Recycling of Discarded Photovoltaic Modules Using Mechanical and Thermal Methods

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Abstract

Photovoltaic installations have experienced very significant growth worldwide since the early 2000s, driven by growing industry and government interest in mitigating climate change, decarbonization, and increasing energy demand. The most prevalent worry with photovoltaic (PV) panels is that their age is limited and they will eventually need to be decommissioned. With the expansion of PV production capacity worldwide, a large amount of PV panel waste will be generated in the future. Since PV panels contain heavy metals such as lead, cadmium and tin, this can have a significant impact on the environment. In addition, they also contain valuable metals (e.g. silver, gallium, indium and germanium) and standard materials (e.g. aluminum, glass) that represent a valuable opportunity when recovered. Developing a sustainable, environmentally friendly recycling process and maximizing the recovery of components from PV panels at the end of their life is expected to solve the PV waste problem. In this work, three alternative methods for recycling silicon-based (mono/polycrystalline) PV panels were investigated based on a combination of mechanical and thermal processes. The three alternative methods are a hammer crusher followed by thermal treatment and square sieve, a shredder crusher followed by thermal treatment and square sieve, and thermal treatment followed by a slotted sieve. X-ray diffraction (XRD) and X-ray fluorescence (XRF) were performed to evaluate the properties of the obtained products. The results showed that thermal treatment followed by slotted sieve is the most effective method for direct glass recovery for all types of photovoltaic modules studied.

Keywords: *PV panel, crystalline silicon, recycling, waste, mechanical and thermal processes*

1. INTRODUCTION

Photovoltaic installations have experienced a very significant growth worldwide since the early 2000s driven by growing industry and government interest in mitigating climate change, decarbonization, and increasing energy demand [1]. From an estimated 1.3 – GW in 2000, global installed PV capacity reached 586 – (GW) in 2019, with a further increase to 4,500 GW projected by 2050 [2]. PV panels have the following main benefits: low carbon emissions, no dependency on fossil fuels, low payback period, ease of installation, freedom from maintenance, and cost-free energy sources [3; 4; 5]. Today, three major classes of photovoltaic panel technologies coexist: crystalline technologies (1st generation), thin-film technologies (2nd generation), and various technologies (3rd generation). Currently, the dominant PV technology uses crystalline silicon (monocrystalline and polycrystalline) as semiconductors (more than 90% of solar cells), but thin-film photovoltaic panels use cadmium telluride (CdTe), amorphous silicon, copper indium gallium selenide (CIGS), and copper indium selenide (CIS), which have been gaining momentum recently [6]. The third-generation includes technologies that are not yet available on a large scale, such as concentrator photovoltaics or organic solar cells [7]. Silicon based PV panel (monocrystalline and polycrystalline) generally comprises six main components like: solar photovoltaic cells, tempered glass, aluminum frame, encapsulation – EVA film layers, polymer rear back-sheet and junction box as is showing in Fig. 1 [8]. By weight, typical c-Si PV panels today contain about 76% glass (panel surface), 10% polymer (encapsulant and back sheet foil), 8% aluminum (mostly the frame), 5% silicon (solar cells), 1% copper (interconnectors) and less than 0.1% silver (contact lines) and other metals (mostly tin and lead) [9].

In a general environment, the lifetime of a photovoltaic module is 20–30 years, and when the conversion efficiency decreases to a certain degree, the module fails and must be scrapped. With the expansion of global PV production capacity, a large amount of PV panel waste will be generated in the future. Global PV waste (Fig. 2) is estimated to reach 4–14% (1.7 to 8 million tons) of total production capacity by 2030 and 80–89% (about 60 to 78 million tons) by 2050 [10]. The most important end-of-life panels in the waste stream (Fig. 3) will be c-Si (1st generation) panels (more than 40%), followed by 2nd generation panels (a-Si, CdT, CIGS) which will be increasing steadily over the years. The end-of-life quantities of 3rd generation panels (emerging technologies and CPV) will only play a minor role by 2050 [4].

PV waste are generally classified as WEEE in the EU directive 2012/19/EU. According to this directive end of life or discarded photovoltaic panels must be considered as electric and electronic equipment waste (WEEE), and specific goals of collecting, recovering and recycling must be achieved within the next years [11].

According to the existing literature, waste photovoltaic modules, if not properly disposed of, can have the following negative impacts on the environment and human health [12]: leaching of lead, loss of conventional raw materials, mainly glass and aluminium, and loss of rare metals, mainly silver. Nonetheless, the long-term sustainability of photovoltaics will depend primarily on the ability to recycle the enormous

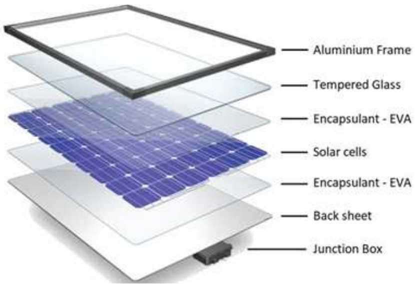


Fig. 1. The 6 main components used in the construction of a solar panel [8]
Rys. 1. Główne komponenty budowy panelu słonecznego [8]

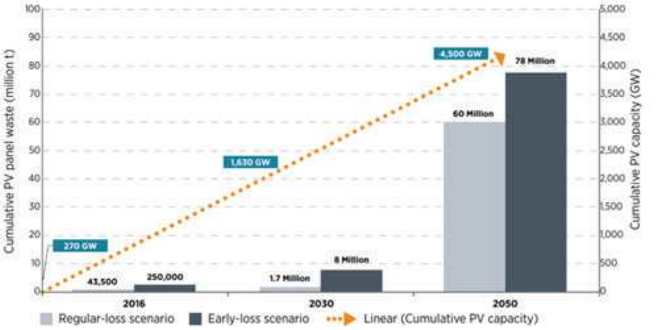


Fig. 2. Overview of global PV panel waste projections, 2016–2050 [10]
Rys. 2. Przegląd globalnych prognoz dotyczących odpadów paneli fotowoltaicznych, 2016–2050 [10]

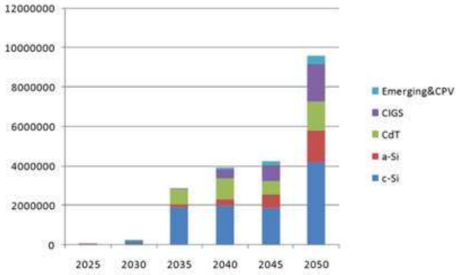


Fig. 3. PV e-waste generated by technology annually (in tonnes) [4]
Rys. 3. Elektroniczne odpady fotowoltaiczne generowane rocznie (w tonach) [4]

quantities of end-of-life modules that are expected to be generated soon, not only to avoid pollution but also to avoid depleting the planet's mineral resources. Various recycling methods have been proposed in the scientific literature, including physical, thermal, chemical, or a combination of several methods, which are most commonly used for solar module waste recycling. Radziemska and Ostrowski discuss the best method for separating the components of silicon modules [13]. They believe that thermal methods are the best because it is a simple and fast methods to separate the components. Kim and Lee studied the dissolution of EVA in crystalline silicon PV using organic solvents (trichloroethylene, O-dichlorobenzene, benzene, and toluene) and ultrasonic irradiation [14]. Granata et al. studied in detail several physical methods for the recycling of Si and CdTe solar modules. Their study showed that recycling by physical treatment with crushing by a two-blade rotor, then by hammer crushing, and finally by heat treatment is the optimal choice for direct glass recovery [15]. Huang et al. proposed a technically, environmentally, and financially sustainable recycling process for wafer Si solar modules that recovers virtually all of the waste PV modules and leaves little for landfill [16]. Fiandra et al. applied thermal treatment to recover the polycrystalline silicon using a high-temperature Lenton crude furnace [17]. Luo et al. conducted a hydrometallurgical study to recover Al, Ag, and Si from EoL silicon-based PV solar cells [18]. Some authors focused on thin-film PV panels. In particular, Sasala et al. investigated the feasibility of recycling CdTe modules by physical and chemical methods [19]. Wang and Fthenakis improved the recovery of Cd and Te from CdTe modules [20]. Berger et al. also investigated the recycling of thin-film PV panels (CdTe and CIS) by wet-mechanical methods such as abrasion and flotation, and by dry-mechanical methods such as vacuum blasting [21]. Existing technologies and processes for PV panel recycling have not been improved to achieve the required quality of recovered raw materials and meet environmental requirements. However, the separation of the different PV panel layers or the delamination process step is the main challenge in the existing recycling process [22; 23]. The efficiency of this stage determines the efficiency of recovery of semiconductor materials and metals as well as the reduction of losses [24]. To address the challenges of PV waste by developing a sustainable recycling process in an environmentally friendly manner and maximizing the recovery of components

Tab. 1. Main characteristics of the photovoltaic panels used in the research

Tab. 1. Charakterystyka paneli fotowoltaicznych wykorzystanych w badaniach

Model No	ECO-400M-66SA	Q.PLUS-G4.3 285
Product Warranty	15 Years	10 Years
Panel Efficiency	21.03 %	17.1%
Panel Dimension (H/W/D)	1646x1140x30 mm	1670x1000x32 mm
Weight	19 kg	18.5 kg
Cell Type	Monocrystalline	Polycrystalline
Cell Size	158.75×158.75 mm	156×156
Cell Number	360	60
Glass Type	Tempered	Tempered
Encapsulant Type	EVA	EVA (Ethylene vinyl acetate)
Back Cover Type	TPT	TPT (Tedlar Polyester Tedlar)
Frame Type	Aluminium	Aluminium

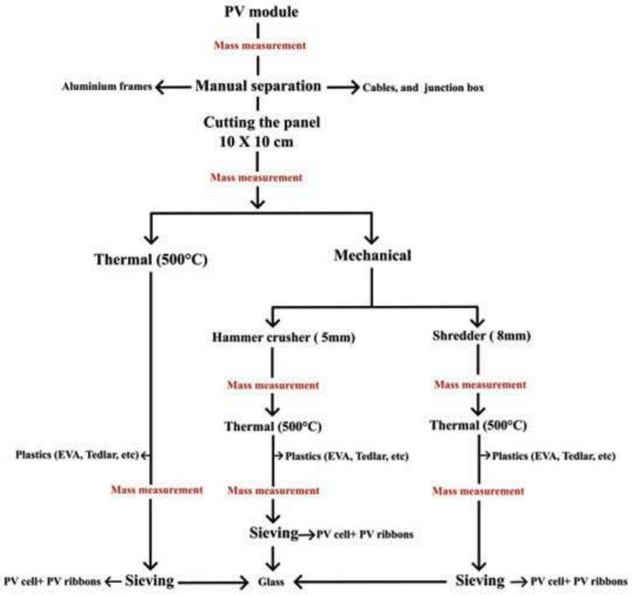


Fig. 4. Diagram of the general methodology applied in the study

Rys. 4. Schemat opracowanej metodyki badań

from PV panels at the end of their useful life. In this study, three alternative processes for the recycling of silicon-based (mono/polycrystalline) PV panels were investigated, based on a combination of physical and thermal processes. The three alternative processes are hammer crusher followed by thermal treatment and sieve, shredder crusher followed by thermal treatment and sieve, and the thermal treatment followed by a slotted sieve. X-ray diffraction (XRD), and X-ray fluorescence (XRF) were performed to evaluate the properties of the obtained products. The novelty compared to the literature data is the application of the process for the treatment of different types of panels: polycrystalline and monocrystalline, beneficiation of particle separation based on size and shape with a simple technology that meets the economic and environmental requirements.

2. MATERIAL AND METHODS

To address PV waste challenges by developing a sustainable recycling process in an environmentally friendly manner and maximizing the recovery of components from PV panels at the end of their useful life, this work has developed a methodology that includes secondary and experimental research.

2.1. Secondary research

For this quantitative literature study, mainly consulting databases such as ResearchGate, PubMed, and ScienceDirect. Since PV module recycling is a concern of academia, industry, and policymakers, Gray literature in the form of government and industry reports was also consulted (e.g. EU Commission, IEA, IRENA, and PV CYCLE), which provide important data to evaluate the most efficient recycling strategy for PV modules. Search terms include PV module, PV recycling, crystalline silicon, sustainable development goals, etc.

2.2. Experimental Research

2.2.1. Target sample

Discarded monocrystalline (ECO-400M-66SA), and Polycrystalline (Q.PLUS-G4.3 285) PV panels were collected from the factory. Some characteristics concerning the two modules used in the study are presented in Table 1.

2.2.2. Method

The diagram of the general methodology applied in the study is outlined in Figure. 4. The first step was the manual removal of the aluminum frame, cables, and a junction box of both panels, using needle-nose pliers and a flat screwdriver to obtain the main body of the photovoltaic panel. Small pieces with a size of 10 mm × 10 mm were cut it by a circular saw from the PV panel in order to be used in the experimental for this work. In the mechanical process, crushing operations were carried out in a hammer crusher using a 5 mm inlet and in a shredder crusher in 8 mm inlet. Thermal treatment was performed at predetermined temperatures (500°C) for 60 minutes to separate the different layers, including the

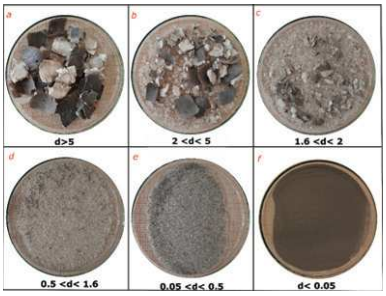


Fig. 5. Fractions obtained after hammer crushing
Rys. 5. Frakcje uzyskane po kruszeniu w kruszarce młotkowej

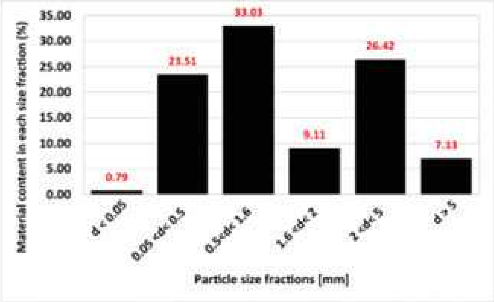


Fig. 6. Total size distribution after hammer crushing
Rys. 6. Rozkład wielkości rozdrobnionych frakcji w kruszarce młotkowej

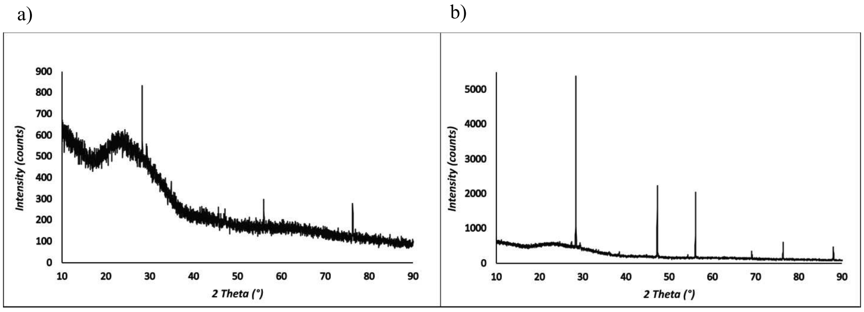
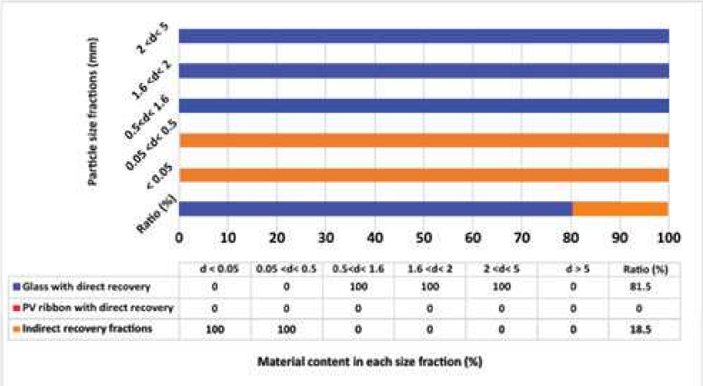


Fig. 7. Products analyzed by XRD: a) d > 0.5 mm and b) d <0.5 mm after hammer crushing and thermal treatment
Rys. 7. Analiza XRD produktów po rozdrabnianiu w kruszarce młotkowej i obróbce termicznej: a) d > 0.5 mmi b) d < 0.5 mm



	d < 0.05	0.05 <d< 0.5	0.5<d< 1.6	1.6 <d< 2	2 <d< 5	d > 5	Ratio (%)
■ Glass with direct recovery	0	0	100	100	100	0	81.5
■ PV ribbon with direct recovery	0	0	0	0	0	0	0
■ Indirect recovery fractions	100	100	0	0	0	0	18.5

Fig. 8. Distribution of Glass Glass+ PV cell, and PV ribbon in wt (%) among the sieving of crushed PV panel after hammer crushing
Rys. 8. Rozkład wielkości ziaren ogniw fotowoltaicznych Glass, Glass+ i taśmy fotowoltaicznej pokruszonego panelu fotowoltaicznego w kruszarce młotkowej, (%)

front EVA layer between the glass and the solar cells and the back EVA layer between the solar cells and the back sheet. The thermal treatment was carried out in the furnace. After size reduction and thermal treatment, a sieving analysis was carried out to evaluate the size and product distribution as well as mass fluxes in the process. For this purpose all samples were sieved by using 5 different sieves: 5.0, 2.0, 1.6, 0.5 and 0.05 mm. The materials were shaken on a Vibratory Sieve Shaker AS 200 digit. X-ray diffraction (XRD), and X-ray fluorescence (XRF) were performed to evaluate the properties of the obtained products.

3. RESULT AND DISCUSSION

3.1. Crushing by Hammer crusher

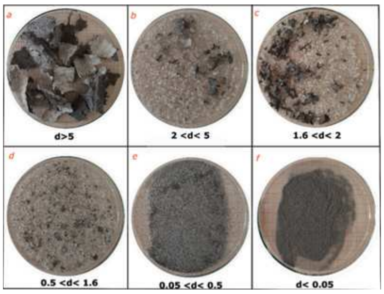


Fig. 9. Fractions obtained after shredder crusher
Rys. 9. Frakcje uzyskane po rozdrabnianiu w kruszarce typu schredder

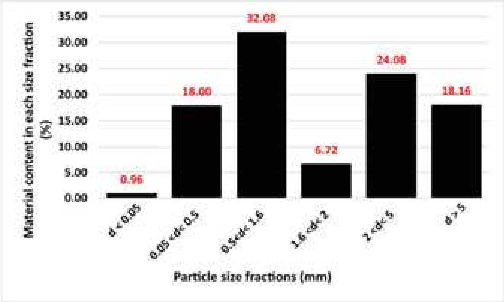


Fig. 10. Total size distribution after shredder crusher
Rys. 10. Rozkład wielkości ziaren po rozdrabnianiu w kruszarce typu schredder

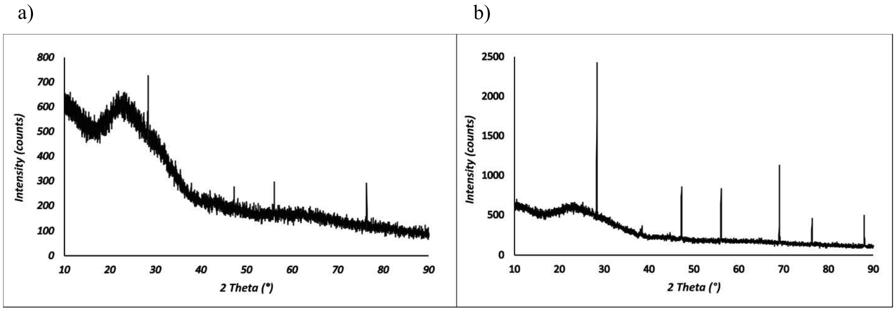
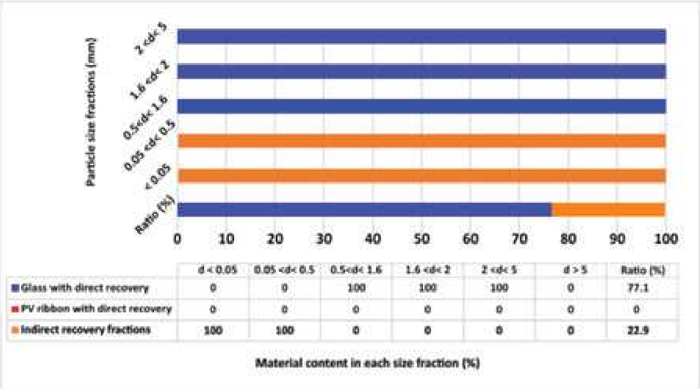


Fig. 11. Products analysed by XRD: a) d > 0.5 mm and b) d <0.5 mm after shredder crusher and thermal treatment
Rys. 11. Analiza XRD produktów po rozdrabnianiu w kruszarce typu schredder i obróbce termicznej: a) d > 0.5 mm, b) d < 0.5 mm



	d < 0.05	0.05 <d< 0.5	0.5<d< 1.6	1.6 <d< 2	2 <d< 5	d > 5	Ratio (%)
■ Glass with direct recovery	0	0	100	100	100	0	77.1
■ PV ribbon with direct recovery	0	0	0	0	0	0	0
■ Indirect recovery fractions	100	100	0	0	0	0	22.9

Fig. 12. Distribution of Glass Glass+ PV cell, and PV ribbon in wt (%) among the sieving of crushed PV panel after shredder crusher
Rys. 12. Rozkład wielkości ziaren ogniw fotowoltaicznych Glass, Glass+ i taśmy fotowoltaicznej pokruszonego panelu fotowoltaicznego w kruszarce typu schredder, (%)

During the comminution of the c-Si PV panels, the separation of the polymer (especially EVA, and Tedlar) associated with the PV structure proved to be difficult due to the very strong bonding between the materials. Achieving the desired particle size requires several comminutions stages. Size reduction of the comminuted materials resulted in the products shown in Fig. 5 with a size distribution in six sizes fractions (d > 5.0 mm, 2.0 < d < 5.0 mm, 1.6 < d < 2.0 mm, 0.5 < d < 1.6 mm, 0.05 < d < 0.5 mm, and d < 0.05 mm) is shown in Fig. 6. It can be seen that the crushing process by the hammer crusher resulted mainly in a fraction with a size of 2.0 < d < 5.0 mm and 0.5 < d < 1.6 mm, (Figs. 5b and d) since several crushing stages were performed. As can be seen, the EVA cut sheets along with Tedlar were mainly contained

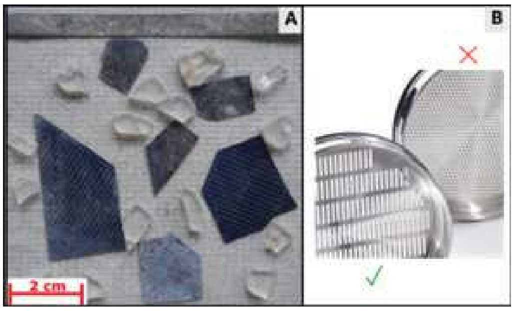


Fig. 13. A. Shape of the silicon and the glass particles after thermal treatment; B. Slotted sieve used
Rys. 13. A. Kształt cząstek krzemu i szkła po obróbce termicznej; B. Używane sito szczelinowe

in the $d > 5.0$ mm (Fig. 5a) and in a mixture with glass in the $2.0 < d < 5.0$ mm and $1.6 < d < 2.0$ mm fractions (Figs. 5b and c). Fractions larger than 1.6 mm were heated under predefined temperatures (500°C) for 60 min in order to break down the EVA aggregates and release more glass and metals. Thermal treatment determined 8.17% of weight loss because of EVA and Tedlar decomposition. The silicon and glass distributions were measured by XRD (X-ray powder diffraction) (Fig. 7). The amorphous phase was assumed to be glass, while the crystalline phase was assumed to be silicon. XRD analysis was performed for fraction $d > 0.5$ (glass fraction) and $d < 0.5$ mm (silicon fraction). According to the results, the glass fraction $d > 0.5$ (Fig. 7a) contains a rather large amount of silicon. Therefore, this fraction cannot be considered a directly recoverable clean glass fraction. The fraction below 0.5 mm (Fig. 7b) contains a considerable amount of silicon. However, the peaks obtained are small because this fraction also contains a considerable amount of amorphous phase (glass). As a result of this process, about 81.5% of the total weight of the sample after thermal treatment was recovered as glass, especially in the fraction with sizes of $2.0 < d < 5.0$ mm, $1.6 < d < 2.0$ mm and $0.5 < d < 1.6$ mm glass while about 18.5% was collected as finer $d < 0.5$ mm (Fig. 8) with a composition as indicated in Table 2. This percentage could be collected and then valorized through operations for further glass recovery.

3.2. Crushing by shredder crusher

The products displayed in Fig. 9 are the outcome of shredder crushing operation. Fig. 10 shows the distribution of various materials among the various size fractions. After crushing around 42.24% of the sample was a $d > 2.0$ mm fraction, in which the multilayer structure is still present and glass, silicon wafers, and back sheet are still glued together by crosslinked ethyl vinyl acetate (EVA). And around 32% of the sample was the fraction $0.5 < d < 1.6$ mm, due to the several crushing stages were performed. Once again, the EVA cut sheets along with Tedlar were mainly contained in the $d > 5$ mm (Fig. 9a) and in a mixture with glass in the $2.0 < d < 5.0$ mm and $1.6 < d < 2.0$ mm fractions (Figs. 9b and c). Fractions that contained polymers were heated under 500°C for 60 min in order to release more glass and metals. Thermal treatment determined 7.7% of weight loss because of EVA and Tedlar decomposition. XRD analysis was performed for fraction $d > 0.5$ (glass fraction) and $d < 0.5$ mm (metal fraction and silicon) (Fig.11). According to the results, the glass fraction $d > 0.5$ contains a rather large amount of silicon (Fig. 11a). Therefore, this fraction cannot be also considered as a directly recoverable clean glass fraction. The fraction below 0.5 mm (Fig. 11b) contains a considerable amount of metals and silicon. It could be recovered by further processes. As a result of this process, about 77.1% of the total weight of the sample after thermal treatment was recovered as glass, especially in the fraction with sizes of $2.0 < d < 5.0$ mm, $1.6 < d < 2.0$ mm and $0.5 < d < 1.6$ mm. About 22.9% of the total input weight was found to be finer than 0.5 mm fraction (Fig. 12) with a composition as indicated in Table 2.

3.3. Thermal treatment

In the thermal treatment, the sample was placed in a ceramic crucible with the glass facing down, and the back sheet was facing up and heated at predetermined temperatures (500°C) for 60 minutes to separate the different layers, including the front EVA layer between the glass and the solar cells and the back EVA layer between the solar cells and the back sheet. At the end of the thermal treatment, the results showed that the silicon particles were mainly smaller and thinner than the glass particles, which were large and thick (Fig. 13a). The difference in particle shape of the silicon particles and the glass particles was used as a method to improve the potential separation by particle shape, so a slotted sieve was used (Fig. 13b). Comminution by thermal treatment resulted in the products shown in Fig. 14. The distribution of the various materials among the different size fractions is shown in Fig. 15. After thermal treatment, most of the glass was contained in the coarse fractions, especially fractions $1.6 < d < 2.0$; $2 < d$, $0 < 5.0$, and $d > 5$ (Figs. 14 a, b and c). Only the smaller glass particles are found in the fraction $d < 1.6$ with metals and silicon particles (Figs. 14 d, e and f). The metallic contacts (busbars) or PV ribbons can be obtained magnetically from the fraction $d < 1.6$. The silicon and glass distributions were measured by XRD. The distributions of glass and silicon for fractions $d > 1.6$ mm and $d < 1.6$ mm are displayed in Figs. 16 a and b respectively. In particular, for the fraction $d > 1.6$ mm (Figs. 14 a, b and c), the XRD data showed an amorphous pattern (Fig. 16a) meaning that it can be considered a recoverable glass fraction. The fraction $d < 1.6$ mm (Figs. 14 d, e, and f) contains a rather large amount of silicon and metals with a very small amount of glass (Fig. 16 b). After thermal treatment, the total direct weight recovery as a glass of total input weight from fractions $d > 1.6$ mm was 90.22%. Direct recovery PV ribbon total input weight was 0.57% from the fraction $0.5 < d < 1.6$. Around 9.21% of total input weight was found to be $d < 0.5$ mm fraction (Fig. 17) having a composition as in Table 2. It could be recovered by further processes.

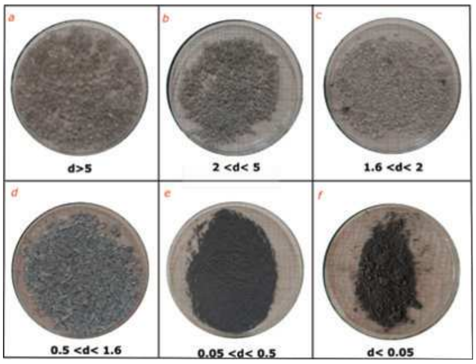


Fig. 14. Fractions obtained after thermal treatment
Rys. 14. Frakcje po obróbce termicznej

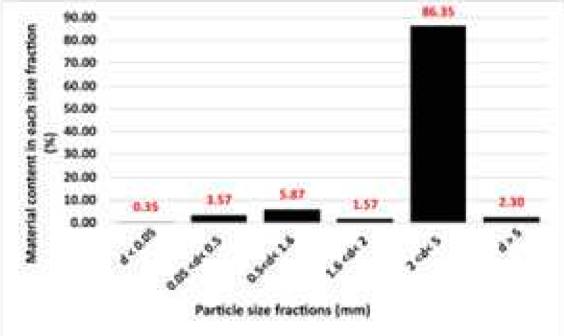


Fig. 15. Total size distribution after thermal treatment
Rys. 15. Rozkład wielkości ziaren po obróbce termicznej

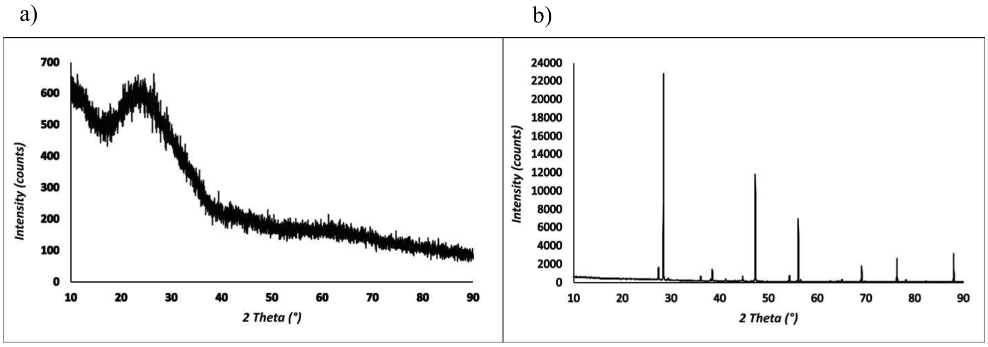
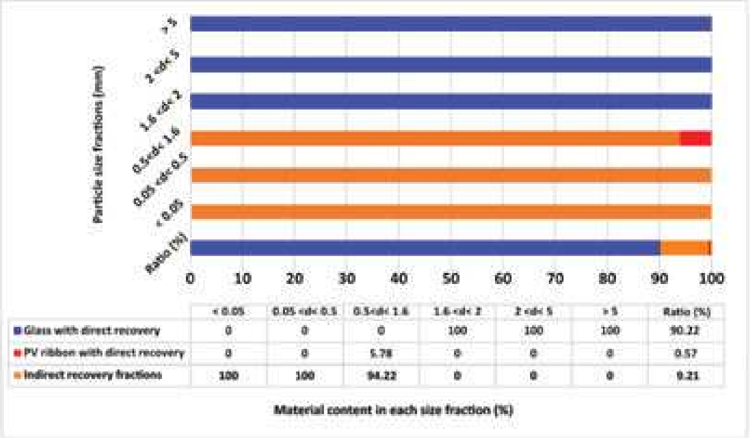


Fig. 16. Products analysed by XRD: a) d > 1.6 mm, b) d < 1.6 mm after thermal treatment
Rys. 16. Analiza XRD produktów po obróbce termicznej: a) d > 0.5 mm, b) d < 0.5 mm



	< 0.05	0.05 <d< 0.5	0.5<d< 1.6	1.6 <d< 2	2 <d< 5	> 5	Ratio (%)
🟦 Glass with direct recovery	0	0	0	100	100	100	90.22
🟥 PV ribbon with direct recovery	0	0	5.78	0	0	0	0.57
🟧 Indirect recovery fractions	100	100	94.22	0	0	0	9.21

Fig. 17. Distribution of Glass, Glass+ PV cell, and PV ribbon in wt (%) among the sieving of crushed PV panel after thermal treatment
Rys. 17. Rozkład wielkości ziaren ogniw fotowoltaicznych Glass, Glass+ i taśmy fotowoltaicznej po obróbce termicznej, (%)

Tab. 2. Results of XRF analysis (the main metal composition of fraction d < 0.5 mm) (HC: Hammer Crusher; SK: shredder crusher; TT: Thermal Treatment; SQS: Square Sieve; SLS: Slotted Sieve)

Tab. 2. Wyniki analizy XRF (główny skład metali frakcji d < 0.5 mm) (HC: kruszarka młotkowa; SB: rozdrabniacz nożowy; TT: obróbka termiczna; SQS: sito kwadratowe; SLS: sito szczelinowe)

Processes	**Si (%)**	**Ag (%)**	**Al (%)**	**Ca (%)**	**Cu (%)**	**Fe (%)**	**Mg (%)**	**Mn (%)**	**Pb (%)**	**Sb (%)**	**Sn (%)**	**Ti (%)**	**Zn (%)**
HC+ TT+SQS	36.851	0.920	4.046	7.040	0.458	3.145	1.272	0.467	0.151	0.195	0.304	3.945	0.176
Sk +TT+SQS	34.708	0.9842	1.6034	7.3454	0.33777	2.5827	1.2869	0.28711	0.11394	0.23437	0.14798	0.6638	0.14366
TT + SLS	49.818	1.369	5.509	4.645	0.045	0.186	0.866	0.006	0.091	0.103	0.079	4.720	0.022

4. CONCLUSION

Nowadays, there has been pressure to reduce the environmental burden and to use primary raw materials in an economic way. This is the reason for the continuous development and search for new materials using mainly recycled secondary raw materials. Crystalline silicon type PV panels in the order of mass are composed of 76% glass (panel surface), 10% polymer (encapsulant and back sheet foil), 8% aluminum (mostly the frame), 5% silicon (solar cells), 1% copper (interconnectors) and less than 0.1% silver (contact lines) and other metals (mostly tin and lead). The recovery of these materials and their return to the economy can be used to manufacture new PV panels. A method for recycling of disposed silicon-based PV panel (mono/polycrystalline) using physical and thermal treatments has been presented in this work. Three alternative methods were investigated: hammer crusher followed by thermal treatment and sieve, shredder crusher followed by thermal treatment and sieve, and the thermal treatment followed by a slotted sieve. The first step was disassembly of the panel to remove the aluminum frame, cables, and a junction box. The results showed that the main difference between the three alternative methods was found in the different fraction percentages and in their composition. As for thermal treatment experimental results reported in this work, they showed about 7–8% of weight loss for Si panels. In order to obtain the highest mass recovery, thermal treatment followed by a slotted sieve proved to be the most effective method for direct glass recovery according to the shape of particles. This process allowed 90% recovery of the module weight (without frame, polymer and other equipment) as glass from fractions d > 1.6 mm and the latter did not contain impurities in terms of Si and metals. The finer fractions can be collected and eventually treated for a further metal recovery process.

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Recykling zużytych modułów fotowoltaicznych metodami mechaniczno-termicznymi

Instalacje fotowoltaiczne stały się bardzo popularnym rozwiązaniem na przestrzeni pierwszego dwudziestolecia XXI wieku. Spowodowane to było głównie rosnącym zainteresowaniem przemysłu i rządów poszczególnych państw dotyczącym skutków i kwestii łagodzenia - zmian klimatycznych, potrzeby dekarbonizacji, jak również rosnącym zapotrzebowaniem na energię. Najbardziej powszechnym problemem związanym z panelami fotowoltaicznymi (PV) jest to, że ich żywotność jest ograniczona, co powoduje, że ostatecznie będą musiały zostać wycofane z eksploatacji. Wraz z rozwojem mocy produkcyjnych PV na całym świecie, w przyszłości będzie generowana duża ilość odpadów związanych z panelami fotowoltaicznymi. Ponieważ panele fotowoltaiczne zawierają metale ciężkie, takie jak ołów, kadm i cyna, może to mieć znaczący wpływ na środowisko naturalne. Ponadto, odpady te zawierają również cenne metale (np. srebro, gal, ind i german) oraz standardowe materiały (np. aluminium, szkło), które po odzyskaniu stanowią cenne źródło tych surowców. Oczekuje się, że opracowanie zrównoważonego, przyjaznego dla środowiska procesu recyklingu i maksymalizacja odzysku komponentów z paneli fotowoltaicznych pod koniec ich życia rozwiąże problem odpadów fotowoltaicznych. W tej pracy zbadano trzy alternatywne metody recyklingu krzemowych paneli fotowoltaicznych (mono/polikrystalicznych) w oparciu o połączenie procesów mechanicznych i termicznych. Trzy metody odzysku polegały na wykorzystaniu kruszarki młotkowej, po której zastosowano obróbkę termiczną i klasyfikację na sicie kwadratowym, kruszarki nożowej typu schredder, a następnie obróbkę termiczną i klasyfikację na sicie kwadratowym oraz obróbkę termiczną, po której następuje klasyfikacja na sicie szczelinowym. Przeprowadzono analizy otrzymanych produktów za pomocą dyfrakcji rentgenowskiej (XRD) i fluorescencji rentgenowskiej (XRF) w celu oceny efektów odzysku. Wyniki wykazały, że obróbka cieplna, a następnie zastosowanie sita szczelinowego jest najskuteczniejszą metodą bezpośredniego odzyskiwania szkła dla wszystkich badanych typów modułów fotowoltaicznych.

Słowa kluczowe: *panele PV, krzem krystaliczny, recykling, odpady, procesy mechaniczne i termiczne*