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# Assessment of the Availability and Recovery Potential of Silicon from Discarded Solar Panels

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Currently, silicon is a base material for more than 95% of photovoltaic (PV) modules. The deployment of PV modules is expected to increase significantly across the European Union (EU), leading to generation of millions of tons of cumulative end-of-life photovoltaic (EOL PV) waste in the coming decades. This huge expansion and waste accumulation emphasize the need for a circular economy approach. QUASAR, an EU-funded project, aims to develop a holistic recycling approach to manage the growing volume of EOL PV panels. With the help of advanced recycling technologies, QUASAR aims to enable efficient recovery of materials such as silicon, silver, polymers, glass, and other metals. As part of QUASAR, this study assesses the expected quantities of EOL PV modules and the silicon embedded within them under chosen scenarios based on historical PV installation data, EU-level installation forecasts, dynamic module mass-to-power ratios, and material composition data. In addition, the characteristics of a recovered silicon sample obtained from a preliminary refining step were evaluated using Inductively Coupled Plasma Mass Spectrometry (ICP-MS) and LECO analysis. Based on the quantity and quality assessments, the potential demand for silicon recovered from EOL PV panels as a secondary raw material in PV and other value chains has been discussed in the context of a circular economy approach.

## 1. INTRODUCTION

The goal of carbon neutrality drives the photovoltaic (PV) deployment at a faster pace, with terawatt annual installations anticipated globally by the end of this decade (Goldschmidt et al. 2021) (ITRPV 2025). In the European Union (EU), PV installation has reached 406 gigawatts (GW) in 2025 (Jäger-Waldau 2025) and is expected to reach 2.3 terawatt (TW) by 2050, according to long-term projections by the EU Joint Research Centre (JRC) (Chatzipanagi et al. 2025). This rapid expansion is expected to result in a substantial accumulation of end-of-life photovoltaic (EOL PV) modules in the coming decades, demanding effective waste management strategies and the valorisation of the recoverable materials. The profitability threshold for the sustainable recycling sector is reported to be 19000 tonnes/year (Bošnjaković et al. 2023). Therefore, understanding future EoL-PV waste generation is essential for planning effective collection, recycling, and material recovery strategies (Mahmoudi, Huda & Behnia 2021). In addition, assessing the quality of recovered materials is crucial to determine their suitability for reuse. QUASAR[1]is an EU-funded project that aims to develop a holistic approach for EOL PV panels, enabling the efficient recovery of key materials such as silicon, silver, polymers, glass, and other metals using advanced recycling technologies such as the water-jet delamination method and the pyrolysis process . Although QUASAR covers the

[1] https://quasar-project.eu/

entire PV recycling value chain, this study focuses specifically on PV waste estimation and the characterization of a recovered silicon sample.

Recent studies (Foster et al. 2025; Kastanaki 2025) estimate that PV waste will reach around 6 million tonnes (mt) and 23 mt of PV waste by 2040 and 2050 based on earlier National Energy and Climate Plans (NECPs) targets of 624 GW by 2030 and 1,116 GW by 2040. This study reassesses future crystalline silicon (c-Si) PV waste generation under the Early Loss scenario using the EU JRC net-zero projection of 2.3 TW installed PV capacity by 2050. A silicon sample recovered from EOL PV panels using the waterjet delamination method and preliminary chemical etching processes was assessed through Inductively Coupled Plasma Mass Spectrometer (ICP-MS) and LECO analysis to identify the presence of metallic and non-metallic impurities. Based on the quantity and quality of the recovered silicon, its suitability as a raw material and potential market demand were discussed. Evaluating the quantity of PV waste and the quality of recovered silicon is essential for supporting circular economy approaches through sustainable resource utilization and secondary raw material integration.

## 2. METHODOLOGY AND MATERIALS

### 2.1 Data

Historical and projected deployment of crystalline silicon (c-Si) PV was derived from PV installation data and the market share of c-Si technology. The mass of c-Si PV was estimated using a dynamic power-to-mass conversion factor (tonnes per megawatt). Based on the Weibull Early Loss (EL) scenario, the distribution of EOL PV waste and embedded silicon was estimated. The methodology of the waste estimation is shown in Figure 1 and the data sources and other assumptions are given in Table I.

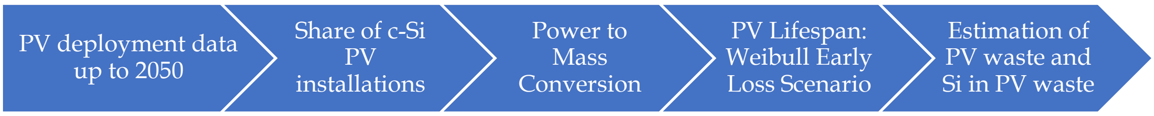


**Figure 1:** Methodology for calculating EOL-PV waste and embedded silicon

Table I Data sources and assumptions

| | |
|---|---|
| PV deployment data in the EU – (1996 – 2021) | (Czajkowski et al. 2023) |
| PV deployment data in the EU – (2021 – 2025) | (Solar Power Europe 2025) |
| Market share data for c-Si PV | (Philipps et al. 2025)(Foster et al. 2025) |
| Dynamic power-to-mass ratio | (Ovaitt et al. 2022) |
| Dynamic Si content in PV modules | (Ovaitt et al. 2022) |
| Specific polysilicon consumption (2026-2030) | (Taylor et al. 2025) |
| Specific polysilicon consumption (2030-2050, assumed constant) | 1.5 tonnes/MW |
| Assumptions on PV deployment projections from (2026-2050) | |
| 2026-2030 (750 GW by 2030 - Solar Power Europe 2025) | 68.7 GW (annual average installations) |
| 2030-2050 (2.3 TW by 2050 - Chatzipanagi et al. 2025) | 77.8 GW (annual average installations) |

PV Lifespan - Weibull Early Loss Scenario: The Early Loss Scenario is modelled using a Weibull function (Equation 1)

$$F(t) = 1 - e^{\left(\frac{t}{\beta}\right)^{\alpha}} \tag{1}$$

Where t is the lifetime of the panel in years, α and β are the shape factors. The failure probability curve is governed by the shape factors α (2.4928) and β (30) (Kastanaki & Giannis 2022); (Joseph M Kuitche 2010). The corresponding failure probability curve is shown in Figure 2. The detailed assumptions of the EL Scenario are provided elsewhere (IRENA 2016).

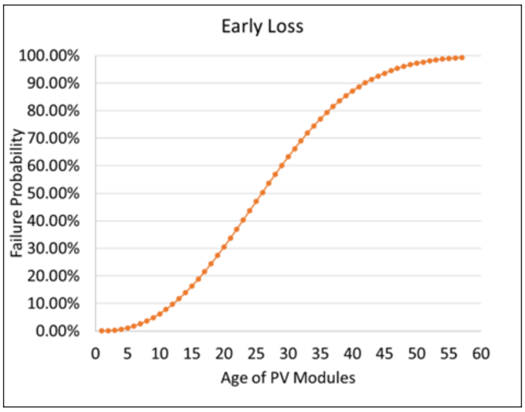


**Figure 1:** Shape function - Early Loss

Silicon content in PV modules: The dynamic silicon composition in PV modules was obtained from (Ovaitt et al. 2022) as shown in Figure 3, to estimate the potential availability of Si embedded in EOL c-Si PV modules

Average specific polysilicon consumption: In 2025, the average polysilicon consumption was around 2 tonnes per MW. Figure 3 shows the average specific polysilicon consumption estimated from the JRC report *Deep Dive on Critical Raw Materials for Solar Photovoltaics in the EU* for 2026-2030 (Taylor et al. 2025). From 2031 to 2050, it is assumed to remain constant at 1.5 tonnes/MW.

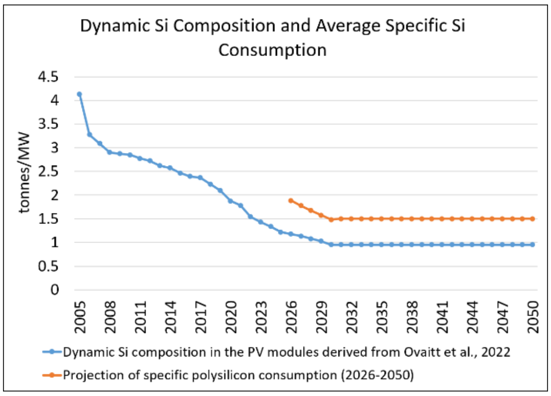


**Figure 3:** Dynamic Si composition in PV modules and Average Specific polysilicon consumption

**2.2 Experimental Methods**

Recovered silicon from EOL PV Modules: The recovered silicon sample was obtained from Luxchemtech GmbH, which uses the water-jet delamination process to separate the cell and polymer layers from the glass, enabling intact glass recovery and producing polymer flakes containing silicon cells. The silicon is then recovered from the polymer fraction through chemical processes. The details of the water-jet delamination and chemical processing steps can be found elsewhere (PVPS Task 12 2024) (Dimd et al. 2026).

Characterization techniques: ICP-MS and LECO analyses were carried out on the recovered silicon sample. ICP-MS detects the presence of metal impurities at the ppm level. For ICPMS, the sample was decomposed in 65% $HNO_3$ and 40% HF in a Milestone microwave and was further diluted with 5% $HNO_3$ and analyzed on an Agilent 8800 Triple Quadropole ICP-MS (ICP-QQQ) with an SPS 4 Autosampler. Further, They were quantified against standards from Inorganic Ventures, with $^{115}$In as the internal standard. LECO analysis uses infrared absorption and thermal conductivity to measure combustion gases within a sample. This process determines the presence and concentration of C, O and N. LECO analysis converts the elements in a sample into their oxidized forms using either the gas fusion method (hydrogen, nitrogen, and oxygen) or the combustion method (carbon).

## 3. RESULTS AND DISCUSSION

### 3.1 Quantity Estimation of EOL PV Modules

Based on historical and projected cumulative PV installations by 2050 and the dynamic market share of c-Si PV modules, approximately 2.25 TW of the total 2.3 TW is estimated to comprise c-Si technology. This corresponds to an estimated mass of 121.14 mt. Under the EL scenario, almost all modules installed by 2050 are projected to reach end-of-life by 2100, resulting in approximately 120.54 mt of cumulative EOL PV waste. Accordingly, cumulative EOL PV waste is estimated to reach 2.31 mt, 9.99 mt and 28.30 mt by 2030, 2040, and 2050, respectively. The annual distribution is expected to increase in the coming years, reaching a maximum of 3.15 mt in 2060 as shown in Figure 4. It should be noted that these estimates are based solely on PV installations up to 2050. Consequently, PV capacity added after 2050 would further contribute to both cumulative and annual EOL PV waste generation beyond 2050 and up to 2100.

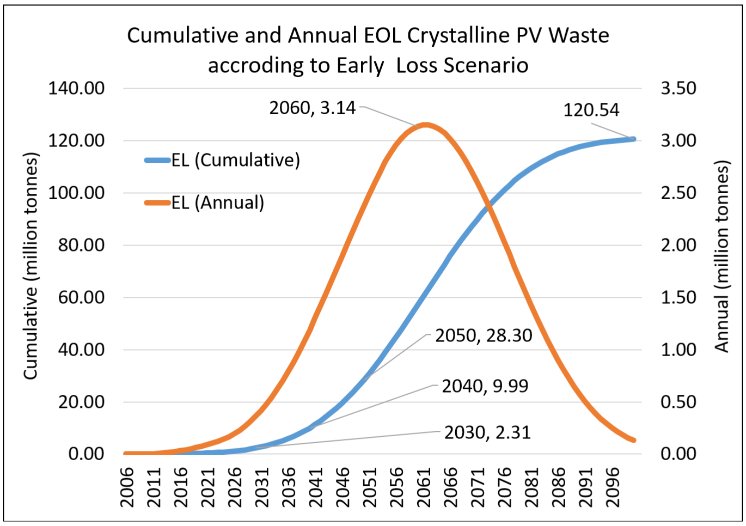


**Figure 2** Cumulative and Annual EOL PV waste generation according to EL scenario

### 3.2 Quantity Estimation of Silicon in EOL PV Modules

Based on the dynamic silicon composition of PV modules, the estimated 121.14 mt of cumulative EOL PV waste contains approximately 2.45 mt of embedded silicon. The embedded silicon in EOL PV modules is estimated to be around 79.4 kt (1000 tonnes (kt)), 289.8 kt, and 706.5 kt by 2030, 2040, and 2050, respectively, as shown in Figure 5.

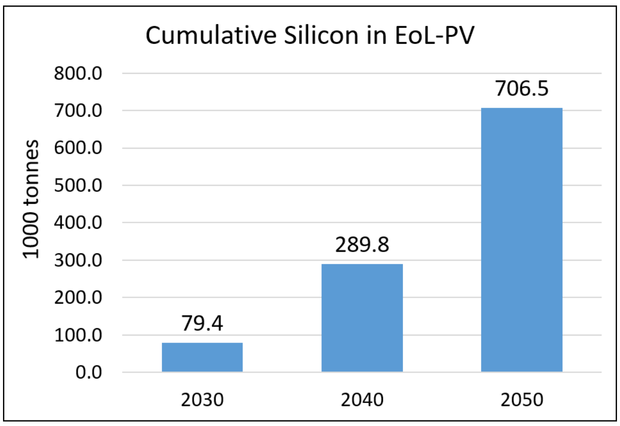


**Figure 5:** Cumulative embedded silicon in EOL PV according to EL scenario

Based on the projected PV deployment from 2026 to 2050 and the average specific polysilicon consumption, the cumulative polysilicon demand of the EU PV industry during 2026–2050 is estimated to reach 2.83 mt. On the other hand, the valorisation of the silicon in the EOL PV waste mainly depends on the recycling practices such as EOL PV modules collection efficiency, silicon recovery efficiency and refining efficiency. Table II shows the assumed efficiencies for the recycling practices under high, medium and low scenarios.

Table II Assumptions on recycling efficiencies

| Scenarios | Collection efficiency | Recovery efficiency | Refining efficiency |
|---|---|---|---|
| High | 100% | 100% | 100% |
| Medium | 85% | 85% | 85% |
| Low | 70% | 70% | 70% |

Based on these assumptions, the silicon availability from EOL PV waste was estimated. Figure 6 shows the cumulative polysilicon demand in the EU PV industry and the cumulative silicon availability from EOL PV waste under low, medium, and high scenarios. By 2050, the amount of silicon recoverable from EOL PV waste is estimated to reach 706.5 kt, 433.9 kt, and 242.3 kt under the high, medium, and low scenarios, respectively, corresponding to 25.0%, 15.3%, and 8.6% of the cumulative silicon demand of the EU PV industry.

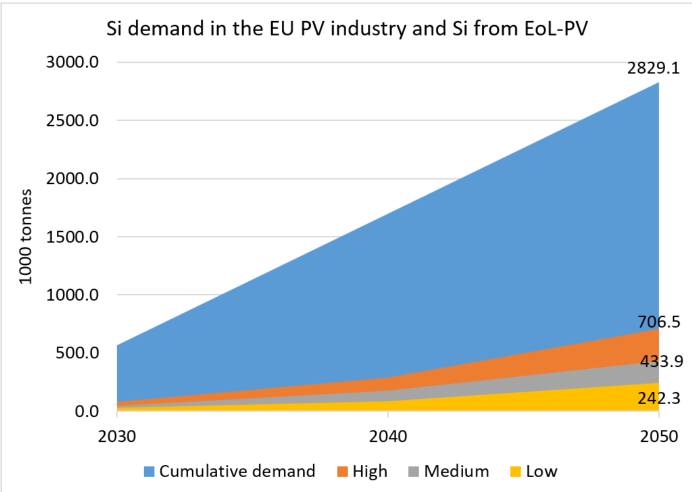


**Figure 3** Polysilicon demand in the EU PV industry and silicon from EOL PV modules

### 3.3 Quality of Recovered Silicon from EOL PV Modules

The results of the ICP-MS analysis, along with the impurity levels in metallurgical-grade silicon (MGS) and compensated solar-grade silicon (SGS) are shown in Table III, where compensated SGS refers to silicon of sufficient quality to manufacture standard solar cells without significant efficiency losses. The compensated SGS values reported by Coletti (2011) are used only as a reference benchmark representing a minimum quality level, as silicon purity requirements have evolved with the development of advanced PV cell technologies. Most impurities in the recovered silicon are significantly lower than those in MGS (Mallah et al. 2025) and approach or fall within compensated SGS-level thresholds (Gianluca Coletti 2011), indicating effective purification during recycling process. Elements such as Fe, Ti and Cu are present at relatively low concentrations, while boron and phosphorus remain below or close to detection limits. However, the recovered silicon exhibits a comparatively high silver concentration (182 ppm) and slightly high aluminium concentration (47 ppm) likely originating from PV cell metallization, highlighting the need for further refining for high-purity applications.

**Table III** Metallic impurities in the recovered silicon by ICP-MS

| Element | MGS | Compensated SGS | Si from EoL-PV | RSD |
|---|---|---|---|---|
| | | In ppmw | | (%) |
| **B** | 14.51 | <0.45 | <0.052 | - |
| **Al** | 4689.30 | <5 | 45 | 4.8 |
| **P** | 8.11 | <0.6 | <5.2 | - |
| **Sb** | 123.44 | <0.05 | 0.43 | 0.8 |
| **Ti** | 733.94 | <0.05 | 5.6 | 5.2 |
| **Fe** | 8230.86 | <5 | 2.9 | 2.8 |
| **Ni** | 92.10 | <1 | <0.52 | - |
| **Cu** | 54.65 | <1 | 14 | 0.9 |
| **Na** | 35.16 | <0.008 | 6.7 | 6.8 |
| **Ag** | 1 | <0.1 | 182 | 0.7 |
| **Sn** | <0.1 | <0.1 | 0.28 | 3.2 |
| **Pb** | <0.1 | <0.05 | <0.52 | - |

The LECO analysis measures the concentrations of C, N and O and the results are shown in Table IV. The recovered silicon contained 244 ppmw C and 940 ppmw O while nitrogen is below the detection limit, indicating the effective removal of $Si_3N_4$ anti-reflection layer. The C and O content remains higher than the low trace-level limits (<1 ppmw) required for SGS (Gianluca Coletti 2011), indicating the need for further process optimization or additional refining before direct reuse in the PV value chain.

**Table IV** Carbon, nitrogen and oxygen in recovered silicon by LECO

| | C | N | O |
|---|---|---|---|
| ppmw | 244 | <20 | 940 |
| RSD (%) | 6.93 | - | 6.03 |

**3.4 Secondary Raw Material Suitability**

To reach the level of solar grade polysilicon (SGS), the purity of the recovered silicon should be in the range of 6N to 9N. However, the purity of the recovered silicon from the preliminary refining processes exhibits a purity of approximately 3N when considering all metallic and non-metallic impurities. Upgrading the preliminary recycling and refining processes to increase the purity of recovered silicon from 3N to 6N may enable its direct use in the PV industry. Several studies report that, despite relatively higher metal concentrations, comparable solar cell performance can still be achieved compared to that obtained by the solar grade feedstock. The typical parameters that differentiate the impact of each element are diffusivity and segregation coefficients. The metal impurities are categorized into three groups: fast diffusing (Cu, Ni, etc.), relatively fast (Fe, Cr, etc.) and slow (Ti, Mo, V, etc.). Al and Ti specifications should not be relaxed because they are not gatterable. The metal impurities with high and relatively high diffusivity in silicon can be better tolerated than slowly diffusing ones, since they can be more easily manipulated during the gettering process in cell manufacturing (Gianluca Coletti 2011). In such cases, the recovered silicon at the current purity level may be considered for blending with pure polysilicon feedstock. However, the impact of different impurities on advanced cell technologies such as tunnel oxide passivated contact (TOPCon) and heterojunction (HJT) cells still requires further investigation.

On the other hand, compared to MGS, EOL PV-derived silicon exhibits much lower metallic impurities. MGS is primarily used in Al-Si alloying, Silicone production and polysilicon production industries. The current purity level of the recovered silicon enables its direct substitution for MGS in Al–Si alloy production, silicone manufacturing, and polysilicon industries. However, from a circular economy perspective, these applications offer relatively low economic value compared to higher-value reuse pathways.

## 4. CONCLUSIONS

This study provides a comprehensive assessment of PV waste generation under the chosen scenarios and the quantity of silicon recoverable from EOL PV modules based on low, medium and high recycling efficiency assumptions. Based on the EL scenario, the cumulative EOL PV waste in the EU is projected to reach 2.31 mt, 9.99 mt and 28.30 mt by 2030, 2040, and 2050, respectively. The estimations indicate that silicon recovered from EOL PV waste could make a meaningful contribution to the EU PV industry's silicon demand, supplying up to 25.0% by 2050 under the high scenario, compared with 15.3% and 8.6% under the medium and low scenarios, respectively. Apart from Al, Ag, O, and C, most impurities in the recovered silicon are considerably lower than those in MGS and are close to or within compensated SGS specifications, indicating effective purification during the recycling process. Although the current purity level of recovered silicon is sufficient for substituting MGS in several applications, its use in PV applications may require either blending with high-purity feedstock or further refining. These findings can support the development of circular economy strategies in the PV value chain.


## 4. ACKNOWLEDGEMENTS

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