Mechanical and Thermal Treatment for Recycling Photovoltaic Modules

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Introduction

The growing volume of end-of-life photovoltaic (PV) modules requires the development of efficient recycling strategies to recover valuable materials, minimize environmental impact, and integrate circular economy concept into the field (Preet and Smith, 2024). PV modules are multilayer composite products manufactured of various materials bonded together. It creates challenges for their effective separation after the module's lifetime. Different technologies are employed for material recovery. Mechanical treatment enables size reduction facilitating the detachment of materials and their separation (Pagnanelli et al., 2017). The use of industrial shredders performs the rapid treatment of diverse PV modules in large volumes, offering improved scalability for recycling operations. Thermal treatment further improves the recycling process by dissolving the encapsulating polymer and backsheet to separate the materials (Fiandra et al., 2019). This study explores the combined application of mechanical and thermal methods to PV waste recycling.

Material and methods

Two PV modules of different construction were used in the study: glass-backsheet (TPT) module with aluminium frame, and frameless glass-glass PV module. The first step of recycling included mechanical shredding to achieve initial material separation and size reduction. The treatment was performed in Kat Metal Estonia OÜ (Tallinn, Estonia) using an industrial shredding machine for one treatment cycle. Following shredding, the resulting material was sieved through five sieves of opening sizes of 0.2, 0.5, 1.0, 2.5, and 5.0 mm.

The largest fraction, consisting of particles larger than 5 mm, was manually sorted based on the visual identification of materials. Pieces of material were divided into four groups: metal frame, multilaminate of solar cells encapsulated with glass and backsheet (ML (glass-backsheet)), multilaminate of solar cells encapsulated with glass on the front and back sides (ML (glass-glass)), rest of material greater than 5 mm. After sorting, each fraction was weighed. Subsequently, 50 g of each fraction was subjected to thermal treatment to detach the materials of multilayer laminate. The treatment was carried out at 500°C for one hour in an oxidized atmosphere. These conditions were found to be sufficient to dissolve the encapsulating polymer and plastic backsheet in various types of PV modules (Fiandra et al., 2019; Zubas et al., 2024). Finally, after thermal treatment, each fraction was reweighed to assess the mass reduction.

Results

The weight distribution across the different fractions after shredding, sieving and manual sorting is presented in Figure 1.

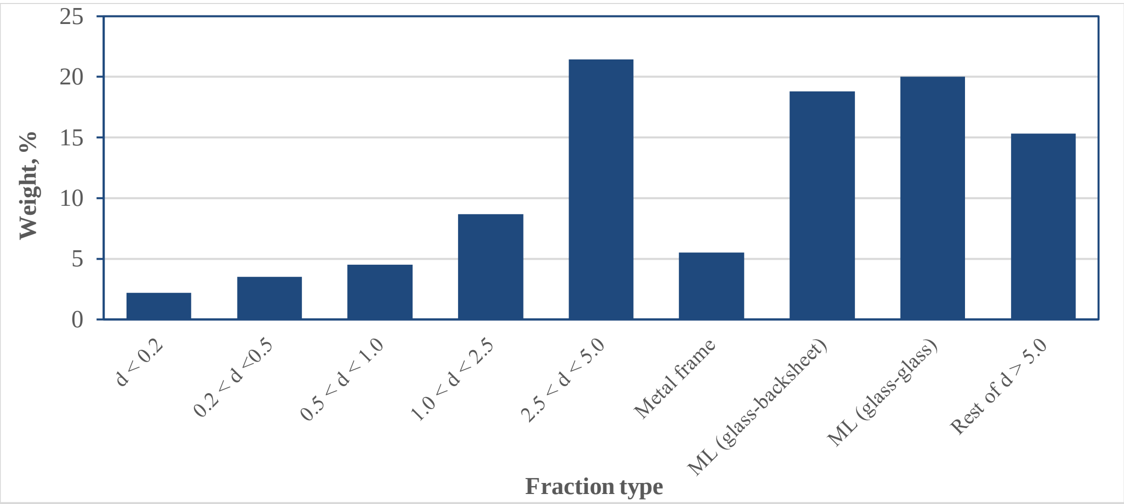

Figure 1. Weight distribution in fractions after shredding, sieving and manual sorting.

A visual inspection revealed that the smallest fraction primarily consisted of a fine grey powder. Bigger fractions were dominated by glass particles. Metal ribbons were observed within the $1.0 < d < 2.5$ mm fraction, where their width corresponded to the dimensions of this range. However, metal ribbons were also observed in larger fractions due to their tendency to tangle and form pieces of bigger sizes.

The largest fraction (d > 5.0 mm) accounted for nearly 60% of the total mass of the shredded material. Within this fraction, most of the metal frame and multilaminates significantly exceeded the sieve's 5.0 mm opening size. Although solar cells remained in the multilaminate structure (glass, encapsulant, solar cells, encapsulant, backsheet/glass), some glass particles were detached from the multilaminate during the mechanical treatment. The rest of the fraction was dominated by glass with some small pieces of metal frame and solar cells (Figure 2).

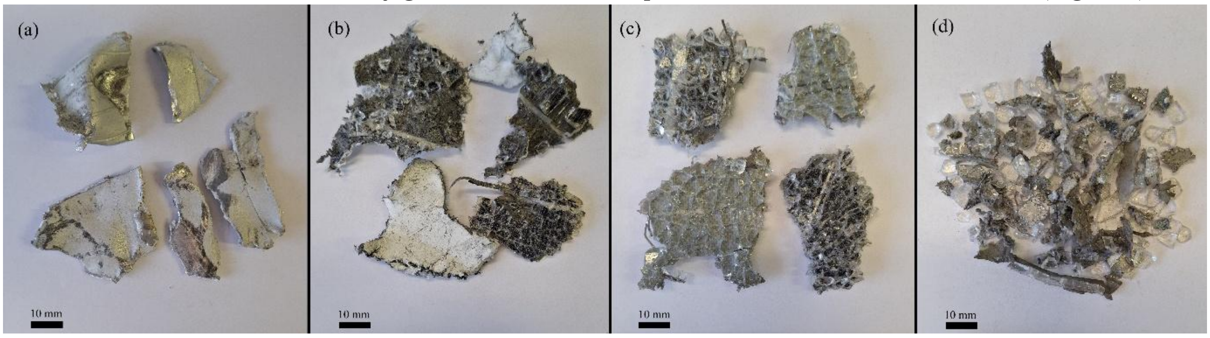

Figure 2. Manually sorted parts of the biggest fraction (d > 5.0 mm): (a) metal frame; (b) multilaminate of solar cells/encapsulant/glass/backsheet; (c) multilaminate of solar cells/encapsulant/glass; (d) rest of d > 5.0 mm.

Weight reduction for each fraction after thermal treatment is presented in Table 1.

Table 1. Weight loss after thermal treatment.

Fraction type	d < 0.2 mm	0.2 < d < 0.5 mm	0.5 < d < 1.0 mm	1.0 < d < 2.5 mm
Weight loss, %	8.65	4.34	2.56	1.75
Fraction type	2.5 < d < 5.0 mm	ML (glass-backsheet)	ML (glass-glass)	Rest of d > 5.0 mm
Weight loss, %	1.39	21.3	7.04	8.55

The weight loss after thermal treatment presented a proportion of encapsulating polymer and plastic backsheet in each fraction. The smallest fraction (d < 0.2 mm) exhibited a weight loss of 8.65%, with the percentage decreasing as particle size increased. The highest weight loss, over 20%, was observed in solar cells attached to glass and backsheet. This was due to the thermal decomposition of both the encapsulating polymer and the plastic backsheet. In contrast, solar cells with glass on both sides exhibited a weight loss of 7%, reflecting the absence of thermally treatable plastic on the back side.

Conclusion

Mechanical treatment provided an effective initial step in PV modules recycling by detaching a significant portion of the glass and crushing the modules. Although additional separation is required for some materials, shredding reduced the amount of material needing further processing and facilitated thermal treatment by producing smaller particle sizes. The variation in weight loss during thermal treatment reflected the content of encapsulating polymer and plastic backsheet, which varied across fractions depending on particle size, and type.

To further optimize the process, increasing the number of shredding cycles should be investigated. Future research should also implement metals leaching from delaminated solar cells. These recommendations aim to enhance material recovery and promote more sustainable management for waste PV modules.

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