detritus | Multidisciplinary Journal for Circular Economy and Sustainable Management of Residues

CISA

MATERIAL RECOVERY FROM PHOTOVOLTAIC PANELS BY MEANS OF THERMAL TREATMENT: THE EFFECT OF BACKSHEET REMOVAL

Francesco Miserocchi [1], Fabrice Coustier [2], Bianca Maria Bresolin [1], Katya Brunelli [3] and Pietrogiovanni Cerchier [1,*]

[1] *9-TECH, via Triestina Bassa 74, Eraclea, 30020, Venezia, Italy*
[2] *University of Grenoble ALPES, CEA, LITEN, DTS, INES, 50 Avenue du Lac Léman, Le Bourget-du-Lac, F-73375, France*
[3] *University of Padova, via Marzolo 9, Padova, 35131, Padova, Italy*

Article Info:
Received:
13 June 2025
Revised:
2 August 2025
Accepted:
26 August 2025
Available online:
16 September 2025

Keywords:
Photovoltaic
Recycling
Thermal delamination
Backsheet

ABSTRACT

The thermal combustion of polymers contained in PV has been studied by 9-Tech, and it has been shown to be an efficacious way to recover from end-of-life (EoL) photovoltaic secondary raw materials with high efficiency and purity. In this work, the removal of the backsheet from photovoltaic (PV) panels has been investigated as a pre-treatment step in the thermal recycling process, assessing its impact on material recovery, energy consumption, and environmental emissions. The backsheet has been removed by means of an innovative technology developed by CEA based on sanding. The analysis of the materials recovered from PV panels with and without backsheet indicated that backsheet removal improves material purity by eliminating contamination with titanium dioxide (TiO_2) powder. Furthermore, it reduced dust emissions and avoided the production of toxic hydrofluoric acid. Finally, it also slightly increased energy consumption due to the removal of combustible polymeric material.

1. INTRODUCTION

The global solar photovoltaic (PV) modules reached an installed capacity of 1 TW at the end of 2022 (IRENA, 2023), and according to the International Renewable Energy Agency, this value is predicted to increase to 5 TW by 2050 (Weckend et al., 2016). With an estimated PV module lifespan of 25-30 years, the volume of end-of-life (EoL) PV panels is expected to rise significantly in the coming decades, creating both environmental challenges and opportunities for resource recovery.

To survive for a long time, PV panels are made of different layers, each of which has a specific function. A soda lime glass is placed on top of the module to ensure mechanical stability and transparency to the incident light. It is characterised by a low iron content since the latter causes light absorption in the glass, which can result in losses. Moreover, the glass is tempered to boost its impact resistance (Jäger et al., 2014). Two encapsulant layers incorporate the solar cells; the most often used material is ethylene vinyl acetate (EVA). The final layer consists of the backsheet, a critical component of PV modules protecting against environmental stressors such as UV radiation, moisture, and mechanical damage (Fraunhofer, 2017). Backsheets are commonly made from materials like polyvinyl fluoride (PVF), polyvinylidene fluoride (PVDF), or polyethylene terephthalate (PET) (Chitra et al., 2022), and they often include additives such as titanium dioxide (TiO_2) (Dobra et al., 2022) for UV resistance and pigmentation.

Recycling PV modules is essential to mitigate waste, recover valuable materials such as silicon, silver, copper, aluminium, and glass, and reduce the environmental footprint of solar energy systems (Fraunhofer, 2017).

The complexity of PV module design, particularly the strong encapsulation, poses significant challenges to efficient recycling processes.

End-of-life (EoL) PV panels contain valuable materials: recovering these materials efficiently is essential for maximising economic and environmental benefits. Among the different recycling techniques, the thermal, mechanical, and chemical are the most traditional according to the panel type (Deng et al., 2022; Rubino et al., 2021; Savvilotidou & Gidarakos, 2020). Investing in advanced and feasible recycling technologies, expanding treatment capacities, and promoting sustainable methods are crucial to scaling up PV recycling. These efforts reduce environmental risks, simultaneously unlocking market opportunities through material recovery and waste valorisation. Thermal-based strategies have recently gained attention as viable end-of-life (EoL) treatment routes for PV modules, especially

* Corresponding author:
Pietrogiovanni Cerchier
email: p.cerchier@9tech.it

https://doi.org/10.31025/2611-4135/2025.19523

when aiming for high-purity material recovery. In its inert atmosphere, pyrolysis allows for the degradation of EVA and the other backsheet polymers at temperatures typically between 400 and 600°C, enabling the recovery of silver and silicon while minimising oxidation of metallic fractions (Dobra et al., 2022). One of the main disadvantages of pyrolysis concerns the generation of a complex mixture of volatiles, requiring sophisticated gas treatment infrastructure. In contrast, combustion processes operating in oxidative environments simplify off-gas composition by oxidising volatile species to CO_2 and H_2O, but introduce challenges when processing fluorinated backsheets due to HF formation (Chitra et al., 2022). Several projects in Europe have already demonstrated the feasibility of thermal approaches at the pilot scale (Fraunhofer, 2017; Weckend et al., 2016). In this framework, a novel approach comprising thermal delamination and mechanical separation has been validated by 9-Tech at the pilot scale (Cerchier et al., 2024).

The process can correctly separate glass, characterised by high purity, copper ribbons and pieces of silicon cells. These cells can further be treated by hydrometallurgical processes to recover the silver. In the abovementioned process, both encapsulant and backsheet are burned during the thermal treatment and therefore are not recovered. Backsheet recovery could have some advantages for the process. Fluorinated backsheets release hazardous hydrogen fluoride (HF) during thermal treatment, requiring mitigation measures. Additionally, TiO_2 powder can be present in the fumes or can contaminate the recovered materials like silicon and glass.

In this study, the removal of backsheets before thermal recycling has been studied as a solution to these challenges. By eliminating fluoropolymer layers, HF emissions during thermal processes can be avoided, reducing environmental risks and simplifying waste treatment. Furthermore, preventing TiO_2 contamination improves the purity of recovered materials, in particular silicon, increasing their potential for reuse in new PV modules or other applications.

This study aims to address this knowledge gap by conducting a comparative analysis of PV module recycling processes with and without backsheet removal.

The backsheet removal in literature has been studied to be obtained with hot knife (Wahman et al., 2014) or chemicals (Xu et al, 2029, Su et al. 2019).

In this study a novel approach, based on sanding, has been used for backsheet removal. In fact, using mature industrial sanding equipment, CEA developed a mechanical delamination process based on the use of abrasive belts. After determining the most suited abrasive nature, shape and size, a process was developed in order to remove all the materials present on the backside of a PV panel. Process control enables precise determination and selective removal of specific material layers from the PV panel. For this study, in order to remove the fluorinated polymers present in the backsheet, CEA was able to remove the backsheet layer from PV panels using this novel abrasion technology. Furthermore, as a complementary step, the encapsulant and the cells can also be removed using the same technique, allowing to the recovery of the front glass sheet in a single piece, clean from metals, allowing the glass to be later recycled in the form of a cullet.

In the present study, by controlling the process, the removal of the backsheet was done using an industrial-sized equipment at CEA. The PV panels without a backsheet were later processed by 9-Tech using their proprietary combustion process. By evaluating key metrics such as material recovery rates, energy inputs, and emission profiles, this research seeks to elucidate the benefits and trade-offs associated with backsheet removal. The findings are intended to inform the development of optimized recycling protocols that align with environmental sustainability and economic viability objectives.

2. MATERIALS AND METHODS

2.1 Sample preparation

In this study, 12 c-Si photovoltaic panels of the same model (Trinasolar TSM-230PC05) were divided into 3 samples (4 PV panels each).

All panels were dismounted from the aluminum frame and junction boxes. After dismounting, the samples underwent different treatments:

- sample (A) has been treated with sanding technology to completely remove the backsheet
- sample (B) has been treated with sanding technology to partially remove the backsheet.
- sample (C), used as a reference, has not been treated and remained with the backsheet.

The sanding process, performed on samples A (Figure 1), and sample B by CEA, was performed using a Format 4 sander from the Felder group. The backsheet was removed using a 3 m/min PV panel speed and 19 m/s abrasive belt speed.

2.2 Recycling process

After dismounting and backsheet removal, the panels were cut into 33 cm wide strips, see Figure 2a, and each of the three samples was processed in the 9-Tech recycling line “9PV”, a system designed for thermomechanical recycling of PV modules (Figure 2b). The thermal treatment, in particular, was conducted in a patented tunnel furnace part of 9PV line that was developed by 9-Tech. It has dimensions 140 cm (L) × 60 cm (W) × 60 cm (H) and insulated with high-density ceramic wool. The panels are placed on a conveyor belt, and combustion gases are extracted through a heat exchanger and multistage filtration system.

The recycling process was conducted in two main phases: thermal treatment and mechanical separation.

The thermal treatment was performed using a controlled heating process designed to separate encapsulant layers and polymeric components from the panels.

The panels were exposed to high-temperature thermal treatment in air (>450°C) to ensure complete degradation of organic constituents (Figure 3).

Following thermal treatment, the panels underwent mechanical separation to recover individual material frac-

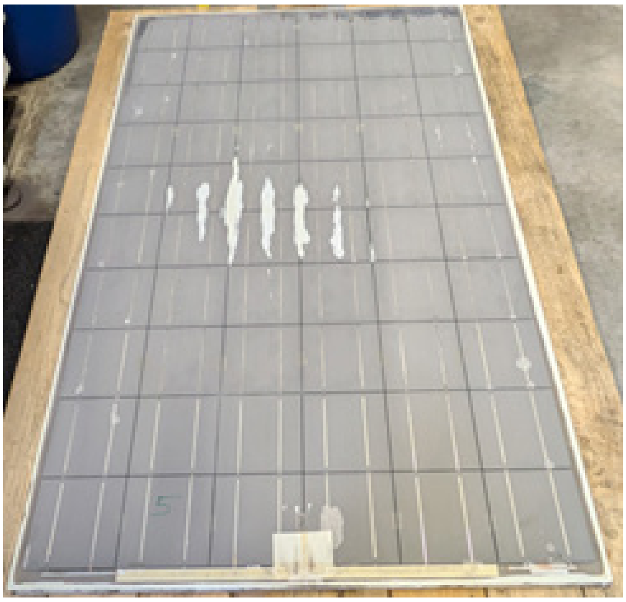

FIGURE 1: The PV panels pre-treated with a sanding process to remove the backsheet.

tions. Mechanical separation was carried out in multiple stages, involving first copper separation and then two sieving processes for separating glass and photovoltaic cells. The four recovered components are glass, PV cells, copper ribbons, and a powder fraction consisting of residual glass and photovoltaic cells.

2.3 Analytical techniques

Before any treatment, a Fourier-transform infrared spectroscopy (FT-IR) was employed to identify the chemical composition of both the encapsulant and the backsheet whereas Scanning Electron Microscopy (SEM) coupled with Energy-Dispersive X-ray Spectroscopy (EDS) was performed to analyze the surface morphology and elemental composition of the recovered materials: glass, PV cells, copper ribbons, and residual powder fractions.

The efficiency of material recovery was evaluated by comparing the weight of the fractions obtained from panels with and without a backsheet, analyzing their composition, integrity, and contamination levels.

The fume analyses covered various parameters, each determined in accordance with specific standardized methods. Each sampling involved a continuous one-hour analysis of the fumes, thereby reducing the influence of transient variations in the measured parameters.

Powder concentration was measured according to UNI EN 13284-1:2017 using the gravimetric method. Carbon monoxide was determined following UNI EN 15058:2006 through a non-dispersive infrared (NDIR) technique, using a Horiba PG 350 analyzer. Hydrofluoric acid was analyzed in compliance with Ministerial Decree 25/08/00, through absorption in solution followed by ion chromatography, and particular attention was given to this acid, as its presence in the off-gases is directly related to the combustion of fluoride-containing materials within the PV panel structure. Metals, excluding mercury, were determined in accordance with UNI EN 14385:2004 using inductively coupled plasma optical emission spectrometry (ICP-OES). Lastly, volatile organic compound (VOCs) was continuously monitored using flame ionization detection (FID), with a Polaris model analyzer.

Finally, dioxin sampling was carried out according to UNI EN 1948-1:2006, using a filter/condenser system without flow diversion. The sampling equipment and the nozzle components in contact with flue gases were made of titanium.

To evaluate the impact of backsheet removal on process efficiency, the energy consumption of the recycling process was measured in two categories: propane consumption for thermal treatment and electricity consumption for flue gas treatment and material separation. Gas consumption was recorded using inline flow meters (Metrix Italia, UG G 2.5 ALU), while electricity usage was monitored with a multifunctional network analyzer (FRER, Nano 5H - Q52P3H005XCQ2U) at various stages of the process.

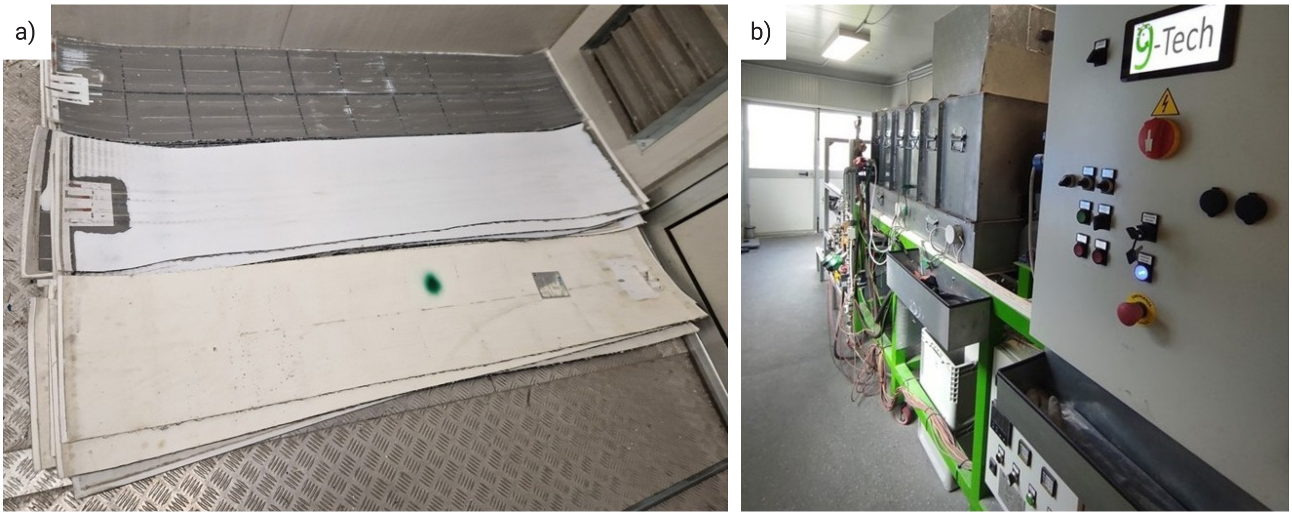

FIGURE 2: The three samples of PV panels strips: A, B, and C (a) and the 9PV pilot plant (b).

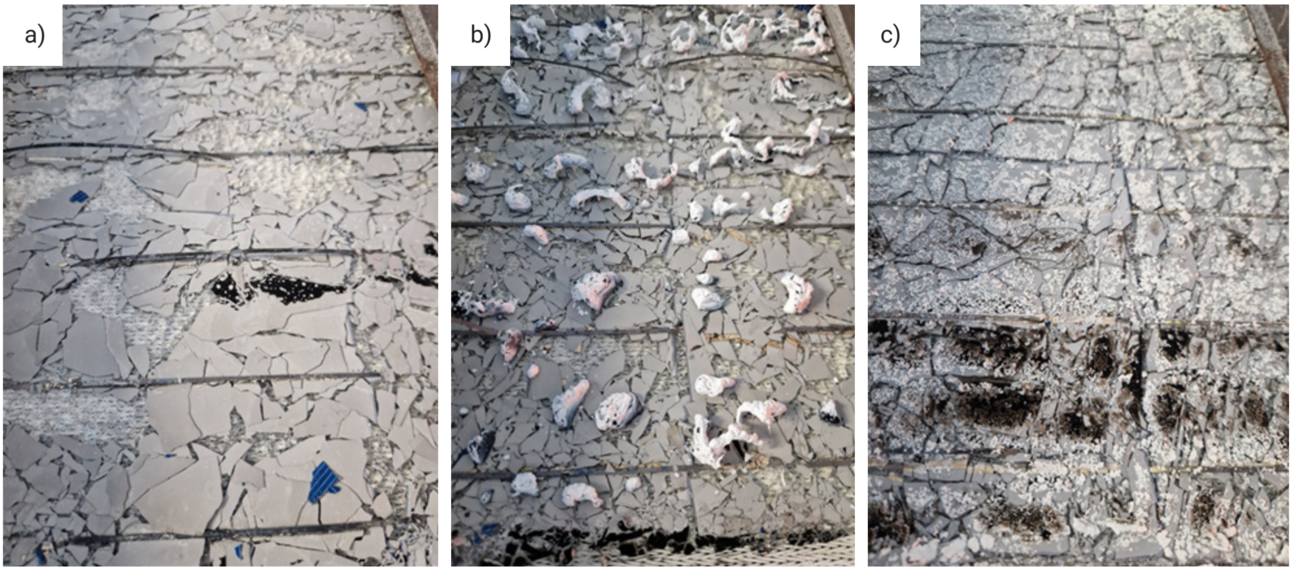

FIGURE 3: The PV samples after the heating treatment: a) sample A; b) sample B; c) sample C.

3. RESULTS AND DISCUSSION

3.1 Material recovery and composition

The analysis confirmed that the encapsulant was composed of ethylene vinyl acetate (EVA), the backsheet, instead, was made of polyvinylidene fluoride (PVDF) in combination with PET. In this study, the backsheet was a typical multi-layer backsheet used in the PV industry in the 2010s. The backsheet is mainly composed of PVDF/PET/PVDF layers with additional adhesive layers and TiO_2 powders. The thickness of the backsheet is 500 µm, and its weight is close to 1 kilogram per PV panel. Owing to the differing responses of the various polymers to abrasive grains, the backsheet can be effectively removed with minimal removal of the encapsulant. This approach was employed in the preparation of Sample A.

In the case of sample B, the sanding process was carried out so it would not remove any encapsulant and rather leave a small layer of the internal layer of the backsheet that may contain some of the fluorinated polymer (PVDF). Depending on the abrasive used during the process, the granulometry of the powders varies, but a typical size of 200 to 300 µm is common. The polymeric constituents of the backsheet powders—poly(ethylene terephthalate) (PET), ethylene-vinyl acetate (EVA), and polyvinylidene fluoride (PVDF)—exhibit distinct physicochemical properties that enable their effective separation, thereby enhancing the feasibility of their individual recovery and recycling.

The mass balance of the process is reported in Figure 4, where are indicated the percentage of recovered material with repect to the initial weight of PV panels treated.

The recovered glass accounted for 62–64% of the total panel weight, with no significant variation between panels with and without a backsheet. The removal of the backsheet before thermal processing did not lead to any noticeable mechanical degradation of the glass, and no significant fracturing or fragmentation was observed. Similarly, the integrity of the PV cells remained largely unaffected by the absence of the backsheet, suggesting that pre-treatment did not introduce mechanical stress that could compromise material recovery.

The recovered materials are aligned with typical composition that can be found in literature, reported in Table 1.

The materials are shown in Figure 5.

The recovery of metallic fractions, including aluminum, copper, and photovoltaic cells, was consistent across all

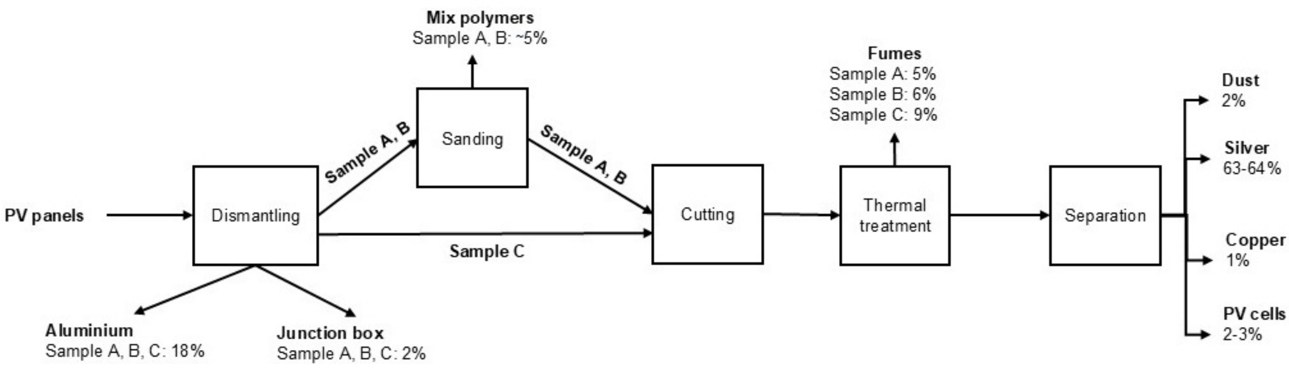

FIGURE 4: Process scheme with mass balance.

TABLE 1: Approximate Bill of Materials for c-Si PV Panel (Belançon et al., 2022; Divya et al., 2023).

Component	Material	Approx. wt%
Front Glass	Tempered solar glass	≈ 66-72 %
Aluminum Frame	Anodized aluminum alloy	≈ 10-12 %
EVA Encapsulant	Ethylene-vinyl acetate	≈ 6-8 %
Silicon Cells	Polycrystalline silicon	≈ 4-6 %
Backsheet	PET/PVF polymer	≈ 2-3 %
Copper Ribbons & JB	Copper, tin, plastic, diodes	≈ 1-2 %

test conditions. The aluminum frame, which comprised approximately 18% of the panel weight, was fully recovered in both cases with no observable contamination. Copper ribbons, constituting approximately 1% of the total panel weight, were successfully extracted and characterised using scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy (SEM-EDS).

The SEM analysis is reported in Figure 6.

The analysis confirmed that the ribbons are composed of copper coated with a tin-lead alloy (Figure 6b). The silver contacts on the PV cells contained trace amounts of lead and zinc, with no significant compositional differences between samples with or without backsheet (Figure 6d).

Notable differences were observed in the composition of the powder fraction, which consists of fine residues of glass and PV cells. In panels that retained the backsheet, the powder contained a high concentration of titanium dioxide (TiO_2), which originates from the degradation of the polymeric backsheet material (Figure 6f). In contrast, the powder recovered from backsheet-removed panels was free from TiO_2 contamination, indicating that backsheet removal significantly improved the purity of this fraction. The elimination of TiO_2 is particularly relevant for downstream

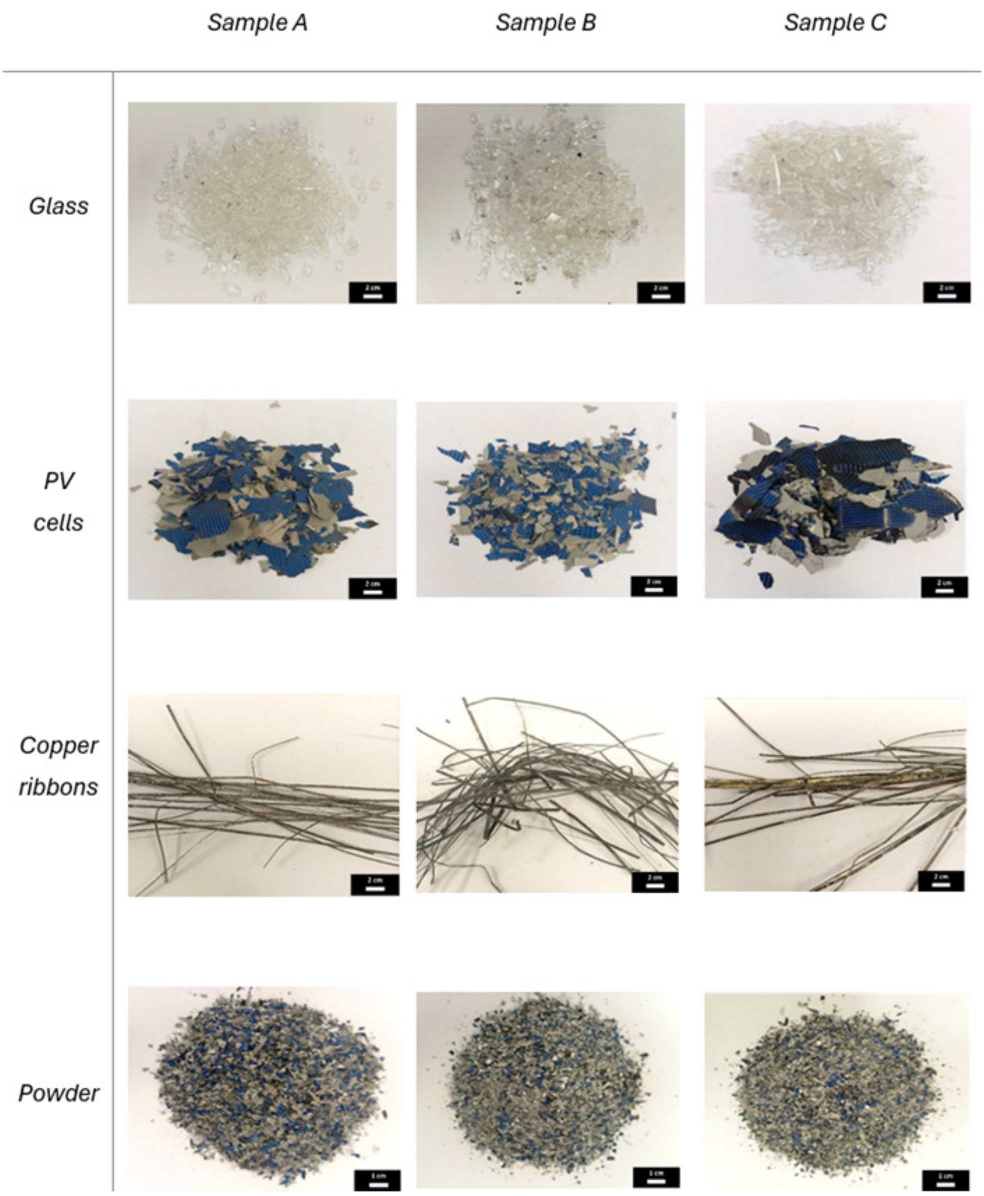

FIGURE 5: Images of the materials recovered from different samples of PV panels.

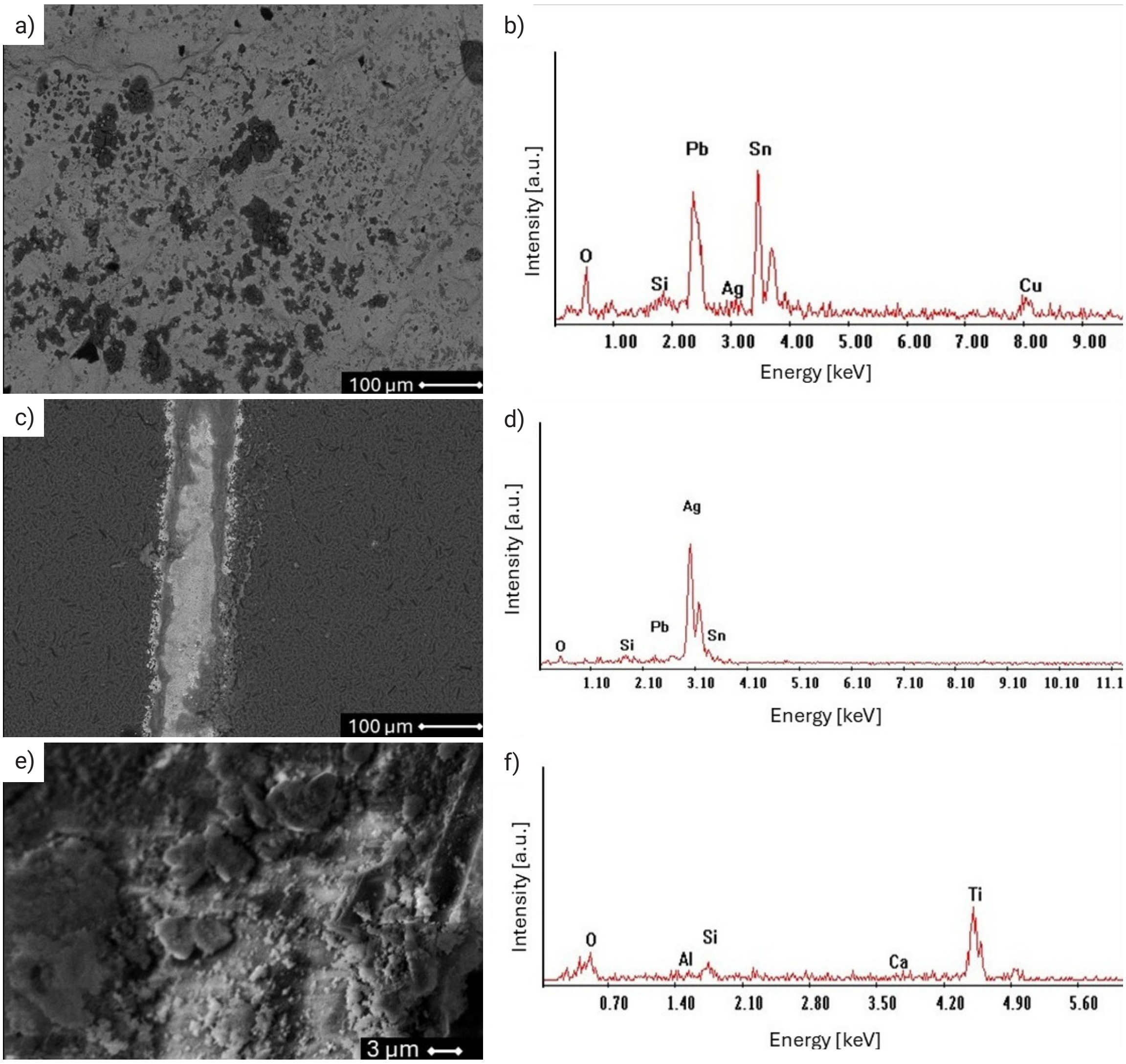

FIGURE 6: BSD-SEM and EDS analysis Images of: a-b) the surface of the copper ribbons; c-d) the front face of the PV cell with contact; e-f) glass surface with TiO_2 powder contamination.

recycling applications, as it reduces the need for additional purification steps.

These findings demonstrate that backsheet removal has no impact on the recovery of glass, metals, or PV cells while significantly improving the purity of the recovered powder fraction by eliminating TiO_2 contamination.

3.2 Energy consumption

A detailed analysis of the energy requirements associated with the recycling process was conducted to evaluate the influence of backsheet removal, considering both electricity and fuel (propane). Polymeric backsheets, typically composed of materials such as poly(ethylene terephthalate) (PET) and polyvinylidene fluoride (PVDF), possess intrinsic calorific values, this can sensibly contribute to thermal energy recovery during combustion-based treatments. Therefore, their presence within the module structure is expected to reduce the energy demand required for achieving and maintaining process temperatures. This analysis aims to quantify such reduction.

In fact, measurements of propane consumption indicated that the removal of the backsheet led to a notable increase in the demand for external thermal energy input. The backsheet is estimated to contribute approximately 21% of the total calorific value of a photovoltaic (PV) module. In comparison with sample C (with intact backsheet), the propane consumption increased by 40% in the case of Sample A, where the backsheet was completely removed, and by 16% in the case of sample B (with partially removed backsheet). The more pronounced increase observed in Sample A suggests that, in addition to the backsheet, portions of the ethylene-vinyl acetate (EVA) encapsulant were also removed during the pre-treatment phase. This further reduction in combustible material likely contributed to the increased external fuel requirement. In contrast, Sample B retained its encapsulant layer, which helped to partially offset the loss of the backsheet's thermal contribution.

Electricity consumption was monitored throughout the process, particularly in relation to the flue gas treatment system and material separation operations. The flue gas treatment system, which includes an extractor fan, was responsible for the majority of electricity consumption, accounting for approximately 2.8 kW of power usage. Additional power was required for the mechanical separation of copper ribbons, powder fractions, and glass-cell mixtures, contributing to an overall electricity consumption of 10.5 kWh per 100 kg of PV panels processed. Unlike propane consumption and as expected, electricity usage was not significantly affected by the presence or absence of the backsheet, as the fundamental requirements for gas extraction and mechanical separation remained constant.

Overall, these results indicate that backsheet removal reduces the internal energy contribution of the panels, necessitating an increase in external fuel consumption. However, the impact on electricity consumption is negligible, suggesting that any additional energy requirements are limited to the thermal phase of the process.

3.3 Environmental performance

The concentrations of key gaseous pollutants were measured in the flue gas stream upstream of any filtration or treatment system, to comprehensively compare the environmental performance of the treatment on the different samples. This approach provided an accurate representation of the raw emissions generated during thermal processing.

The results of the analysis is reported in Table 2.

Gas chromatography and FTIR analysis confirmed the complete elimination of hydrogen fluoride (HF) emissions in cases where the backsheet was removed prior to treatment. This observation is consistent with the known chemical composition of typical PV module backsheets, which may contain fluoride-based polymers such as polyvinylidene fluoride (PVDF) or fluorinated additives.

From an environmental standpoint, the suppression of HF emissions is particularly significant. Hydrogen fluoride is a highly corrosive and toxic compound that poses substantial risks to both human health and industrial equipment. Its presence in flue gas necessitates the deployment of scrubbing systems, typically involving alkaline neutralization and particulate filtration, which increase operational complexity and cost (Le et al., 2021). On the other hand, uncontrolled HF release must be avoided as it contributes to atmospheric acidification and represents a non-trivial regulatory compliance challenge under air quality directives (Ardente et al., 2019). Therefore, the removal of the backsheet prior to thermal treatment not only improves process safety but also reduces the environmental impact and post-treatment burden of the recycling operation.

The concentration of particulate matter in the flue gases was markedly reduced in panels with a totally or partially removed backsheet (Sample A, B). Titanium dioxide (TiO_2) powder, widely used as a filler in polymeric backsheets, was identified as the primary contributor to dust emissions in intact panels (Sample C). The elimination of the backsheet effectively removed this source of particulate contamination, resulting in significantly lower dust concentrations and thereby improving the overall air quality of the exhaust stream. This reduction in particulate emissions is environmentally advantageous, as airborne dust can contribute to respiratory health issues and necessitates filtration infrastructure to meet regulatory standards (Anderson et al., 2012).

Volatile organic compound (VOC) emissions exhibited variability dependent on processing conditions but showed no definitive correlation with the presence or absence of the backsheet. Carbon monoxide (CO) concentrations ranged between 20 and 70 mg/Nm³, while nitrogen oxides (NOx) levels varied from 5 to 30 mg/Nm³, with Sample C demonstrating the highest emissions for both gases. Dust concentrations spanned a broad range, from a low of 20 mg/Nm³ in Sample B (backsheet removed) to a peak of 200 mg/Nm³ in Sample C (intact panels), underscoring the influence of pre-treatment on particulate emissions.

Heavy metal analysis of the flue gas revealed minor reductions in chromium (Cr) and nickel (Ni) emissions following backsheet removal. Conversely, lead (Pb) emissions were elevated in Sample A, likely attributable to the abrasion and subsequent aerosolization of the tin-lead alloy coating on copper ribbons during mechanical pre-treatment. These findings highlight the complex trade-offs inherent in recycling processes, where material removal can mitigate certain pollutant sources while potentially exacerbating others.

TABLE 2: Fumes produced during the panel's thermal treatment (before treatment).

Pollutant	Sample A [mg/Nm³]	Sample B [mg/Nm³]	Sample C [mg/Nm³]
Carbon monoxide, CO	24.2 ± 1.5	31.8 ± 1.9	73.9 ± 4.4
Dust	54.8 ± 1.8	18.6 ± 0.61	205 ± 6.7
Volatile organic compounds, VOCs	2.5 ± 0.22	2.8 ± 0.25	2.1 ± 0.18
Hydrofluoric acid, HF	< 0.2	< 0.2	0.37
Sulphur dioxide, SO_2	< 0.5	< 0.5	< 0.5
Lead (Pb)	0.107 ± 0.0200	0.017 ± 0.0040	0.042 ± 0.0098
Total Chromium (Cr)	0.004 ± 0.0011	0.014 ± 0.0034	0.020 ± 0.0048
Copper (Cu)	0.005 ± 0.0011	0.005 ± 0.0012	0.005 ± 0.0012
Nickel (Ni)	< 0.003	0.046 ± 0.0093	0.006 ± 0.001
Sb + As + Pb + Cr + Co + Cu + Mn + Ni + V	0.12	0.093	0.073

Importantly, analyses of dioxins and polychlorinated biphenyls (PCBs) demonstrated negligible emissions across all samples, indicating that the thermal treatment of photovoltaic panels under the conditions tested does not produce significant quantities of these highly toxic and persistent organic pollutants.

Overall, the data suggest that the removal of polymeric backsheets prior to thermal recycling significantly reduces particulate and hydrogen fluoride emissions, thereby mitigating critical environmental hazards associated with flue gas treatment. However, this benefit must be balanced against the potential increase in lead emissions due to mechanical processing of copper components.

4. CONCLUSIONS

The present study systematically analyzed the impact of backsheet removal on the thermal recycling of photovoltaic (PV) panels, focusing on material recovery, energy consumption, and environmental performance. The comparative analysis between panels with and without backsheet demonstrated that the pre-treatment technique aimed at removing the backsheet offers distinct advantages, particularly in terms of material purity and emission reduction, while also introducing some challenges related to energy consumption.

Specifically, the study found that:

- Backsheet removal did not affect the efficiency or structural integrity of recovering key materials such as glass, PV cells, aluminum, and copper ribbons.
- Removal of the backsheet significantly improved the purity of recovered powder by eliminating titanium dioxide (TiO_2), reducing the need for additional purification steps.
- Backsheet removal eliminated hydrofluoric acid (HF) emissions by avoiding the processing of fluoride-containing materials.
- Dust emissions were substantially reduced due to the absence of TiO_2, a primary source of particulates.
- Backsheet removal process led up to a ~40% increase in external fuel consumption, attributed to the complete lot of backsheet material and of partial loss of EVA encapsulant, which reduced the panel's overall calorific value.
- Electricity consumption remained stable, as downstream processing steps were unaffected.

In conclusion, the study highlights an important trade-off: while backsheet removal improves material quality and environmental performance, it also increases fuel consumption in the thermal phase of recycling. This raises questions about the overall energy demand of the process and suggests that further optimization is needed to compensate for the loss of internal energy provided by the backsheet during combustion.

From a future perspective, the feasibility of valorizing the removed backsheet material is also crucial and should be further investigated. The backsheet powder recovered with sanding process must not become a waste and alternative pathways such as chemical recycling, material upcycling, or secondary applications in other industries are under investigations. The backsheet recovery and recycling would further enhance the circular economy potential of PV panel recycling and minimize material losses within the system.

ACKNOWLEDGEMENTS

This study was conducted as part of the EVERPV project under Horizon Europe (Grant Agreement No. 101122208). The analysis was performed by the University of Padova in the framework of Parsival, a RIS capacity building project supported by EIT RawMaterials, which is supported by the European Institute of Innovation and Technology (EIT), a body of the European Union. Profound thanks also to Intesa SanPaolo Vita and Fideuram Vita, who in 2022 financially supported the construction and test of the pilot plant in Porto Marghera and to Green Propulsion Laboratory of Veritas s.p.a., which hosted the pilot plant.

REFERENCES

Anderson, J. O., Thundiyil, J. G., & Stolbach, A. (2012). Clearing the Air: A Review of the Effects of Particulate Matter Air Pollution on Human Health. In Journal of Medical Toxicology (Vol. 8, Issue 2, pp. 166–175). https://doi.org/10.1007/s13181-011-0203-1

Ardente, F., Latunussa, C. E. L., & Blengini, G. A. (2019). Resource efficient recovery of critical and precious metals from waste silicon PV panel recycling. Waste Management, 91, 156–167. https://doi.org/10.1016/j.wasman.2019.04.059

Belançon, M. P., Sandrini, M., Tonholi, F., Herculano, L. S., & Dias, G. S. (2022). Towards long term sustainability of c-Si solar panels: The environmental benefits of glass sheet recovery. Renewable Energy Focus , 42, 206–210. https://doi.org/10.1016/j.ref.2022.06.009

Cerchier, P., Miserocchi, F., Pezzato, L., Nisato, F., Tassinato, G., Grigolato, C., Dabalà, M., & Brunelli, K. (2024). Photovoltaic Panel Recycling: Tests in the Pilot Plant in Venice and Silicon Applications for Ferroalloy Production. Detritus, 29, 54–62. https://doi.org/10.31025/2611-4135/2024.19436

Chitra, C., Sah, D., Saini, P., & kumar, S. (2022). Extraction and analysis of back-sheet layer from waste silicon solar modules. Chemical Reports, 4(1), 256–263. https://doi.org/10.25082/cr.2022.01.004

Deng, R., Zhuo, Y., & Shen, Y. (2022). Recent progress in silicon photovoltaic module recycling processes. In Resources, Conservation and Recycling (Vol. 187). Elsevier B.V. https://doi.org/10.1016/j.resconrec.2022.106612

Divya, A., Adish, T., Kaustubh, P., & Zade, P. S. (2023). Review on recycling of solar modules/panels. In Solar Energy Materials and Solar Cells (Vol. 253). Elsevier B.V. https://doi.org/10.1016/j.solmat.2022.112151

Dobra, T., Vollprecht, D., & Pomberger, R. (2022). Thermal delamination of end-of-life crystalline silicon photovoltaic modules. Waste Management and Research, 40(1), 96–103. https://doi.org/10.1177/0734242X211038184

Fraunhofer. (2017). End-of-Life Pathways for Photovoltaic Backsheets. Fraunhofer UMSICHT. https://www.coveme.com/files/immagini/green-solutions/Final_Report_End-of-Life_Pathways_For_Photovoltaic_Backsheets.pdf

IRENA. (2023). IRENA (2023), Renewable energy statistics 2023, International Renewable Energy Agency, Abu Dhabi. www.irena.org

Jäger, K.-D., Isabella, O., Smets, A. H. M., Swaaij, R. A. C. M. M. van, & Zeman, M. (2014). Solar Energy Fundamentals, Technology and Systems. UIT Cambridge. https://doi.org/DOI:10.1007/Springer-Reference_29746

Le, T. C., Hong, G. H., Lin, G. Y., Li, Z., Pui, D. Y. H., Liou, Y. L., Wang, B. T., & Tsai, C. J. (2021). Honeycomb wet scrubber for acidic gas control: modeling and long-term test results. Sustainable Environment Research, 31(1). https://doi.org/10.1186/s42834-021-00094-8

Rubino, A., Schiavi, P. G., Altimari, P., & Pagnanelli, F. (2021). Valorization of polymeric fractions and metals from end of life photovoltaic panels. Waste Management, 122, 89–99. https://doi.org/10.1016/j.wasman.2020.12.037

Savvilotidou, V., & Gidarakos, E. (2020). Pre-concentration and recovery of silver and indium from crystalline silicon and copper indium selenide photovoltaic panels. Journal of Cleaner Production, 250. https://doi.org/10.1016/j.jclepro.2019.119440
Su P., He Y., Wang J., Feng Y., Wan Q., Zhang Y., Pang Z. (2024). Green separation and decomposition of crystalline silicon photovoltaic module's backsheet by using ethanol, Waste Management, 179, 144-153. https://doi.org/10.1016/j.wasman.2024.03.001.
Wahman M., Surowiak A., Ebin B., Berent K. (2024). PV back sheet recovery from c-Si modules using hot knife technique, Solar Energy Materials and Solar Cells, 276. https://doi.org/10.1016/j.solmat.2024.113067.
Weckend, S., Wade, A., & Heath, G. (2016). End-Of-Life Management: Solar Photovoltaic Panels. International Renewable Energy Agency and the International Energy Agency Photovoltaic Power Systems. https://doi.org/10.2172/1561525
Xu C., Li B., Yuan X., Liu C., Shen C., Dai G. (2019). Separation of backsheets from waste photovoltaic(PV) modules by ultrasonic irradiation. IOP Conference Series: Earth and Environmental Science 242, 032046. https://doi.org/10.1088/1755-1315/242/3/032046