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Sustainability Victoria

Resource Recovery Strategies & Programs Division

PV Panel Reprocessing: Research into Silicon-Based Photovoltaic Cell Solar Panel Processing Methods, Viable Materials Recovery and Potential End Market Applications.

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1. Scope of Work

Sustainability Victoria (SV) has requested the services of HRL Technology Group (HRL) to conduct research into processing methods for damaged, unusable, and 'end-of-life' (EOL) silicon-based photovoltaic cell solar panels. The project will operate using pilot-scale level equipment, specifically focusing on processing panels through conventional shredder equipment; subsequently, the shredded panel material will be assessed to determine:

PART ONE:

- Process silicon-based PV panels through conventional shredder equipment.
- Recover and separate mixed PV panel materials.
- Identify level of quality and contamination of shredded materials, including: re-use potential, possible commodity resale options, and value of materials.
- Assess material recovery rates and residual components of shredded panels.

PART TWO:

- Determine suitability and practicability of panel pre-treatment prior to shredder processing and/or further treatment methods in refining recovered materials from shredded panels (i.e.: glass separation, chemical treatment processes, etc).
- Identify levels of quality and contamination of materials following further treatment options, including: re-use potential, possible commodity resale options, and value of materials.
- Assess material recovery rates and residual components of pre-treated and/or further processed materials.
- Identify any markets (local and overseas) for possible recirculation of recovered resources, including: purity levels required and associated values.

Following panel processing (Part One & Part Two), materials recovery and quality assessment, HRL will attempt to identify any local or international markets for possible recirculation of the recoverable materials portion of the panels. The identification will include details of any specifications or limitations related to purity or chemistry of the recovered materials.

Further to processing panels through conventional shredding equipment, SV has requested for HRL to determine the suitability and practicality of panel pre-treatment methods that may be applied before panel shredding to maximise the separation of recoverable reusable materials. HRL will also apply these treatment methods to the post-shredded panel materials to achieve maximum separation and recovery of reusable materials.

After panel processing, materials recovery and quality assessment has been completed, HRL will develop a formal methodology for processing damaged, unusable or EOL panels and recovering the reusable materials. The methodology will be compiled at the pilot-scale level and will be used as a basis to estimate the efficiency and practicability of expanding the process to a commercial scale level.

2. Part One: Processing Panels on Conventional Shredder Equipment

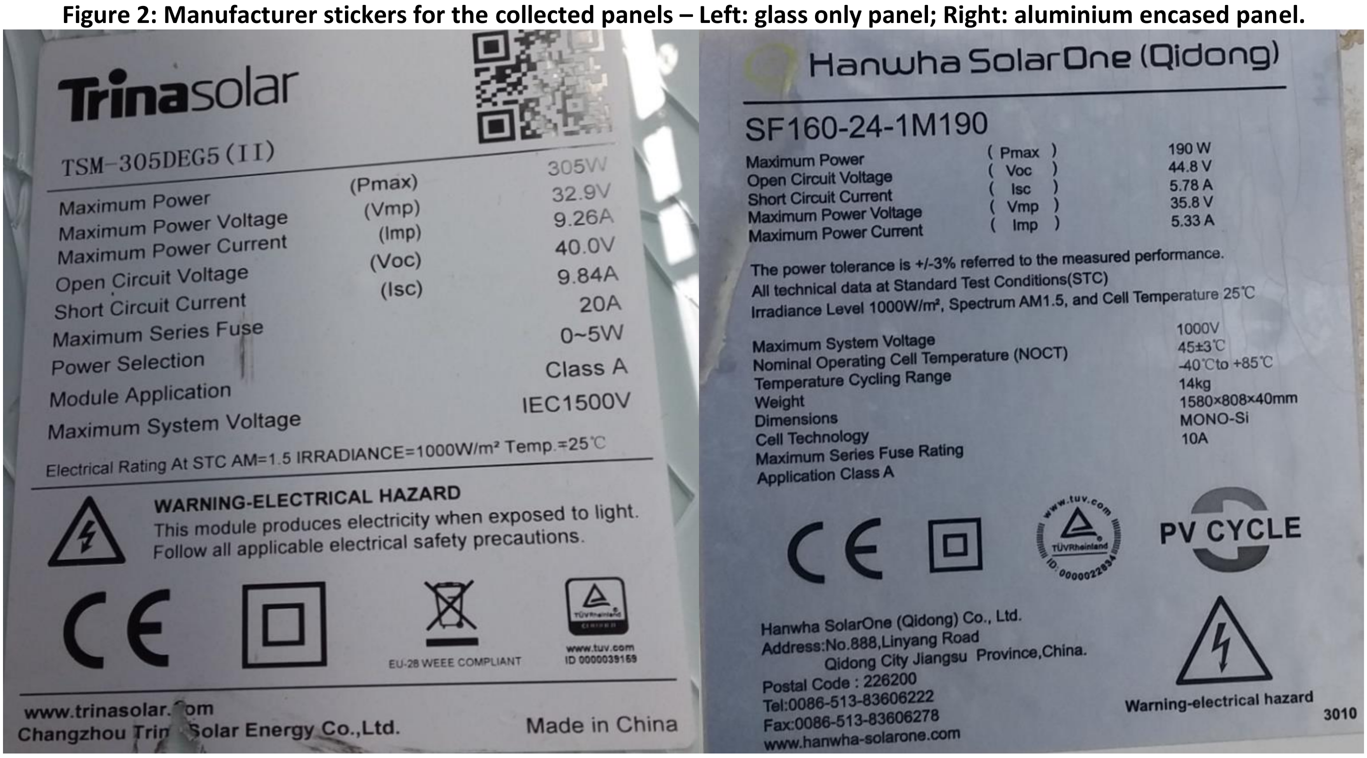
2.1 Pre-Shredding: Panel Properties

The panels used in the processing and assessment were donated from a third-party source that contacted SV about disposal of EOL panels. HRL collected the panels from the supplier; upon collection there were three panels with what appeared to be weather damaged on the panel face, and seven panels that were fully intact with no observed damage to the panel face.

Figure 1: Collected PV panels – Left: damaged panel face; Middle & Right: intact panel face.

Two varieties of panel were collected from the supplied source, one variety that was encased in an aluminium frame (Figure 1 Left & Right) and the other that was not encased in a frame (Figure 1 Middle). The manufacturer details and operating capacities of each variety of panel is captured below in Figure 2.

Figure 2: Manufacturer stickers for the collected panels – Left: glass only panel; Right: aluminium encased panel.



Before processing panels HRL conducted desktop research to determine the typical component breakdown of solar panels in order to predict the expected types of materials that may be collected once the panel was shredded. Silicon-based photovoltaic cell solar panels are typically manufactured using several distinct layers[1]:

- Aluminium Framing – extruded.
- Tempered Glass – 3 to 4mm thick.
- Photovoltaic Cells – crystalline silicon cell.
- Adhesive Layer(s) / Encapsulant.
- Backing Layer – silicon polymer sheet – the photovoltaic cells attach to this layer with adhesives.
- Relay box – diodes and connectors.

The dimensions and mass of the intact 'as received' panel were recorded before processing.

Table 1: Intact panel mass and dimensions.

Length (mm)	Width (mm)	Depth (mm)	Panel mass (kg)
1580	810	40	14.80

2.2 Shredder Equipment Specifications

HRL used pilot-scale shredding equipment to process the panels. The unit specifications are listed below in Table 2.

Table 2: Shredder equipment specifications.

Machine Name:	Single Shaft Shredder
Manufacturer:	Genox
Model No.:	V600
kW / HP:	18.5kW / 25HP
Barrel type:	Single shaft, protruding teeth individually bolted to barrel
Hopper:	760 L
Lower Guide Block:	Hydraulic ram driven to push sample into spinning barrel
Teeth type:	AISI D2 Steel, individually bolted into shaft, removable
Screen size:	25 mm*

[1] Clean Energy Reviews – Jason Svarc (2018) How are solar panels made? https://www.cleanenergyreviews.info/blog/solar-panel-components-construction

*The 25 mm screen was used for processing panels with this equipment and is the basis for any particle sizing measurements made within this report. A difference in the screen size used during shredding may change the particle size distribution (See Section 2.4) and the physical separability of materials from the intact panel, however, any chemical assay of recovered materials will not be altered.

Figure 3: Shredder details (L to R, top to bottom): spec plate, single shaft barrel with teeth, 25mm screen.

2.3 Panel Preparation for Shredding

Several steps were conducted to prepare the intact panel for introduction into the shredding equipment:

1. The relay box was stripped of components and removed as well as practicable before the panel was shredded. The empty relay box could not be completely removed from the back of the panel because of the strength of the adhesive.

2. The aluminium frame was removed from the panel before shredding, as the shredding equipment was not capable of processing aluminium or any other structural metal materials. The frame was detached by initially cutting one of the four corner joins with a hacksaw to break the 'L-join' connection (See Figure 4). This step was omitted for the panel without framing.

3. Impact force was applied to the 'L-join' was broken, which caused the adhesive holding the frame in place to break, therefore allowing the frame to be removed whilst keeping the remaining layers of the panel intact.

Figure 4: 'L-join' connection of aluminium frame after cutting through with a hacksaw.

Once the aluminium frame was completely removed, the panel lost its rigidity causing the remaining layers to slightly fold in on themselves similar to a rolled piece of paper (Figure 5). This loss of rigidity proved useful for fitting the panel into the hopper of the shredder; the panel fitted in wholly without needing to remove individual pieces before shredding.

Figure 5: Panel after successful removal of aluminium framing and clearing of relay box components.

2.4 Post-Shredding: Panel Component Classification – Physical Analysis

Once the panel was processed through the shredder, the material was collected, and several physical analysis assays were conducted.

The initial material classification of the panel was determined by recording the mass of each component removed before the panel was fed through the shredding equipment; this is detailed below in Table 3. The classification of components in the intact panel was key for establishing the baseline of expected materials produced through shredding. The baseline also enabled HRL to make an accurate estimation of the amount of and type of potentially recoverable and reusable materials in the panel.

Table 3: Percentage of components in intact panel after removal of aluminium frame and relay box.

COMPONENT	%
Intact 'as received' panel	100.0
Aluminium framing	16.8
Plastics (not backing layer)	1.6
MIXED: Glass / Photovoltaic cells / adhesive & backing layers	81.4
Other Materials	0.2

A representative subsample of the entire pile of shredded panel material was taken according to analysis method(s): I.S. EN 15413:2011[2] & I.S. EN 15443:2011[3]. The subsample was sorted by hand to determine the percentage of each component separated during the shredding process. The percentage of each component identified in the shredded material was then used to calculate the percentage of that material as a portion of the total intact panel.

Table 4: Percentage of each component identified after shredding the glass portion of the panel.

COMPONENT	% of shredded material	% of intact PV panel
Total	100.0	81.4
Glass	36.1	29.4
MIXED: Glass / adhesive & backing layers	54.0	44.0
Metallic	0.9	0.7
Backing layer	8.9	7.2

The expanded component breakdown (Table 4) was factored back into the initial component classification (Table 3) of the intact 'as received' panel. The newly expanded component classification indicated that shredding the panel separated approximately 30% of the glass from the mixed component layer in the intact panel; the potential for producing recyclable material after shredding increased beyond the initial 17%, which comprises only the recyclable aluminium framing, to approximately 46%.
Shredding a panel can recover up to 46% of the materials on a mass basis (%w/w), which consists predominantly of the aluminium frame and glass layer.

Table 5: Expanded component classification of panel after glass portion had been shredded and sorted.

COMPONENT	%
Intact 'as received' panel	100.0
Aluminium framing	16.8
Plastics (not backing layer)	1.6
Glass	29.4
MIXED: Glass / adhesive & backing layers	44.0
Backing layer	7.2
Metallic	0.7
Other Materials	0.2

The collected shredded material was lastly passed through a series of sieve screens to understand the size distribution of particles after shredding through a 25mm screen. The diameter of the sieve screens used at pilot scale level is 500mm.

Table 6: Particle size distribution of PV panel after shredding through a 25mm screen.

SIEVE SIZE	%
Total	100.0
>25.0 mm	14.2
25.0 – 16.0 mm	19.9
11.2 – 16.0 mm	8.7
6.3 – 11.2 mm	10.5
<6.3 mm	46.7

[2] I.S. EN 15413: 2011 - Solid Recovered Fuels - Methods for the Preparation of the Test Sample from the Laboratory Sample
[3] I.S. EN 15443: 2011- Solid Recovered Fuels - Methods for the Preparation of the Laboratory Sample

2.5 Post-Shredding: Panel Component Classification – Chemical Analysis of Materials

A subsample of the separated glass material was collected after shredding and analysed to determine the elemental composition. Understanding the elemental composition of the recovered glass is necessary to determine the quality, conformance to recycler specifications, and potential contamination of the glass material in the panels. Elemental assays were conducted using the following analytical methods:

- Major Elemental Analysis (Ash Analysis) – used for backing material: I.S. EN 15410:2011[4]
- Trace Elemental Analysis – used for backing material: I.S. EN 15411:2011[5]
- Major Elemental Analysis (XRF) – used for recovered glass and metal: ISO EN 12677:2011[6]

The recovered glass and the recovered backing layer material were analysed separately to determine the major elemental composition; the backing material was also analysed for trace elemental components.

Table 7: Major elemental assay of recovered glass material and backing layer material from shredded panel.

Full Element Name	Element (as Oxide)	Recovered Glass %	Backing Layer %
Silicon oxide	SiO_2	72.3	7.0
Sodium oxide	Na_2O	14.0	0.12
Potassium oxide	K_2O	0.03	<0.01
Calcium oxide	CaO	9.1	0.09
Magnesium oxide	MgO	3.5	0.02
Barium oxide	BaO	<0.01	0.01
Aluminium oxide	Al_2O_3	0.67	3.7
Titanium oxide	TiO_2	0.02	5.1
Iron oxide	Fe_2O_3	0.04	0.01
Chromium oxide	Cr_2O_3	<0.01	<0.01
Sulphur oxide	SO_3	0.26	<0.01
Lead oxide	PbO	<0.01	<0.01
Vanadium oxide	V_2O_5	<0.01	<0.01
Manganese oxide	MnO	<0.01	<0.01
Nickel oxide	NiO	<0.01	<0.01
Copper oxide	CuO	<0.01	<0.01
Strontium oxide	SrO	<0.01	<0.01
Zirconium oxide	ZrO_2	<0.01	<0.01
Cadmium oxide	CdO	<0.01	<0.01
Antimony oxide	Sb_2O_5	0.06	<0.01
Phosphorous oxide	P_2O_5	<0.01	0.02

[4] I.S. EN 15410: 2011 - Solid Recovered Fuels - Methods for The Determination of the Content of Major Elements (Al, Ca, Fe, K, Mg, Na, P, Si, Ti)
[5] I.S. EN 15411: 2011 - Solid Recovered Fuels - Methods for The Determination of the Content of Trace Elements (As, Ba, Be, Cd, Co, Cr, Cu, Hg, Mo, Mn, Ni, Pb, Sb, Se, Tl, V & Zn)
[6] ISO 12677:2011 Chemical analysis of refractory products by X-ray fluorescence (XRF) -- Fused cast-bead method

Table 8: Trace elemental assay of recovered backing layer material from shredded panel.

Full Element Name	Element in Sample	Backing Layer (mg/kg)
Silver	Ag	<1
Arsenic	As	<1
Barium	Ba	41
Beryllium	Be	<1
Bismuth	Bi	53
Cadmium	Cd	<1
Cobalt	Co	16
Chromium	Cr	<1
Copper	Cu	4
Mercury	Hg	<0.05
Manganese	Mn	<1
Molybdenum	Mo	<1
Nickel	Ni	<1
Lead	Pb	53
Antimony	Sb	373
Selenium	Se	<1
Tin	Sn	6
Strontium	Sr	8
Tellurium	Te	3
Thallium	Tl	7
Vanadium	V	3
Zinc	Zn	20
Zirconium	Zr	17

The results of the assays on the backing material (Table 7 & 8) show that after major elemental analysis the prominent constituents are: silicon, titanium, and aluminium. The loss on ignition[7] (LOI) was 88.5% after combustion of the backing material for analysis; the LOI accounts for the missing percentage when normalised to 100% of sample used in analysis. In terms of overall component percentage, the trace elements make up a very insignificant portion of the backing layer, therefore, the analysis suggests that there does not appear to be any form of contaminant elements present in the backing layer.

Portions of the metallic strips running both across the ends of the panel, and between the photovoltaic cells was removed from the panel prior to shredding for elemental analysis. The assay was conducted to determine the types of metals present in the two strips, and also to ascertain the percentage of any potentially recoverable precious metals (i.e.: silver – Ag). The assay was also used to identify any potential contaminant elements in the metallic components of the panel.

[7] Loss on Ignition (LOI): Strongly heating a sample of material at a specific temperature to allow volatile matter to escape. Heating is continued until the mass of the remaining material ceases to change.

Figure 6: Portions of metallic strips for elemental assay (L to R: Coating, substrate, ribbon).

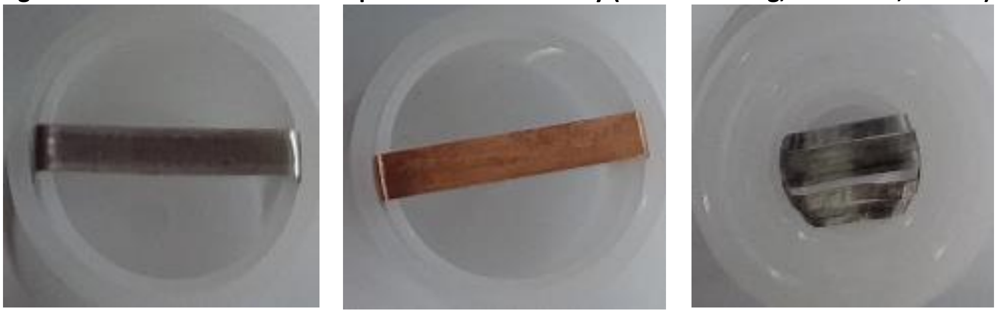


Table 9: Elemental assay of recovered metallic materials from panel.

Element	**Coating** – strip running across the top and bottom of the panel **(mg/kg)**	**Substrate** – strip running across top and bottom of panel, buffed to remove the coating **(mg/kg)**	**Ribbon** – strip running through photovoltaic cells **(mg/kg)**
Mg	<100	<100	600
Al	1,100	1,500	7,700
Si	<50	15,000	76,000
Ca	<5	16	<5
Ti	<1	<1	<1
V	<1	<1	<1
Cr	39	<1	<1
Mn	170	<1	<1
Fe	140	<2	1,400
Co	<1	<1	<1
Cu	170,000	980,000	270,000
Zn	90	38	120
Ag	<50	<50	140,000
Cd	<1	<1	<1
Sn	530,000	1,300	280,000
Sb	<1	<1	<1
Te	<1	<1	<1
Pb	300,000	390	220,000
Bi	<1	<1	<1

The results in Table 9 show that the metallic strips running across the top and bottom of the panel are coated copper metal. The coating mainly comprises a tin and lead alloy, as well as small amounts of aluminium. The ribbon – the metallic strip running through the photovoltaic cells – also comprises copper coated in a tin and lead alloy, however, the coating also contains silver, iron, and a higher amount of aluminium. Due to the overall minimal percentage of metallic component in the intact panel (approx. 1.0%), the potential recovery of any of the metallic components would theoretically incur higher cost and effort than the expected returns.

2.6 Recycling and Re-use: End Product Uses and Potential Market Options

After completion of the shredding, HRL calculated that approximately 46% of the separated materials recovered from the intact panel were in a form that could be recycled for manufacturing of renewable or reusable products. The 46% consisted of two (2) components, the aluminium framing and the separated glass cullet. The end-product market options for these components will vary depending on the quality of the materials recovered during panel processing. Sections 2.6.1 through 2.6.4 defines where applicable:

- Some potential markets for materials reuse in production of renewable products.
- Some specific end-user companies or organisations that could make use of the separated materials.
- The quality limitations the materials must meet for the specific end-user if available and applicable.
- An estimated return of profit versus the amount of recovered materials at the pilot level (i.e.: on a single panel separated into its base component materials).[8]

Where applicable, the quality data determined through analytical assays of panel components was compared to the quality limitations defined the identified end user or end use market.

2.6.1 Recycled Glass Cullet

The glass cullet was the largest component portion recovered during the panel processing and comprised approx. 47% of the total recovered materials. The collected glass cullet is recyclable and can be reused in the production of new products, such as glass bottles.

Table 10: Recycled glass cullet – examples of end use markets and associated returns at pilot level

Potential Market	End-User Company	Quality Limitations	Returns ($AUD value at pilot level)
Production of new glass products such as glass bottles and other glass containers or jars.	O-I: Global organisation that uses recycled glass cullet in the manufacture of new glass containers.	See Appendix A: Table 21 for cullet quality specification against recovered cullet from processed panels.	Mixed glass: $30 / tonne. Source separated glass: $70 / tonne.[9] Total 13c market return at $30 / tonne mixed cullet per panel processed. Total 30c market return at $70 / tonne separated cullet per panel processed.
	Orora: One of Australia's leading glass bottle manufacturers.	Quality specification for glass cullet only available to prospective suppliers.	

2.6.2 Aluminium Framing and Metallic Components

The aluminium framing of the panel is the second largest portion at 17% of the materials recovered for recycling and re-use. The other metallic components of the panel comprised approx. 1% of the total and was primarily copper strips

[8] All associated market returns are correct at the time of publication of this document and are subject to change at end-user discretion or market discretion. HRL takes no responsibility for the future 'correctness' of the denoted market value returns presented in this document.

[9] Envisage Works for Sustainability Victoria (2019) Recovered Resources Market Bulletin – August 2019.

and copper wiring. Market options for scrap aluminium and other metals are already well established in Australia; there are many and varied companies willing to purchase scrap metals from suppliers for reuse in manufacturing new metal products.

Table 11: Recycled metals – examples of end use markets and associated returns at pilot level

Potential Market	End-User Company	Returns ($AUD value at pilot level)
Scrap metal recycling to manufacture new metal products.	Cobral Metals	$1.00 / kg aluminium. Total of $2.49 market return per panel processed.
	Norstar	
	Sims Metals	

2.6.3 Backing Layer Material

The backing layer comprised approximately 7% of the recovered materials after the intact panel was processed through the shredding equipment. The analytical assay on the backing layer determined it is comprised predominantly of silicon oxide as expected, but, also contains a significant amount of titanium and aluminium oxide.

There are very limited end use markets for the recovered backing material, and there does not appear to be any established market use in Australia. There may be potential for the silicon to be recovered from the backing layer to be re-used in the manufacture of silicone oil, however, the process would be expensive for the minimal recovery potential.[10]

2.6.4 Remaining Fraction: Un-separated Panel Materials

The remaining materials collected from the panel processing – glass adhered to backing layer – comprised 44% of the total component materials. These material components would need to undergo further treatment options to achieve better separation of the mixed portions into base component materials.

[10] ECO U.S.A (2014) Recycled Silicone Oil – Siloxane. http://www.siliconerecycling.com/recycled-silicone-oil-siloxane

3. Part Two: Further Treatment of Shredded Panel Material

3.1 Suitability of Treatment Options on Post-Shredded Panel

After the panel was shredded through the 25mm screen, approximately 44% of the collected material was a mixture of glass still adhered to the backing layer. Two different treatment options were considered for removing the glass from the backing layer to facilitate further glass recovery; the two options were chemical and heat treatment methods.

3.1.1 Option 1: Chemical Treatment

Four (4) small portions, between 11 – 15g, of the shredded mixed panel material was taken for chemical treatment. Each portion of panel material was completely submerged in 100ml of a different chemical solvent for 48 hours. After soaking for 48 hours, the solvent was decanted, and the portions of panel material were collected and dried at 40°C for 1 hour to remove residual solvent. The portions were then assessed for the ability of the solvent soak to separate the glass from the backing layer.

Table 12: Solvent soak separation ability.

SOLVENT NAME	ASSESSMENT OF SEPARATION ABILITY
Toluene	Causes the backing layer to peel off from the glass layer. The solvent may have the capability to essentially dissolve the adhesive holding the glass and backing together. There would still be a requirement for manually pulling the glass and backing layer apart after soaking.
Acetone	Appears to have no separation ability – glass and backing still adhered to each other.
Iso-Propyl Alcohol (IPA)	Appears to have no separation ability – glass and backing still adhered to each other.
Di-Chloro-Methane	Appears to have no separation ability – glass and backing still adhered to each other.

The four solvents used in the post-treatment of panel materials were deemed not a very effective means to separate the remaining glass from the backing layer; the toluene soak has the ability to separate the layers, but still requires further manual separation to fully separate the glass from the backing.

A commercial scale operation that intends to apply chemical treatment for further component separation should also consider, as part of the business model, the cost effectiveness of purchasing, safe storage, safe handling, and correct disposal of flammable chemicals, and potential emissions that may be generated from chemical use. Information regarding chemical handling practices and potential emissions from solvent treatment methods is not assessed in this document.

3.1.2 Option 2: Heat Treatment

The mixed glass and backing layer materials from the shredded panel were collected and heat-treated in a muffle-furnace at 550°C for 24 hours. The approximate volume capacity of the muffle-furnace used at pilot scale is 5L. The temperature used for the treatment is the standard temperature for ashing recoverable materials as defined in analytical method I.S. EN 15403:2011[11]. Treating the mixed material at 550°C enabled combustion of the backing layer and adhesive layer, while keeping the glass intact. Any metallic components that were still in the mixed portion were also separated and could be segregated from the glass portion; all separation was conducted by hand sorting at the pilot scale level, however, different sorting options may be more cost-effective on a commercial level. Table 13 below details the breakdown of components collected after heat treatment at 550°C; the recovered material percentages are also calculated as a percentage of the intact panel.

Table 13: Percentage of components identified after heat treatment of mixed shredded panel portion.

COMPONENT	% of shredded material	% of intact panel
Total	100.0	44.0
Glass	71.5	31.5
Metallic	0.8	0.4
MIXED: Fines <1.00mm / Ash	12.0	5.3
Loss on Ignition (LOI) – materials completely combusted during heat treatment	15.5	6.8

A commercial scale operation that intends to apply heat treatment for further component separation should also consider, as part of the business model, the potential for harmful emissions to be generated from component materials during heating, and the energy cost associated with running furnaces. The information regarding energy cost for running furnaces or the potential to generate harmful emissions during heating of component materials is not assessed in this document.

[11] I.S. EN 15403: 2011 - Solid Recovered Fuels - Determination of Ash Content

3.2 Panel Post Treatment: Chemical Analysis on Heat Treated Recovered Glass

The glass recovered post heat treating at 550°C was analysed for elemental composition to determine constituents and potential contaminants (Table 14). There does not appear to be any significant variation in results when compared with the elemental composition of the glass recovered post panel shredding.

Table 14: Elemental assay of recovered glass material from shredded panel post heat treatment at 550°C.

Element (as Oxide)	Recovered Heat Treated Glass %
SiO_2	72.2
Na_2O	14.0
K_2O	0.03
CaO	9.0
MgO	3.6
BaO	<0.01
Al_2O_3	0.72
TiO_2	<0.02
Fe_2O_3	<0.04
Cr_2O_3	<0.01
SO_3	0.26
PbO	<0.01
V_2O_5	<0.01
MnO	<0.01
NiO	<0.01
CuO	<0.01
SrO	<0.01
ZrO_2	<0.01
CdO	<0.01
Sb_2O_5	0.08
P_2O_5	<0.01

3.3 Final Overview: Expanded Panel Component Breakdown

Upon completion of panel shredding, elemental analysis, and suitable post-shredding treatment options, the expanded list of panel components was collated into a single table to compile a detailed overview of the materials found within the panel, along with their potential to be recycled.

Table 15: Expanded component classification after shredding, analysis, and post-treatment options are applied.

COMPONENT	%	Potentially Recoverable? (Y/N)
Intact 'as received' panel	100.0	-
Aluminium Framing	16.8	Y
Hard plastics (Not including backing layer)	1.6	N
Glass cullet[12] (Post shredding)	15.7	Y
Glass dust / aggregate (<6.3 mm)	13.7	Y
Glass cullet (Post heat treatment)	31.5	Y
Metallic (Post shredding)	0.7	Y
Metallic (Post heat treatment)	0.4	Y
Backing layer (silicon polymer)	7.2	Maybe?[13]
LOI of mixed materials (During heat treatment)	6.8	N
MIXED: Ash / Fines material (<1.00mm)	5.3	Y
Other unclassifiable materials	0.2	N

Based on all of the physical identification and chemical assays conducted during this pilot scale research project, it is feasible to recover and recycle up to approximately 90.0% of the individual component materials from silicon-based photovoltaic cell solar panels that have been damaged, are deemed unusable, or have reached EOL. The majority of the recoverable components are the glass (Approx. 60.9%) and the aluminium framing (Approx. 16.8%). There is the possibility that some of the recoverable materials may require further analysis before they are accepted by potential recyclers; this will be addressed in Section 4 below.

[12] All instances of glass cullet is a mixture of both the tempered glass and photovoltaic cell layers (see Section 2.1), which were separated from the silicon polymer backing layer during the shredding phase, and are primarily silicon-oxide based material.
[13] At the time this research was conducted, HRL could not identify any potential local or international key stakeholders or end-market uses for this portion of the recovered panel materials.

4. Recycling and Re-use: End Product Uses and Potential Market Options

After completion of the shredding and heat treatment process, HRL calculated that approximately 90% of the separated materials recovered from the intact panel were in a form that could be recycled for manufacturing of renewable or reusable products. The end-product market options will vary depending on the quality of the materials recovered during panel processing. Sections 4.1 through 4.4 discuss the major categories of separated materials and defines:

- Some potential markets for materials reuse in production of renewable products.
- Some specific end-user companies or organisations that could make use of the separated materials.
- The quality limitations the materials must meet for the specific end-user if available and applicable.
- An estimated return of profit versus the amount of recovered materials at the pilot level (i.e.: on a single panel separated into its base component materials).[14]

Where applicable, the quality data determined through analytical assays of panel components was compared to the quality limitations defined the identified end user or end use market. This information is presented in Appendix A.

4.1 Recycled Glass Cullet and Aggregate

4.1.1 Glass Cullet

The glass cullet was the largest component portion recovered during the panel processing and comprised approx. 47% of the total recovered materials. The collected glass cullet is recyclable and can be reused in the production of new products, such as glass bottles.

Table 16: Recycled glass cullet – examples of end use markets and associated returns at pilot level

Potential Market	End-User Company	Quality Limitations	Returns ($AUD value at pilot level)
Production of new glass products such as glass bottles and other glass containers or jars.	O-I: Global organisation that uses recycled glass cullet in the manufacture of new glass containers.	See Appendix A: Table 21 for cullet quality specification against recovered cullet from processed panels.	Mixed glass: $30 / tonne. Source separated glass: $70 / tonne.[15] Total 20c market return at $30 / tonne mixed cullet per panel processed. Total 49c market return at $70 / tonne separated cullet per panel processed.
	Orora: One of Australia's leading glass bottle manufacturers.	Quality specification for glass cullet only available to prospective suppliers.	

[14] All associated market returns are correct at the time of publication of this document and are subject to change at end-user discretion or market discretion. HRL takes no responsibility for the future 'correctness' of the denoted market value returns presented in this document.

[15] Envisage Works for Sustainability Victoria (2019) Recovered Resources Market Bulletin – August 2019.

4.1.2 Glass Fines <6.3 mm

The glass fines <6.3mm comprised about 14% of the material produced when the panel was shredded. There is potential for the glass fines to be used in asphalt aggregate in Australia as a replacement for coarse sand as the glass fines exhibit similar permeability when crushed properly.[16]

Table 17: Recycled glass fines – examples of end use markets and associated returns at pilot level

Potential Market	End-User Company	Returns ($AUD value at pilot level)
Aggregate in road base. Aggregate in tiles. Aggregate in decorative concrete for architectural facades. Alternative to sand in golf courses. Aggregate in concrete or cement.	Alex Fraser: is a civil construction company based in Victoria and Queensland that use recycled materials in production of aggregates, asphalt, road-base and sand.[17]	\$0 – 49 per tonne.[18] Total of 10c market return per panel processed.
	Vic Roads	
	GHD	

4.2 Aluminium Framing and Metallic Components

The aluminium framing of the panel is the second largest portion at 17% of the materials recovered for recycling and re-use. The other metallic components of the panel comprised approx. 1% of the total and was primarily copper strips and copper wiring. Market options for scrap aluminium and other metals are already well established in Australia; there are many and varied companies willing to purchase scrap metals from suppliers for reuse in manufacturing new metal products.

Table 18: Recycled metals – examples of end use markets and associated returns at pilot level

Potential Market	End-User Company	Returns ($AUD value at pilot level)
Scrap metal recycling to manufacture new metal products.	Cobral Metals	\$1.00 / kg aluminium. Total of \$2.49 market return per panel processed.
	Norstar	
	Sims Metals	

4.3 Ash and Fines <1.00 mm: Post Heat Treatment Materials

The combination ash and fines remaining after heat treating the shredded panel materials comprised only 5% of the total panel. Re-use of recycled combustion ash is another well-recognised market option in Australia. As with glass fines, combustion ash can be used in a number of ways:[19]

[16] GHD (2008) The use of crushed glass as both an aggregate substitute in road base and in asphalt in Australia.
[17] Alex Fraser Group (2017) About Alex Fraser Group. http://www.alexfraser.com.au/section/Home/About_us
[18] Sustainability Victoria (2014) Fact Sheet: Market summary – recycled glass.
[19] Ash Development Association of Australia (2019) CCP utilisation. http://www.adaa.asn.au/resource-utilisation/ccp-utilisation

Table 19: Combustion ash – examples of end use markets and associated returns at pilot level

Potential Market	End-User Company	Returns ($AUD value at pilot level)
Cement and concrete products. Pavement aggregates. Structural fills. Road-base aggregates. Agricultural uses. Geopolymers and zeolite materials.	Alex Fraser: is a civil construction company based in Victoria and Queensland that use recycled materials in production of aggregates, asphalt, road-base and sand.[20]	N/A
	Vic Roads	

4.4 Non-Recyclable Separated Panel Materials

The remaining materials collected from the panel processing – rigid plastics and other materials – comprised 2% of the total component materials. These material components would generally be deemed non-recyclable materials and would likely need to be safely disposed of. Alternatively, the non-recyclable portion of material remaining may be suitable for use in advanced waste treatment techniques such as Energy-from-Waste.

4.5 Market Value Comparison of Processing Methods

Table 20 shows the comparative market value return of panels after only shredding, and after shredding and heat treatment, as calculated above in Section 2.6 and 4.1 – 4.4. The market return is based on the amount of recyclable material recovered from a single panel processed at the pilot scale level.

Table 20: Comparing potential market value uptake of 'shredding only' vs 'shredding and heat treatment' of panels.

COMPONENT	COMPONENT PERCENT	MARKET VALUE	COMPONENT	COMPONENT PERCENT	MARKET VALUE
Intact panel mass: 14.80 kg					
Process method: *Shredding only*			Process method: *Shredding and heat treatment applied*		
Glass cullet	29.4	$70 / tonne (separated)	Glass cullet	47.2	$70 / tonne (separated)
Aluminium	16.8	$1.00 / kg	Aluminium	16.8	$1.00 / kg
Mixed material	44.0	N/A Further processing	Glass dust (<6.3mm)	13.7	$0 – 49 / tonne
Backing layer	7.2	N/A	Backing layer	7.2	N/A
Plastics	1.6	N/A Safe disposal	Plastics	1.6	N/A Safe disposal
Other metals[21]	0.7	$1.50 – 2.00 / kg	Other metals	1.1	$1.50 – 2.00 / kg
Other materials	0.2	N/A Safe disposal	Other materials	0.2	N/A Safe disposal
---	---	---	Ash fines	5.3	N/A
TOTAL ESTIMATED MARKET RETURN AT PILOT SCALE LEVEL					
AUD: $3.00 (per processed panel)			**AUD: $3.41** (per processed panel)		

[20] Alex Fraser Group (2017) About Alex Fraser Group. http://www.alexfraser.com.au/section/Home/About_us
[21] Avada (2019) Scrap Metal Prices in Australia. https://www.scrapsmetalprices.com/

5. Up-scaling from Pilot Level to Commercial Process

The main steps in the pilot level process, as detailed in the preceding sections, and the estimated implementation time for each step has been mapped below in Table 21. The entire process was handled manually by two personnel using hand tools and a laboratory sized crusher and muffle-furnace for shredding and heat treatment respectively.

Table 21: Pilot Level Process Panel Dismantling and Material Recovery Timeline.

PANEL PROCESSING STEP	TIMEFRAME (hh:mm)
PART ONE – Intact Panel	-
Removal of aluminium framing with hacksaw and ball-peen hammer – *Approx. 2.5 kg.*	00:20
Removal of relay box contents with pliers. Stripping of plastic coating from copper wiring.	00:10
Panel shredding with pilot scale shredder.	00:20
Collection of shredded materials – *Approx. 12 kg.*	00:10
Sieving all shredded materials through a 6.3mm screen to separate glass dust – *Approx. 2 kg.*	00:10
Manually separate shredded components by hand. (i.e.: Glass, backing layer, mixed glass and backing, metallic, plastics, other, etc.) – *Approx. 10 kg.*	03:00
PART TWO – Further Treatment of Shredded Materials	-
Ashing mixed materials in muffle-furnace at 550°C – *Approx. 5 kg.*	24:00
Cooling of heat treated materials.	01:00
Sieving all heat treated materials through a 1.00mm screen to remove ash and fines.	00:10
Manually separate heat treated components by hand. (i.e.: Glass, metallic, other, etc.) – *Approx. 4 kg.*	01:30
Total process time from intact panel to separated recovered materials (Table 13).	**30:50**

At pilot scale level, the time for two (2) personnel to process one (1) intact panel into separated recovered materials was slightly more than one day at 30 hours and 50 minutes. Up-scaling to a commercial level panel recovery process would see improvements for the following parameters:

- Increased throughput – number of panels processed at one time, especially through large-volume-hopper shredding equipment, could be drastically improved.
- Improved removal time of aluminium framing using mechanical tools.
- Improved sieving time using mechanical sieve-shaker and improved sieving capacity using larger diameter sieves.
- Improved efficiency of separating components with more personnel manually sorting.
- Improved heat treatment capacity with larger volume furnace. The heat treatment time could potentially be reduced by half where the surface area of the furnace allows material to be evenly spread out in a single layer – this would ensure that panel material is heated evenly to remove all combustibles during the shortened time in the furnace.

6. Further Analysis and Other Considerations

6.1 Further Analysis

Consideration should be given to conducting further analytical assays that were not included in this research. There are a few key reasons for conducting further analysis on the recovered materials:

- Further analysis of the recovered components would allow recycling parties to determine more detailed quality and potential contaminant information about each particular recovered material component. Further analysis is particularly recommended for the 2% of components that are deemed non-reusable and must be safely disposed of; detailed knowledge of the waste materials will enable the use of 'best-practice' disposal techniques.

- The recycling party may have an edge over competitors where further analysis has allowed them to determine extra details and information about the chemistry of the recovered materials.

- There may be other constituents of the recovered materials that are identified through further analysis; these constituents may then be recovered using more complex recovery processes.

Two examples of further, more complex analytical assays that would provide a recycler with more detailed knowledge of the material, which may be performed on specific components recovered during the panel processing are discussed below:

- **Leachability of metals and organic materials:** This assay would be performed on the ash and fines <1.00mm material retained after heat treatment of the shredded mixed glass and backing layer component. This assay would provide the recycler with an in depth understanding of what elements are retained in the ash after heat treatment, whether there are any organic contaminant compounds remaining in the ash, what EPA waste classification would be assigned to the ash if it were sent to landfill, and which of the elemental or organic compounds present have the potential to leach into soil or ground-water if used in an aggregate, as well as the amount of these chemicals that could leach.

- **Total halides:** this assay would be performed on the backing layer material separated after shredding the intact panel. The assay determines the total concentrations of fluorine, sulphur, and chlorine, as well as a few others, in the sample material. Knowledge of the halide levels would enable a recycler to understand the potential emissions the backing layer may produce if used in a combustion system as an alternative to landfill.

6.2 Considerations and Remarks on the Process Methodology

The decisions about which treatment methodologies HRL implemented during the panel processing were made with regards to the scalability of the pilot level process up to an industrial level process. HRL aimed to balance the panel processing with scalability in mind, to ultimately design a methodology that was simplistic in its implementation, whilst allowing for the best recoverability of materials at the highest cost-effectiveness of recovery.

There were some pre and post treatment methodologies trialled for component separation that were deemed not feasible to the process methodology when best recoverability was compared to cost-effectiveness of recovery.

- **Solvent washing:** This post shredding treatment did not separate the glass from backing layer after a 48-hour soak. There would remain an element of manual separation needed to completely separate the two materials. This treatment was deemed to be too labour intensive versus efficient when scaled to an industrial level.

- **Acid soak:** This pre-treatment process was used to try and extract silver from a portion of the intact cell. Further analysis of metallic components identified an insignificant amount of silver metal in the overall panel, as such the treatment method was deemed very inefficient and cost intensive on an industrial level once cost for using and storing acid was considered.

- **Steam or heat application:** this pre-treatment method was initially considered an option for removing the adhesive layer of the panel to have the glass and cell and backing layer remain intact for separation. Due to the nature of the use of a solar panel and the weathering it is designed to withstand, these methods showed no ability to melt or destroy the adhesive.

Appendix A: O-I Specification for Glass Cullet

Table 22 below details the O-I specification for Flat Glass Cullet; it compares the analysis results of the glass cullet collected after panel shredding and after heat treating of mixed glass and backing layer against the O-I limitations to determine if the glass is suitable for recycling purposes.

Table 22: O-I Specification for Flat Glass Cullet material vs quality of glass recovered during panel processing.

FLAT GLASS CULLET – SOLAR (PROCESSED)				
Chemical Description	Soda-lime-magnesia-silica glass	**LIMITATION**	**Shredded Glass Cullet**	**Heat Treated Glass Cullet**
SPECIFICATION	**DEFINITION**			
Chemical Composition			%	%
	Na2O + K2O	12 – 15 %	14.0	14.0
	CaO + MgO	11 – 14 %	12.6	12.6
	Al2O3	0 – 2 %	0.67	0.72
	Other oxides (excl. SiO2)	0 – 1 %	0.43	0.48
	SiO2	Balance	72.3	72.2
Heavy Metals			ppm	ppm
	Lead (Pb)	100 ppm max	10	15
	Mercury (Hg)	100 ppm max	<10	<10
	Cadmium (Cd)	100 ppm max	<10	<10
	Chromium (VI) / Hex-Chrome (Cr^{6+})	100 ppm max	<10	<10
Physical Properties			%	%
	Materials passing through 50mm screen	All recovered material	>99.9	>99.9
	Materials passing through a 1mm screen	5 % max	<0.1	<0.1
Contaminant Limits			%	%
	Tinted, coloured, or mirrored glass	5 % max	<0.1	<0.1
	Organic matter (i.e.: plastics or silicon materials)	0.3 % max OR 3 kg/tonne	<0.3	<0.3
	Magnetic materials (i.e.: ferrous materials)	0.0001 % max OR 1 g/tonne	<0.0001	<0.0001
	Non-Magnetic organic materials	0.0005 % max OR 5 g/tonne	<0.0005	<0.0005
	Non-magnetic inorganic materials (i.e.: ceramic, clay, stone, brick glass ceramic, pyro ceramic sheet glass, ovenware)	0.0005 % max OR 5 g/tonne	<0.0005	<0.0005

The comparison of the quality data from the recovered panel glass material versus the O-I Specification showed, that for the panels used in the pilot level activity, the recovered glass from the processed panel would be suitable for use in the manufacture of new glass containers.