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Very Large Difference Between Real and Declared Volumes of PV Panel Recycling: Economic Motivation for Environmental Sustainability

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Abstract

Technical recyclability does not ensure that decommissioned photovoltaic (PV) modules enter recycling. A published estimate of approximately 10% global PV waste recycling provides context rather than a new global inventory. In this study, economic incentives for increasing actual PV module recycling are examined. Three treatment routes are compared using published experimental and industrial data: room-temperature delamination of double-glass modules with soft polydimethylsiloxane (PDMS), milling of ethylene-vinyl acetate (EVA) modules with polymer backsheets, and hot-knife separation of the same EVA construction. In a mass-based cost-and-revenue scenario, an assumed gross processing rate of USD 0.65/kg is applied to the 37 kg PDMS and 24 kg EVA reference modules. With stated material credits and a common USD 3.5 aluminum frame credit, the respective NET BALANCES are approximately +USD 6.8, −USD 12.1, and −USD 10.8 per module. The technical basis is the preservation of two intact glass sheets (approximately 30 kg) and a separately recovered silicone fraction (approximately 3.0 kg). After cleaning and verification, suitable recovered sheets may serve as rear glass in compatible new PV modules. Direct glass reuse avoids remelting, whereas nonincinerating PDMS delamination avoids direct encapsulant-combustion emissions. The positive scenario balance suggests that preserving reusable components can strengthen economic incentives for recycling, supporting circular material use and environmental sustainability.

Keywords: photovoltaic modules; PV waste; recycling economics; environmental sustainability; PDMS; EVA; circular economy; direct reuse; recycling cost

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1. Introduction

The difference between potential recyclability and actual recycling is central to the environmental sustainability of photovoltaic (PV) systems. Peer-reviewed literature reports that only approximately 10% of total PV waste worldwide is recycled [1]. The complementary share should not automatically be interpreted as landfilled waste because it can include storage, reuse, export, and insufficiently documented end-of-life pathways. Nevertheless, this value provides a quantitative indication that technical recyclability and realized recycling operate at very different scales. PV sustainability is influenced

throughout the life cycle, including operational design. Recent studies have examined PV tilt-angle optimization using a hybrid ANN-transfer function framework [2] and neural-network modeling of the system energy balance [3]. Repowering intervals also affect end-of-life material flows: In a 30-year scenario, module replacement every five years requires six full module sets [4]. The present study addresses the complementary end-of-life stage, where module construction and separation technology determine whether material and component value can be retained after decommissioning.

Two distinct gaps must therefore be distinguished. First, decommissioned modules may remain outside of documented recycling, as illustrated by field-verified multiyear onsite storage after being repowered in Czechia [5]. Second, a module delivered to a recycling facility may yield recovered glass and metals while polymeric fractions are thermally treated or destroyed. Actual recycling must therefore be evaluated by both treatment entry and the final form of the recovered outputs.

This study focuses on the part of the problem that can be influenced by recycling technology. Transport to the recycling facility and legislative design are outside the comparative boundary. The analysis focuses on the separation mechanism, preservation of components, the fate of the encapsulant and backsheet, treatment-related emissions, environmental protection requirements, and the cost consequences arising from these technical differences.

Three technological routes are compared in the order: (A) room-temperature mechanical delamination of glass/soft-PDMS/glass modules; (B) milling of glass/EVA/TPT modules; and (C) hot-knife delamination of glass/EVA/TPT modules. The aim is to identify the processing-cost and recovered-output-value conditions under which the defined comparison scenario has a positive net balance. A conventional cost-and-revenue table, processing-cost sensitivity analysis, and break-even thresholds distinguish the value of preserved components from the assumptions used to price their treatment. International evidence provides context; this study does not audit individual recycling declarations or derive a new global recycling inventory.

The module constructions, delamination experiments and reported recovery results were described previously [6,7]. The present study uses these findings as inputs for an economic comparison of room-temperature PDMS delamination, EVA milling, and EVA hot-knife separation. Its contribution is the calculation of net balances and the assessment of how processing costs and the value of recovered components influence the economic incentive for recycling.

2. Materials and Methods

2.1. Scope, Module Construction, and Material Balance

The assessment combines published experiments, industrial process data, and calculations performed in this study. The comparison uses complete module constructions so that common components such as the aluminum frame remain visible but do not determine the ranking of the laminate-recycling routes. Route A is glass/soft-PDMS/glass mechanical delamination, Route B is conventional glass/EVA/TPT milling, and Route C is hot-knife separation of glass/EVA/TPT. Thin 1.6/1.6 mm EVA double-glass modules are outside the main numerical comparison.

The published experimental results, industrial process inventories, and calculations performed in this study are distinguished throughout the analysis.

The evidence review uses selected field cases, national reports, and industry surveys to distinguish disposal, storage, and export from completed recycling. Each quantity retains its geographical scope, observation year, and denominator. Reported technical recovery potential, collection, facility capacity, and completed treatment are different indicators and are not interchangeable measures of recycled volume. The examples identify

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pathways and financing constraints and are not combined into a new global inventory. The approximately 10% estimate is used as reported in [1], with its underlying global coverage and observation period not independently reconstructed here.

The whole-module, glass, encapsulant, and aluminum frame masses follow the approximate reference values in Table 2 in [6]. The 2.0 kg TPT backsheet mass and the detailed allocation to cells, the junction box, cables, and other minor components are adopted inputs for the present reference mass balance, which totals 24.0 kg for EVA/TPT and 37.0 kg for PDMS.

The mass-based comparison retains the approximate whole-module reference masses reported in [6]: 24.0 kg for glass/EVA/TPT and 37.0 kg for glass/soft-PDMS/glass. For the component mass balance adopted in the present study, the 24.0 kg EVA/TPT reference module consists of approximately 15.0 kg of front glass, 3.0 kg of EVA encapsulant, a 2.0 kg TPT backsheet, a 2.0 kg aluminum frame, 0.9 kg of c-Si cells, a combined 0.6 kg for the junction box and cables, and a 0.5 kg mass-balance remainder representing other minor module components. The latter category includes interconnection ribbons and busbars, solder, edge-sealing materials, adhesives, labels, and other small assembly materials. These components sum to the complete 24.0 kg reference module mass used in the economic calculation.

The 37.0 kg PDMS reference module consists of two approximately 15.0 kg glass sheets (30.0 kg total), approximately 3.0 kg of soft gel, a 2.0 kg aluminum frame, 0.9 kg of c-Si cells, a combined 0.6 kg for the junction box and cables, and a 0.5 kg mass-balance remainder representing other minor module components. These components sum to the complete 37.0 kg reference module mass. The same publication reported up to 30 kg, or approximately 81% of the module mass, as directly reusable glass and an overall recycling efficiency of 95–98% [6]. Figure 1 illustrates the layer arrangement and main components of the glass/soft-PDMS/glass and glass/EVA/TPT reference module constructions.

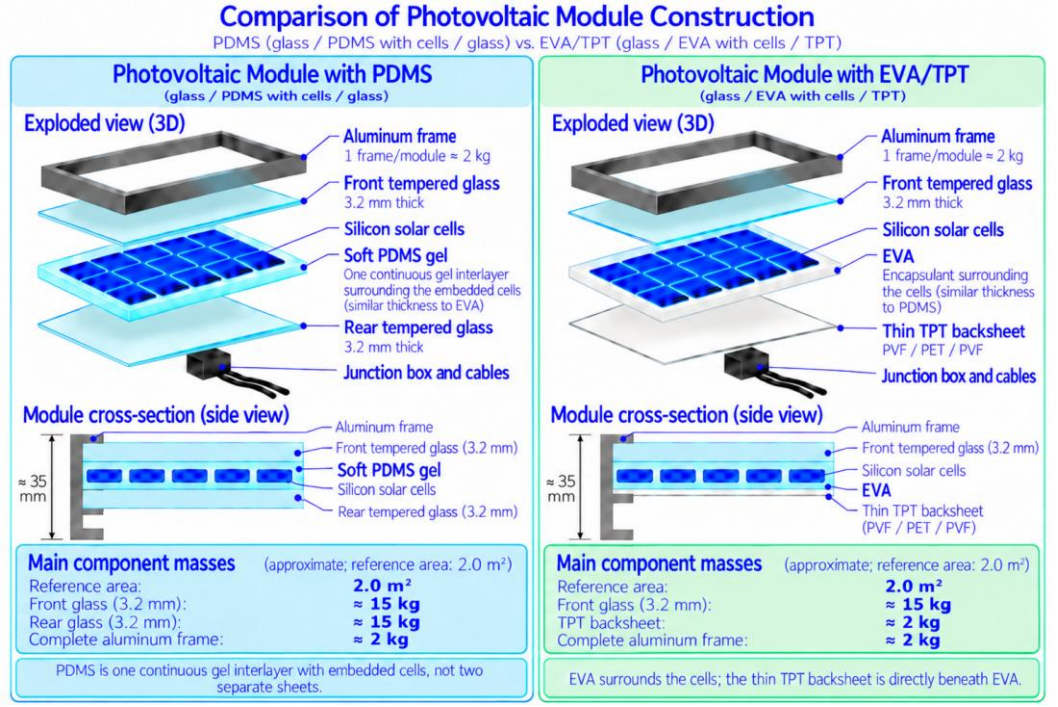


Figure 1. Schematic comparison of the glass/soft-PDMS/glass (left) and glass/EVA/TPT (right) photovoltaic module constructions. Exploded views and cross-sections show the layer arrangement and main components. The schematic is not to scale.

For the assessment process, approximately 3.0 kg of PDMS inventory is collected separately for sale. Only the separately collected gel is credited in Table 1.

The emission comparison uses a defined EVA-case combustion model based on the 3.0 kg encapsulant input in [6]. This quantity denotes EVA alone in the calculation, not the combined EVA/TPT laminate. The combustion term is applied only if the separated EVA fraction is subsequently completely oxidized; neither milling nor hot-knife separation is treated as complete EVA combustion. The separate TPT backsheet is addressed qualitatively for fluorine-related thermal treatment requirements. The TPT backsheet is assigned a mass of 2.0 kg in the reference module, but the mass fractions of its individual polymer layers are unspecified; therefore, TPT-derived CO_2 and fluorinated-gas quantities are not calculated. The selected soft-PDMS route involves the collection of a separate gel fraction for material use and includes no encapsulant combustion during delamination.

2.2. Technical, Environmental, and Cost Boundaries

The economic comparison starts with a complete PV module at the treatment facility. Removal from the PV installation and incoming transport are excluded. The reference scenario uses a common processing benchmark of USD 0.65/kg to assess the role of retained component value under a uniform cost assumption. For context, TNO reports estimated costs of EUR 466–931/t for a route recovering metallurgical-grade silicon [8,9], equivalent to approximately USD 0.53–1.06/kg at the stated conversion factor [10]. The selected benchmark lies within this range but does not represent measured costs of the three technologies. In particular, the greater mass of the PDMS module does not establish that its actual processing cost is higher. No cost is derived from an operation time or a supplier-rated throughput.

$$\begin{aligned} C_i &= m_i\, c_i \\ B_i &= R_i - C_i \end{aligned} \tag{1}$$

In Equation (1), m is the complete-module mass in kg, c is the assumed processing rate in USD/kg, C is the assigned gross processing cost in USD/module, R is the sum of credited outputs, and B is the net balance for route i. The reference case sets c to USD 0.65/kg for all routes. Material credits, including the frame, are counted once and separately from gross costs. No waste-acceptance fee is credited. Unquantified output preparation, qualification and subsequent material treatment, together with any associated revenues, remain outside the numerical balance. Their omission does not establish zero actual cost or value. The assigned processing costs, credited outputs, and net balances are summarized in Figure 2.

Published cost estimates provide context rather than matched quotations for Table 1. TNO separates equipment-related and operating expenditures, but its broader recovery-route cost ranges are adopted from Deng et al., without a complete technology-specific breakdown [8,9]. These are not two independent measurements of a hot-knife price or direct measurements of PDMS processing costs.

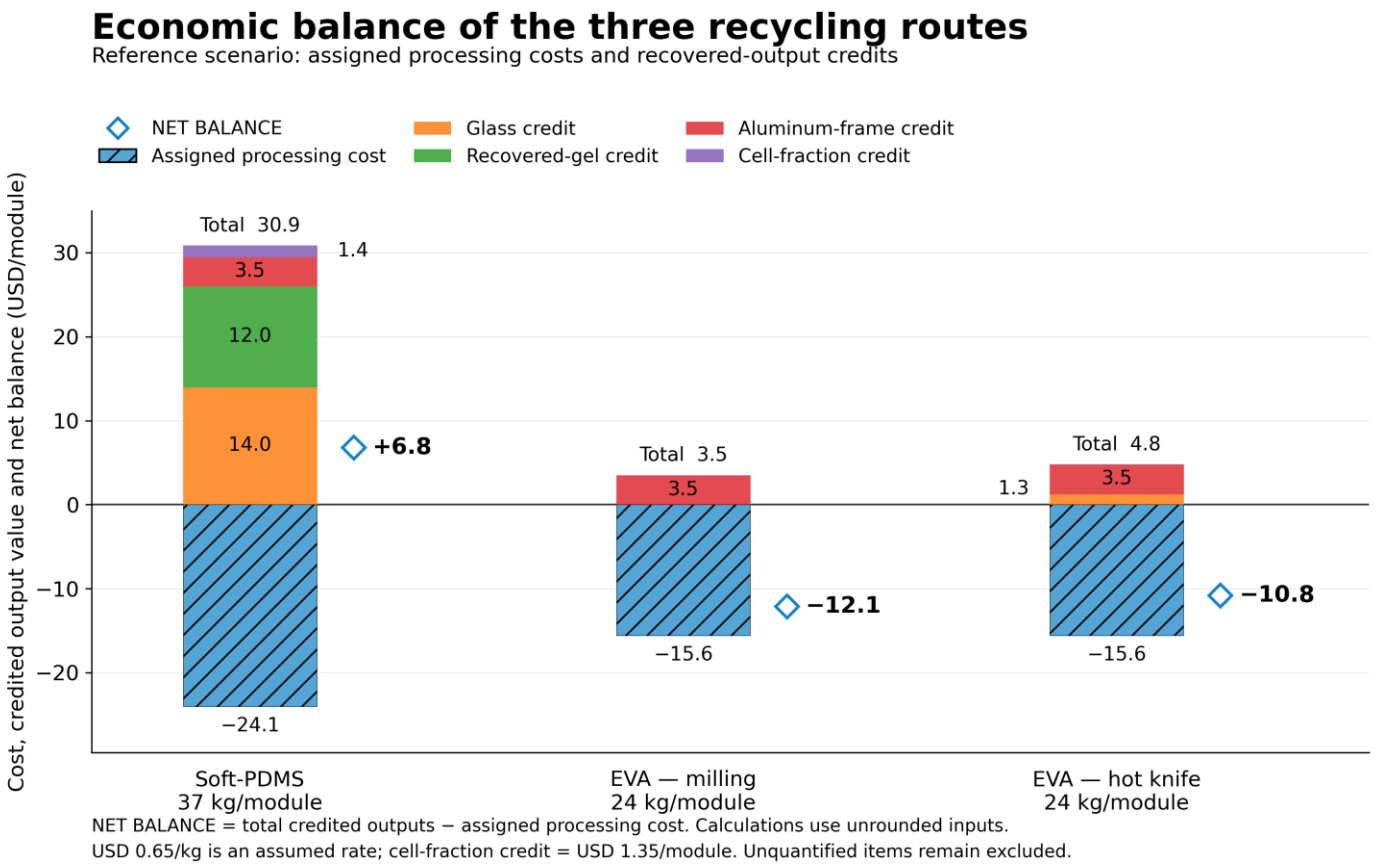


Figure 2. Economic balance of the three PV module recycling routes in the Table 1 reference scenario. The positive stacked bars show the credited glass, separately collected gel, aluminum frames, and the PDMS cell fraction; the hatched negative bars show the assigned gross processing costs. Diamonds indicate NET BALANCE, calculated as total credited outputs minus gross processing cost: +USD 6.8/module for soft-PDMS, −USD 12.1 for EVA milling, and −USD 10.8 for hot-knife separation. The values are scenario calculations under the boundaries in Section 2.2, which do not measure plant profits. The displayed cell-fraction credit of USD 1.4 is calculated using USD 1.35 before rounding.

The March 2017 Recycle Tech Japan (RTJ) report provides a separate example of gross-cost accounting. Its process-cost assumptions include management costs and exclude recovered-material sales, while sales and residual cell-sheet treatment are listed separately (Tables 5.1-2 and 5.2-2) [11]. This supports keeping material credits outside gross processing costs. The report concerns a historical Japanese model with 15 kg modules; its tariffs, frame masses, and transport boundaries are not transferred directly to the 24 kg and 37 kg reference constructions.

Similarly, Rozing et al. distinguished disassembly from subsequent recycling and disposal [12]. Their material-treatment parameter of EUR 0.65/kg applies to separated fractions, with disassembly accounted for separately; it is not a USD-denominated quotation for complete-module PDMS recycling. The monetary inputs of Tables 1 and 2 are specified directly in USD. Contextual TNO values originally reported in EUR retain the manuscript conversion basis of 1 EUR = 1.1355 USD [10], without inflation adjustment. Neither these external comparisons nor the four-minute separation benchmark [7] are used as an independent cost cross-check.

2.3. Emissions and Recovery Indicators

The EVA-case calculation treats the 3.0 kg encapsulant mass as EVA with 28 mass% vinyl acetate, a representative composition for PV-grade EVA [13]. The complete oxidation of fossil polymer carbon without carbon capture is calculated using the carbon-balance principle [14]:

$$m_{CO_2} = \Sigma(m_j \times w_{C,j} \times 44/12) \quad (2)$$

For EVA with 28% mass vinyl acetate, the derived direct combustion factor is 2.83588 kg CO_2/kg EVA. The complete combustion of 3.0 kg EVA therefore yields approximately 8.5 kg CO_2 per module. Additives and the separate TPT backsheet are excluded from this stoichiometric CO_2 value; fluorine-related treatment concerns are considered separately. Electricity-related emissions are kept separate from direct polymer combustion. No carbon price equivalent is included in the economic results.

Direct reuse means retaining a component for another use without remelting it. Material recycling refers to recovery as a secondary raw material and is reported separately from energy recovery. For the construction of the assessed soft-PDMS, published reference values of 95–98% recycling efficiency and up to 81% direct reuse are retained [6].

2.4. Sensitivity Scenarios and Break-Even Calculations

The sensitivity analysis increases the Table 1 gross processing costs by 5%, 10%, 15%, and 20% while holding the module masses and all credited outputs constant. The base case is included for comparison. These deterministic changes are selected stress tests, not measured cost ranges or probability estimates. The same proportional increase is applied to all three routes; it does not imply that their actual costs change together. Because the assigned cost is not divided into capital and operating components, this is a processing-cost sensitivity rather than an operating-expenditure-only analysis.

An additional sensitivity test varies the processing rate for each route separately by ±20% around the reference value of USD 0.65/kg, giving USD 0.52 and 0.78/kg. In each case, the rates for the other two routes remain at USD 0.65/kg and all output credits are unchanged.

For a proportional processing cost increase δ, the calculation is as follows:

$$\begin{aligned} C_i(\delta) &= C_{i,0}\,(1 + \delta) \\ B_i(\delta) &= R_i - C_{i,0}(1 + \delta) \end{aligned} \quad (3)$$

Here, C in the base case is the cost from Table 1, and δ takes values of 0, 0.05, 0.10, 0.15, and 0.20. Break-even thresholds are found by setting the corresponding net balance to zero. Dependence on the glass and gel values is assessed separately in Section Sensitivity and Break-Even Conditions. The aluminum credit of USD 3.5, the hot-knife glass credit of USD 1.3, and the PDMS cell-fraction credit of USD 1.35 are fixed scenario inputs at the stated precision. The resulting processing cost sensitivity is shown in Figure 3.

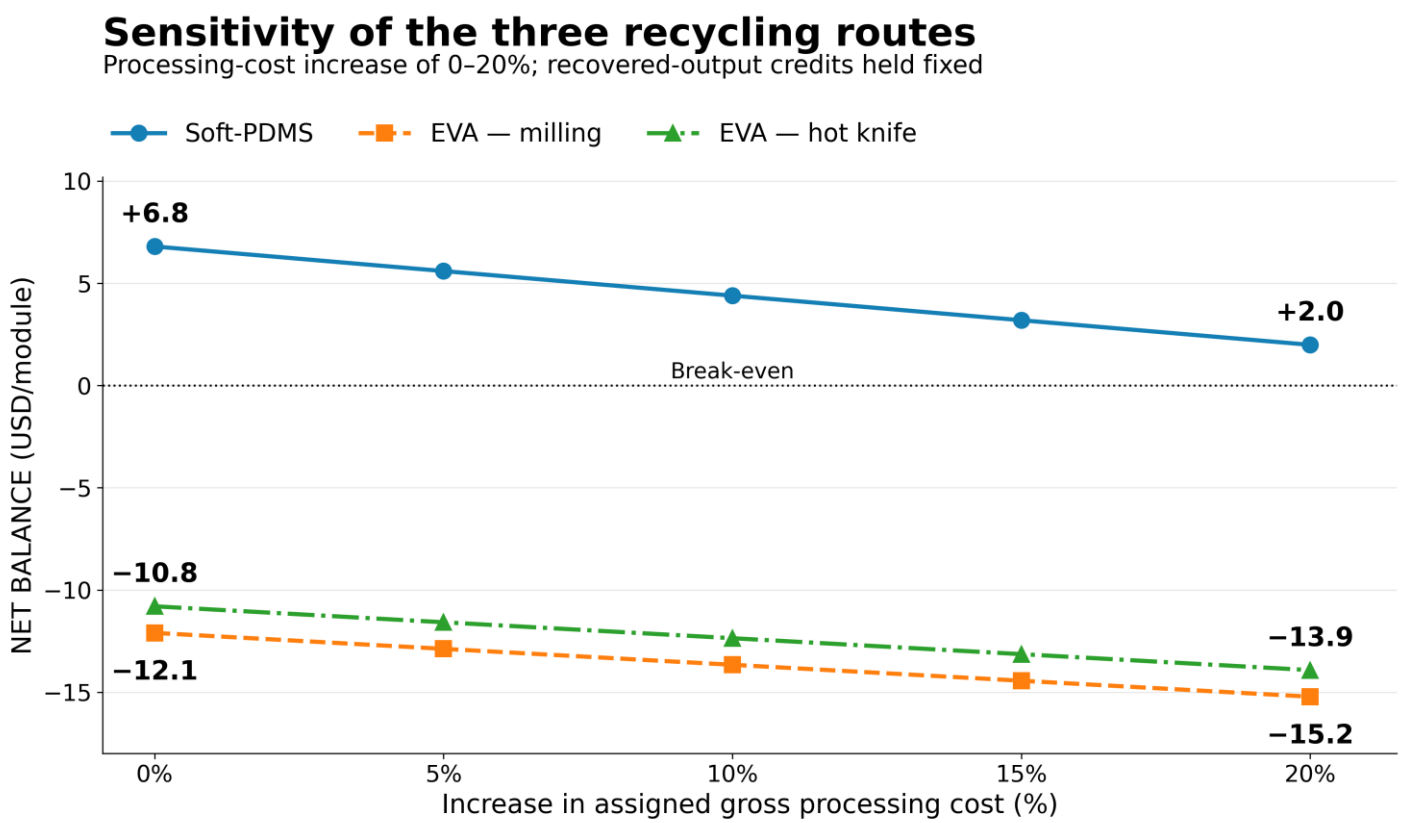


Figure 3. Sensitivity of the three recycling route NET BALANCES to increases of 0–20% in assigned gross processing costs, calculated from Tables 1 and 2 with module masses and material credits held fixed. With a 20% cost increase, the balances are +USD 2.0/module for soft-PDMS, −USD 15.2 for EVA milling, and −USD 13.9 for hot-knife separation. The dotted horizontal line indicates zero net balance; the analysis tests processing cost changes only.

3. Results and Discussion

3.1. Pathways That Bypass or Delay PV Module Recycling

Approximately 10% of global PV waste is reported to be recycled [1]. By comparison, the EU figure above 86% for 2019–2023 concerns collected modules recycled or prepared for reuse [15]. The denominators differ. National and industry reports distinguish between collection, storage, and completed treatment [16–18]. Five pathways can bypass or delay recycling, with high treatment costs providing an economic incentive in some cases.

(1) Disposal on land. Landfilling and uncontrolled dumping bypass material recovery [15,17]. U.S. service providers reported in-house recycling costs of USD 14–30/module in 2023 compared with USD 1–5/module for landfill disposal [18]. This difference illustrates why less expensive disposal can be financially attractive.

(2) Storage at existing PV plants after repowering. Replacement modules can enter service while the removed modules remain on-site. Approximately 1800 and 2000 damaged modules stored outdoors for at least three and four years, respectively, have been documented in Czech field cases [5]. Repowering can therefore precede end-of-life treatment by several years.

(3) Stockpiling at collection and recycling facilities. Collection can be reported before processing has occurred. The 2025 IEA PVPS report recorded 80,000 intact modules held by an Australian recycler while processing facilities were planned [16]. Such

inventories represent material awaiting treatment and must be distinguished from completed recycling.

(4) Export with a risk of disposal in the receiving country. Used modules may be shipped to developing countries under a reuse designation without adequate testing; overseas buyers may pay for modules that would otherwise incur domestic recycling fees [16]. If modules are unusable or fail soon after arrival, this can transfer the waste-management burden to the importing country [15]. Verified second use of functioning modules remains a separate, legitimate pathway.

(5) Incineration after frame removal. An earlier LCA considered removing the aluminum frame, incinerating the remaining module and landfilling the residues [19]. Where accepted, preparation of the furnace feed may include crushing and mixing with other waste [20]. This disposal scenario does not recover the silicon cell material and is separate from the recycling routes compared in Table 1.

After collection, recycling also requires financing. In France, Soren's 2025 material revenues covered approximately 31.7% of its reported collection and treatment expenditures [21]. This measures the share financed by material sales, not the organization's overall profit or loss.

These pathways may occur sequentially; their global shares and operators' motives remain uncertain. Collection or export alone does not establish completed recycling. The following analysis examines processing costs and recovered-output values in a mass-based comparison scenario after treatment entry. The service cost comparisons above provide context, not Table 1 inputs.

3.2. Technical and Economic Comparison of the Three Recycling Routes

Table 1 retains a conventional cost-and-revenue format. The common assumed rate of USD 0.65/kg is USD 24.1/module for soft-PDMS and USD 15.60/module for each EVA/TPT route. The credits for the glass and gel are USD 14.00 and USD 12.00, respectively; the hot-knife glass credit is fixed at USD 1.3. A common USD 3.5 frame credit is applied once to every route. These values define the comparison scenario; the references establish material balances, recovery pathways and cost context rather than matched commercial quotations [6–9,11].

Usual "recycling" way of the EVA/TPT back sheet laminate is simple (low cost) burning including solar cells. Unlike EVA based solid PV laminates it is very easy to extract solar cells (strings) from the very soft PDMS gel at room temperature. The PDMS reference scenario assigns the 0.9 kg recovered cell fraction a value of USD 1.50/kg, using the metallurgical-grade silicon price reported by Tao et al. for 25 June 2021 as a valuation benchmark [22]. This gives a credit of USD 1.35/module. Kuśmierczyk et al. experimentally demonstrated ferrosilicon (FeSi) production using silicon recovered from end-of-life PV modules [23].

Table 1 compares selected value-retention scenarios within the stated accounting boundary and does not establish a definitive economic ranking of recycling technologies.

Table 1. Mass-based reference cost-and-revenue scenario for the three PV module treatment routes. Reference area: approximately 2 m². The monetary values are in USD/module, except for the processing rate.

Indicator	Soft-PDMS (A) Glass/PDMS/Glass 2 × 3.2 mm; 37 kg	Milling (B) Glass/EVA/TPT 1 × 3.2 mm; 24 kg	Hot Knife (C) Glass/EVA/TPT 1 × 3.2 mm; 24 kg
Assumed processing rate (USD/kg)	0.65	0.65	0.65
Gross processing cost *	−24.1	−15.6	−15.6
Low iron glass credit	+14.0 **	0.0	+1.3 †

Recovered PDMS gel credit	+12.0 **	0.0	0.0
Aluminum frame credit ‡	+3.5	+3.5	+3.5
Recovered cell-fraction credit §	+1.4	0.0	0.0
TOTAL CREDITED OUTPUTS	**+30.9**	**+3.5**	**+4.8**
NET BALANCE	**+6.8**	**−12.1**	**−10.8**

Notes: Gross cost = complete-module mass × the assumed USD 0.65/kg rate; this is not a verified technology-specific tariff. ** low iron glass: approximately 4 m^2 × USD 3.5/m^2 = USD 14.00, with new PV-glass listings as component-value comparators [24]; separately collected gel: 3.0 kg × USD 4.00/kg = USD 12.00, with literature pricing context [25]. † The hot-knife glass credit is fixed at USD 1.3 and rounded from 15 kg × USD 0.085/kg before the balance calculation. ‡ USD 3.5 is an equal scenario credit for each frame, not a verified sale price. The negative values are costs; the positive values are credits. NET BALANCE excludes the unquantified items defined in Section 2.2. Reference prices inform the credit but do not constitute verified sales of the recovered materials. § The PDMS cell-fraction credit is calculated as 0.9 kg × USD 1.50/kg = USD 1.35/module [22]; no additional silver or copper revenue is credited from that fraction. Displayed values are rounded to one decimal place; balances use unrounded inputs.

For milling (route B), the USD 15.6 assigned processing cost and USD 3.5 frame credit yield a NET BALANCE of −USD 12.1/module. Glass, polymer, and additional metal revenues are not credited in this scenario. This does not establish that those fractions have zero market value: TNO and the RTJ report describe material-recovery pathways with output values dependent on quality and further treatment [9,11].

For the hot-knife treatment (route C), the credited outputs total USD 4.8/module: USD 3.5 for the frame and USD 1.3 for the glass cullet. Subtracting the assigned USD 15.60 processing cost gives a NET BALANCE of −USD 10.8/module. Separation, residue removal, and downstream laminate management remain distinct technical operations [9,26]. The IEA PVPS case reports a paid transfer of the residual laminate to a refinery [26]; no corresponding sale credit or disposal charge is assigned here without a matched value for the scenario. The need for later treatment does not by itself determine the sign of that transfer value.

Soft-PDMS (route A) is the only route with a positive NET BALANCE in the Table 1 scenario. The two low-iron glass sheets, 3.0 kg of separately collected optical-quality PDMS gel, the frame, and the cell fraction are credited at USD 14.00, USD 12.00, USD 3.50, and USD 1.35, totaling USD 30.85/module. Subtracting USD 24.05 gives +USD 6.8/module. The physical basis is the preservation of approximately 30 kg of glass and the recovery of a separate silicone fraction [6,7]. The positive balance depends on realizing the assumed output values within the stated cost boundary; it is not a measured plant profit.

The USD 14.0 low iron glass credit corresponds to two preserved intact sheets with a combined area of approximately 4 m^2, valued at USD 3.5/m^2. Published supplier listings give USD 3.80–4.50/m^2 for new 3.2 mm tempered PV glass at a minimum order of 2500 m^2 [24].

Another way to calculate/estimate glass credit is to evaluate the possibility of direct reuse of intact recycled glass in the production of new PV panels. Recycled glass could be used on the back side of the new PV panels [6]. Importantly, early-replacement scenarios of approximately 5–10 years [4] provide a context for component reuse. Therefore, it is possible that after 5–10 years, rear glass with the same dimensions/format could be used. Applied to the reference area, the retained price range corresponds to USD 15.2 –18.0. The selected USD 14.0 credit lies below this range and represents a component-value assumption for acceptable intact sheets, not a cullet price.

The separately collected 3.0 kg of optical quality PDMS fraction is assigned an assumed credit of USD 4.0/kg, yielding USD 12.00/module. For price context, Chen et al.

reported USD 5.8/kg for new two-component RTV silicone rubber [25]; this is a comparator material price rather than a measured sale price for the recovered gel.

Both credits depend on acceptance of the recovered outputs for their intended uses. Additional cleaning, testing, or downstream processing remains subject to the boundary in Section 2.2. The reference prices are not guaranteed sale prices. The USD 1.3 hot-knife cullet credit remains a separate scenario input and is not derived from these new-glass listings.

Aluminum frame removal is common for all three routes. The USD 3.5 credit is an identical comparison assumption for the 2 kg reference aluminum scrap [6], equivalent to USD 1.75/kg before rounding (USD 1.8/kg when rounded to one decimal place); it is not attributed to a verified buyer quotation. It affects each absolute balance equally and does not determine the differences between routes. Other metal revenues remain unquantified; the PDMS cell-fraction credit is included separately. The RTJ report supports separate gross-cost and revenue accounting, not direct transfer of its different frame masses into this comparison [11].

The output credits refer to the condition in which the separated material is transferred to its next user. The PDMS credits concern acceptable recovered sheets, gel and the cell fraction, not finished certified glazing or regenerated silicone. Their qualification yield and additional preparation costs are not quantified. Similarly, the hot-knife credit presupposes acceptable cullet; subsequent laminate treatment and any associated revenues require a route-specific assessment. The necessary preparation depends on the intended application [6,9,26].

The common mass-based rate assigns the heavier PDMS module USD 8.5 more in processing cost than either the EVA/TPT module does: (37 − 24) kg × USD 0.65/kg. Its positive balance therefore comes from the assumed value of two preserved sheets, the separate silicone fraction and the recovered cell fraction, not from a lower assigned processing cost. This comparison identifies the role of the retained component value without establishing identical actual costs per kilogram for the three processes.

Sensitivity and Break-Even Conditions

In Table 2, the processing cost increases directly to that in Table 1. The soft-PDMS NET BALANCE decreases from +USD 6.8/module to +USD 4.4 at a 10% increase and +USD 2.0 at a 20% increase, with output credits unchanged. Both EVA/TPT routes remain negative throughout this cost-increase range.

No operation times, hourly rates, or equipment-throughput assumptions are included in these calculations. The +20% case corresponds to USD 0.78/kg and processing costs of USD 28.9/module for PDMS and USD 18.7/module for each EVA/TPT route. Table 2 tests cost tolerance only; output price and acceptance risks are considered below.

Table 2. Sensitivity of the Table 1 NET BALANCES to increases in gross processing costs up to 20%. Material credits remain fixed. As calculated in this study, the balances are in USD/module.

Processing-Cost Increase	Soft-PDMS	EVA Milling	Hot Knife
Base case	**+6.8**	**−12.1**	**−10.8**
+5%	+5.6	−12.9	−11.6
+10%	+4.4	−13.7	−12.4
+15%	+3.2	−14.4	−13.1
+20%	**+2.0**	**−15.2**	**−13.9**

Note: Each row multiplies the Table 1 processing cost by the stated factor. Module masses and glass, gel, frame, and cell-fraction credits are unchanged. The same scope and exclusions as in Table 1 apply. The results are rounded only after calculation.

With the output credits in Table 1, the PDMS net balance remains positive throughout the selected ±20% processing-rate range, varying from USD 2.0 to 11.6/module. The corresponding ranges are −USD 15.2 to −USD 9.0/module for milling and −USD 13.9 to −USD 7.7/module for hot-knife separation.

With all reference credits retained, the PDMS balance reaches zero when the assigned processing cost equals USD 30.85/module. This corresponds to approximately USD 0.8338/kg, or a 28.3% increase over the reference cost. In the +20% case, an additional net cost or loss of credited revenue of approximately USD 2.0/module would bring the balance to zero. A positive cost-only sensitivity result does not establish robustness to simultaneous adverse changes in costs and output values.

For PDMS, let G be the combined credit for both glass sheets and S the total separately collected gel credit, both in USD/module, and let c be the gross processing rate in USD/kg. The reference case uses G =USD 14.0/module and S = USD 12.0/module, corresponding to 3.0 kg of gel at the assumed USD 4.0/kg. With the USD 3.5 frame credit and USD 1.35 cell-fraction credit retained, the net balance and glass break-even conditions are as follows:

$$B_A = G + S + 3.5 + 1.35 - 37c$$
$$G^* = 37c - S - 3.5 - 1.35 \quad (4)$$

At c = USD 0.65/kg and S= USD 12.0/module, the exact combined glass break-even value is approximately USD 7.2. Without gel revenue, it is approximately USD 19.2. A positive balance requires a glass credit above the corresponding exact threshold. These are calculated conditions, not observed buyer prices; they shift if output acceptance, preparation requirements, or other unquantified costs and revenues change.

The output value checks make the remaining dependency explicit. At the reference cost, removing only the USD 12 gel credit changes the PDMS balance to −USD 5.2/module. Halving only the joint glass credit from USD 14 to USD 7 gives −USD 0.2/module. Neither check asserts that the recovered material is unusable. They show that the positive reference balance requires sufficient combined value from the recovered outputs and cannot be interpreted as unconditional profitability. Under the reference PDMS assumptions, the net balance remains positive when the combined reduction in credited output value and additional costs beyond those already included is less than USD 6.8/module.

A plant-specific extension must add both additional revenues and additional costs to the same boundary. The paid transfer of hot-knife residual laminate reported in [26] must not be treated automatically as a disposal charge; neither may an intermediate sale and the eventual final-metal revenue be credited twice within one integrated chain. No unverified downstream price or fixed surcharge is assigned here.

3.3. Room-Temperature Soft-Gel Delamination and Comparison with a Hot Knife

The experimental basis for soft-PDMS disassembly was established in two stages. In a 2025 peer-reviewed study, eight modules yielded 15 intact glass sheets out of 16, corresponding to 93.75% successful sheet separation in that experimental series [6]. The same study reported 95–98% recycling efficiency for the assessed construction and direct reuse of up to 81% of the total module mass [6].

Frame and junction box removal are common operations for the PDMS and standard EVA/POE modules [6]. The technological distinction begins at delamination: the soft-PDMS route uses progressive mechanical opening at room temperature, whereas standard EVA laminates require destructive mechanical treatment or thermal/mechanical delamination followed by further polymer handling.

A subsequent optimization study evaluated seven full modules with 3.2 mm double glass and reported successful opening times decreasing from 16 to 4 min, with both sheets preserved in the listed optimization trials [7]. The shortest successful 4-min result is used

here as a technical separation benchmark, not as a complete recycling cycle time or an industrial-average throughput. The reference scenario credits both glass sheets, consistent with their intact recovery in the seven complete-module delamination trials reported by Poulek and Kozelka [7].

This design-for-disassembly behavior is relevant because the circular-economy output is a preserved component rather than glass chemistry recovered only after crushing and remelting. The final preparation of a recovered sheet still depends on its intended next use.

The mechanical explanation is progressive local opening, not simultaneous detachment of the complete module area. Thicker sheets resist the local bending imposed by the wedges. For otherwise identical glass plates, the bending stiffness varies with the thickness cubed, so the 3.2-to-1.6 mm ratio is eight. This is a glass-stiffness ratio, not an eightfold measured module strength or proof that every thin-glass design is unrecoverable [7].

Hot-knife separation can result in the recovery of an intact glass sheet, but residual encapsulant requires additional treatment. TNO describes a blade temperature of approximately 300 °C and adherent polymer residue on the separated glass [9]. TNO discusses the remelting of suitably cleaned recovered glass as a potential route to new solar applications [9]. The report does not establish direct reuse of recovered sheets in new PV modules without remelting. The IEA PVPS inventory lists glass cullet as a recovered output and describes an outlet to glass-product manufacturers [26]. Post-separation mechanical cleaning may include steel-wire brushing: a published patent describes roller brushes following separation with a heated blade [27]. An author-generated schematic of the process is presented in Figure 4.

Wire-assisted approaches further illustrate the importance of the complete process boundary. Surowiak and Wahman combined wire separation with hot-air heating to approximately 200 °C and subsequently used five minutes at 400 °C to remove polymer residues [28]. Zagorski et al. tested resistance-heated wires at approximately 120–170 °C on small, pre-cracked samples [29]. These studies demonstrate delamination concepts but do not provide a directly comparable commercial full-module recycling cost.

Recovered glass must therefore be classified by output quality and by the amount of post-treatment needed. Milling directly produces cullets, hot-knife systems preserve the sheet during separation but can leave EVA residue, requiring further cleaning before high-value glass recycling [9], and soft-PDMS preserves two intact sheets that can be prepared for direct industrial reuse without remelting [6]. Direct component reuse and material recycling are consequently reported as different circular-economy outcomes rather than being merged into a single mass-recovery percentage.

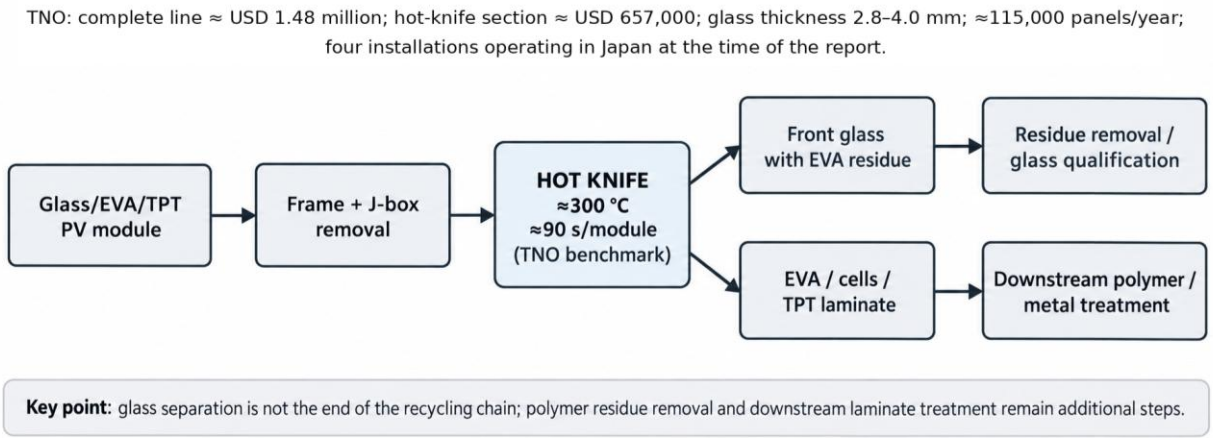


Figure 4. Author-generated schematic of hot-knife delamination and subsequent treatment based on TNO [9]. After the frame and junction box are removed, heated separation produces glass with

EVA residue and a residual EVA/cell/TPT laminate, which requires separate downstream operations. The approximately 90 s/module cycle and equipment-investment figures are historical TNO benchmarks; they are not used to derive the per-module costs in Table 1. Equipment purchase prices are distinct from per-module operating costs.

3.4. Direct Reuse of Recovered Glass as Rear Sheets in New PV Modules

In the PDMS route assessed here, both recovered glass sheets are intended for direct use as rear glass in compatible new PV modules. The assessed route includes no crushing, remelting, brushing, or solvent cleaning of the glass. The receiving module design must accommodate the sheet dimensions, thickness, and condition. As a proposed configuration, where both recovered sheets meet the acceptance criteria, one dismantled double-glass module could supply rear glass for two new modules of comparable size. This pathway retains the glass component without remelting and provides a practical basis for comparison with suitable replacement glass rather than cullets.

Before reuse, manual dark-field optical inspection is proposed, adapting the surface-inspection principles of ISO 14997:2017 [30]. Both faces, edges, and corners would be examined against a matte-black background under oblique white LED illumination from several directions, with magnification of suspect areas. Sheets with detected cracks would be withheld from reuse. This screening identifies optically detectable defects; it does not measure residual mechanical strength.

Early-replacement scenarios of approximately 5–10 years [4] provide a relevant context for planning component reuse. In the present study, a shorter interval between manufacturing and recovery is considered a potential advantage for matching sheets to compatible production formats. This is a proposed implementation benefit, not a demonstrated compatibility rate. The interval concerns replacement, not a universal technical lifetime; age alone guarantees neither acceptance nor price.

A manufacturer-specific arrangement covering the accepted dimensions, inspection requirements, quantities, and transfer price defines the intended outlet. For internal reuse, the relevant value is the avoided purchase of suitable replacement glass, net of additional preparation costs. A sale credit and an avoided-purchase credit must not both be counted for the same sheet. Table 1 retains a single conditional credit for each recovered output.

3.5. From Recovered Soft-PDMS Gel to Secondary Silicone Products

Approximately 3.0 kg of soft gel is collected as a separate fraction. Poulek et al. described clusters of high-purity PDMS that can be collected after delamination and recycled into consumer silicone/siloxane-rubber products; room-temperature electron-beam processing is identified as one possible downstream route [6]. The separately collected fraction is retained as silicone feedstock rather than being destroyed during delamination.

Independent experimental work by Oyama et al. demonstrated electron-beam modification of silicone rubber at approximately 25 °C using 1 MeV irradiation [31]. The samples were prepared from silicone rubber rather than recovered PV gel; thus, this study supports the physical feasibility of room-temperature electron-beam modification but does not establish a complete industrial recycling route for PV-derived PDMS. For the 3.0 kg separately collected fraction, an illustrative dose of 100 kGy corresponds to 300 kJ, or 0.0833 kWh, of absorbed energy; this is absorbed dose energy only and must not be interpreted as the electrical consumption of an industrial accelerator, whose efficiency, cooling, shielding auxiliaries, beam utilization, and throughput would also contribute to electricity demand.

3.6. Direct Emissions, Energy, and Useful Material Recovery

Applying Equation (2) to the defined 3.0-kg EVA case gives 8.5 kg CO_2 per module. This value represents direct CO_2 from complete EVA combustion only; it excludes TPT combustion products, electricity use, and other treatment emissions. The selected non-incinerating soft-PDMS route has zero direct CO_2 from encapsulant combustion within the defined delamination boundary. This is an avoided treatment-stage term, not a claim of atmospheric carbon removal or a zero-footprint module.

The same EVA-case calculation is used consistently in Table 3: 3.00 kg × 2.835 kg CO_2/kg EVA = 8.5 kg CO_2 per module. No PDMS is burned during the assessed delamination step. Approximately 3.0 kg of the separately collected gel fraction is retained for material use.

Table 3. Environmental, energy, and recovery indicators for the selected routes. Separation and subsequent glass remelting are listed as distinct operations. Reference module area: approximately 2 m^2.

Indicator	Soft-PDMS (A) Glass/PDMS/glass	Milling (B) Glass/EVA/TPT	Hot knife (C) Glass/EVA/TPT
Circularity	Up to 30 kg (≈81%) direct reuse; 95–98% recycling; two intact glass sheets preserved [6]	0 kg direct reuse; ≈15–90% recycling; published reference range [6]	Direct reuse not quantified; no single complete-route efficiency reported [9]
Separation/delamination	Room-temperature opening; total electricity not quantified [6,7]	Crushing/sorting energy not quantified in this model	≈0.035 kWh/kg in the cited inventory; heated blade ≈300 °C [9,26]
Subsequent glass remelting	0 MJ remelting when intact glass is directly reused; not a total-process energy value [6]	≈169 MJ for the 15 kg reference glass quantity [6]	Remelting of suitably cleaned recovered glass is a potential downstream route [9]; energy not quantified here
Direct CO_2 from encapsulant combustion (EVA case; TPT excluded)	0 kg CO_2 during delamination [6]; ≈3.0 kg gel collected separately;	8.5 kg CO_2/module if the defined 3.0-kg EVA case is completely combusted [6,13,14]	8.5 kg CO_2/module for the same downstream EVA-combustion scenario [6,13,14]
TPT/fluorinated-gas treatment	No TPT backsheet; no PDMS-combustion flue gas during delamination [6]	HF/fluorinated gases possible if TPT is thermally treated; off-gas control required [32,33]	Same TPT-specific issue if the residual laminate is thermally treated [26,32,33]

Note: The ≈81% glass-mass share (30/37), 15/16 intact-sheet recovery, and reported 95–98% recycling potential use different denominators [6]. The 169 MJ refers to remelting 15 kg of glass—not milling—and is avoided only through actual reuse without remelting. The ≈110 MJ for non-glass components is not the PDMS-delamination energy [6]. The 0.035 kWh/kg hot-knife inventory excludes glass residue removal and laminate treatment [26]. Missing operation-specific energy values are not treated as zero.

TPT denotes a Tedlar/PET/Tedlar backsheet with polyvinyl fluoride (PVF) outer layers and a polyethylene terephthalate (PET) core [33]. Fluorine is therefore present in the backsheet polymer, separately from EVA. Danz et al. demonstrated fluorine transfer into the gas phase during the pyrolysis and incineration of fluorinated backsheets [33]. Zhang et al. investigated HF and organic fluorine species generated during TPT thermal treatment [32]. These findings identify additional off-gas capture and treatment requirements. Module-level HF and TPT-derived CO_2 quantities are not calculated because the polymer-layer mass fractions of the 2.0 kg backsheet are unspecified. Gas generation before abatement must not be equated with uncontrolled release to the environment. The selected

glass/PDMS/glass construction contains no TPT backsheet and avoids this TPT-specific requirement during room-temperature delamination.

Environmental protection expenditure should therefore not be represented by an identical fixed amount for the three routes. Milling creates glass grit and comminution-related dust-control requirements [6,8]; hot-knife systems require heated separation, residue removal, and downstream management of EVA/TPT laminates [9,26], whereas thermal treatment of fluorinated backsheet material can require acid–gas control [32]. The soft-PDMS delamination step does not create a flue-gas-cleaning requirement from encapsulant combustion because no such combustion occurs [6]. The common mass-based cost assumption in Table 1 does not independently quantify these route-specific environmental protection requirements.

Thermal treatment requirements depend on the actual downstream fraction and the selected process. No generic hazardous-waste gate fee is assigned to an EVA/TPT module. A route-specific assessment would need the transferred mass, composition, applicable acceptance conditions, and the treatment or sale contract; the need for further processing alone does not determine the sign of that transfer value [26,32].

The distinction between direct reuse and material recycling is therefore central to the comparison. Milling destroys the glass component and returns the glass through cullet; the hot knife preserves the sheet geometry but can require polymer residue removal, and soft-PDMS preserves the glass component for reuse without remelting. An equal recovered mass does not imply an equal circular value.

The published 95–98% soft-PDMS recycling efficiency and up to 81% direct reuse are treated as the factual results of a peer-reviewed reference study [6].

The energy comparison in [6] further supports the material-quality result, but the boundary must be stated precisely. The published remelting balance assigns approximately 169 MJ to remelting the 15 kg glass sheet in the reference EVA/TPT module, whereas this term is zero when an intact sheet is reused in the soft-PDMS route. The approximately 110 MJ total shown for the PDMS case represents the listed remelting requirements of common non-glass components and not the energy consumption of the mechanical PDMS delamination operation itself.

The environmental assessment identifies treatment requirements that may be avoided by component preservation. The economic scenario assigns a gross processing cost and credits selected outputs, but it does not separately quantify all the expenditures associated with those environmental requirements. A lower actual complete-route cost is therefore not inferred solely from the treatment-stage comparisons.

Direct use of both glass sheets recovered from PDMS modules preserves component value without remelting. Life-cycle comparisons should account for recovery yields, output quality, and actual replacement of new products, with consistent boundaries for electricity use, emission control, and downstream treatment [34].

3.7. Economic Implications of Component Preservation

The mass-based scenario separates the value of preserving components from the assigned processing cost. With the stated processing cost and output value assumptions, soft-PDMS has a positive net balance of USD 6.8/module. At fixed output values, this balance remains positive through the tested +20% increase in processing cost. The separate glass and gel checks show the limit of this result: output-value uncertainty can eliminate the positive balance even without a cost increase.

TNO reports an estimated total recovered material value of approximately USD 7.5–23.8 per panel after currency conversion, with crushed glass contributing approximately USD 0.6–2.7 and aluminum and silver contributing greater shares [9,10]. Deng et al. reported cullet values of approximately USD 3–75/t, depending on contamination and

quality [8]. These benchmarks concern different output states and do not validate the Table 1 prices. They also show why assigning no credit to an unquantified fraction must not be interpreted as proving that the fraction has no value.

The retained supplier listing in Section 3.2 provides context for the USD 14.00 component-value assumption [24] but does not eliminate this uncertainty. The 50% glass-credit reduction therefore remains a relevant sensitivity check. Similarly, the silicone price comparator [25] complements the downstream-use evidence [6,31] without establishing a transaction price for a PV-derived gel.

The analytical contribution is the set of cost-and-value conditions that can be tested against plant and buyer data. With the reference gel, frame, and cell-fraction credits, the two glass sheets must jointly exceed USD 7.2 at the assumed processing rate; without gel revenue, they must exceed USD 19.2. The shortest successful four-minute opening [7] supports disassemblability but does not independently validate the cost input. An independent cross-check would require comparable process boundaries and separately documented costs rather than matching a time calculation to the same assumed result.

The comparison does not claim that every silicone formulation has the same behavior; the result applies to the specific very soft PDMS construction evaluated experimentally.

Preserving saleable components can reduce the net end-of-life cost of module replacement [4,6]. Replacement decisions should compare the benefits and costs of repowering with continued operation; recovery of the initial investment alone does not determine the optimal replacement date [35].

4. Scope and Implementation

The conclusions concern the three defined treatment routes and the specific soft-PDMS construction evaluated in the cited experiments. A complete cradle-to-grave assessment would additionally include module manufacturing, transport, electricity generation during service, and all subsequent product uses. These elements are outside the scope of the present treatment-stage comparison.

The thin 1.6/1.6 mm double-glass EVA modules are outside the main three-route numerical comparison. The TNO hot-knife benchmark in [9] Appendix D.1 covers glass thicknesses of approximately 2.8–4.0 mm [9], so its performance should not be transferred directly to thin double-glass modules.

5. Conclusions

Reports in the published literature indicate that only approximately 10% of global PV waste is recycled [1]. The PV panel landfill fee is in the range of just 1–5 USD [18]. Recently, the recycling cost of PV panels has usually been above 10 USD/panel [18]. Improving the economics of end-of-life treatment is therefore important for increasing actual recycling. This is in accordance with environmental sustainability targets. Reducing processing costs while preserving saleable components can substantially improve the prospects for profitable recycling.

1. In the mass-based Table 1 scenario, soft-PDMS is the only route with a positive NET BALANCE: +USD 6.8/module, compared with −USD 12.1 for milling and −USD 10.8 for the hot knife. The positive net balance calculated for the PDMS scenario indicates potential to improve the economic attractiveness of recycling. Increasing the assigned processing costs by 20% leaves soft-PDMS at +USD 2.0/module when material credits remain unchanged. These results quantify conditional cost tolerance and dependence on recovered-product value, not verified complete-route profit margins.

2. The principal benefit of the soft-PDMS design is the preservation of recoverable components with potential reuse value, which is very important from the point of view of a circular economy. For the 37 kg reference module, approximately 30 kg of glass represents approximately 81% of the module mass. The preservation of intact glass sheets and separate recovery of the soft-PDMS encapsulant support the reported potential for 95–98% material recycling by mass [6]. Suitable recovered sheets may be reused as rear glass in compatible new glass/glass PV modules after cleaning and verification, retaining component value without remelting [6].
3. Preserving glass for direct reuse can avoid the energy demand associated with remelting. For the 15 kg glass quantity used in the reference calculation, the estimated remelting demand is approximately 169 MJ [6]. The complete incineration of 3 kg of EVA would release approximately 8.5 kg of CO_2 [6,13,14]. Nonincinerating soft-PDMS delamination has zero direct CO_2 emissions from encapsulant combustion within the defined process boundary. A full life-cycle assessment must additionally account for energy supply, equipment, transport, cleaning and subsequent material treatment.

These findings support the further development of PV modules designed for disassembly and component reuse. Industrial validation should establish complete processing costs, achievable throughput, recovery yields, and acceptance criteria and prices for the recovered outputs.

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