribution, and dopant background must be regulated according to battery-performance requirements [11].

PV glass and PV-derived metals also have potential roles in battery systems. Recycled glass may be used as an inorganic filler, separator-related phase, or polymer-electrolyte additive after cleaning, milling, or morphology control [10]. Recovered Ag, Cu, and Al may be further considered for conductive networks, current collectors, or interfacial/catalytic functions [12]. Hence, PV-to-battery upcycling is a quality-controlled transformation route connecting renewable-energy generation waste with energy-storage material manufacturing, rather than an extension of recycling.

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2. PV module architecture, recyclable and impurity-controlled feedstock evolution

2.1. C-Si module architecture and material-value map

The unique "sandwich"-structure of c-Si modules—comprising glass, Ethylene-Vinyl Acetate (EVA) encapsulant, solar cells, and backsheet—directly determines the difficulty of layer separation and the evolution of impurities during recycling. A recent highlighted research is the pronounced techno-economic disparity between mass and value distribution while glass and aluminum frames collectively constitute approximately 85%–90% of the modules [3]. This perspective establishes a theoretical foundation for subsequent exploration of "PV-to-battery upcycling," whereby controlled material regeneration pathways transform recycled outputs into key precursors or auxiliary materials suitable for lithium- or sodium-ion batteries.

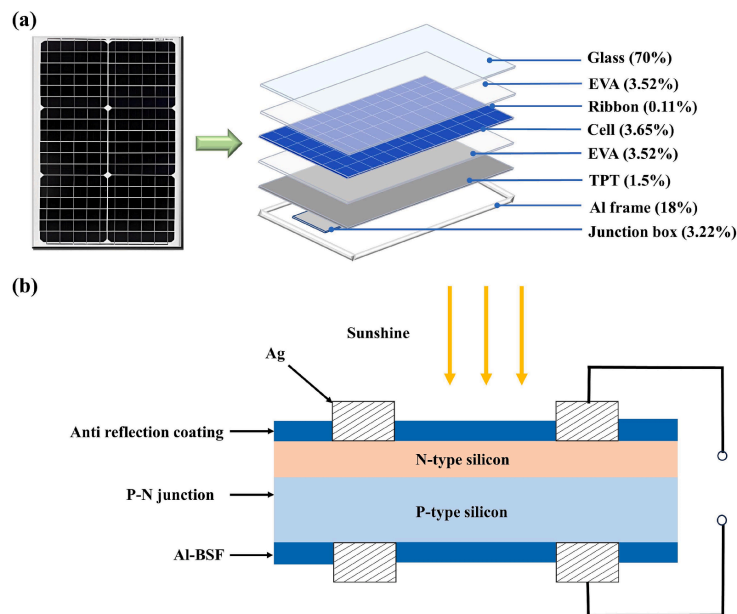


Figure 1. (a) C-Si PV panel structure with percentage mass composition (b) schematic diagram of C-Si PV cell structure (reprinted from reference [13] copyright from Elsevier)

Crystalline silicon (c-Si) photovoltaic modules are not singular silicon-based devices, but sophisticated highly integrated, multi-layer laminated assemblies. From the incident light-facing to the rear, conventional modules are typically constructed from low-iron tempered cover glass, polymer encapsulation materials such as Ethylene-Vinyl Acetate (EVA) or Polyolefin Elastomer (POE), crystalline silicon solar cells (featuring silver/aluminum metallized contacts), tin-coated copper ribbons (busbars and interconnects), a rear-side encapsulation layer, and a polymeric backsheet—typically composed of PET/PVF laminate—or glass backsheet [3]. Externally, the module is robustly reinforced by an aluminum frame, junction box, cables, and sealing materials to provide essential mechanical support and electrical connectivity. As illustrated in Figure 1, the encapsulation layers fulfill a critical multi-functional role within the module. These include fixing the position of the solar cells, providing electrical insulation, preventing moisture ingress, buffering mechanical stress, and ensuring environmental stability over the 25–30 year service life [4]. However, it is precisely this high interfacial adhesion strength—engineered for maximum durability and "bankability"—that constitutes a

major technical bottleneck during end-of-life stages. For instance, the interfacial peel strength between EVA and glass commonly exceeds 40 N/cm [2]. Due to insufficient consideration of "circular design" or disassembly-friendly architecture during initial design phases, individual functional layers cannot be physically separated efficiently at the end of their lifecycle, that significantly complicates high-quality material recovery and resource recycling [13].

For c-Si modules, a critical distinction have to be drawn between gravimetrically dominant components and those that are functionally or economically paramount [3]. From a mass-distribution perspective, the tempered front glass and aluminum frames constitute the most substantial fractions of the module. Glass typically accounts for the preponderant portion of the modules weight, while aluminum frames also contribute a considerable recoverable fraction. Polymers, silicon cells, copper ribbons, silver gridlines, solder materials, and other minor metals occupy smaller proportions. Therefore, if the module is assessment is solely predicated on weight, it may be considered mainly as a glass–polymer–aluminum composite system [4, 6].

However, this purely gravimetric understanding proves inadequate for achieving high-value valorization. The silicon wafer, silver gridlines, copper ribbons, solder layers, and aluminum contacts are more important for electrical function, resource value, and battery-oriented upcycling. Silver has a very small mass fraction but a high economic and conductive value [14]. Silicon is not the largest component by weight, but it is the key semiconductor material and can be further considered as a promising precursor for Li-ion or Na-ion battery anodes after appropriate purification, surface regulation, particle-size control, and composite design [13]. Copper ribbons and busbars are important for electrical interconnection, while aluminum frames or contacts may provide recyclable metallic resources [7, 15]. Thus, the material-value map of c-Si modules shows a clear mismatch: the components that dominate the mass are not always the components that dominate the recovery value or functional reuse potential.

Hence, a simple mass-recovery strategy is always insufficient for enabling high-value utilization. Conventional recycling pathways primarily focused on the bulk separation of glass and aluminum, may indeed enhance overall material recovery rates, however, they are inherently incapable of automatically yielding battery-suitable precursors [4, 13]. For battery-oriented upcycling, the key issue is not only whether a component can be recovered, but also whether the recovered stream has suitable purity, morphology, surface chemistry, and compositional stability for downstream applications. From this perspective, c-Si module recycling should move from a weight-based recovery logic to a quality-based upgrading logic. During process such as dismantling, crushing, thermal treatment, or chemical delamination, different module components do not behave as isolated materials. Instead, interfaces and residues strongly influence the quality of recovered products. Polymer decomposition may introduce carbonaceous residues on glass, silicon, or metal surfaces. Mechanical crushing may generate glass fines and cause cross-contamination between glass, silicon, and metallic particles. Metallic components may be oxidized during thermal treatment, while solder layers may introduce Sn/Pb-related contamination. For recovered silicon, surface SiO_x or SiN_x layers, residual Ag/Cu/Al, dopant elements such as B and P, and polymer-derived carbon residues may all affect its later use as an anode precursor [3, 16]. For recovered glass, residual polymers, metal particles, and mixed fines may limit its direct reuse unless further cleaning and upgrading are conducted [9].

Therefore, the architecture of c-Si modules is directly linked with material quality evolution: i) Front glass is the mass carrier; aluminum frame is the major structural metal; ii) Silicon cells are the key functional semiconductor and possible battery-anode precursor; iii) Silver and copper are low-mass but high-value conductive components; iv) Solder layers are minor but important contamination sources; v) Encapsulants are necessary for module durability but problematic for end-of-life separation. This structure determines that c-Si

module recycling is not merely a dismantling problem, but a process of controlling impurity transfer and reconstructing recovered outputs into usable secondary resources.

2.2. Boundary cases: thin-film and emerging PV systems

Thin-film and emerging photovoltaic systems are retained in this review as boundary cases rather than being treated as equal-length sections. This treatment is necessary because their recycling logic is different from that of crystalline silicon (c-Si) modules. For second-generation thin-film technologies, CdTe and CIGS are the two main commercialized examples. Although their market share is much lower than that of c-Si, they involve elements with higher material criticality and environmental sensitivity. In CIGS modules, recycling studies mainly focus on the selective recovery of Cu, In, Ga, and Se, while CdTe modules are more directly related to Cd toxicity control and Te resource recovery [4, 7, 17]. Previous supply-risk assessments have indicated that Te, In, Ga, and Se may face medium- to long-term supply risks, which makes thin-film module recycling more dependent on the recovery of specific critical elements rather than bulk material separation. Meanwhile, landfill simulation studies have shown that CdTe modules may release Cd and Te under certain acidic and reducing conditions, suggesting that thin-film recycling should address both resource recovery and environmental risk mitigation [18]. Therefore, compared with c-Si modules, the recyclable targets in thin-film PV systems show stronger elemental selectivity and higher dependence on controlled separation processes.

Compared to c-Si modules, where the main concern is how to dismantle the module and upgrade Si, glass, Ag, Cu, and Al into usable feedstocks, perovskite modules focus on how to prevent Pb and halogen leakage and how to preserve valuable functional layers [19]. Pb-containing perovskites cannot be treated simply as conventional lead-bearing electronic waste, because their environmental behavior and bioavailability may be different. At the same time, Pb salts are not the only valuable components in these devices. Transparent conductive oxide glass, ITO-coated substrates, charge-transport layers, encapsulation glass, and metallic electrodes also contribute significantly to the economic value and environmental footprint of perovskite modules. Recent reports have shown the strategies including staged dismantling, green-solvent recovery, thermal delamination, and synergistic recovery of Pb. Basically, the transparent conductive layers enable the reuse of regenerated PbI₂ and recycled ITO/glass substrates in device remanufacturing [20].

2.3. Impurity sources and migration pathways

Rather than being a straightforward post-recycling impurity list, impurity migration in c-Si photovoltaic modules should be viewed as a process-evolution problem spanning both service life and recycling. Prior to being recycled, recovered components already have impurity contamination and chemical deterioration due to encapsulant aging, interfacial interactions, and acetic acid-induced metallization corrosion during long-term operation [6, 8].

During dismantling and delamination, these pre-existing degradation features may be further amplified. Mechanical treatments tend to redistribute glass fines, solder fragments, metal particles, and polymer residues into mixed fractions, increasing the difficulty of obtaining high-purity outputs. Thermal routes can improve delamination efficiency, but they may also produce carbonaceous residues on silicon surfaces, promote oxidation of metals from Ag fingers, Cu ribbons, solder layers, and Al contacts, and increase the burden of exhaust treatment [21]. If the backsheet contains fluorinated layers such as PVF or PVDF, pyrolysis or combustion may also release fluorine-containing emissions, which has been experimentally confirmed during the thermal treatment of fluorinated backsheets [22, 23]. While solvent-assisted techniques can lessen direct thermal damage and better protect some interfaces, they also impose limitations on processing time, swelling control, and solvent recovery. As a result, the assessment of recycling pathways should take into account the

introduction of secondary pollution and the amplification of impurity migration in addition to separation efficiency.

2.4. Delamination pathways: mechanical, thermal, solvent, and hybrid methods

From a battery-oriented upcycling standpoint, PV module disassembly and delamination should be evaluated not only for separation efficiency, but also for the functional compatibility of recovered outputs with downstream energy-storage applications [13]. Mechanical, thermal, solvent-assisted, and hybrid methods should be viewed as process combinations that involve trade-offs between precursor purity, morphology, throughput, energy demand, impurity redistribution, and environmental impact. Mechanical procedures, for example, provide high throughput but may raise cross-contamination, whereas heat ways can improve surface cleanliness while causing metal oxidation and increasing emission-treatment requirements [23]. Figure 2 sketches the process of traditional recycling technologies (a) Mechanical recycling, (b) Thermal recycling, (c) Chemical recycling. This multifaceted evaluation logic becomes the essential basis for enhancing next-generation recovery methods when the recycling goal shifts from bulk material reclamation to the creation of high-value energy-storage precursors.

Mechanical approaches, while offering simplicity and high throughput for preliminary PV module processing, are primarily suited for upstream enrichment or pre-treatment steps. This is because their comminution processes often induce significant cross-contamination, rendering them suboptimal for directly producing the high-quality precursors required for battery-oriented upcycling [7].

Thermal delamination and pyrolysis, which allow for the relatively full removal of encapsulants and the separation of glass, solar cells, and metal ribbons, are best suited for the delamination and material liberation processes in PV module recycling. Although these routes have been demonstrated to support the recovery of high-value secondary raw materials and can be combined with air classification and etching to improve Ag and Al removal, their high energy demand, exhaust gas treatment requirements, residual carbon formation, and possible oxidation of metals or silicon surfaces may compromise the quality of battery-oriented precursors [23, 24].

While solvent-assisted and swelling-based routes provide a gentler delamination strategy that can reduce heat-induced damage and improve the integrity of glass, silicon wafers, and interfacial layers, they are best suited for cases requiring relatively clean surfaces or intact recovered structures [19]. Although cross-linked EVA can be dissociated under appropriate solvent and temperature conditions, and controlled swelling with dibasic esters has been shown to separate encapsulated module structures, their long processing time, solvent consumption, solvent recycling requirements, operating costs, and safety concerns continue to limit large-scale application unless closed-loop solvent management and process optimization are achieved [19].

Hybrid approaches are mostly appropriate for balancing delamination efficiency, impurity control, cost, and environmental compatibility, even though they provide a more practical route for industrial PV recycling and battery-oriented upcycling [25]. Segmented combinations of mechanical enrichment, thermal or solvent-assisted delamination, and subsequent chemical purification or surface modification may be more practical, with the process design guided by the target precursor quality rather than separation efficiency alone, as a single method is unlikely to satisfy all quality requirements.

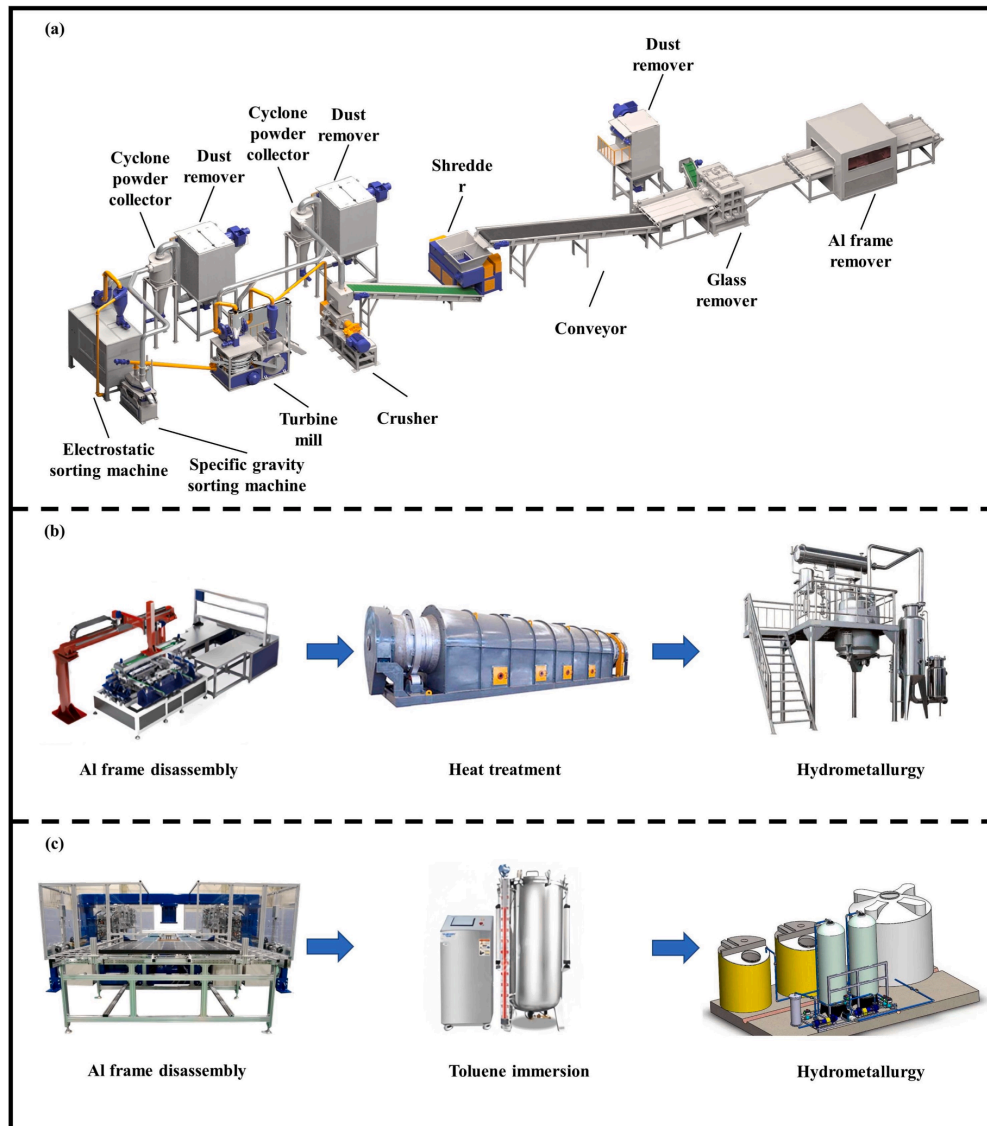


Figure 2. The process of traditional recycling technologies (a) mechanical recycling, (b) thermal recycling, (c) chemical recycling (reprinted from reference [13], copyright from Elsevier)

2.5. From "recycling products" to "battery precursors": a system of quality descriptors

The results of recycling PV modules are not simply referred to in this study as "recycled products," as this phrase just characterizes their source and does not assess their potential for battery production. The question of whether the recovered Si, glass, and metals have controllable purity, surface state, residual impurity level, shape, and processing compatibility is increasingly crucial for battery-oriented upcycling. High-value PV recycling requires not only on material separation but also on impurity detection, purification technique, and economic viability, according to earlier research [13, 26]. In order to link recovered PV fractions with downstream battery requirements, this review suggests a quality-descriptor architecture. These characteristics aid in determining if a recovered percentage can be utilized directly, needs focused upgrading, or should be excluded from battery-related applications, as shown in Table 1. While PV glass and Ag/Cu/Al fractions require application-specific control of composition, particle size, surface condition, and impurity residues before being redirected into electrolyte fillers, separators, current collectors, or interfacial functional phases,

PV-derived Si must be evaluated beyond elemental purity because surface oxides, residual metals, and particle morphology can significantly affect anode performance [9, 15, 27, 28].

Table 1. Battery-precursor quality descriptors derived from PV-recovered outputs based on references [3, 9, 11, 24]

Recovered output	Required descriptors	Why it matters for battery use
PV-derived Si	purity; residual Ag/Cu/Al/Fe/Sn/Pb; SiO _x /SiN _x layer; particle size; morphology; carbon residue; dopant background	Controls SEI formation, initial Coulombic efficiency, volume buffering, conductivity and slurry behavior
PV glass	composition; Fe/Sb content; residual polymer; metal contamination; particle size; surface hydroxyl groups; dispersion stability	Controls filler compatibility, electrolyte wetting, thermal stability and membrane/electrolyte processing
PV-derived Ag/Cu/Al	elemental purity; oxidation state; Sn/Pb solder; morphology; surface roughness; chloride/nitrate residues after leaching	Controls current-collector quality, electrical contact, corrosion behavior and interfacial functionalization
Process-level outputs	yield; energy demand; chemical use; wastewater/exhaust burden; batch-to-batch reproducibility	Determines whether laboratory upcycling can become an industrially meaningful route

3. PV-derived silicon for Li/Na-ion battery anodes

3.1. Status of photovoltaic silicon sources and recycling

There are two main sources of silicon from Photovoltaic (PV) materials used as anodes in sodium-ion and lithium-ion batteries. Kerf loss, wire-cutting slurry, and silicon-containing sludge are examples of cutting losses that occur during PV manufacture [29]. The second technique involves recovering silicon phases from used battery cells or retired modules [8]. According to earlier research, 40–55% of high-purity silicon is lost when crystalline silicon wafers are sliced, giving this waste silicon a substantial potential for reuse. Redirecting PV waste silicon toward battery anodes is a logical and high-value valorization strategy because it has already undergone energy-intensive purification and crystal growth processes, unlike the direct synthesis of high-purity silicon from quartz and metallurgical-grade silicon [5].

It is crucial to remember that main battery-grade silicon cannot be readily replaced by silicon recovered via Photovoltaic (PV) recycling. Complex impurity backgrounds, such as residual cutting fluids, metallic wear particles, surface oxide coatings, localized carbon residues, and non-uniform particle size distributions, are commonly seen in both cutting waste and end-of-life module recyclates. As a result, rather than being a completely specification-compliant commercial silicon powder, such silicon is better understood as an improved anode precursor.

3.2. Characteristic issues of PV recycling silicon compared to native silicon

Recycled Photovoltaic (PV) silicon should be considered a "reconstructed anode precursor" with a complicated impurity profile and changing surface chemistry in contrast to commercial-grade native silicon powder. In addition to the elemental silicon content, residual metallic impurities, non-uniform SiO_x/SiN_x interfacial layers, surface oxygen-containing functional groups, and the particle size distribution and

agglomeration state all work in concert to limit its electrochemical performance [30]. The uncontrolled surface oxide layer ($\text{SiO}_x/\text{SiO}_2$) is a common consequence of PV silicon recycling, exposure, and reprocessing from the standpoint of interfacial chemistry. Improper regulation of the oxide layer's thickness, continuity, and compositional ratio triggers vigorous interfacial side reactions and severe initial irreversible lithium loss, subsequently degrading the electrode's electronic conductivity network during cycling [11]. Furthermore, while cycling, this weakens the electrode's electronic conductivity network. And another significant obstacle is the physical shape and size effects of PV silicon materials. The majority of recycled silicon is found in irregular micron-sized particles, which suffer from extreme stress concentration during lithiation because there is little structural buffering space. Particle pulverization and the separation of active materials from the conductive network are easily caused by this, which eventually leads to a quick decline in capacity [8, 31].

These features can influence the anode through several coupled mechanisms. Residual Ag, Cu, Al, Fe, Sn, or Pb may change local conductivity, catalyze side reactions, or destabilize the electrode/electrolyte interface. A non-uniform SiO_x layer may consume lithium during the initial cycle and reduce initial Coulombic efficiency, whereas a controlled oxide layer may help buffer interfacial reactions [9]. Irregular micron-sized particles can suffer from severe pulverization and electrical isolation during cycling unless porosity, carbon coating, binder design, or composite architecture is introduced [11]. Therefore, upgrading PV-derived silicon does not necessarily mean returning it to solar-grade purity. A more practical strategy is to remove harmful impurities to a tolerable level, tune the surface oxide state, regulate particle morphology, and construct a conductive/buffering network that is compatible with electrode slurry processing and full-cell operation [32].

3.3. Key upgrade strategies: metal removal, oxidation layer tuning, pore creation/carbon composites/particle size regulation

The current effective upgrade strategy for addressing the aforementioned issues can be summarized in three steps.

i) Metal removal and purification: Acid washing, heat treatment, selective etching, and gentler fluoride salt treatments are common methods. The goal is to remove contaminants that are most harmful to electrochemical cycling, not to reach photovoltaic-grade purity [9]. Common pretreatment techniques include acid washing and heat treatment to eliminate metallic and organic residues, or NH_4F to eliminate remaining SiO_2 and create nanoscale pores [32].

ii) Controlling the oxide layer and interfacial states: The main goal of this step is to create a more controlled surface condition rather than totally remove the oxide layer. Recent research has shown that interface engineering, pre-oxidation, or mild surface oxidation can improve structural stability; nevertheless, a too thick or uneven oxide layer reduces initial efficiency and rate capability. As a result, the surface oxide layer of recycled silicon from Photovoltaic (PV) sources is more suited for "tuning" as opposed to being forced to choose between "retention" and "complete removal" [30].

iii) Last but not least, structural engineering: Pore creation, hollowing, carbon coating, CNT/CNF compositing, nanowire structuring, and particle size refining are examples of techniques. The goal of these methods is to improve electron transit and interparticle connection while accounting for volume variations. Designs like ZIF-derived nitrogen-doped carbon shells, yolk-shell pSi@void@C architectures, Si/Cu@GLC composites, Si/CNTs/C hybrids, and silicon nanowire electrodes with ultra-high areal capacity can greatly enhance cycling stability and rate capability, according to earlier research [33]. From a materials engineering standpoint, these techniques have significant reference value for reducing volume effects and stabilizing interfaces in the setting of sodium-ion systems, despite the fact that direct literature is still scarce [34].

4. Upcycling PV glass for ion batteries

4.1. Value-added utilization prospect of recycled PV glass for ion batteries

Compared with recovered silicon and metals, Photovoltaic (PV) glass has long been considered a low-value bulk component. It is usually recycled into aggregate, remelted glass, or building material additives. Glass in crystalline silicon modules, however, is not wholly a "low-function" waste stream from a material perspective. According to current research, PV glass usually makes up between 67% and 76% of the module's mass and is mostly a member of the low-iron soda-lime-silicate glass system [35]. It has intrinsic benefits in terms of chemical uniformity, optical purity, and industrial scalability. Therefore, this glass need not be restricted to aggregate-level applications, but it could be used as a substrate for battery separators, and inorganic fillers. Moreover, it could be used as a part of polymer electrolytes if the recycling process can successfully control impurities, particle size distribution, and surface condition within acceptable ranges [10].

4.2. Composition, cleanliness, and particle size requirements of PV glass

With SiO_2 as the primary glass-forming component and Na_2O , CaO , MgO , and Al_2O_3 as typical modifying or stabilizing oxides, PV glass should be viewed from a compositional standpoint as a low-iron soda-lime silicate glass rather than regular waste glass [36, 37]. As Fe_2O_3 has to be tightly regulated to maintain good optical transmittance and since ultra-white patterned or float PV glass may need Fe_2O_3 values below 150 ppm, the low-iron characteristic is especially crucial. Antimony-related chemicals are also present in some PV glass formulations, which can enhance glass clarity but raise additional issues during recycling and remelting. Further research reveals that different PV technologies employ different kinds of glass: thin-film modules typically utilize ultra-white float glass due to its smoother surface, while crystalline silicon modules mostly use ultra-white rolled front glass. Since the composition, surface condition, and impurity profile of waste PV glass might vary depending on the module type, production pathway, and recycling method, it should not be viewed as a uniform "glass waste" stream. Contaminants like Si, Al, and Cu may alter glass coloring and melting behavior during disassembly or melting-based recycling, suggesting that impurity control is required prior to high-value reuse [38]. This means that recovered PV glass should first be compositionally identified for battery-oriented upcycling before being guided into appropriate applications, such as solid-polymer-electrolyte additives or inorganic fillers, based on its particle properties and purity [9].

Reclaimed PV glass should be considered as a secondary feedstock for battery-oriented upcycling, with its value contingent upon composition, impurity tolerance, surface cleanliness, particle size distribution, and filler loading, rather than only on SiO_2 concentration. During dismantling, delamination, crushing, or remelting, polymer residues and inorganic contaminants such as Cu, Al, Si, and Ag may infiltrate the glass fraction, resulting in discoloration, redox reactions, and interfacial contamination that compromise both chemical purity and surface quality [37, 39]. Accordingly, rather than only aiming for extreme size reduction or ultimate purity, PV glass upcycling should match glass composition, impurity level, surface state, particle size, and loading with the safety and ion-transport criteria of the target battery component [40, 41].

5. PV-derived metals (Ag/Al/Cu) for battery systems

Rather than being perceived merely as gravimetrically dominant recycling products, PV-derived metals should be viewed as resources that are concentrated in value and function. Ag originates from the minute metallization gridlines on solar cells, Cu from ribbons, wires, and interconnections, and Al from frames and back-contact regions within conventional crystalline silicon modules. The strategic reintegration of recovered

Ag, Al, and Cu into battery manufacturing serving as current collectors, conductive scaffolds, or interfacial functional phases, rather than just as scrap metals—makes it more significant than bulk glass recovery [6, 7, 14]. Table 2 indicates the comparison of direct-use and upgraded-use windows for PV-derived material streams. Consequently, "whether the recovered metal can satisfy battery-component requirements in purity, surface state, and morphology" should replace "how much metal can be recovered" in the assessment rationale.

Table 2. Comparison of direct-use and upgraded-use windows for PV-derived material streams based on references [9, 11, 24, 42]

Material stream	Direct use window	Upgraded use window	Key judgement
PV-derived Si	Possible when impurity level is low, performance target is moderate, and electrolyte/binder system can tolerate micron-sized particles	Needed for high-loading, long-cycle, full-cell or high-rate applications; requires metal removal, oxide tuning, carbon/porous/composite design	Direct use is narrow; upgraded use has higher performance ceiling
PV glass	Limited to low-value aggregate or rough filler when contamination and size control are not strict	Can be used as separator/filler/electrolyte additive after cleaning, milling, fiberization or surface compatibility control	Function depends on morphology and interface, not only composition
Ag/Cu/Al	Scrap-level reuse or simple metal recovery	Battery current collectors, conductive networks, seed layers or interfacial/catalytic functions after purification and surface restoration	Element recovery does not equal battery-ready metal component

Recent reported for recovering PV-derived metals, including mechanical separation, hydrometallurgical leaching, electrowinning, electrolyte-assisted recovery, and more environmentally friendly leaching systems. Yashas et al. investigated silver recovery from end-of-life polycrystalline silicon PV cells using leaching and catalytic/electrowinning-related techniques [42], while Han et al. reported stepwise hydrometallurgical recovery of Cu, Al, and Ag from spent solar panels with high recovery efficiency and product purity [25]. Mwase et al. created a two-step leaching route for Ag and Al separation [43]. PV metal recycling appears to be shifting from straightforward strong-acid extraction to more selective, scalable, and environmentally friendly procedures, according to more recent research on continuous stirred-tank recovery and evaluations with a silver focus. Nevertheless, battery-grade consumption is not equivalent to extraction. Interfacial impedance, film formation, adhesion, and long-term electrochemical stability may be significantly impacted by residual oxide layers, corrosion flaws, Sn/Pb solder residues, chloride or nitrate species, and uncontrolled powder shape [15, 27, 44]. Therefore, surface reconfiguration and application-oriented certification are just as important as purification for PV-derived metals.

As established current-collector materials in lithium-ion batteries, Al and Cu offer direct pathways for battery applications, with Cu being particularly pertinent to anode-side or lithium-metal systems where surface characteristics are presented. Recovered Al/Cu current collectors can be reused after appropriate chemical treatment, according to evidence from spent lithium-ion battery recycling. However, their performance depends more on whether the surface has been regenerated than on elemental composition alone [15]. Ag, on the other hand, is better suited for low-loading, high-functionality roles like lithiophilic sites, conductive interlayers, and interface-modulation layers in anode-free or lithium-metal systems than it is for bulk structural

reuse [45, 46]. Thereby, directing PV-derived Al/Cu toward conductive scaffolds or regenerated current collectors while positioning Ag for high-value interfacial functionalization is a practical upcycling technique. Future research should shift from metal recovery efficiency to battery-component qualification, including impurity thresholds, surface reconstruction, interfacial stability, and manufacturing compatibility, as there are currently few direct demonstrations of PV-recovered Ag/Al/Cu in full battery systems [14].

6. Cross-cutting assessment: from recovered outputs to battery-grade materials

An integrated framework of technical compatibility, environmental impact, and economic viability should be used to assess the switch from PV-derived recovered outputs to battery-grade materials. The impurity tolerance, surface state, morphology, processability, energy demand, carbon footprint, and scale-up feasibility should be evaluated collectively before it is deemed battery-grade, even if it has been separated from a module or demonstrated satisfactory performance in a limited cell test [3, 35]. As a result, "sufficient quality for the next manufacturing stage" should replace "maximum recovery" as the primary requirement. While a moderately purified stream may be valuable if its impurity profile is compatible with the intended battery component, a highly purified stream may be unappealing if it requires intensive energy input, strong chemical consumption, or complex wastewater treatment.

Rather than being a static parameter, impurity tolerance is fundamentally dictated by the requirement of targeting application. Compared to its utilization as a battery anode, where residual surface oxides, dopants, or metallic traces may be tolerated or even beneficial if their chemical state and distribution are controlled, the requirements for reentering the photovoltaic supply chain for PV-derived silicon are far more stringent [11, 31, 47]. This flexibility, however, does not suggest that contaminants can be tolerated without limitation. The unpredictable distribution, poor repeatability, and detrimental effects on irreversible capacity loss, interfacial resistance, slurry dispersion, and cycling stability are the main risks associated with trace impurities [32, 46]. Consequently, purification should be viewed as the creation of a stable impurity window rather than an exhaustive pursuit of absolute purity: neutral or beneficial species should be maintained within a reproducible operational range, whereas hazardous residues like excessive metal particles, thick oxide layers, carbon derived from polymers, or glass/backsheet fragments should be minimized.

Manufacturing and structural compatibility are equally paramount. Battery manufacturing necessitates specific physical forms—such as powders, fillers, foils, or functional phases with tailored particle sizes, surface chemistry, wettability, and rheological behavior—rather than abstract elemental constituents like "Si," "glass," or "metal. Before PV-derived silicon can be used in slurry-based anode manufacture, it frequently needs surface modification, particle-size control, or carbon composite design [5, 33, 44]. This point is also illustrated by PV glass, which, despite having a high SiO₂ content, typically requires cleaning, ball milling, and interfacial role redesign before it can function as an inorganic filler in polymer electrolytes. Tay et al. directly illustrated this process by transforming end-of-life solar glass into a PEO-based solid polymer electrolyte filler [9]. The primary problem is considerably more surface-sensitive for Ag, Al, and Cu. Beyond elemental purity, other factors that affect reuse as current collectors or conductive/interfacial phases include oxide layers, corrosion resistance, surface roughness, electrical contact, and adhesion stability [15, 48]. Table 3 illustrates the correlations between the monocrystalline silicon module components, material valuation, recycling-related impurity challenges, and battery-oriented implications, thereby elucidating the paradigm shift from conventional recycling to high-value upcycling.

Table 3. c-Si module components, material value, recycling-related impurity concerns, and battery-oriented implications based on references [1, 6, 7, 48]

Component / layer	Mass or functional role	Major impurity concern after recycling	Battery-oriented implication
Front glass	Mass-dominant component; low-iron soda-lime glass	Glass fines, residual EVA/backsheets, metal particles, Si contamination	Potential filler/separator-related phase after cleaning, milling, or fiberization
Encapsulant (EVA/POE)	Adhesion and sealing; major delamination barrier	Organic residues, acetic-acid-related corrosion, carbon residue after thermal treatment	Requires control to avoid carbon/organic contamination in Si and glass streams
c-Si cells / wafer	Functional core; high-value Si source	Surface SiO _x /SiN _x , Ag/Al/Cu residues, dopant background, particle-size nonuniformity	Potential Li/Na-ion Si/C anode precursor after purification and structural engineering
Ag gridlines	Low mass but high economic and conductive value	Dispersed morphology, chloride/nitrate residues after leaching, coexisting metals	Potential conductive or interfacial functional phase; not necessarily bulk metal reuse
Cu ribbons / busbars	Conductive interconnection	Sn/Pb solder, oxide layer, surface defects, mixed metal contamination	Potential current collector/conductive scaffold after purification and surface restoration
Al frame / Al contacts	Large recyclable metal fraction; current collector relevance	Oxide layer, corrosion, mixed residues, geometry change	Potential reuse in Al-related current collector or metal precursor routes
Backsheet / rear glass	Protection layer; may contain fluorinated polymers	F-containing emissions/residues, polymer fragments	Controls environmental burden and secondary contamination during delamination

The availability of the technically feasible route is further determined by economic and environmental assessment. When compared to landfills or incineration, LCA studies typically demonstrate that well-designed PV recycling can lessen environmental effects. However, this benefit is highly dependent on the electricity mix, transport distance, delamination route, chemical use, and purifying intensity [4, 21, 25]. However, high-value recovery does not always ensure commercial viability, according to techno-economic research, particularly when the process requires lengthy thermal treatment, multi-step acid/alkali leaching, complicated fractionation, or reshaping. Thus, excessive purification and low-value mass recovery should be avoided in PV-to-battery upcycling. Indeed, application-oriented upgrading is a more practical approach, since recovered Si should be routed in accordance with anode tolerance windows, glass in accordance with filler or separator needs, and metals in accordance with current-collector or interfacial-function demands. Ultimately, the battery-component qualification with acceptable environmental and economic cost will be the final answer rather than only considering the value of recovered materials.

7. Conclusions and outlook

In conclusion, end-of-life solar modules, rather than being merely discarded as straightforward solid waste, ought to be recognized as valuable composite secondary resources. Indeed, glass, silicon, silver, aluminum,

and copper all possess considerable utility for prevalent crystalline silicon modules; however, their battery-oriented upcycling hinges not only on recovery efficiency but also on precursor quality, impurity state, surface chemistry, and manufacturing compatibility. Recent investigations disclose that discarded PV glass can be repurposed as an inorganic filler for polymer electrolytes after cleaning and size reduction, while reclaimed PV silicon can be transformed into Li/Na-ion battery anodes via purification, particle-size regulation, surface-oxide control, and carbon composition. While the economic viability of PV recycling is enhanced by the recovery of Ag, Al, and Cu, their effective reuse remains contingent upon their purity, oxidation state, morphology, and interfacial stability.

Nevertheless, the variability in feedstock quality, impurity migration, inadequate process–performance correlation, and the absence of established quality descriptors are still obstacles to PV-to-battery upcycling. Although a large number of researches indicate either electrochemical performance or recovery efficiency, there is still no evidence linking module source, recycling path, precursor characteristics, and battery-level output. Therefore, material separation should give way to application-oriented qualification in future research. Standard descriptors for PV-derived silicon, glass, and metals must comprehensively address particle size, surface oxides, phase purity, processability, and both metallic and organic residues. Hence, future research needs to establish a traceable chain linking the entire lifecycle—from recycling and module structural design to precursor reconstruction, electrode fabrication, cell performance, and ultimate TEA and LCA.

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