Development of High-Purity Glass Recovery Technology from End-of-Life Solar Panels for Applying to Materials for Glass Wool Productions

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***Abstract*—This study aims to develop a material recycling process for end-of-life solar panels, focusing on the recovery of high-purity glass and its application in glass wool production. Solar panels contain more than 60% glass by weight, and their disposal is expected to increase significantly in the coming decades. Because of this, the researchers developed a thermal decomposition and multi-stage sorting process to separate glass, copper wires, and silicon cells. The process successfully recovered glass cullet with a purity of 99.999%, which accounted for 86% of the panel weight after treatment. Copper and silver were also recovered at concentrations of 55% and 8539 mg/kg, respectively, which shows potential for reuse as valuable materials. The recovered glass cullet was used at 100% to produce glass wool prototypes. Performance evaluation showed that the thermal conductivity of the prototype was 0.040 W/m·K, which is comparable to conventional products made from window glass (0.041 W/m·K). Environmental safety was confirmed through leaching tests, with all measured values well below regulatory limits. These results show the feasibility of converting waste solar panel glass into high-value insulation materials. The proposed system offers a practical solution for resource circulation and landfill reduction, which contributes to sustainable waste management and environmental protection.**

***Keywords*—used solar panels, recycling, glass wool, glass recovery**

I. Introduction

Solar panel numbers have been increasing in Japan since the introduction of the fixed-price purchase system for surplus solar power. Additionally, as measures to achieve carbon neutrality and stabilize power supply, Tokyo and Kawasaki City have mandated the installation of solar panels in new homes by residential manufacturers on a certain scale. This trend is expanding to other municipalities, such as Kyoto Prefecture, and the installation of solar panels is expected to continue increasing. Solar panels are typically decommissioned owing to malfunctions or aging, and a significant number will reach the end of their operational lifespan simultaneously, approximately 20 to 30 years after installation. The Ministry of the Environment and the New Energy and Industrial Technology Development Organization (NEDO) have forecast the amount of waste and predict that the number of discarded panels will gradually increase after 2030 and peak after 2035 [1]. According to estimates by Japan's Ministry of the Environment and the New Energy and Industrial Technology Development Organization (NEDO), the annual amount of waste from end-of-life solar panels is expected to peak at approximately 170,000 to 280,000 tons, accounting for roughly 17–27% of the total volume of industrial waste being disposed. Currently, solar panels are mainly recycled as easily recoverable aluminum, and most of the discarded solar panels are landfilled. Even during recycling, these materials are often used as roadbed materials following melting treatment. To effectively recycle panels that are expected to be generated in large quantities, the development of recycling technology that converts them into higher-value-added products is required.

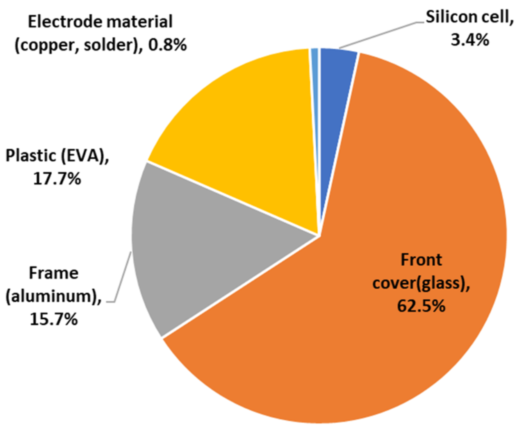

Fig. 1. Composition of solar panels (created by the authors based on NEDO, 2009).

Solar panels comprise aluminum frames, glass, solar cells, Ethylene-Vinyl Acetate (EVA) resin, and other resins, with glass accounting for more than 60% (Fig. 1). To achieve material recycling of used solar panels, it is necessary to upgrade the recycling of glass, which has a high composition ratio. Additionally, to upgrade the recycling of glass, it is necessary to develop technologies to recover glass in a state with almost no impurities.

Against this background, the current study focused on pyrolyzed products that are suitable for material recovery as the resin components decompose, and the separation of materials was examined by combining sorting equipment. This study aimed to recover glass cullet with very few impurities to meet the high-quality requirements for recycled raw materials.

This study aimed to achieve upgraded recycling of glass recovered from end-of-life solar panels by examining its use as a raw material for glass wool manufacturing. In this context, upgraded recycling refers to the process of reusing recovered glass in higher-value applications, such as insulation materials, rather than in low-grade uses such as roadbed materials. To date, no previous studies have reported the production of glass wool using 100% solar panel-derived glass. This investigation is therefore a novel and valuable contribution to material recycling research.

The objectives of this study are twofold: (1) to establish a technology for recovering high-purity glass cullet with minimal contamination from end-of-life solar panels and (2) to evaluate the feasibility of using the recovered glass cullet in glass wool production, with a focus on product quality and environmental impact.

Parts of the results presented in this paper were previously reported by Umetsu *et al.* at the Spring Meetings of the Mining and Materials Processing Institute of Japan (MMIJ) held in 2021 and 2022. Murayama contributed to the research as a co-author. These earlier presentations focused on the development and optimization of the glass recovery process. The present study expands on those findings by including additional experimental data, detailed analysis, and prototype evaluations.

II. Literature Review

Various recycling methods for end-of-life Photovoltaic (PV) panels have been studied (Table 1). These methods include organic solvent techniques that use solvents such as trichloroethylene, hot-knife methods in which a heated blade is inserted between the cover glass and EVA to separate them, and thermal decomposition techniques. The organic solvent method, which uses trichloroethylene to recover silicon cells [2], enables the recovery of cells without damage. However, this method requires immersion in the solvent at 80 °C for 10 days, which presents challenges in processing efficiency. Researchers have studied the limonene method as a way to swell and soften EVA resin, which facilitates the separation of cells and glass [3]. The hot-knife method has been applied as a pretreatment for silver recovery [4], particularly before nitric acid treatment. While this method is effective for silver extraction, residual resin remains on the surface of the recovered glass, which limits its direct reuse as a raw material. The thermal decomposition method under a nitrogen atmosphere involves heating to approximately 520 °C in an inert gas environment to remove EVA. This approach is cost-effective and allows for the recovery of intact solar cells [5]. However, potential NOx emissions and degradation of cell performance because of high temperatures are notable drawbacks. The combustion method using a fluidized bed involves burning off EVA and the backsheet at around 450 °C. In this process, quartz particles abrade the surface of the solar cells, which enables recovery in wafer form [6]. A disadvantage is the need to manage sand contaminated with lead. Thermal decomposition in an air atmosphere allows EVA combustion at slightly lower temperatures than in nitrogen, but requires a prolonged treatment time of approximately three hours to remove the resulting carbonaceous residues [7]. Thermal decomposition-based methods facilitate the removal of resin from glass and metal surfaces, which makes it easier to recover individual materials, provided the cover glass remains intact. However, in many cases, the cover glass of used PV panels is already broken, which leads to material mixing after decomposition and reduces the value of the recovered materials as recyclable resources.

In addition to these established methods, recent international studies have provided new insights into photovoltaic glass recycling. Gracia *et al.* [8] highlighted that glass accounts for approximately 75% of the panel weight, making it the most critical material for recycling. Several facilities in the U.S. employ mechanical separation and thermal treatment to recover glass. Meanwhile, Jiang *et al.* [9] emphasized the economic and environmental benefits of recovering materials including glass, and stressed the importance of international collaboration for technology sharing and standardization. These studies support the global relevance of the high-purity glass recovery technology proposed in this research.

Table 1. Overview of solar panel recycling technology

Method	Description
Organic Solvent Method	Recovery of silicon cells using trichloroethylene.
Limonene Method	Separation of glass using a solution mainly composed of d-limonene.
Hot-Knife Method	Insertion of a heated knife blade (hot knife) between the cover glass and EVA for separation.
Thermal Decomposition (Nitrogen Atmosphere)	Heating to approximately 520 °C in a nitrogen gas atmosphere to remove EVA.
Combustion Method (Fluidized Bed)	Combustion and removal of EVA and backsheet using a fluidized bed at approximately 450 °C.
Thermal Decomposition (Air Atmosphere)	Combustion and removal of EVA in an air atmosphere.

In this study, the researchers selected an air table as a sorting device to recover high-quality glass cullet from thermally treated PV panel residues. Air tables were originally developed for grain sorting, but they have recently gained attention for recycling applications, such as the recovery of metals from municipal solid waste incineration bottom ash, as demonstrated by Owada *et al.*, separation of precious metals from shredded electronic components [10], non-ferrous metal recovery from Automobile Shredder Residue (ASR), as applied by Furuya *et al.*, and plastic separation from packaging waste [11]. Some studies have addressed multi-material separation of crushed PV panels however, no prior research has focused on the use of thermally treated panels.

To the best of our knowledge, no prior research has focused on the application of air tables to thermally treated PV panel residues, highlighting the novelty of this study.

III. Materials and Methods

A. Description of the Target Solar Panels

This study focused on 36 types of solar panels used in various countries, and emphasized the upgrade recycling of glass while also reporting the differences in the glass composition analysis results. Glass composition analysis was conducted using a Rigaku X-ray fluorescence spectrometer (ZSX Primus IV), employing the Fundamental Parameter (FP) method. The FP method is a quantitative analysis technique used to determine the composition at which the theoretical intensity matches the measured intensity. As a pretreatment for this measurement, approximately 30 g of the sampled glass was placed in a tungsten carbide grinding container and ground for 3 min using a grinder. Subsequently, a disk was formed via pressure molding (approximately 150 kg/cm² for 1 min).

B. Processing Methods for Used Solar Panels

Used solar panels undergo two main processes: the decomposition of resin components through thermal treatment, and sorting of the products from the thermal treatment. The thermal decomposition method includes primary and secondary thermal decompositions. Primary thermal decomposition is conducted in a reducing atmosphere with an oxygen concentration of less than 1%, while secondary thermal decomposition is conducted in an oxygen atmosphere to decompose the resin components. A processing test was conducted using the plant shown in Fig. 2, where the conditions were changed from primary to secondary thermal decomposition within the same plant. Both primary and secondary thermal decompositions were set at a temperature of 500 °C, with the primary decomposition taking 30 min per panel and the secondary decomposition taking 20 min. The thermal-decomposition conditions are listed in Table 2.

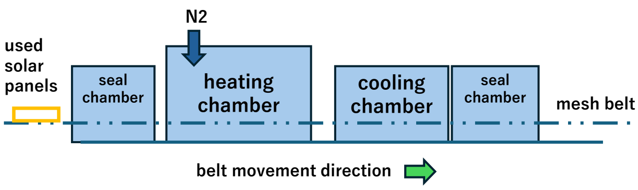

Fig. 2. Schematic diagram of heat treatment plant.

Table 2. Pyrolysis stage

Process Step	Speed (m/h)	Time (min/sheet)	Temperature (°C)	Oxygen Concentration (%)
Primary Pyrolysis	8	30	500	<1
Secondary Pyrolysis	12	20	500	20.9

To further explain, the nitrogen atmosphere used in the primary pyrolysis stage creates a reducing environment that allows for the safe thermal decomposition of organic resins, such as EVA, without combustion. This setup reduces the generation of harmful gases and prevents thermal damage to other materials. The reducing atmosphere also helps preserve the surface quality of the glass and prevents oxidation of metallic components, such as copper wires and solder. The primary pyrolysis is designed to decompose organic resins under controlled conditions, which facilitates the separation of glass, metals, and silicon cells while maintaining their integrity. In contrast, the secondary pyrolysis, conducted in an air atmosphere, oxidizes and removes residual carbon and organic matter remaining on the surfaces of the recovered materials. This two-step pyrolysis process ensures high-purity recovery of glass cullet and increases the efficiency of subsequent sorting operations.

The EVA layer underwent thermal decomposition during the treatment process. To prevent secondary pollution, the exhaust gas produced by thermal decomposition was treated with an alkaline scrubber. The wastewater from the scrubber was properly processed to ensure environmental safety.

Fig. 3. Appearance of panel after pyrolysis. (Overall view of the panel after heat treatment).

Fig. 4. Appearance of panel after pyrolysis. (Close-up view of the glass section after heat treatment).

Fig. 3 and Fig. 4 present the appearance of the panels after thermal decomposition and a close-up of the glass parts, respectively. after thermal decomposition, organic materials such as EVA are decomposed, leaving only glass, copper wires, and silicon cells. Fig. 5 shows the state of the glass when thermal treatment is conducted without breaking the glass. Under these conditions, the glass can be recovered in a plate-like state, allowing it to be used as a glass recycling raw material without impurities. However, when the glass of used panels is broken, the entire glass is cracked and mixed with copper wires and silicon cells. In this state, it is difficult to recover materials separately, making it challenging to use them as recycling raw materials, thus necessitating the examination of sorting processes for each material.

Fig. 5. Appearance of panel after pyrolysis. (Panel with intact cover glass).

Additionally, close observation of the processed materials revealed that the solder used in the panels became granular and mixed after the thermal treatment (Fig. 6). Because the solder contains lead, there are concerns about its impact on environmental quality when mixed with recovered glass. Therefore, these conditions were examined to prevent solder balls from mixing with the recovered glass during the sorting process.

Fig. 6. Solder balls (0.6~2.5 mm) recovered from panel after heat treatment.

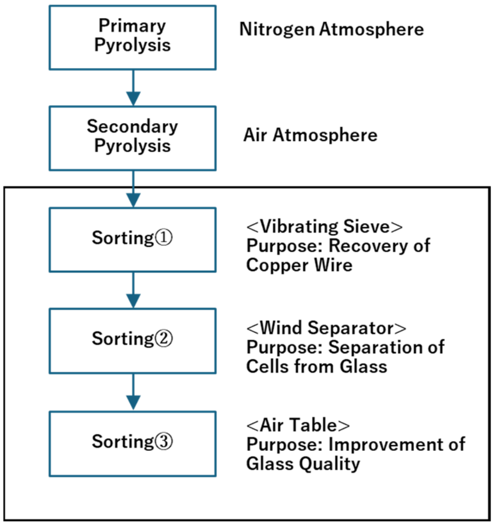

Fig. 7. Processing flow of used solar panels.

After thermal treatment, the mixed materials were sorted into individual materials using a three-stage sorting process. Special attention was paid to preventing impurities from mixing with the recovered glass. The processing flow is illustrated in Fig. 7. In the first sorting process, a vibrating sieve with a mesh size of 20 mm was used to recover copper wires and large silicon cells. Subsequently, air separation was employed to recover the fine silicon cells. In the final sorting process, an air table was used to remove fine silicon cells and copper wires that had not been recovered from the glass cullet in the first and second stages. Additionally, conditions were examined to prevent small amounts of solder balls from mixing with the recovered glass on the air table in the third stage.

The recovered materials were evaluated by analyzing the recovered glass and other metallic materials. The glass recovery was analyzed using the FP method, as described above. For the other metal components, the sorted samples were prepared using the matte smelting method (JIS M 8082) as a pretreatment. The composition analysis was conducted according to the quantitative method for gold and silver in ores (JIS M 8111) for silver and measured via Inductively Coupled Plasma (ICP) for copper.

C. Method for Prototyping Glass Wool

Glass wool prototypes were manufactured to evaluate the recovered glass. The glass cullet used for manufacturing came from this study, and resulted from processing multiple panels. For comparison, the study used a glass cullet derived from window glass, which is typically used in manufacturing.

A glass wool manufacturer carried out the prototyping and evaluation of glass wool using approximately two tons of glass cullet obtained in this study. The manufacturer used the glass cullet as the only raw material in the production process, completely replacing conventional raw materials with a 100% substitution. Fig. 8 shows the manufacturing flow of the prototype. The glass cullet underwent processes including melting, processing, spinning, coating with adhesive resin, collection, thermoforming, width cutting, length cutting, packaging, and storage to produce the glass wool prototypes.

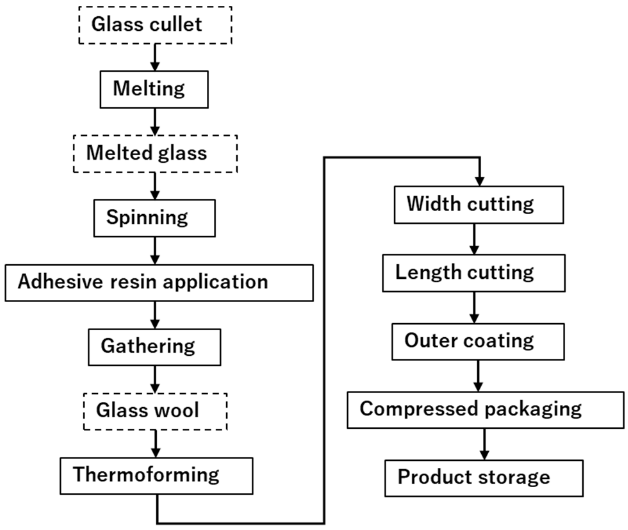

Fig. 8. Glass wool prototype flow.

Additionally, the prototypes were evaluated through visual inspection and by measuring thermal conductivity as an indicator of product quality. We selected thermal conductivity because it is a fundamental and widely accepted parameter for evaluating the thermal insulation performance of glass wool. They conducted the measurement in accordance with JIS A 9521.

IV. Result and Discussion

A. Glass Composition

Table 3 presents the average, minimum, and maximum values for the compositions of 36 types of solar panel glass. These 36 types correspond to distinct product models produced by 23 companies in seven countries. Each type represents a unique model or specification, and the compositional data were collected from individual samples for each model. The results shows that the SiO_2 content ranged from 70.20% to 72.40%, with an average of 71.13%. The CaO content ranged from 9.19% to 11.86%, and the Na_2O content ranged from 12.83% to 15.00%, with average values of 10.08% and 13.93%, respectively. This composition is comparable to that of typical soda-lime glass (Table 4).

Sb_2O_3 is added during glass manufacturing to minimize bubbles in the furnace and improve the transparency of the produced glass. It is also a substance of concern because of its impact on equipment during glass manufacturing. Sb_2O_3 was detected in 33 of the 36 samples, with an average value of 0.21% and a maximum value of 0.32%. As an item related to waste disposal laws, As_2O_3 was detected in eight out of 36 samples, with a maximum value of 0.013%. PbO was detected in some samples but was below the quantification limit.

Table 3. Summary of analysis results for PV cover glass (Unit: mass%)

Analytical Method	Composition	Lower limit of quantification	Ave	Max	Min
Fixed angle measurement	SiO_2	0.03	71.13	72.40	70.20
	Al_2O_3	0.01	1.09	1.61	0.14
	MgO	0.02	3.18	4.15	0.10
	CaO	0.01	10.08	11.86	9.19
	Na_2O	0.04	13.93	15.00	12.83
	K_2O	0.01	0.03	0.05	<0.01
	SO_3	0.01	0.24	0.38	0.17
	Fe_2O_3	0.01	0.02	0.03	0.01
	TiO_2	0.01	0.04	0.26	<0.01
	ZrO_2	0.001	0.01	0.02	<0.01
	SrO	0.001	0.02	0.23	<0.01
	BaO	0.1	<0.1	<0.1	<0.1
	As_2O_3	0.002	0.01	0.013	<0.001
	Sb_2O_3	0.01	0.21	0.32	<0.05
	Bi_2O_3	0.01	<0.01	<0.01	<0.01
	PbO	0.002	0.00	0.005	<0.002
Qualitative Analysis	F	0.2	<0.2	<0.2	<0.2
	P_2O_5	0.01	<0.01	<0.01	<0.01
	Cl	0.02	0.03	0.04	<0.02
	V_2O_5	0.05	<0.05	<0.05	<0.05
	Cr_2O_3	0.05	<0.05	<0.05	<0.05
	NiO	0.01	<0.01	<0.01	<0.01
	ZnO	0.01	<0.01	<0.01	<0.01
	SnO_2	0.05	<0.05	<0.05	<0.05

Table 4. Composition of typical soda-lime glass

Composition	Content	Remarks
SiO_2	70–74%	Main component
Al_2O_3	0–2%	Increases hardness
CaO	6–12%	Increases water resistance
MgO	0–4%	Increases water resistance
Na_2O	12–16%	Improves fusibility

B. Evaluation of the Sorted Recovered Materials

After thermal treatment, the solar panels were processed using a three-stage sorting process to recover the materials separately. The first stage involved the use of a vibrating sieve, which recovered approximately 2% of the weight after thermal treatment. The vibrating sieve and photographs of the recovered materials before and after sorting are shown in Fig. 9. The composition was 55% copper and 8539 mg/kg silver.

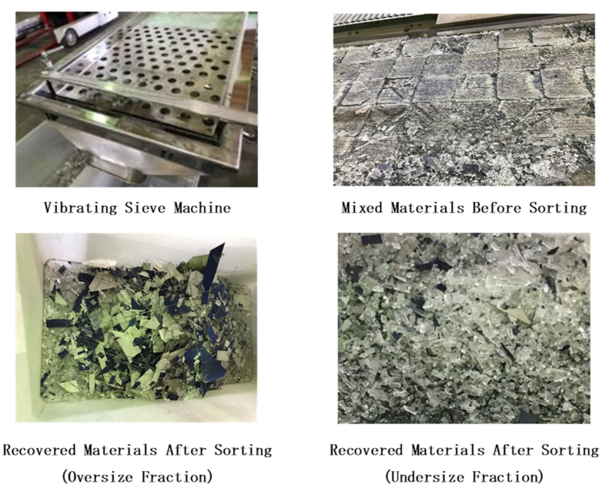

Fig. 9. Appearance of the vibrating sieve machine and the appearance of the sorted objects and recovered sorted objects.

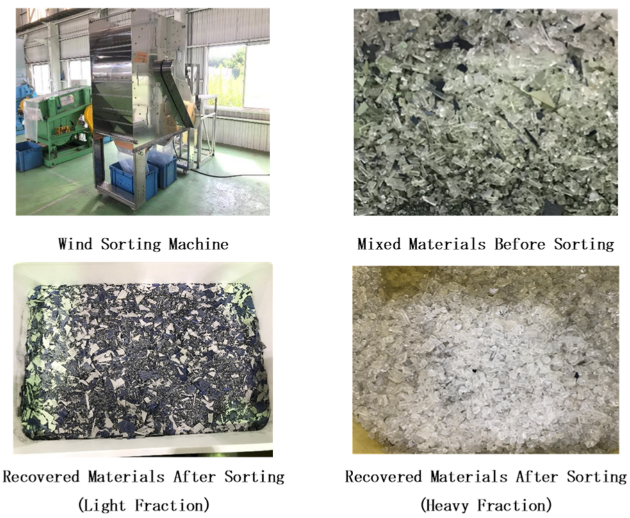

Fig. 10. Appearance of the wind sorting machine and the appearance of the sorted objects and recovered sorted objects.

The second stage involved air separation, that is, dividing the recovered materials into light and heavy fractions. The air separator and photographs of the recovered materials before and after sorting are shown in Fig. 10. The light fraction contained 2% copper and 5683 mg/kg silver. The materials recovered from the vibrating sieve and air separator had high concentrations of copper and silver, confirming that they could be sold as valuable materials to smelting companies at current market prices.

The heavy fraction was further processed in the third stage using an air table to separate small impurities, such as copper wires and silicon cells, from the glass cullet. The air table was adjusted to minimize the inclusion of fine particles, such as solder balls, in the recovered glass cullet. The structure of the air table is illustrated in Fig. 11.

The equipment and operating conditions, such as the deck hole diameter, deck height, sieve angle, sample layer thickness, and feed rate, were adjusted as shown in Table 5. Additionally, modifications were made to prevent rebound into the light-fraction side and change the sample feed location. Six cases were tested to verify the number of solder balls mixed into the glass cullet (heavy-fraction side of the air table). Approximately 400 kg of the sample was processed per test. The results, shown in Table 6, confirm that no solder balls were mixed into the glass cullet under multiple conditions. The number of fine silicon cells mixed into the glass-recovery side was also examined, with the results showing that equipment modifications and condition changes successfully produced glass cullet with minimal impurities. The air table and photographs of the recovered materials before and after sorting are shown in Fig. 12.

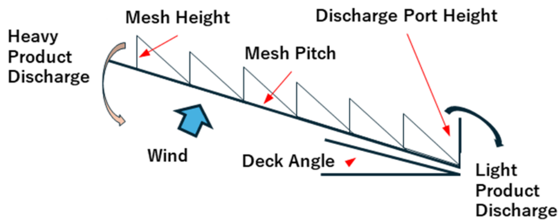

Fig. 11. Structure of air table deck.

Table 5. Consideration of equipment conditions for air table

Condition Scenario	Conditions					Equipment Improvement Light Side Bounce Prevention
	Hole Diameter (Φmm)	Mesh (mm)	Angle (°)	Layer Thickness (Visual)	Feed Rate (kg/h)	
Case 1	1	50	10.5	Thick	739	-
Case 2	1	75	10.5	Thick	1266	-
Case 3	1	50	10.5	Thick	1129	○
Case 4	3	50	11.0	Thick	810	○
Case 5	3	50	11.0	Thick	991	○

Note: "○" indicates that equipment improvement to prevent bounce into the light-fraction side was implemented; "-" indicates that no such improvement was made.

Table 6. Number of foreign objects in recovered glass

Condition Scenario	Weight of Recovered Glass (kg)	Solder Balls (Quantity)	Cells (Quantity)
Case 1	403	2	16
Case 2	482	2	25
Case 3	375	0	6
Case 4	411	0	5
Case 5	429	0	2

Fig. 12. Appearance of the air table and the appearance of the sorted objects and recovered sorted objects.

The quality of the recovered glass cullet was extremely high, with a purity of 99.999%. The silicon cells identified as contaminants in this context correspond to 2 mg/kg in the recovered glass cullet. The recovered glass cullet accounted for 86% of the weight after thermal treatment. It is noteworthy that the mentioned weight did not include an aluminum frame. The main loss observed during the process is the light fraction recovered by the air table. In this system, the heavy fraction consists of glass cullet, while the light fraction contains various materials. About 2% of the total processed material is transferred to the light fraction, which includes a mixture of glass cullet, copper wires, and silicon cells. The continuous processing system examined in this study has been evaluated at a level similar to full-scale operation and can handle tens of thousands of solar panels each year. Compared to existing recycling systems, the proposed method allows for the recovery of glass with much higher purity. The yield is also favorable, which shows that the system is efficient and practical.

C. *Results of Glass Wool Prototyping*

The glass cullet used for the glass wool prototyping was obtained from sorted recovered materials. The results of the compositional analysis are presented in Table 7.

Photos of the glass wool prototypes are shown in Fig. 13. The left photo in the figure shows the prototype made from a glass cullet derived from solar panels, whereas the photo on the right shows the prototype made from a cullet derived from window glass. Visually, there is no noticeable difference between the prototype made from the solar panel glass cullet and the conventional product made from the window glass cullet.

Table 7. Example of composition analysis results for selected PV glass cullet (Unit: mass%)

Analytical Method	Composition	Lower limit of quantification	Composition
Fixed angle measurement	SiO_2	0.03	70.3
	Al_2O_3	0.01	1.12
	MgO	0.02	3.15
	CaO	0.01	10.2
	Na_2O	0.04	14.6
	K_2O	0.01	0.03
	SO_3	0.01	0.34
	Fe_2O_3	0.01	0.02
	TiO_2	0.01	0.02
	ZrO_2	0.001	0.010
	SrO	0.001	0.005
	BaO	0.1	<0.1
	As_2O_3	0.002	0.007
	Sb_2O_3	0.01	0.15
	Bi_2O_3	0.01	<0.01
	PbO	0.002	<0.002
Qualitative Analysis	F	0.2	<0.2
	P_2O_5	0.01	<0.01
	Cl	0.02	0.03
	V_2O_5	0.05	<0.05
	Cr_2O_3	0.05	<0.05
	NiO	0.01	<0.01
	ZnO	0.01	<0.01
	SnO_2	0.05	<0.05

Fig. 13. Appearance of the prototype. (Left: prototype derived from solar panel glass; Right: product made from conventional materials).

Table 8. Composition of glass wool

Composition	PV raw material prototype	Normal raw material product
SiO_2	72.81%	71.34%
CaO	17.21%	16.60%
Na_2O	6.33%	5.99%
MgO	1.60%	1.88%
Al_2O_3	1.10%	1.82%
Sb_2O_3	0.09%	<0.01%
SO_3	0.43%	0.41%
K_2O	0.30%	1.73%
Fe_2O_3	0.13%	0.23%
P_2O_5	<0.01%	<0.01%
BaO	<0.01%	<0.01%
StO	<0.01%	<0.01%
TiO_2	<0.01%	<0.01%
As	22mg/kg	<10mg/kg
Cd	1mg/kg	<1mg/kg
Cr	5mg/kg	<5mg/kg
Hg	<5mg/kg	<5mg/kg
Pb	7mg/kg	7mg/kg
Se	<10mg/kg	<10mg/kg

The quality tests for the prototypes included thermal conductivity, leaching tests, and chemical composition analysis. Table 8 shows that the recovered glass cullet contains major components such as SiO_2, CaO, and Na_2O in proportions comparable to standard raw materials used in industrial glass wool production. However, trace amounts of Sb_2O_3, up to 0.09 percent, were detected. This may have long-term effects on manufacturing equipment. Therefore, further investigation into its potential effect is warranted. The results of the thermal conductivity test are shown in Table 9. The test results indicate that the prototypes meet the required performance for insulation products, with a thermal conductivity (λ) of 0.045 or less, similar to conventional raw materials. In addition, leaching tests were conducted to assess the environmental impact of the prototypes after market distribution. The evaluation results are listed in Table 10.

Table 9. Thermal conductivity result for the prototype (Unit: W/m·K)

Parameter	PV Raw Material Prototype	Normal Raw Material Product
Analysis Results	$\lambda = 0.040$	$\lambda = 0.041$
Standard Values	$\lambda < 0.045$	

Table 10. Leaching test results of glass wool prototypes (Unit:mg/L)

Composition	Results	standard
Mercury or its compounds	<0.0005	<0.005
Cadmium or its compounds	<0.009	<0.09
Lead or its compounds	<0.03	<0.3
Hexavalent chromium compounds	0.13	<1.5
Arsenic or its compounds	<0.03	<0.3
Trichloroethylene	<0.002	<0.1
Tetrachloroethylene	<0.002	<0.1
Dichloromethane	<0.002	<0.1
benzene	<0.002	<0.1
Selenium or its compounds	<0.03	<0.3
Fluoride	<0.8	-
Boron or its compounds	<0.1	-
Antimony	0.05	-

The evaluation was conducted in accordance with the "Test Methods for Metals in Industrial Waste" (Environmental Agency Notification No. 13, 1973). The standards referenced were based on the "Waste Management and Public Cleansing Law Enforcement Regulations" (Ministry of Health and Welfare, Ordinance No. 35, 1973).

The evaluation results suggest that the leaching tests were conducted under more severe conditions than those expected when glass wool is incorporated into the walls of houses. Therefore, it can be concluded that there are no issues with the raw materials used in this study. Although trace amounts of hexavalent chromium compounds were detected, they were below one-tenth of the standard value, indicating no significant concerns.

V. Conclusion

This study developed processing technologies to recover cover glass, cells, and copper wires with high precision from used solar panels. An investigation into the glass composition of the solar panels confirmed that the composition is comparable to that of typical soda-lime glass. In examining methods used to recover each material from used solar panels, this study focused on the upgrade recycling of glass, confirming that glass cullet can be recovered with minimal impurities. Additionally, it was confirmed that the recovered glass cullet could be used in glass wool without affecting product quality. The recovered copper and silver were also found in concentrations that could be recovered as valuable materials by smelting companies, establishing an effective means of material recycling for a large number of solar panels expected to be discarded in the future. Specifically, it was demonstrated that glass, which accounts for approximately 60% of the weight of solar panels, can be recovered at a level suitable for upgrade recycling and that the quality of the prototype glass cullet is acceptable.

In cases where the cover glass is damaged during use or disposal, making it difficult to recover materials separately, this system, which can recover each material at a level suitable for recycling, is considered highly beneficial from the perspective of circulating material resources in Japan. In particular, glass, which is economically challenging to reuse because of its low raw material price and is often landfilled, can be used as a recycled raw material in this system. this approach helps address the issue of landfill capacity which could have significant effects on reducing pollution and improving people's general quality of life. The recycling technologies must be estimated not only from the view of technological feasibility and material evaluation, but also compliance with relevant laws. The proposed system in this study was confirmed to be complied with relevant Japanese regulations in installed and operated process, including the Waste Management and Public Cleansing Act and Fire Service Law.

Future challenges include confirming the long-term manufacturing and environmental impacts of glass as a raw material.

Conflict of Interest

Author 1 (Akihiro Murayama) conducted this research as an employee of Shinryo Corporation. Shinryo Corporation holds commercial interests in the outcomes of this study, including ownership of patents related to the developed technology. Author 1 was involved in the invention. While the study was conducted within the company, the design, data interpretation, and conclusions were based on scientific principles and were not influenced by corporate interests. There are no institutional policies or contractual agreements that restrict data sharing or compromise the independence of publication.

The other authors declare no conflict of interest.

Author Contributions

Akihiro Murayama conducted the research and wrote the manuscript. Shuji Owada supervised the experimental design and contributed to data analysis. Toru Matsumoto supported the prototype evaluation and reviewed the final manuscript. All authors approved the final version.

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