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RESEARCH

The coming photovoltaic glass wave: techno-economic sensitivity, learning effects, and material flow insights

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Abstract

The prime objective of this study is to develop a cost-based sensitivity analysis of recycling perovskite solar module glass and to project future glass availability for recycling in Europe. To do this, we use global average prices data and an extended bottom-up cost model, with modifications to account for the recycling of perovskite photovoltaic glass. We conduct sensitivity analyses with 0, 2, and 5% changes in technical and economic factors, and learning-rate-based projections, to identify the key process steps that improve the economic benefits of glass recycling. For the PV glass projections, we employ the combination of the Weibull distribution and material flow analysis methods. While applying learning rate projections based on the EU-installed volume, we use conservative, base, and optimistic approaches with 10, 15, and 20% learning rates, respectively. The sensitivity analysis outcomes demonstrate that chemical/thermal treatment, washing, emission control, size reduction, and transport are key contributors to glass recycling costs. The learning rate projections for recycling costs indicate that recycling costs can be reduced by up to $7 per square meter with scalability up to 4 TW, based on current recycling infrastructure and technologies. Lastly, the results of the material flow analysis indicate that Europe alone will produce 10 to 25 million tons of glass per year from 2035 to 2070, depending on module life cycle and installation scenarios. The study suggests that there will be an urgent need for glass recycling infrastructure and reforms, recycling startups, and PV manufacturing businesses (SDG-7: clean and affordable energy) to support PV recycling and enhance circularity, thereby reducing the EU's resource dependence.

Keywords Glass recycling · Europe · Sustainability · Bottom-up cost model · Sensitivity analysis · PV glass availability · Learning rate · Material circularity

1 Introduction

Solar energy has emerged as a leading solution to meet global energy demand for industrial activities, mitigate climate change, and achieve net-zero emissions (Ding et al., 2026). As per recent data, global PV installed capacity has surpassed 2.8 terawatts (TW) in 2025, with China alone having more than 1 TW; the European Union 406 GW, the US 224 GW, Germany and Japan both passed 100 GW installation in 2025, India and Pakistan are expected to surpass 133 GW[1] & 50 GW[2] installation respectively (Masson, 2025). More recently, research has suggested that to achieve climate change mitigation, PV installations of up to 4.5 TW annually by 2050 are required (Chowdhury et al., 2025). Recently, another study argued that at least 3.4 TW per year should be installed by 2037 to combat climate change, leading to cumulative PV installations of 75 TW by 2050 (Nancy Haegel et al., 2023). These dramatic growth projections highlight a substantial demand for PV modules and, consequently, a PV recycling industry in the foreseeable future (Chen et al., 2020). More specifically, for a standard c-silicon module, the glass accounts for 67% of the module mass (T. Chowdhury et al., 2025). In parallel with conventional silicon modules, perovskite PV has emerged as a highly promising option with higher efficiency, tandem integration capability, and low-temperature processing (Al-Saleem et al., 2025). Unlike

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2 https://www.arabnews.com/node/2628379/pakistan.

Fig. 1 Perovskite Glass Recycling Process Source: Authors own based on Supplementary Information SI1

traditional modules, perovskite modules can be encapsulated in thick glass-glass or thin, flexible glass substrates, resulting in different glass thicknesses, intensities, and recycling implications (Prince et al., 2025). For perovskite modules, glass is also a major component, depending on the module type and whether it is rigid or flexible. From an economic perspective, the global PV glass market was valued at €14.4 billion in 2023 and is projected to reach €205 billion over the next 8 years, with a compound annual growth rate of 30% (Allied Market Research, 2024). According to recent Euro Inox reports, glass currently has a recovery value of €0.1 to € 1/kg, compared to other materials recovered in Europe (Sarah, 2025). While the European PV glass market size is estimated at around €110.4 million, it is expected to reach €255 million by 2030 (Gupta & Shukla, 2025).

In a more recent study, Peters et al. (2024) concluded that PV glass volume could exceed 100 Mt by 2034, while Goldschmidt et al. (2021) projected that global demand for PV glass could reach 200 Mt over the coming decades. Figure 1 elaborates on the perovskite glass recycling process used in this study for the overall technoeconomic analysis. Notably, the cost considerations in PV glass recycling include collection, transportation, processing, inspection, disassembly, glass separation, glass size reduction, and chemical treatment, which together determine the economic feasibility of closed-loop systems[3].

The tremendous growth of PV demand, and PV glass in particular, will drive the development of circular recycling to create an alternative market to absorb materials and glass from the existing PV value chain (Chowdhury et al., 2025; Peters et al., 2024). Despite the high weight of glass in modules, solar glass recovery remains economically vulnerable

[3] The cost considerations and recycling framework are developed based on the literature review.

due to its low material value, the lack of large-scale recycling infrastructure, and higher transport and processing costs (Dias et al., 2022). Uncertain end-of-life pathways lead to high costs and revenue uncertainties that conventional PV recycling models do not capture (Mukwevho et al., 2025). Hence, the current study empirically analyzes the key cost drivers of PV glass recycling, the effect of scaling up recycling operations, and the specific economic implications for glass circularity under different scenarios.

Meanwhile, the sensitivity analysis is essential to evaluate how fluctuations in energy, technical, and economic processes, as well as chemical treatment, transport, washing, drying, and glass size reduction, among others, affect overall recycling profitability. These assessments provide critical insights for academic scholars, policymakers, and other stakeholders to identify cost-effective ways and enhance the financial resilience of circular glass value chains. The current research further examines the full circular model loop costs of PV glass recycling, and attempts to conclude vis-à-vis glass materials circularity and policy interventions or strategies to enhance the PV sector's circular economy performance.

In addition, the study aims to examine learning rate projections based on current recycling costs, which can guide us on the level of scalability at which glass recycling might be profitable and economically feasible. Lastly, the current study projects glass availability in Mt/year from 2026 to 2070 based on current PV installations in Europe, under three scenarios: worst-case (current installation rate), moderate case (EU Green Deal-3.5 TW by 2050), and best-case (7 TW by 2050). Based on the detailed analysis, the study draws novel implications for future PV glass availability in Europe and for glass recycling in the context of Sustainable Development Goal 7 (clean & affordable energy).

Although the existing literature has widely documented the technical feasibility of PV glass recycling (Sim et al., 2025), large-scale adoption ultimately depends on whether recycled materials can compete with original materials on purity, reliability, supply chain, and costs. More recently, Liao et al. (2026) researched the optimal siting of PV waste treatment facilities in China. The study concluded that large-scale recycling plants can achieve low-cost recycling, whereas small-scale plants face multidimensional limitations in achieving economically sustainable recycling. Along the same lines, Sun et al. (2026) argued that it is possible to achieve economically viable and environmentally friendly localized recycling of PV glass by reducing transport distances and costs. In the case of double-glass module recycling by First Solar, Preeti & Kumar (2025) concluded that economically sustainable glass recycling of PV is possible at a larger scale. Notably, the existing literature has not emphasized the comprehensive mechanisms involving the quantity of PV glass, the in-depth costs of inputs, and future glass availability. There lies the key novelty of this study: documenting an integrated framework that combines perovskite PV glass analysis, bottom-up cost modeling with sensitivity analysis, learning curve-based cost projections, and dynamic material flow analysis within a European context.

From a theoretical perspective, industrial ecology guides us toward a system-oriented approach to analyze energy & material flows across a product's life cycle to improve resource efficiency and mitigate waste (Heath et al., 2020; Mahmoudi et al., 2019). Notably, the future projection of PV glass availability is grounded in the principles of industrial ecology and stock-driven material flow analysis. The installed capacity, as per industrial ecology, is treated as an in-use material stock that is transformed into waste. However, the timing and magnitude of material flows are estimated using lifetime distributions that capture the probabilistic retirement of PV systems over time (Li et al., 2025). Further, by integrating the deployment scenarios with the lifetime assumptions and glass content, the material flow analysis provides a more robust mechanism for estimating future glass availability. Within this framework, a dynamic material flow analysis is employed to quantify the stocks and flows of materials over time, enabling the prediction of future waste generation based on historical deployment, lifetimes, and technological advancements (Zimmermann, 2013). For PV systems and PV glass, the material flow analysis allows the projection of future end-of-life volumes and the identification of relevant material streams under different installation & lifetime scenarios (Cucchiella et al., 2015). Consequently, identifying the financial landscape and supply availability under which recycled glass becomes an attractive input for solar manufacturing is a significant factor to enable industry-driven circularity at the terawatt scale. More specifically, this study elaborates on specific conditions under which it would be beneficial for PV industries to integrate recycled materials.

2 Materials and methods

2.1 Data and approach

In this study, we employ the bottom-up cost model for PV developed and used by Powell et al. (2013) to estimate the minimum sustainable price of crystalline silicon photovoltaic manufacturing. While the original model dates back to 2013, and the findings and data of Powell et al. (2013) are much higher than today's industry data; hence, the cost model is adapted and updated to reflect current industry conditions as per PV glass recycling. We apply the estimation strategy described by Powell et al. (2013) and have adopted the method for estimating the MSP for PV glass recycling. More specifically, key parameters such as CAPEX, OPEX, energy costs, and process assumptions have been updated based on recent data. Further, the model has been improved to reflect the characteristics of PV glass recycling, including material composition and process-specific considerations relevant to merging perovskite technologies. In the first step, we use the bottom-up cost model and design it for a PV perovskite glass recycling[4]. Transport costs are based on a 100 km distance from the collection point to the recycling factory. As a virtual factory, including all operational costs, fixed costs of machinery, labor & overhead, tools, buildings, capital expenditures, operating expenditures, and step-by-step costs, as demonstrated in Fig. 1, the baseline minimum sustainable price is estimated for a 1 GW virtual PV factory. All data files, supplementary materials, and replication code are provided in the supplementary materials ZIP package accompanying this manuscript.

Notably, the module area is considered to be 1.6× 2 m, module power at 0.4 kW, annual operating hours at 8000 h per year, operating wages at € 0.61/hour, indirect labor ratio at 0.055 as a fraction of labor cost, and operating hours at 0.03 h per m^2. Among the other inputs, the electricity price is €0.024 per kWh, the CAPEX is €111.03 million, and the OPEX is €3.4846 million for a 1 GW plant. The data for all the steps, processes, and all the costs were obtained from different published reports of the IEA PV power systems programme, Alibaba.com, and vendor quotations of industrial suppliers such as SUNY Group, Shanhong Energy Development (China), Henan Recycle Environmental Protection (China), Yushunxin / Solutions For E-Waste (China) and NPC Incorporated (Japan). Overall, this data is used as a global average. We employed overall values as the baseline global average and further adjusted them to reflect European conditions, specifically for input parameters such as energy costs and other operations. Such an approach is considered appropriate given region-specific data constraints for PV glass recycling.

In the second step, we used the results of the bottom-up cost model and conducted a sensitivity analysis. In the third step, we further employ the findings of the bottom-up cost model and apply the learning rate projections across three different scenarios. Finally, we use the historical data on EU photovoltaic installations from ITRPV published reports (VDMA, 2026) and extended the analysis to PV installation projections and glass availability in the EU until 2070.

[4] In the bottom-up cost model, the tax rate is assumed to be 0%, and other financial components are set to rational values. The European-specific values are reported in euros, and the global average prices are represented in USD.

2.2 Methodology

To examine the impacts of different input factors on the minimum sustainable price of PV glass recycling, we conducted a deterministic one-at-a-time (OAT) sensitivity analysis. Notably, the OAT approach is used to identify first-order cost drivers rather than to characterize uncertainty propagation fully. The OAT sensitivity analysis does not account for parameter interactions or joint variability, as each variable is varied independently while others are held constant (Azzini et al., 2020). Consequently, it provides only a first-order assessment of model sensitivities and may underestimate non-linear or combined effects. Hence, the findings should be interpreted as indicative of key cost drivers rather than overall comprehensive uncertainty analysis (Saltelli et al., 2019). We visualized the results using a tornado diagram. The sensitivity analysis was conducted at 2%, 3%, and 5% levels for robustness. The main reason for using the tornado approach is that it clearly ranks input factors by their marginal effects on the outcome metric (MSP in this case). In addition, the sensitivity approach is widely used in techno-economic analyses of PV systems and recycling studies (Liu et al., 2025; Roy et al., 2025).

$$S_i = \left(\left(Y_i^{\wedge} + -Y_i^{\wedge}-\right)/\left(2 * Y_0\right)\right) * 100\% \quad \text{(i)}$$

$$\Delta Y_i = Y_i^{\wedge} \pm -Y_0 \quad \text{(ii)}$$

In equation (i), S_i denotes the percentage change in output resulting from changing a single parameter, used to rank the factors of the recycling process in the tornado chart. Meanwhile, in equation (ii), ΔY_i depicts the output change when any single factor is changed by the corresponding percentage, referring to the definition of the upper and lower bar limits in the chart. For each process step, we apply the symmetric perturbations around the base value, with typical ranges of 0%, ± 2%, and ± 5%, depending on the documented uncertainty and precedent in the solar recycling literature (Liu et al., 2025). The percentage changes were used to rank the parameters by impact. This OAT approach allows us to isolate marginal effects, thereby facilitating interpretation in policy and engineering contexts.

$$C_n = C_1 * n^{\wedge}(-b)C_1 n^{-b} \quad \text{(iii)}$$

$$b = \log(learning\_rate)/\log^2 \quad \text{(iv)}$$

whereas, in equation (iii), C_n denotes the unit cost at cumulative installation n, C_1 expresses the cost of the first installation, and b is the learning exponent. The learning rate curve was used to project cost reductions with cumulative PV installations using Eqs. (iii) and (iv), where the learning rate defines the learning exponent b according to Eq. (iv).

2.3 Dynamic material flow analysis (dMFA)

As mentioned above, we extended the analysis to project future PV deployments in the EU through 2050 across three scenarios and, based on these findings, estimated PV glass availability in Europe. Following the recent literature on energy economics and PV, we employ a dynamic, cohort-based material flow analysis. Lifetime assumptions and estimates were derived using Weibull distributions (Carrasco et al., 2008; Wang et al., 2019; Westbroek et al., 2021). In the first process of PV installation projections, we employ the deterministic capacity growth approach, in which historical installations are derived from cumulative PV capacity using a stock-difference method (year-by-year change in cumulative capacity). Then we developed three forward-looking scenarios for 2026: worst case with constant annual installations; moderate case, as per the EU Green Deal, with 9% exponential growth; and best case, with 7 TW of installations by 2050 and 12% exponential growth. Notably, these scenarios reflect policy- and market-driven deployment pathways, consistent with the energy systems analysis used in the green energy transition literature (P. Chowdhury et al., 2026).

We apply a dynamic cohort-based material flow analysis to estimate PV glass availability in the EU until 2070. Annual installations were linked to end-of-life flows via a Weibull lifetime distribution, indicating gradual module failure rather than fixed retirement. For each installation cohort, the probability of reaching end-of-life was calculated based on characteristic lifetimes of 25, 30, and 32 years. The lifetime values were chosen to represent the current lifetimes of modules as well as potential future improvements in durability and reliability (Kuitche, 2021; Mirletz et al., 2024). Such an approach helps capture the temporal dynamics of PV installations, uncertainty, and recycling availability across alternative deployment scenarios (Baek et al., 2025). Equation (v) shows the annual PV installations, where I_t represents the annual PV installations in year t, while $C_t - C_{t-1}$ shows the cumulative installed PV capacity in current and previous years. The equation (vi) below captures the module failure at age (a) as per the Weibull distribution. In equation (vi), $f(a)$ shows the probability density function of module failure, k denotes the shape parameter, and λ is the scale parameter. In the third step of dMFA, equation (vii) captures the total end-of-life-based flow, where E_t highlights the total end-of-life PV capacity in year t, calculated by adding the contributions of all installation cohorts I_τ, and $t-\tau$ shows the age of the cohort.

Annual installations;

$$I_t = C_t - C_{t-1} \tag{v}$$

Weibull distribution lifetime;

$$f(a) = \frac{k}{\lambda}\left(\frac{a}{\lambda}\right)^{k-1} e^{-(a/\lambda)^k} \tag{vi}$$

End-of-life Cohort-based flow;

$$E_t = \sum_{\tau=0}^{t} I_\tau \cdot f(t-\tau) \tag{vii}$$

The cumulative PV capacity flows were further converted to glass mass (e.g., Mt of glass) using a glass intensity of 70 kt/GW per unit of PV capacity. Notably, the constant glass intensity was employed to convert the PV capacity to glass mass, as this value lies within the traditional range of 60–80 Kt/GW, derived from the module weight (~ 18–20 kg/m^2), glass fraction (~ 70–75%), and module power density (~ 180–220 W/m^2) (Chowdhury et al., 2025). In the last step (equation viii), G_t shows the total glass mass availability from the end-of-life modules in year t, and α denotes the glass intensity per unit of PV capacity (tonnes per GW).

Glass Mass Conversion;

$$G_t = E_t \times \alpha \tag{viii}$$

For each cohort, we use the Weibull function to estimate the fraction of modules that might reach the end of life each year as the cohort ages. Further, each year we added the end-of-life glass from all installation cohorts[5]. Finally, we obtained the annual glass waste and recycling potential, projected under all three baseline scenarios, for each Weibull distribution. We further employ the linear method to check the robustness of the dynamic material flow analysis as a final sanity check. Development of advanced recycling protocols and standards aligned with current and future EU policies, resulting in future standards for recyclable European solar module production in line with the EU circular economy action plan and WEEE.

3 Analysis, results, and discussion

3.1 Minimum sustainable price and sensitivity

In the first step of the analysis, we estimate the minimum sustainable price for PV glass recycling using the procedures outlined in the literature (Fig. 1). For a 1 GW virtual PV factory, we have analyzed three cost scenarios: low, average, and high. These three scenarios in the cost model assume that recycling costs can be lower, stay on average, or be inflated by more than 10%. The three recycling cost models under the mentioned scenarios have provided us with

[5] The dMFA method argues that waste in a given year comes from many past installation years, not just one.

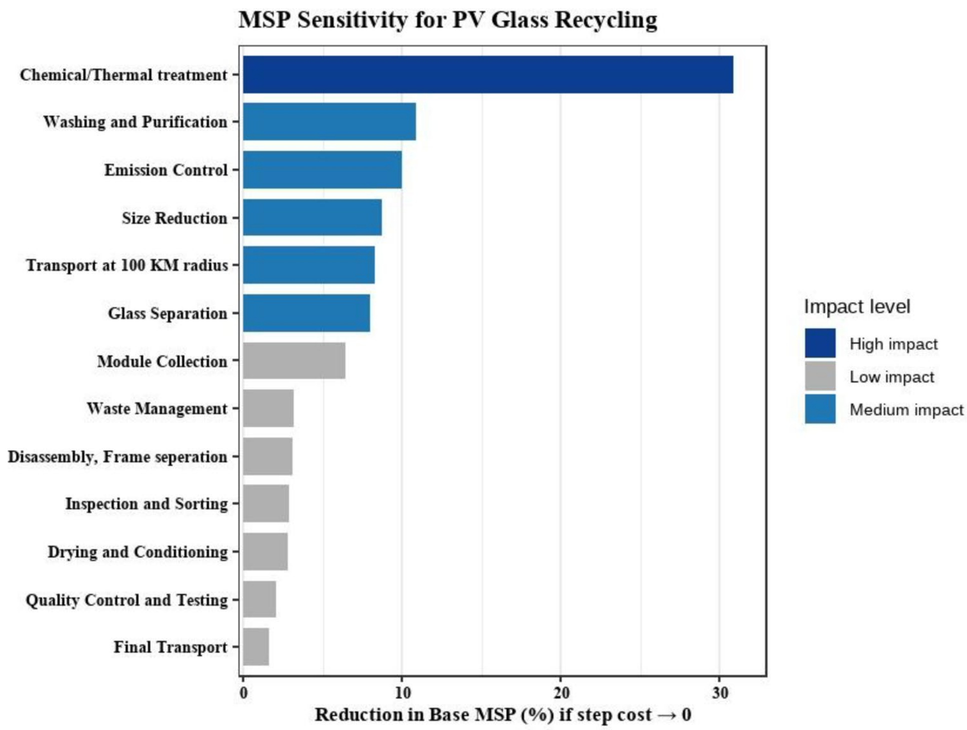

Fig. 2 Sensitivity analysis at 0% Change Source: Authors estimates based on Supplementary Information SI2

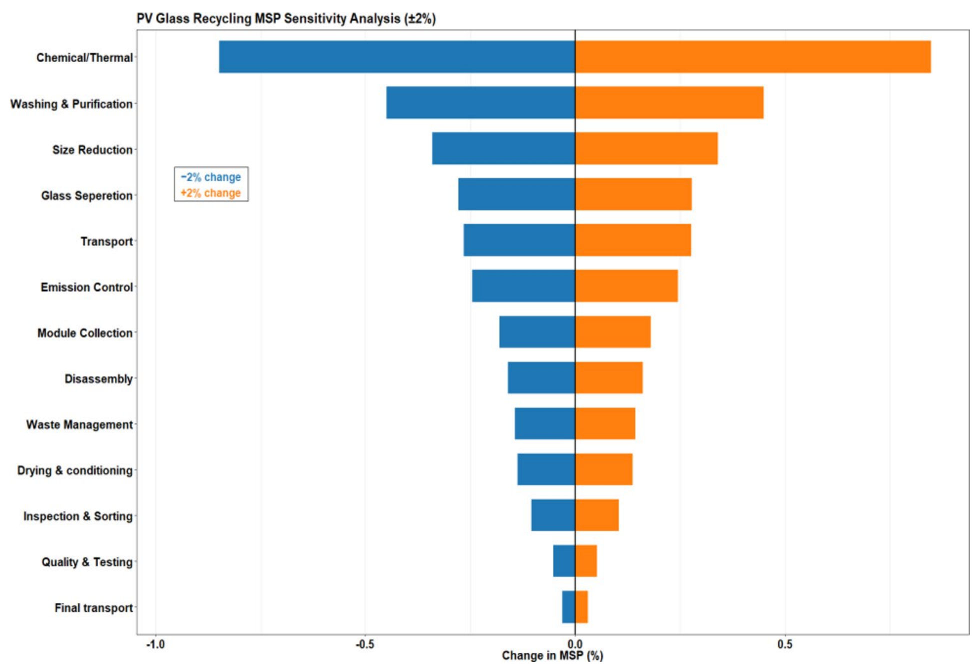

Fig. 3 Sensitivity analysis at 2% Change Source: Authors estimates based on Supplementary Information SI2

the sustainable price of \$20.25 per square meter (low cost), \$25.78 (average cost), and \$30.27 (high cost).[6]

In the second step of the empirical analysis, we employ a sensitivity analysis approach and develop tornado charts for 0, 2, and 5% changes in the relevant process steps and their impact on the corresponding minimum sustainable price for recycling (Figs. 2, 3, and 4). Figure 2 illustrates the sensitivity of the minimum sustainable price to each recycling step by evaluating the change in MSP when the cost of each step is hypothetically dropped to zero. This method underscores the relative significance of each process step in the overall cost structure. The results argued that chemical or thermal

[6] CapEx and OpEx are estimated at €111.0 million and €3.4846 million, respectively.

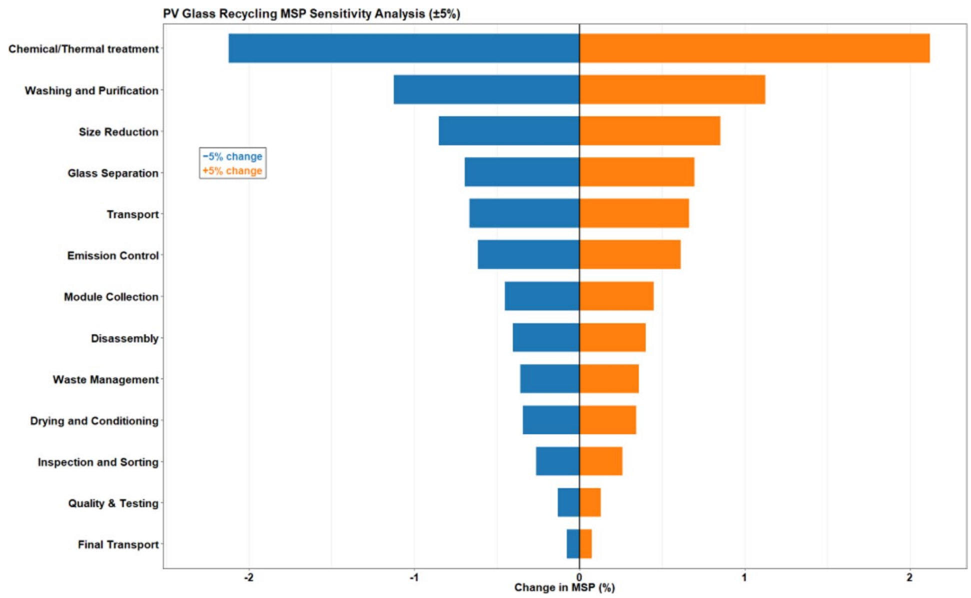

Fig. 4 Sensitivity analysis at 5% Change Source: Authors estimates based on Supplementary Information SI2

treatment, washing & purification, emission control, size reduction, and transport are the key process steps for reducing the minimum sustainable price in glass recycling.

Furthermore, Figs. 3 and 4 show sensitivity changes of 2 and 5% across all recycling steps. The sensitivity analysis empirics indicate that chemical or thermal treatment, size reduction, washing & purification, glass separation, transport, drying, and frame disassembly are the leading process factors for glass recycling costs. The findings of the sensitivity analysis are highly consistent across all levels. Notably, the PV industry might need to focus on alternative methods for collection, technical processing, washing, and other steps to gain an economic edge in integrating recycled materials. From an economic perspective, the PV industry can be facilitated by new recycling systems backed by feed-in-tariff and subsidies programs (Johnson & Mayfield, 2020). For instance, China has initiated new plans for PV recycling systems that will synchronize PV manufacturers and all stakeholders to steadily promote PV development and remanufacturing industries (Yuen, 2023). More specifically, as recycling costs are currently higher than manufacturing costs, assuming that PV recycling or PV glass recycling has become more cost-effective, manufacturers would be better off using recycled materials for PV remanufacturing. The ongoing discussions and plans of the National Development and Reform Commission (NDRC) in China align with and aim to establish remanufacturing industries for sustainability and resource circularity (Bai et al., 2024).

In the third step of our empirical analysis, we apply a projection-based analysis of the current PV installed volume in the EU, based on the outcomes of the high-, average-, and low-cost scenarios used in the minimum sustainable price. The recycling cost projection is based on learning rates of conservative (10%), base (15%), and optimistic (20%) from the current installed capacity of 406 GW in the EU to 3 TW and 4 TW.

The learning rate projections indicate that, with massive future installations in the EU, the amount of glass recycling can be reduced. Notably, in the learning rate approach, we employ the conservative, base, and optimistic approaches with learning rates of 10, 15, and 20% for the cost projections. The 10, 15, and 20% learning rates correspond to conservative, base, and optimistic technological improvement conditions, respectively, and are closely aligned with empirical findings for analogous recycling and green energy technologies (Bai et al., 2024; Wei et al., 2025). The applied learning rates (10, 15, and 20%) are consistent with the values reported in the PV literature for different PV technologies, including energy systems and electricity supply technologies (Goldschmidt et al., 2021; Nemet, 2006; Rubin et al., 2015). We employ three learning rates to estimate how PV glass recycling costs may decrease across different installation scenarios, accounting for technology maturity and system boundaries. More specifically, applying multiple rates enables us to reflect plausible PV evolution trajectories and ensure that sustainable price projections remain grounded in real-world economic and financial dynamics.

Figure 5 illustrates the cost projections for PV glass installations up to 3 TW and 4 TW, respectively. The finding indicates that the recycling price under different scenarios can decrease with scalability in future life cycles, reaching $7 per square meter. This finding is reported for the high-cost scenario of the cost modeling as done in the first step.[7]

[7] Cost projections for the low-cost modeling and average-cost scenarios can be requested from the authors.

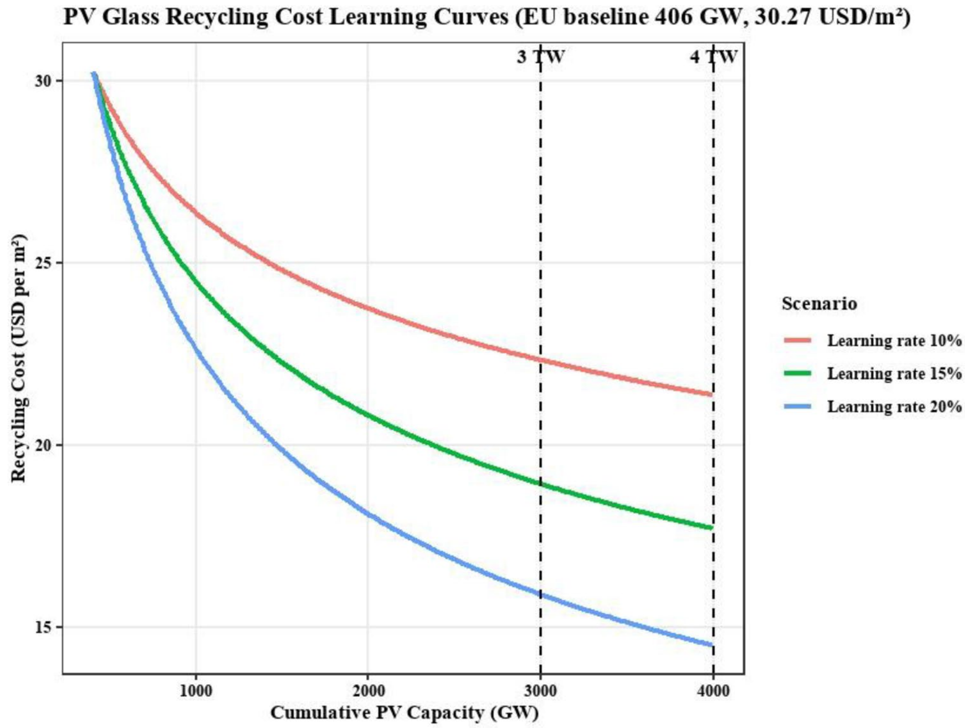

Fig. 5 Glass recycling cost projection based on current volume Source: Authors estimates based on Supplementary Information SI3 & SI4

Such findings are novel and eye-catching, and they allow us to conclude that large-scale implementation of PV glass recycling will help enable an economically viable recycling process, significantly reducing material costs and enhancing the sustainability of energy systems. In addition, across multiple PV life cycles, scalable, cost-effective recycling can be a significant tool for achieving environmentally sustainable solar deployment on a global scale. More recently, Sah and Kumar (2024) argued that, in the recycling process at lab scale, input costs (materials) exceed the output value generated by mechanical, thermal, and chemical treatments. The current study extends the arguments of Sah & Kumar (2024) that, at an industrial scale, recycling and recovery costs can be reduced.

More specifically, the results argue that across multiple PV lifecycles, recycling costs will be reduced, thereby significantly enhancing the benefits of PV recycling. The basic principle of green energy highlights the importance of recycling used modules, perovskite, silicon, and metals. In addition, to enhance the economic and circularity benefits of recycling, it is crucial to introduce PV recycling subsidies; such initiatives will motivate producers and distributors to share the associated recycling obligations in an eco-environment where attractive commercial incentives for green recycling are currently unavailable. The findings of the current study align with those of Peters et al. (2024), who concluded that carbon neutrality will require massive PV installations and production. As of today, recycling costs of PV and glass are a significant bottleneck for material circularity and sustainability (Saidi et al., 2025).

Meanwhile, the market value of low-quality recycled materials is low, approximately 20% of the initial value. However, across PV's multiple lifecycles, the market value of recycled materials is expected to increase as material purity improves, recovery technologies mature, and demand for recycled components grows within the circular economy (Burinskienė et al., 2025; van Gaalen & Chris Slootweg, 2025). Hence, the scalability of PV will be conducive to overall cost mitigation and to achieving circular recycling and carbon neutrality goals. The overall findings of this study align with the conclusions of Burinskienė et al. (2025), who argued that scaling up the use of recycled materials and their trade can be beneficial for climate change and resource conservation objectives. It is worth noting that the scalability of photovoltaic (PV) technology is not only technically feasible but is already being realized worldwide (Nancy Haegel et al., 2023).

3.2 PV installation projection and PV glass availability in the EU

In addition to the empirical analysis, we have conducted projections of EU PV installations under worst-case, moderate, and best-case scenarios. In doing so, we employ the using stock-based and exponential growth approach; where the worst cost scenario assumes consistent 65GW/year installation as of in 2026, the moderate scenario is accordance with

European green deal (green energy installation of 3.2 TW till 2050 to reach net zero) with 3.5 TW installations till 2050 with exponential growth of 9%, while the best case scenario assumes the double installation as compared to EU green deal and as moderate hypothesis with cumulative 7 TW installation till 2050 with exponential growth rate of 12.06%. Notably, the best-case scenario is motivated by historical evidence of rapid PV deployment across all global regions, driven by rising energy demand and evolving geopolitical conditions. Figure 6 reports PV installation projections through 2050 per the above-mentioned scenarios. Lastly, based on the outcomes of the PV projection scenarios, we further employ the Weibull distribution and dynamic material flow analysis (dMFA Method) to project PV glass availability in Mt/year till 2070 for our three baseline scenarios (worst, moderate, and best).

Figure 7 shows the EU PV glass availability (Mt/year) until 2070, with the Weibull distribution (module end-of-life at 25, 30, and 32 years), under worst, moderate, and best installation scenarios. The projections from the material flow analysis indicate that there will be glass waste under the worst-case and moderate scenarios, ranging from 5 Mt/year to 10 Mt/year, until 2070. While under the moderate scenario (vis-à-vis the EU Green Deal), there will still be a massive amount of PV glass in the EU from 2035 to 2070. Notably, assuming a module life of 25 years results in more glass and overall PV waste, whereas longer module lifetimes lead to less glass and less overall PV waste. Furthermore, in the best-case scenario, there is a possibility of 5 Mt/year to 23 Mt/year of glass availability from 2040 to 2070. It is worth noting that in the dynamic material flow analysis, annual PV installations after 2065 might slow, while end-of-life cohorts peak and then shrink. The slight downward curves in our analysis indicate a cohort-driven effect, suggesting that after 2070, the EU might witness a slowdown in glass and overall PV waste. The cohort-driven approach captures the temporal dynamics of PV deployment, as well as the uncertainty in module lifetimes and recycling availability across the studied scenarios. More recently, Baek et al. (2025) concluded that existing collection and recycling infrastructures in the EU and the United States require strengthened deposit-return schemes (DRS), improved EPR systems, and a more digitalized ecosystem to enhance future glass collection and recycling rates. In a recent study, Agnusdei et al. (2022) found that the DRS system was effective in increasing the collection and recycling rates of glass packaging in Europe; however, even with the DRS system, glass packaging waste remains unaddressed.

Figure 8 further highlights EU photovoltaics glass availability using the linear method as a robustness check of our baseline findings from the material flow analysis. Notably, the linear method indicates that, in the worst-case scenario, the glass availability flows remain low and plateau after 2050, depending on the module lifetimes. The moderate scenario shows a sharp post-2040 surge in glass waste, while the best-case scenario reports a steady rise after 2050, noting that there will be substantial future PV glass in Europe. Across three scenarios, the shorter lifetime will result in higher glass availability, whereas the longer module lifetimes might contribute to delay and smoother recycling flows. Overall, the results are consistent with our outcomes from the dynamic material flow analysis and allow us to draw some novel insights and relevant implications.

Our study argues that there is an urgent need for technical and institutional support from governing bodies and the recycling industry to enable PV glass businesses to

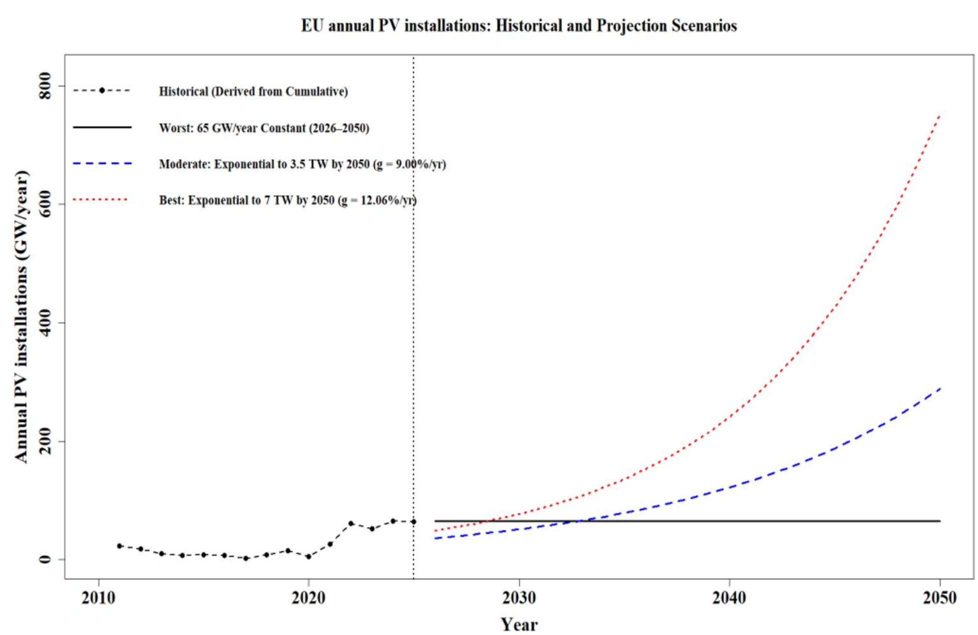

Fig. 6 EU PV projection Scenarios (using stock-based and exponential growth approach) Source: Authors estimates based on Supplementary Information SI3 & SI4

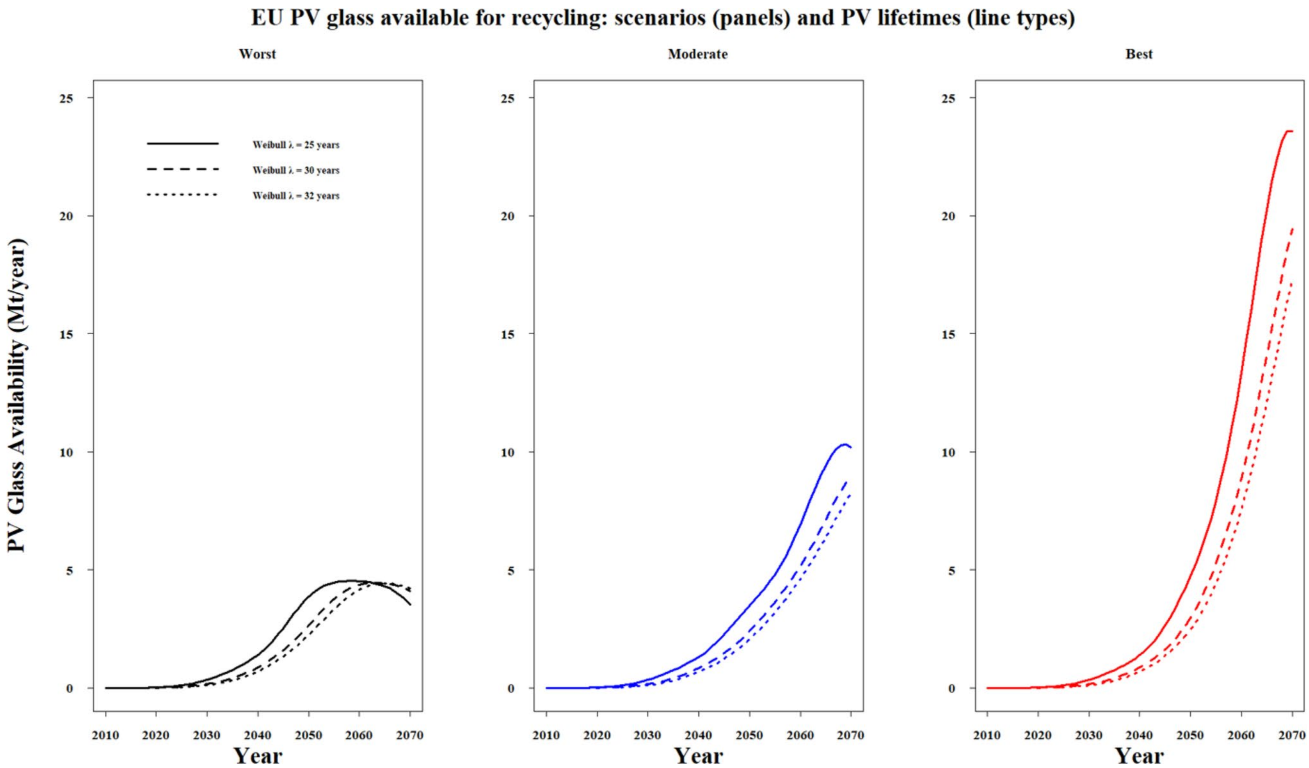

Fig. 7 EU PV Glass availability (using Weibull Distribution & dMFA Method) Source: Authors estimates based on Supplementary Information SI3 & SI4

enhance material circularity. PV glass recycling would ultimately contribute to sustainable production and consumption as an alternative to other materials (Baek et al., 2025). It can help achieve the Sustainable Development Goal for clean and affordable energy (SDG-7) by enabling glass to be remanufactured into new modules. From an environmental and sustainability perspective, glass production is an energy-intensive process and accounts for more than 86 Mt of annual CO_2 emissions (Westbroek et al., 2021), while glass recycling can help reduce this pollution.

It is important to note that the EU has clear aims to enhance glass packaging collection & recycling, with a target of 75% by 2030, and to achieve a fully circular, climate-neutral status by 2070. Currently, more than 12 Mt/year of glass packaging is collected for recycling in the EU (Eurostat, 2025), while the results suggest that the PV industry alone will contribute 5–20 Mt/year of glass waste under different circumstances and scenarios. Consequently, our study argues that the current infrastructure, regulations, and policies regarding glass recycling may require further reforms to accommodate future PV glass and to enable a PV circular industry in the EU, with less reliance on non-EU countries for resources. Currently, Europe imports up to €15 billion in green energy products annually, mainly from China and India. While establishing a circular PV industry alone can be a conducive factor in reducing energy-related imports, it can also enhance revenue, job opportunities, and significant growth for Europe (European Commission, 2025). The results align with those of Sun et al. (2026) & Preeti & Kumar (2025), highlighting the need for scalable module volumes and large-scale recycling plants to achieve low-cost recycling and meet circularity objectives. However, unlike the existing literature, the current study also projects the large-scale future availability of PV glass in the EU across different scenarios. The novelty of this study lies in highlighting pathways toward achieving EU energy independence through enhanced large-scale circularity and underscoring the need for large-scale recycling infrastructure.

4 Conclusion and implications

To address end-of-life management bottlenecks posed by the rapid global PV expansion, the current study examined the minimum sustainable price for PV glass recycling, conducted a sensitivity analysis, and further extended the analysis by incorporating learning rate projections and PV glass availability in Europe across three scenarios. Notably, for the projection of PV glass availability, we employ the dynamic material flow analysis and used three scenarios, worst case (consistent PV growth as of 2026), moderate case (PV deployment as per EU green deal to have 3.5 TW PV),

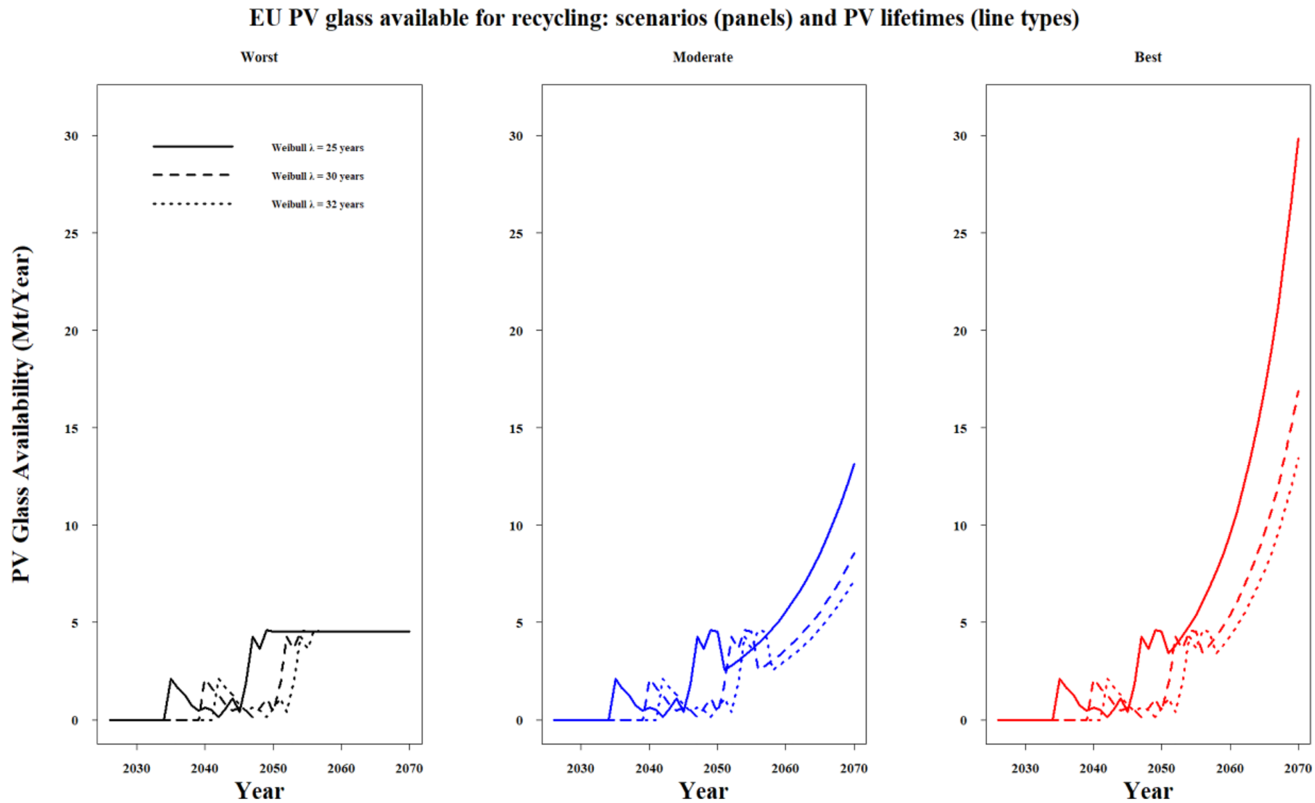

Fig. 8 Robustness Check-EU PV Glass availability (using Linear Method) Source: Authors estimates based on Supplementary Information SI3 & SI4

best case (double installation as per EU green deal), with the module life times estimated with Weibull distribution at 25, 30 and 32 years. The comprehensive analysis of bottom-up cost modeling, sensitivity, and learning rate projections allows us to draw the following key conclusions. The current study reinforces that PV glass recycling is a pivotal element of PV circularity, with far-reaching sustainability benefits. By examining the European context in depth, the current study shows that the recovery and recycling of PV and PV glass might help keep materials in circulation and reduce dependence on virgin resource extraction.

Overall, the study concludes that it is crucial to find novel ways to reduce costs across chemical or thermal treatment, transport, washing & purification, size reduction, and glass separation. For instance, PV recycling units can be established within 50 to 100 km to enable the entire PV value chain to be recycled and promote PV circular business. Secondly, scaling up PV glass can be beneficial for resource conservation, circularity, reduced dependence, and the glass trade. This guide indicates that there is a need to promote recycling infrastructure with robust investments, waste recovery efforts, and to encourage recycling through funding, targets, and innovation support. Notably, the results of dynamic material flow analysis conclude that there will be substantial amount of PV glass from 5 Mt/year to 20 Mt/year in Europe; while Europe needs more reformed systems such as; deposit-return schemes (DRS), improved EPR systems, and a more digitalized ecosystem to enable the 90 percent PV glass collection and recycling in accordance with the framework of close the glass loop for Europe and to achieve 100 percent circularity and climate neutrality by 2050 (Ever-Glass, 2024). Currently, at the industry level, materials and chemicals are cheaper while machinery is expensive. In future scenarios, the situation and conditions might change due to the growing importance of critical materials and rising geopolitical issues.

Finally, this research offers a forward-looking perspective by developing a projection model for glass recycling costs and glass availability in Europe. The projection of recycling costs indicates that across multiple lifecycles of PV, there is a higher probability that recycling costs will be significantly reduced due to ongoing innovations, reforms, and recycling-related regulations. Future projections with higher scalability, origin-specific data, and more controls can help determine whether policies and investments are on track to cover future demand for resources or whether additional solutions are needed. In summary, the study underscores that enhancing novel PV recycling methods, establishing recycling units through public–private partnerships, and introducing subsidies or feed-in tariffs for recycling can accelerate and motivate stakeholders to recycle and recover PV glass and materials (Abnett & Alkousaa, 2025).

From a policy perspective, manufacturers can gain a greater advantage by integrating recycled glass or other materials into the existing value chain, due to cost-effectiveness, energy efficiency, a smooth transition, and reduced dependence on virgin resources. Further, the projected amount of PV glass waste underscores the need for proactive policy measures and appropriate infrastructure development. Regarding the regulatory implications, existing frameworks, such as the WEEE Directive, have provided a regulatory basis for collection and recycling. However, scaling up the required infrastructure to support future multi-terawatt deployment scenarios requires substantial targeted investments in recycling capacity, improved collection systems, and the identification of relevant markets for secondary glass materials. Further, aligning these initiatives with the European Green Deal and the Circular Economy Action Plan is critical to ensure reduced resource dependency, greater efficiency, and lower environmental impacts.

Additionally, regulations such as extended producer responsibility schemes, deposit-return schemes, or public–private partnerships for recycling facilities can directly impact materials circularity. In any specific region, a stable, consistent, and sound policy is needed to sustain a virtuous cycle: enhanced recycling, more trade in recycled materials, economic viability and scalability, and encouragement of the sustainability loop. Lastly, the current study concludes that PV systems undergo significant evolution across multiple lifecycles, underscoring the technical and logistical challenges of incorporating recycled components.

The caveats of this study include the use of global average data for cost modeling due to data availability constraints, the oversight of sector-specific differences, and the neglect of institutional quality and economic shocks. Similarly, the cost model is adapted from the silicon PV recycling framework and may not fully capture the characteristics of perovskite PV materials, potentially introducing uncertainty into cost and sensitivity estimates. Another possible limitation regarding sensitivity analysis is that the applied sensitivity method captures only first-order assessments and does not consider relevant uncertainties in future projections. The researchers should also apply global sensitivity analysis methods, such as variance-based approaches & Monte Carlo, as well as advanced methods to improve the robustness of PV glass cost modeling and forecasting, capturing parameter interactions and non-linear effects in comprehensive cost modeling. In addition, future research can extend this with country-specific data, more detailed variables, and longer time series.

While this study infers PV glass recycling costs and the scalability of glass recycling across different scenarios, future research could extend it to aluminum and other PV materials, to specific materials recycling, and to specific countries and regions. Addressing the issues mentioned would deepen understanding of glass recycling and the scalability of recycling as a key component of the circular economy, and ensure that the expansion of secondary raw material markets translates into the desired sustainability gains, aligning with social and economic goals.

5 Summaries:

Supplementary Information SI1:

This supporting information provides the PV glass recycling steps in Figure 1 that show all the recycling processes as a virtual factory. No data was used to generate Figure 1.

Supplementary Information SI2:

This supporting information provides numerical data used for EU PV installation and then further used for PV glass waste estimates, inputs used in the cost modelling, Capex and Opex estimations. In addition, this supporting information includes the sensitivity analysis at 0%, 2%, and 5% for all the PV glass recycling steps.

Supplementary Information SI3:

This supporting information provides detailed bottom-up cost model on average numbers and data that was employed. The high cost and low-cost data are also available on request, but template and methodology same as in this file. The bottom-up cost model for glass recycling includes all the steps from start till end including collection, preprocessing, glass cleaning, operations & capital expenditures and all other factors.

Supplementary Information SI4:

This supporting information file provides all the R codes (using data in SI2) used to do the sensitivity analysis, recycling learning curve, EU PV projections using stock-based and exponential growth approach, PV glass availability using Weibull distribution and linear methods.

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Author contributions US did the Conceptualization, Methodology, analysis, Writing – original draft, Visualization. IMP worked on the Conceptualization, Resources, Validation, Writing – review & editing, Supervision.

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Data availability The data used in the bottom-up cost model are publicly available from the sources cited in the manuscript. The full replication package including the data of the cost model, sensitivity analysis, projections, data, and codes, is provided as supplementary material accompanying this manuscript.

Declarations

Competing interest The authors declare no competing interests.

References

Abnett, K., & Alkousaa, R. (2025, July 24). *EU solar energy rollout slows for first time in decade as subsidies cut | Reuters*. EU Solar Energy. https://www.reuters.com/sustainability/climate-energy/eu-solar-energy-rollout-slows-first-time-decade-subsidies-cut-2025-07-24/

Agnusdei, G. P., Gnoni, M. G., & Sgarbossa, F. (2022). Are deposit-refund systems effective in managing glass packaging? State of the art and future directions in Europe. *Science of the Total Environment*. https://doi.org/10.1016/j.scitotenv.2022.158256

Allied Market Research. (2024, April 1). *Solar Photovoltaic Glass Market Size, Share & Trends: 2033*. Solar Photovoltaic Glass Market Size. https://www.alliedmarketresearch.com/solar-photovoltaic-glass-market

Al-Saleem, N. K., Al-Naghmaish, A., Madani, M., Alfawwar, W., Elbasiony, A. M., Alharthi, S., Haque, M. A., & Ghobashy, M. M. (2025). Multifunctional roles and advances of polymers in solar cell technologies: a review. *In RSC Advances, 15*(43), 35998–36049. https://doi.org/10.1039/d5ra05820a

Azzini, I., Listorti, G., Mara, T. A., & Rosati, R. (2020). Uncertainty and Sensitivity Analysis for policy decision making An introductory guide. https://doi.org/10.2760/922129

Baek, C. R., Kim, H. D., & Jang, Y. C. (2025). Exploring glass recycling: Trends, technologies, and future trajectories. *In Environmental Engineering Research, 30*(3), 1–16. https://doi.org/10.4491/eer.2024.241

Bai, B., Wang, Z., & Chen, J. (2024). Shaping the solar future: An analysis of policy evolution, prospects and implications in China's photovoltaic industry. *Energy Strategy Reviews*. https://doi.org/10.1016/j.esr.2024.101474

Burinskienė, A., Lingaitienė, O., & Byčenkaitė, G. (2025). Dynamics of trade of recycled raw materials and the connection with the circular economy. *Discover Sustainability*. https://doi.org/10.1007/s43621-025-01502-4

Carrasco, J. M. F., Ortega, E. M. M., & Cordeiro, G. M. (2008). A generalized modified Weibull distribution for lifetime modeling. *Computational Statistics & Data Analysis, 53*(2), 450–462. https://doi.org/10.1016/j.csda.2008.08.023

Chen, D. M. C., Bodirsky, B. L., Krueger, T., Mishra, A., & Popp, A. (2020). The world's growing municipal solid waste: Trends and impacts. *Environmental Research Letters*. https://doi.org/10.1088/1748-9326/ab8659

Chowdhury, P., Chowdhury, H., Chowdhury, T., & Corkish, R. (2026). Standardization as a pathway to a circular PV industry: addressing material recovery and design challenges. *Solar Energy Materials and Solar Cells*. https://doi.org/10.1016/j.solmat.2025.114067

Chowdhury, T., Dehghanimadvar, M., Chang, N. L., & Corkish, R. (2025). Review of issues and opportunities for glass supply for photovoltaic production at multiterawatt (TW) scale. *In Sustainable Energy and Fuels, 9*(6), 1414–1431. https://doi.org/10.1039/d4se01567c

Cucchiella, F., D'Adamo, I., Lenny Koh, S. C., & Rosa, P. (2015). Recycling of WEEEs: an economic assessment of present and future e-waste streams. *In Renewable and Sustainable Energy Reviews, 51*, 263–272. https://doi.org/10.1016/j.rser.2015.06.010

Dias, P. R., Schmidt, L., Chang, N. L., Monteiro Lunardi, M., Deng, R., Trigger, B., Bonan Gomes, L., Egan, R., & Veit, H. (2022). High yield, low cost, environmentally friendly process to recycle silicon solar panels: Technical, economic and environmental feasibility assessment. *Renewable and Sustainable Energy Reviews*. https://doi.org/10.1016/j.rser.2022.112900

Ding, N., Zhang, Z., Yang, J., Li, X., Sun, S., & Zhao, S. (2026). Implications for PV module ecodesign from a life cycle perspective under the framework of the EU ecodesign sustainable products regulation. *In Renewable and Sustainable Energy Reviews*. https://doi.org/10.1016/j.rser.2025.116325

European Commission. (2025). *EU imports €14.6 billion in green energy products–News articles–Eurostat*. https://ec.europa.eu/eurostat/web/products-eurostat-news/w/ddn-20251009-2

Eurostat. (2025, October 10). *Packaging waste statistics—Statistics Explained—Eurostat*. Statistics Explained. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Packaging_waste_statistics

EverGlass. (2024, July 9). *How glass can fill Europe's Circular Economy and Climate Goals—Everglass project*. How Glass Can Fill Europe's Circular Economy. https://www.everglassproject.eu/how-glass-can-fill-europes-circular-economy-and-climate-goals/

Goldschmidt, J. C., Wagner, L., Pietzcker, R., & Friedrich, L. (2021). Technological learning for resource efficient terawatt scale photovoltaics. *Energy and Environmental Science, 14*(10), 5147–5160. https://doi.org/10.1039/d1ee02497c

Gupta, A., & Shukla, P. (2025). *Solar PV Recycling Market Size 2025–2034, Global Report*. https://www.gminsights.com/industry-analysis/solar-pv-recycling-market

Heath, G. A., Silverman, T. J., Kempe, M., Deceglie, M., Ravikumar, D., Remo, T., Cui, H., Sinha, P., Libby, C., Shaw, S., Komoto, K., Wambach, K., Butler, E., Barnes, T., & Wade, A. (2020). Research and development priorities for silicon photovoltaic module recycling to support a circular economy. *Nature Energy, 5*(7), 502–510. https://doi.org/10.1038/s41560-020-0645-2

Johnson, R. C., & Mayfield, M. (2020). The economic and environmental implications of post feed-in tariff PV on constrained low voltage networks. *Applied Energy*. https://doi.org/10.1016/j.apenergy.2020.115666

Kuitche, & Joseph. (2021). *Statistical Lifetime Predictions for PV Modules*. https://www1.eere.energy.gov/solar//pdfs/pvrw2010_kuitche.pdf
Li, C., Dong, F., & Nian, V. (2025). Global photovoltaic waste under ratcheting climate ambition: spatio-temporal distribution and future pathways. *Resources, Conservation and Recycling*. https://doi.org/10.1016/j.resconrec.2025.108388
Liao, Q., Wang, G., & Xu, H. (2026). Optimal siting of photovoltaic waste treatment facilities in China: a mixed-integer linear programming approach. *Environmental Impact Assessment Review*. https://doi.org/10.1016/j.eiar.2025.108153
Liu, X., Yang, H., Shen, C., Lu, L., & Wang, J. (2025). Quantifying the parameter interaction of photovoltaic double skin façade: a sensitivity analysis based on second-order Morris method. *Applied Energy*. https://doi.org/10.1016/j.apenergy.2025.125579
Mahmoudi, S., Huda, N., & Behnia, M. (2019). Photovoltaic waste assessment: forecasting and screening of emerging waste in Australia. *Resources, Conservation and Recycling, 146*, 192–205. https://doi.org/10.1016/j.resconrec.2019.03.039
Masson, G. (2025). *Snapshot of Global PV Markets 2025 Task 1 Strategic PV Analysis and Outreach PVPS*. www.iea-pvps.org
Mirletz, H., Ovaitt, S., Sridhar, S., & Barnes, T. M. (2024). Prioritizing circular economy strategies for sustainable PV deployment at the TW scale. *EPJ Photovoltaics*. https://doi.org/10.1051/epjpv/2024015
Mukwevho, N., Mkhohlakali, A., Ntsasa, N., Sehata, J., Chimuka, L., Tshilongo, J., & Letsoalo, M. R. (2025). Methodological approaches for resource recovery from end-of-life panels of different generations of photovoltaic technologies: a review. *In Renewable and Sustainable Energy Reviews*. https://doi.org/10.1016/j.rser.2024.114980
Nancy Haegel, B. M., Verlinden, P., Victoria, M., Altermatt, P., Atwater, H., Barnes, T., Breyer, C., Case, C., De Wolf, S., Deline, C., Dharmrin, M., Dimmler, B., Gloeckler, M., Christoph Goldschmidt, J., Hallam, B., Haussener, S., Holder, B., Jaeger, U., Jaeger-Waldau, A., & Bett, A. W. (2023). Photovoltaics at multi-terawatt scale: waiting is not an option Annual electricity generation (TW-hour) Regional electricity demand supplied by solar PV. *Science, 380*(6640), 6640. https://doi.org/10.1126/science.adf6957
Nemet, G. F. (2006). Beyond the learning curve: Factors influencing cost reductions in photovoltaics. *Energy Policy, 34*(17), 3218–3232. https://doi.org/10.1016/j.enpol.2005.06.020
Peters, I. M., Hauch, J., & Brabec, C. (2024). Cradle-to-cradle recycling in terawatt photovoltaics: a vision of perpetual utility. *In Joule, 8*(4), 899–912. https://doi.org/10.1016/j.joule.2024.01.025
Powell, D. M., Winkler, M. T., Goodrich, A., & Buonassisi, T. (2013). Modeling the cost and minimum sustainable price of crystalline silicon photovoltaic manufacturing in the United States. *IEEE Journal of Photovoltaics, 3*(2), 662–668. https://doi.org/10.1109/JPHOTOV.2012.2230056
Preeti, & Kumar, S. (2025). A novel recycling approach: separation and analysis of TCO-coated glass from discarded CdTe PV modules. *Journal of Material Cycles and Waste Management, 27*(3), 1737–1751. https://doi.org/10.1007/s10163-025-02212-9
Prince, K. J., Mirletz, H. M., Gaulding, E. A., Wheeler, L. M., Kerner, R. A., Zheng, X., Schelhas, L. T., Tracy, P., Wolden, C. A., Berry, J. J., Ovaitt, S., Barnes, T. M., & Luther, J. M. (2025). Sustainability pathways for perovskite photovoltaics. *Nature Materials, 24*(1), 22–33. https://doi.org/10.1038/s41563-024-01945-6
Roy, T. K., Mahmud, M. A., & Oo, A. M. T. (2025). Techno-economic feasibility of stand-alone hybrid energy systems for a remote Australian community: optimization and sensitivity analysis. *Renewable Energy*. https://doi.org/10.1016/j.renene.2024.122286
Rubin, E. S., Azevedo, I. M. L., Jaramillo, P., & Yeh, S. (2015). A review of learning rates for electricity supply technologies. *In Energy Policy, 86*, 198–218. https://doi.org/10.1016/j.enpol.2015.06.011
Sah, D., & Kumar, S. (2024). Experimental, cost and waste analysis of recycling process for crystalline silicon solar module. *Solar Energy*. https://doi.org/10.1016/j.solener.2024.112534
Saidi, H., Ozturk, I., & Hakimi, A. (2025). Patents on environment-related technologies, research and development, and sustainable development: Investigating the moderating role of climate finance in OECD and non-OECD countries. *Finance Research Letters, 86*, Article 108646. https://doi.org/10.1016/j.frl.2025.108646
Saltelli, A., Aleksankina, K., Becker, W., Fennell, P., Ferretti, F., Holst, N., Li, S., & Wu, Q. (2019). Why so many published sensitivity analyses are false: a systematic review of sensitivity analysis practices. *Environmental Modelling & Software, 114*, 29–39. https://doi.org/10.1016/j.envsoft.2019.01.012
Sarah. (2025, March 1). *Real Solar Panel Recycling Costs: Breaking Down Europe's Green Investment—INOX Solar*. Real Solar Panel Recycling Costs. https://www.euro-inox.org/real-solar-panel-recycling-costs-breaking-down-europes-green-investment/
Sim, Y., Ankit, Tay, Y. B., Ravikumar, D., & Mathews, N. (2025). Open challenges and opportunities in photovoltaic recycling. *Nature Reviews Electrical Engineering, 2*(2), 96–109. https://doi.org/10.1038/s44287-024-00124-8
Sun, J., Zeng, D., Liu, X., Wang, B., & Xiao, R. (2026). Pyrolytic recycling of glass-removed photovoltaic laminates: Kinetics, product evolution, fluorine migration, and economic and environmental assessment. *Journal of Analytical and Applied Pyrolysis, 195*, Article 107676. https://doi.org/10.1016/j.jaap.2026.107676
van Gaalen, J. M., & Chris Slootweg, J. (2025). From critical raw materials to circular raw materials. *Chemsuschem*. https://doi.org/10.1002/cssc.202401170
VDMA. (2026, January 1). *ITRPV 16th Edition published—vdma.eu—VDMA*. International Technology Roadmap for Photovoltaics Annual Editions. https://vdma.eu/en/viewer/-/v2article/render/143159365
Wang, J., Qian, Z., Wang, J., & Pei, Y. (2019). A study on the lifetime estimation of photovoltaic modules under accelerated environmental conditions. *2019 IEEE 28th International Symposium on Industrial Electronics* (pp. 1035–1040). NewYork: IEEE.
Wei, G., Zhou, Y., Hou, Z., Li, Y., Liu, Q., Chen, J., & He, D. (2025). Review of c-Si PV module recycling and industrial feasibility. *EES Solar, 1*(1), 9–29. https://doi.org/10.1039/d4el00017j
Westbroek, C. D., Bitting, J., Craglia, M., Azevedo, J. M. C., & Cullen, J. M. (2021). Global material flow analysis of glass: From raw materials to end of life. *Journal of Industrial Ecology, 25*(2), 333–343. https://doi.org/10.1111/jiec.13112
Yuen, S. (2023, August 21). *China to build solar recycling system by 2025 - PV Tech*. https://www.pv-tech.org/china-to-build-solar-recycling-system-by-2025/
Zimmermann, T. (2013). *Dynamic material flow analysis of critical metals embodied in thin-film photovoltaic cells* [University of Bremen Germany]. http://www.uni-bremen.de/artec