Sustainable Built Environment National Research Centre AUSTRALIA

Resource circular economy: Opportunities to reduce waste disposal across the supply chain

Glass

Research Report 5

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EXECUTIVE SUMMARY

Glass is a hard substance that may be transparent or translucent and is brittle in nature. The use of glass in the building sector has a long history, however, with new technological advances, its application has become very broad. glass is now being used in the building industry as insulation material, structural component, external glazing material and cladding material. In infrastructural projects, the application of glass includes but is not limited to sound barriers, tunnels, ingredients for road surface such as asphalt and insulators.

Australia generated 1,078,831 tonnes of waste glass in all waste streams in the period 2016-17. However, the construction industry is not a significant contributor to glass waste generation; from the total glass waste, only 0.62% came from the C&D waste stream. Despite a higher level of recycling of glass waste relative to landfilling in all waste streams, landfilling is very prominent in the C&D waste stream. The average landfilling rate of glass waste in the C&D stream is 82.3%. To improve this situation, there are opportunities for minimising landfilled waste throughout the glass material lifecycle that are discussed in this report.

While there is an established market for some applications of glass waste, there are some other areas of application that need further investigation. The glass waste market is currently not efficient due to several reasons that are reviewed in this report. Economic analysis of using recycled glass with all the issues attached to it, including contamination and the undesirable marketability of recycled glass, an economic incentive for recyclers as well as manufacturers in Australia is not currently present. The main reason is the low-cost overseas outsourcing of glass materials. However, with promising results from new national and jurisdictional initiatives, it is likely that the current trends in the market will change for the better. The following is a selection of recommendations for improved glass waste management:

1. Promote the use of glass aggregate in asphalt;
2. Change jurisdictional landfill levy regulations in favour of glass recycling;
3. Design a partial levy exemption for residual waste in the recycling industry;
4. Conduct more research projects to establish new applications for glass waste such as application in the landscape industry;
5. Grow consumer awareness and desire to buy “green” products—such activity may win more work;
6. Establish legislation for public and social housing that requires the contracts for window replacement to include recycling of all removed materials in closed-loop schemes so that the significant opportunities and quantities of potential materials are not overlooked in this sector; and
7. Improve the purity of cullet and prevent colour contamination to increase the value and recyclability of cullet.

1 INTRODUCTION

There is no exclusive definition of “glass”, a term describing a variety of inorganic materials with different mechanical and optical properties. What all glass materials have in common is a vitreous or amorphous state, originated by the relatively fast cooling and solidification of an initial molten state[1]. glass is a hard substance that may be transparent or translucent and is brittle in nature. It is one of the oldest and most useful materials made by humans. The Phoenicians discovered it more than 5,000 years ago[2]. For 2,000 years, hand-blowing glass was the principal way of making glass bottles. In the last hundred years, mechanised glass-blowing techniques have revolutionised the production of glass containers and other glass products. Production of Clear glass, by the introduction of manganese dioxide, saw glass being used for architectural purposes. Cast glass windows began to appear in the most important buildings and villas in Rome and Pompeii. Glass is now widely used in the construction and architectural purposes in engineering. Figure 1 depicts the various applications for such purposes.

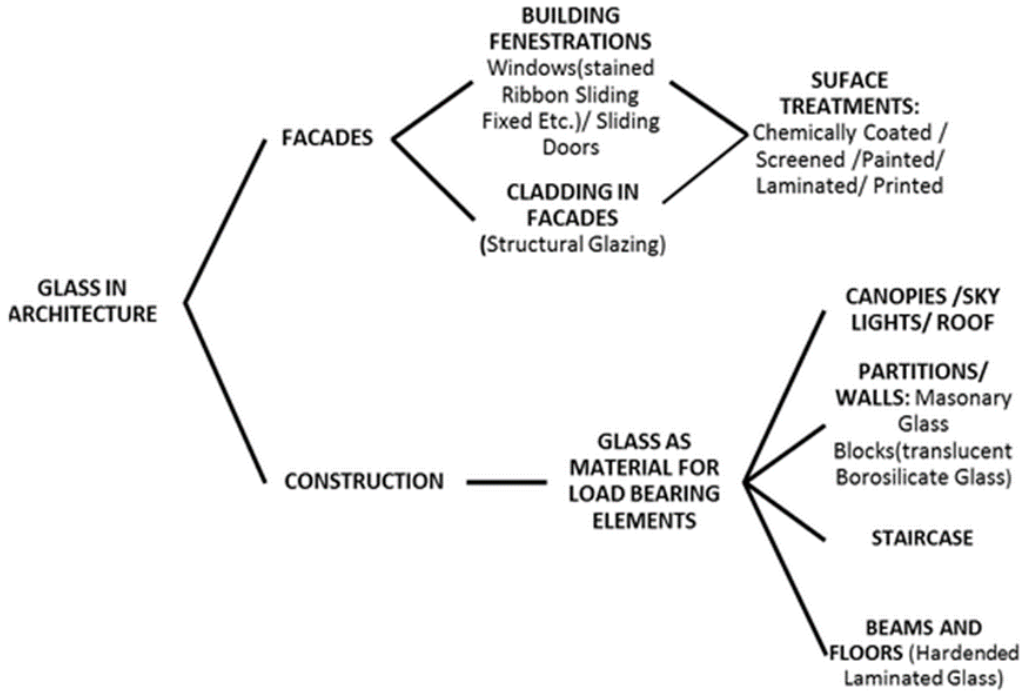

Figure 1. The application of glass in the construction and architectural sector
Source: Understand construction.com (2014)[3]

Safe, sustainable and green buildings have gained popularity worldwide in recent years. This has given a major boost to the market for construction glass. Technological advancements in the manufacturing process further bolster demand for construction glass. The main properties of glass that make it suitable in the construction industry include transparency, workability, U value, recyclability, transmittance and strength. A description of each property is provided in Table 1.

[1]Pharosproject: Background information on waste glass reclamation and recycling. https://pharosproject.net/uploads/files/cml/1335905464.pdf

[2]Waste Authority. 2015. Glass Fact Sheet. The Waste Wise School Program. https://www.wasteauthority.wa.gov.au/media/files/wws/glass-fact-sheet.pdf

[3]Understand construction.2015. Glass. http://www.understandconstruction.com/glass.html

Table 1. Main properties of glass in the construction industry

Property	Description
Transparency	Transparency is the main property of glass, which allows the vision of the outside world through it. The transparency of glass can be from both sides or from one side only. In one side transparency, glass behaves like a mirror from the other side.
Workability	Glass can be moulded into any shape, or it can be blown during melting. So, the workability of glass is a superior property of glass.
U value	U value represents the amount of heat transferred through the glass. If a glass is said to be an insulated unit, then it will have a lower u value.
Recyclability	Any glass can be 100% recyclable. It can also be used as a raw material in the construction industry.
Transmittance	The visible fraction of light that passing through the glass is the property of visible transmittance.
Strength	Strength of glass depends on the modulus of rupture value of glass. In general, glass is a brittle material, but by adding admixtures and laminates, we can make it stronger. It is resistant to weather conditions and chemicals.

1.1 Various types of glass in the construction industry

The following table (Table 2) shows the most common types of glass that are used in the construction industry.

Table 2. Various types of glass used in the construction industry

Glass	Description
Float Glass	Float glass is made of sodium silicate and calcium silicate so it is also called soda-lime glass. It is clear and flat, causing glare. These glasses are available from 2mm to 20mm thickness ranges. They have a weight range of 6 to 36 kg/m^2. These are used as shop fronts, in public places etc.
Shatterproof Glass	Shatterproof glass is used for windows, skylights, floors etc. Some types of plastic polyvinyl butyral is added in its making process. Therefore, it does not form sharp-edged pieces when it breaks.
Laminated Glass	Laminated glass is the combination of layers of normal glass. So, it has more weight than a normal glass. It has more thickness and is UV proof and soundproof. These are used for aquariums, bridges etc.
Extra Clean Glass	Extra clean glass has two special properties, photocatalytic and hydrophilic. Because of these properties, it acts as stain proof and gives a beautiful appearance. Maintenance is also easy.
Chromatic Glass	Chromatic glass is used in ICU's, meeting rooms etc. it can control the transparent efficiency of glass and protects the interior from daylight. The chromatic glass may be photochromic, which has light-sensitive lamination, thermos-chromatic, which has heat-sensitive lamination or electrochromic, which has electric lamination over it.
Tinted Glass	Tinted glass is nothing but coloured glass. A colour producing ingredients are mixed into the normal glass mix to produce coloured glass, which does not affect other properties of glass.
Toughened Glass	Toughened glass is strong glass that has low visibility. It is available in all thicknesses and, when it is broken, it forms small granular chunks, which are

	dangerous. This is also called as tempered glass. This type of glass is used for fire-resistant doors, mobile screen protectors etc.
Glass Blocks	Glass block or glass bricks are manufactured from two different halves, and they are pressed and annealed together during the melting process of glass. These are used for architectural purposes in the construction of walls, skylights etc. They provide an aesthetic appearance when light is passed through it.
Glass Wool	Glass wool is made of fibres of glass and acts as a good insulating filler. It is a fire-resistant glass.
Insulated Glazed Units	Insulated glazed glass units contain glass that is separated into two or three layers by air or vacuum. Heat is not allowed through it because of the air between the layers, meaning it acts as a good insulator. These are also called double glazed units.

Source: The Constructor.org (2017)[4]

[4] The Constructor. Types of Glass and its Engineering Properties for Use in Construction. https://theconstructor.org/building/types-of-glass-properties-uses-construction/14755/

2 GLASS INDUSTRY OVERVIEW

The Glass and Glass Product Manufacturing industry (GGPMI) comprises firms that manufacture glass containers and flat glass products. Industry revenue is expected to increase at an annualised 2% over the five years through 2019-20, to reach $4.2 billion. Glass product imports are anticipated to increase at an annualised 2.8% over the five years through 2019-20, to capture 18.3% of domestic demand in the current year. Exports accounted for an estimated 1.6% of industry revenue in 2019-20. Growth in the commercial building and apartment construction markets has underpinned demand for flat glass products over the past five years. The industry's performance has also benefited from stronger demand for glass bottles for packaging wine and spirits, along with premium non-alcoholic beverages.

In 2019-20, weakening demand for glass products from downstream residential and commercial building markets is expected to erode domestic demand for flat glass products. Industry revenue is projected to contract by 2.8% in the current year, contributing to declines in industry employment and enterprise numbers. Favourable trends in the local beer and wine production are expected to support demand for glass containers in 2019-20[5].

The industry's performance is forecast to continue to deteriorate over the short term. Demand for flat glass products from the apartment construction and commercial building markets will continue to contract over the two years through 2021-22, due to the completion of several large-scale office, hotel and casino projects. The industry is forecast to benefit from recovering demand from the residential building market from 2022-23 onwards, as demand rises for glass bottles used in wine production and beer manufacturing markets. Industry revenue is forecast to increase at an annualised 0.4% over the five years through 2024-25, to reach $4.3 billion[5]. This limited rise reflects subdued growth in domestic demand for glass products, and industry firms continuing to lose market share to imports.

The primary activities of this industry[5] include manufacturing of glass blocks, glass bottles and other glass containers, domestic glassware (kitchenware, ornamental and drinking glasses, flat glass (stained and laminated) laboratory and scientific glassware. Other activities include mirrors, optical glass, safety glass, windscreens. The major products in this industry are glass containers, architectural glass (formed and finished) and float glass.

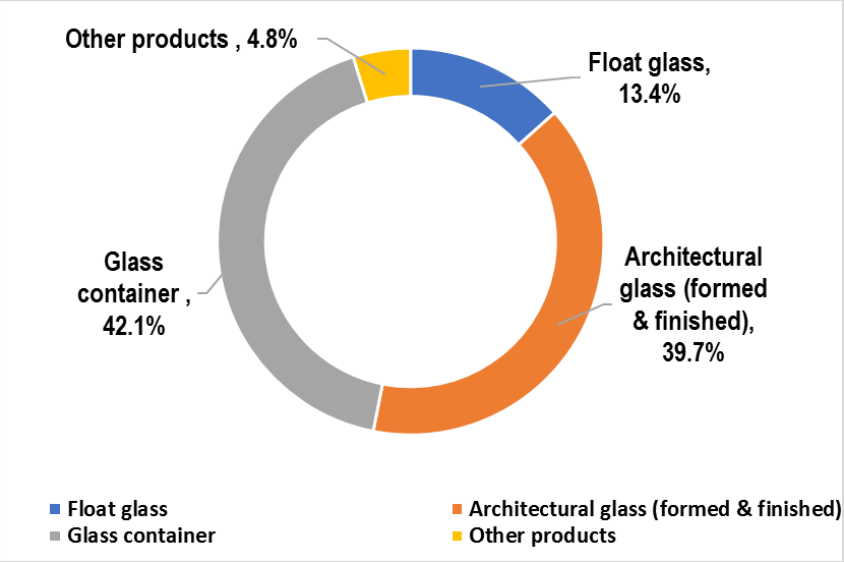

Figure 2. The major products of GGPMI. Source: Kelly (2019)[5]

[5] Kelly, A: IBISWorld. 2019. Glass and Glass Product Manufacturing in Australia.

The key economic drivers for the industry are directly related to the demand from (residential and non-residential) construction activities and beverage manufacturing (Table 3). Similarly, the main demand industries include those related to construction, and food and beverage production and processing.

Table 3. Key drivers and the major industries that are dealing with timber wholesaling

Key Economic Drivers	Demand Industries	Supply industries
Demand from residential building construction	Fruit and Vegetable Processing	Corrugated Paperboard Container Manufacturing
Demand from non-residential building construction	Beer Manufacturing	Mineral Sand Mining
Demand from beer manufacturing	Wine Production	Printing
Demand from wine production	Aluminium Door and Window Manufacturing	Rock, Limestone and Clay Mining
Household consumption expenditure	Construction	
Per capita alcohol consumption	Glazing Services	

Source: IBISWorld 2019[5]

2.1 Major producers in Australia

In Australia, the major players of the glass production market produce 37.8% of glass products annually[5]. The glass market is dominated by three companies including “Owens-Illinois Holding (Australia) Pty Ltd (22.5%)”, “Crescent Capital Partners Holdings Pty Ltd (8.6%)” and “Orora Limited (6.7%)”. The rest of the market is supplied by small to medium-sized companies that have a small percentage of the market.

2.2 Demand determinants

The dynamics of the impact of the key economic factors which are tabulated in Table 3 are described below:

1. **Demand from non-residential building construction**
   Increased investment in non-residential building construction has driven demand for flat glass products over the past five years. Higher demand has been derived from firms constructing commercial buildings, particularly offices and retail buildings, representing a substantial source of demand for glass wall panels, windows, glass bricks and blocks, doors, shower screens and mirrors. Demand from non-residential building construction is expected to contract in 2019-20. However, some manufacturers may benefit from sales of flat glass products for completion work on major office and hotel developments.

2. **Demand from residential building construction**
   Trends in the downstream residential building market significantly affect demand for flat glass products, notably windows. Glass consumption is highest in the construction of large-scale apartment complexes, which are often clad in glass and have glass balconies. Demand from residential building construction has varied significantly over the past five years. Demand is expected to decline in 2019-20, following the completion of many large-scale apartment developments. This fall represents a significant threat to the industry's performance.

3. **Demand from beer manufacturing**
   Demand for glass bottles heavily depends on demand from the local beer manufacturing sector. Local brewers use cans and bottles for packaging beer. Demand from beer manufacturing has fallen slightly over the past five years. However, demand is expected to increase in 2019-20, supporting demand for glass beer bottles.

4. **Demand from wine production**
   Many industry firms supply glass containers used to bottle locally produced wine. Demand from wine production has risen over the past five years. However, the shift towards exporting bulk wine in PVC bladders has limited demand from this market. Demand from wine production is expected to expand in 2019-20, underpinning stronger demand for glass wine bottles.

5. **Household consumption expenditure**
   Household consumption expenditure indicates households' capacity to purchase products that may contain glass. These products include glass containers used to package beverages and food products (e.g. jam), glass-based furniture products (e.g. mirrors) and products used for household window repairs. Household consumption expenditure has risen steadily over the past five years and is expected to continue growing in 2019-20.

6. **Per capita alcohol consumption**
   Alcoholic beverages represent the main market for glass bottle production. Alcohol consumption has significantly fallen since 2006-07 due to government policies and rising health consciousness. Per capita alcohol consumption is expected to decrease slightly in 2019-20, weakening demand for glass wine, beer and spirit bottles.

2.3 Raw materials

In this section, the raw materials needed for the manufacturing of float glass is described. Float glass is the main type of glass that is used in the construction industry. Float glass is a sheet of glass made by floating molten glass on a bed of molten metal, typically tin, although lead and other various low-melting-point alloys were used in the past. This method gives the sheet uniform thickness and very flat surfaces. The following are the principle constitutes of float glass:

1. **Silica Sand:** the main ingredient of glass which makes up 60% of the composition. It has a very high melting point of over 2,000 ˚C.
2. **Sodium Carbonate:** helps glass endure a range of temperatures without melting. It basically lowers the melting point of Silica down to about 1,000˚C and is therefore added to make the process more efficient. The Sodium Carbonate will, however, cause the finished glass to be water-soluble, which is not desirable in glass making. Sodium Carbonate was originally found in the ash of certain plants—soda ash—but is now commonly produced from table salt.
3. **Limestone:** Calcium Oxide, extracted from limestone, contributes to strength properties to glass. This material negates the effects of the Sodium Carbonate, making the glass non-soluble in water. Magnesium Oxide and Aluminium Oxide can also be used to enhance the properties of the glass.
4. **Dolomite:** Dolomite that is composed of calcium and magnesium carbonate, contributes to glass resistance to melting. It also improves general resistance to natural or chemical attack or weathering.
5. **Glass Cullet:** commonly known as 'broken glass'; this accelerates the melting of glass as it goes through the float glass process. Glass cullet is 100% crushed material that is generally angular,

flat and elongated in shape. This fragmented material comes in colour or colourless forms. The size varies depending on the chemical composition and method of production[6].

6. **Other additives**: include lead, Boron, Lanthanum Oxide, iron and colour-producing agents.

2.4 Products overview

The use of glass in the building sector has a long history; however, with new technological advances, its application has become very broad. Glass is now being used in the building industry as insulation material, structural component, external glazing material and cladding material. In infrastructural projects, the application of glass includes but is not limited to the sound barrier, tunnel, ingredients for road surface such as asphalt and insulators. Figure 3 shows multiple applications of glass products in the construction industry.

[6] GHD. 2008. Packaging Stewardship Forum, Australian Food and Grocery Council. The use of Crushed Glass as both an Aggregate Substitute in Road Base and in Asphalt in Australia Business Case. https://higherlogicdownload.s3.amazonaws.com/IPWEA/c7e19de0-08d5-47b7-ac3f-c198b11cd969/UploadedImages/Glass%20Recycling/081104%20ghd%20crushed %20glass%20final%20report[1].pdf

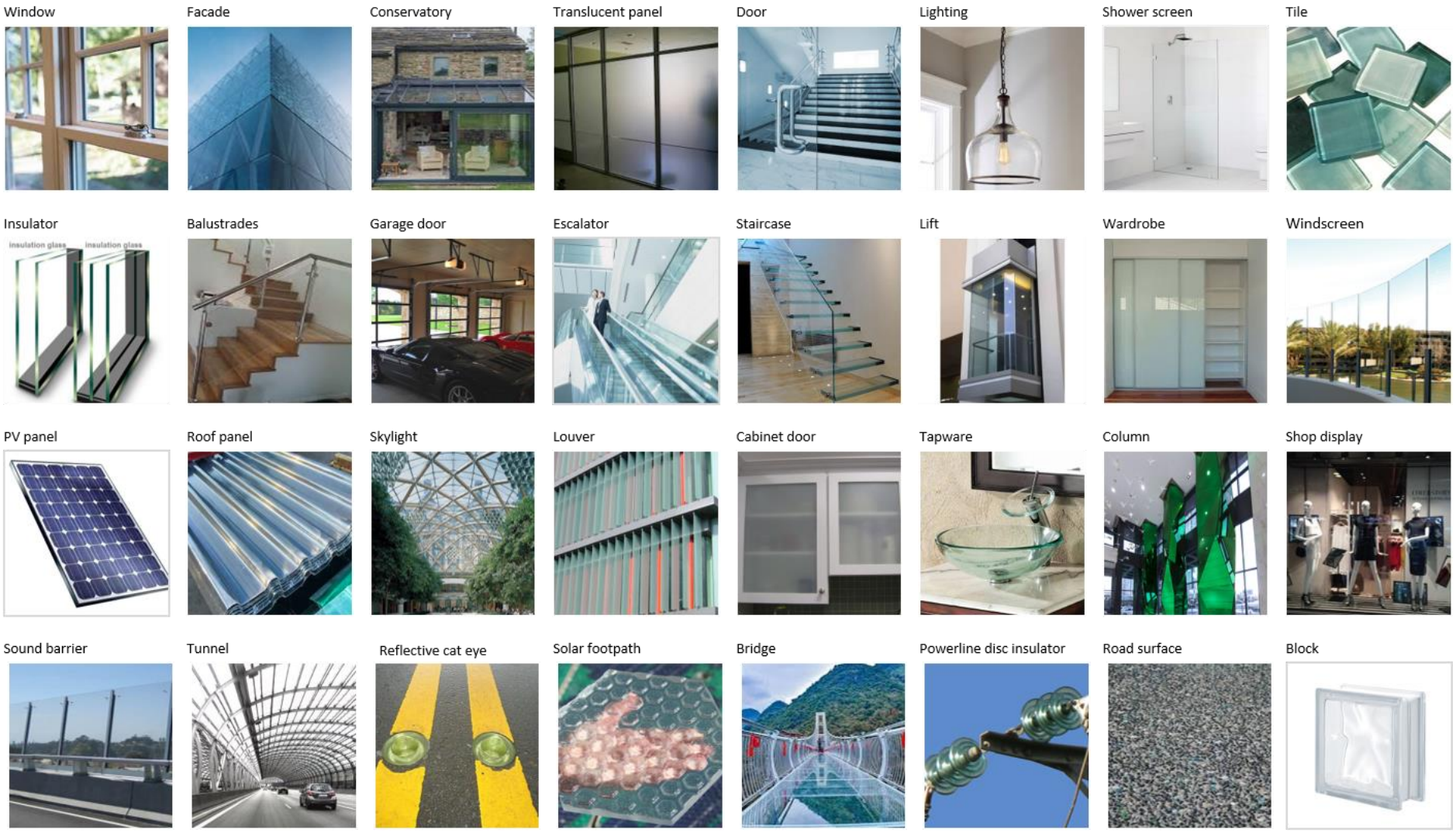

Figure 3. Various applications of glass products in the construction industry

2.5 Manufacturing process

There are various manufacturing processes for several types of glass products that are used in the construction industry. However, float glass is the most commonly used type of glass (Table 2). As a result, the production process for float glass is provided below. The process can be divided into five universal steps, as follows:

1. **Batching of raw materials:** The main components, namely, soda-lime glass, silica sand (73%), calcium oxide (9%), soda (13%) and magnesium (4%), are weighed and mixed into batches to which recycled glass (cullet) is added. The use of 'cullet' reduces the consumption of natural gas. The materials are tested and stored for later mixing under computerised control.
2. **Melting of raw materials in the furnace:** The batched raw materials pass from a mixing silo to a five-chambered furnace where they become molten at a temperature of approximately 1500°C.
3. **Drawing the molten glass onto the tin bath:** The molten glass is "floated" onto a bath of molten tin at a temperature of about 1000°C. It forms a ribbon with a working width of 3210mm, which is normally between 3 and 25mm thick. The glass, which is highly viscous, and the tin, which is very fluid, do not mix, and the contact surface between these two materials is perfectly flat.
4. **Cooling of the molten glass in the annealing lehr:** On leaving the bath of molten tin, the glass—now at a temperature of 600°C—has cooled down sufficiently to pass to an annealing chamber called a lehr. The glass is now hard enough to pass over rollers and is annealed, which modifies the internal stresses, enabling it to be cut and worked in a predictable way and ensuring the flatness of the glass. As both surfaces are fire finished, they need no grinding or polishing.
5. **Quality checks, automatic cutting and storage:** After cooling, the glass undergoes rigorous quality checks and is washed. It is then cut into sheets of sizes of up to 6000mm x 3210mm, which are in turn stacked, stored and ready for transport.

3 REGULATIONS, POLICIES AND GUIDELINES

Legislation of glass waste management occurs at the jurisdictional level. As a result, there are various policies and requirements for glass waste in Australia. However, the inconsistencies in these jurisdictions are regarded as a challenge for successful management of glass waste.

Another set of regulations deals with the use of recycled glass waste materials in construction projects such as roads and pavements. The Standard Specifications regulate and maintain the quality and provide producers, as well as consumers, an assurance of uniformity and consistency in the quality of the recycled aggregate. For instance, in Victoria, Vicroads, which is a state authority managing the road and traffic, has provided a code of practice[7] that outlines the specifications of recycled crushed glass for application in the state road and pavement bases/subbase. In NSW, Roads and Maritime Services (RMS) has set specifications for granular pavement base and subbase materials[8]. Later, EPA NSW published a guideline entitled "Specification for Supply of Recycled Material for Pavements, Earthworks and Drainage 2010 (Greenspec)"[9], which was set to encourage local government professionals and other key players within both the private and public works engineering sector to use recycled concrete, brick and asphalt materials. Other states also have their own version of codes of practice for recycled concrete. However, similar to environmental regulations, the specifications provided in the codes are not uniform[10].

Table 4. The standards and specifications guiding the use of recycled concrete

State	Title
ACT	N/A
NSW	Specification for Supply of Recycled Material for Pavements, Earthworks and Drainage 2010 (Greenspec)
QLD	Transport and Main Roads Specifications MRTS35 Recycled Material Blends for Pavements
NT	Standard specification for roadworks
SA	The standard for the production and use of Waste Derived Fill Recycled Fill Materials for Transport Infrastructure - Operational Instruction 21.6 Policy Specification: Part 215 Supply of Pavement Materials
TAS	Unbound Flexible Pavement Construction
VIC	VicRoads Standard Specifications for Roadworks and Bridgeworks VicRoads Codes of Practice
WA	Main roads Western Australia specification 501 – pavements

[7]Vicroads. 2017. Code of Practice RC 500.02. Registration of Crushed Rock Mixes. https://www.vicroads.vic.gov.au/-/media/files/technical-documents-new/codes-of-practice-rc500/code-of-practice-rc-50002--registration-of-crushed-rock-mix-designs-july-2017.ashx

[8]RMS. 2008. ROADS AND MARITIME SERVICES (RMS) . RT 3051 https://www.rms.nsw.gov.au/business-industry/partners-suppliers/documents/specifications/3051.pdf

[9]EPA NSW. 2011. IPWEA Roads & Transport Directorate https://www.epa.nsw.gov.au/~/media/EPA/Corporate%20Site/resources/waste/100004-supply-recycled-material.ashx

[10] Gabr, A.R., Cameron, D.A., Andrews, R. and Mitchell, P.W., 2011. Comparison of specifications for recycled concrete aggregate for pavement construction. *Journal of ASTM International*, 8(10), 1-15.

The other aspect of regulation that has an impact on glass waste management is landfill levies. The jurisdictional landfill levy regulations need to change in favour of glass recycling. For instance, in Europe, the glass industry has been driving legislation to ensure that it attracts the highest rate of landfill levy and, therefore, the most significant incentive to recycle the glass at higher value opportunities[11]. At the same time, tax levy exemptions are needed for glass waste residual for recycling facilities. According to the Australian Sustainable Business Group (ASBG), to counter the impact of the landfill levy on recycling, options such as the provision of a partial levy exemption for the recycling industry, better funding and grants to support the recycling industry, and the use of Product Stewardship programs, should be considered[12].

[11] DeBrinca, G and E. Babic. 2013. Arup: Re-thinking the life-cycle of architectural glass. Construction flat glass recycling Viability study & value report. https://www.arup.com/perspectives/publications/research/section/re-thinking-the-life-cycle-of-architectural-glass

[12] Environment and Communications References Committee. 2018. Never waste a crisis: the waste and recycling industry in Australia, 53.

4 GLASS WASTE GENERATION

Previous literature suggests that glass waste can emerge throughout the lifecycle of this building material. Various reasons are given to outline the source of waste generation, but it seems that cutting is the most frequently mentioned in research studies.

Table 5. Main reasons for glass waste generation

Reference	Description
Tam (2011)	• Damages during transportation; and • Improper cutting to the required dimensions
UK's Glass and Glazing Federation (2000)	• Cutting activities: • Poor storage and handling techniques; • Inadequate maintenance of equipment and machines; • Lack of checks leading to downstream processing problems; and • Poor staff awareness of optimum operating techniques and process settings.

4.1 How much glass waste is generated

Generally, glass waste only takes up a small portion of waste generated during construction and demolition activities. However, glass waste takes 1 million years to break down naturally[13]. A study in Hong Kong reported that the volume of glass waste from 5 construction projects ranged from as little as 0.3% to 16.5%[14]. The construction industry is not a significant contributor to glass waste generation in Australia. According to the latest data released by the federal Department of Environment and Energy in the national waste report[15], Australia generated 1,078,831 waste glass in all waste streams in the period 2016-17 (Table 6). The largest producers of the glass waste in Australia were NSW (338, 255), Queensland (240, 753) and Victoria (212, 253). From the total glass waste generated, only 0.62% came from the C&D waste stream. Among the jurisdictions, NSW, Victoria and SA had the highest rate of C&D waste-based glass waste to total glass waste ratio, with 1.90%, 0.58% and 0.23%, respectively.

[13] Suez. 2017. Fact sheet: Glass Recycling. https://www.suez.com.au/-/media/suez-au/files/publication-docs/waste-tips-and-facts/suez_anz_glass_factsheet.pdf

[14] Tam, V.W., 2011. Rate of reusable and recyclable waste in construction. *Open Waste Management Journal*, 4(1), pp.28-32.

[15] Department of Environment and Energy. 2018. National Waste Report 2018. https://www.environment.gov.au/ protection/waste-resource-recovery/national-waste-reports/national-waste-report-2018

Table 6. Glass waste generation and fates in Australia

	Waste Generation		Waste Landfill		Waste Recycling	
STATE	**C&D**	**TOTAL**	**C&D**	**TOTAL**	**C&D**	**TOTAL**
ACT	21	20,661	21	6,539	n/a	14,122
NSW	6,442	338,255	0	136,926	6,442	201,329
NT	5	13,036	5	7,864	0	5,172
QLD	60	240,753	60	133,534	0	107,219
SA	192	81,959	192	14,959	0	67,000
TAS	1	38,199	1	14,521	0	23,678
VIC	1,238	212,253	1,238	74,935	0	137,318
WA	14	133,715	14	77,978	0	55,717
TOTAL	**6,735**	**1,078,831**	**1,531**	**467,256**	**6,442**	**611,555**

Source: Department of Environment and Energy. 2016-17[15]
Note: the values for waste generation are the result of adding together waste landfilling and recycling values.

4.2 Types of glass waste

Table 7 presents various glass waste types that are categorised based on different characteristics. There are five types of glass waste, including internal glass cullet, external glass cullet, glass (powder) fine, mixed cullet and clear cullet.

Table 7. Various types of glass waste

Type	Description
Internal glass cullet	A glass that is crushed and ready to be remelted is called cullet. Internal cullet is composed of defective products detected and rejected by a quality control process during the industrial process of glass manufacturing, transition phases of product changes (such as thickness and colour changes) and production off-cuts.
External glass cullet	Waste glass that has been collected or reprocessed with the purpose of recycling. External cullet (which can be pre- or post-consumer) is classified as waste. The word "cullet", when used in the context of end-of-waste, will always refer to external cullet.
Glass (powder) fine	A lower grade product which is used in asphalt, sand/abrasive grit blasting, asphalt (glassphalt), construction and road aggregates, concrete aggregate, sports turf/drainage, brickmaking, water filtration, insulation batts and an alternate day cover for landfills.
Mixed cullet	Contain a mixture of glass types (sealed window units, laminated glass, mirrored glass, tinted glass, printed glass, old glass from wooden frames). A lower price will be paid for mixed cullet as it requires additional processing to remove contamination.
Clear cullet	It consists of standard flat glass only.

Glass cullet management

While it is possible to minimise the total amount of cullet generated, it is generally not possible to eliminate its production. Cullet is produced during manufacturing and in secondary activities. It is important to consider cullet management from all processes in any waste management strategy. Flat glass cullet can be recycled into the flat glass, glass fibre or glass wool insulation. Good cullet management will improve cullet quality and thus increase the amount that can be recycled. The level of contamination in the cullet load has a direct influence on its value and saleability. Generating contaminant-free cullet is, therefore, vital to the financial viability of cullet recycling. There are two main types of contamination:

- Inclusions—non-glass materials, e.g. sealed unit and window frame materials or laminated glass;
- Colour contamination—mixed cullet of different colours.

Improving the purity of cullet and preventing colour contamination will increase the value and recyclability of cullet. There are techniques to improve the purity of cullet, such as thermal treatment, which is conducted in a batch, high-temperature electric oven and then in the continuous infra-heated thermal reactant[16]. The following table presents some strategies that facilitate subsequent recycling activities of glass cullet generated during glass production.

[16] Isa, H. 2008. The need for waste management in the glass industries: A review. *Scientific Research and Essay*. 3(7), 276-279.

Table 8. Strategies to better manage glass cullet.

Theme	Description
Reducing contamination	• Prevent non-glass materials from becoming mixed with cullet contamination. • Segregate waste streams to prevent mixing of different colours and types of glass. Provide alternative skips for other waste materials. • Label all skips clearly.
Management	• Make one person responsible for ensuring that cullet skips are: inspected daily for inclusions and colour contamination, well-maintained and clearly labelled. • Mark skips clearly with which types of cullet are acceptable and which are unacceptable. • Provide skips for unacceptable waste next to cullet bins. This will reduce inclusions. • Make workers aware of the cullet specification required by the cullet collector. • Ensure that cullet generated off-site (e.g. breakage during window fitting) is returned and Placed—without any inclusions—in the appropriate skips.
Training	• Provide staff with regular training in cullet management. • Provide clear, written procedures so that everyone knows exactly what to do. • Ensure that contractors do not use cullet skips for their waste.
Pick-up	• Check that the cullet in the skips has no inclusions before cullet collectors collect the skips. • Use a limited number of cullet collectors to ensure training and communication on cullet handling remain effective. • Ensure that contaminated loads are not forwarded to recyclers. Prices for consignments may change if minimum requirements are not met.

Source: UK's Glass and Glazing Federation (2000)

5 GLASS WASTE MANAGEMENT

The aim of this section is to provide an insight into the sustainable management of glass waste through various opportunities that emerge throughout the glass lifecycle. It also discusses the various waste management methods, which are supplemented by some case studies that showcase success stories in sustainable glass waste management.

5.1 Waste during manufacturing

Pre-consumer waste is generated during manufacturing (before reaching the consumer) and has an industrial origin exclusively. It represents approximately 25% of waste glass generated in the EU[1]. There are plenty of opportunities to reduce glass waste during the manufacturing of glasses used in the construction industry. Due to technical and economic reasons, there is a minimum glass to glass market in Australia. However, from the environmental protection perspective, the use of recycled glass in manufacturing glass products is a viable option. According to Writer (2018),[17] recycled glass requires a lower melting temperature than the raw materials used to produce glass from scratch, meaning production that utilises recycled glass can extend the lifetime of the furnace and save large amounts of energy. The recycling process does not generate any harmful by-products either, making it extremely efficient. Because recycled glass also lowers the demand for raw materials, its use supports natural resource conservation—1 t for every tonne of glass recycled—and decreased manufacturing costs. On top of those savings, glass recycling has a critical impact on the reduction of carbon dioxide emissions: for each metric ton of material recycled, manufacturers avoid producing approximately 315 kg of carbon dioxide emissions.

A selection of the strategies that are identified by Tangram Technology[18] based on the recommendations of the UK's Glass and Glazing Federation (2000) to improve glass waste management in the glass production industry is provided in Table 9. These strategies have come under 11 categories that cover the entire production system.

Table 9. Strategies to reduce waste during various stages of glass production

No	Title	Description
1	Walk-around	A 'walk-around' is designed to gain an overview of the processes and to identify some rapid no-cost or low-cost improvements to save money. Take an unannounced walk around the site at mid-shift. If there is no night shift, it can also be profitable to take a walk around the factory when there is no production being carried out.
2	Storage and handling	• Avoid breakages by improving storage and handling techniques (especially after the value has been added by processing). • Stack glass correctly to avoid problems with de-stacking. • Ensure that the correct lifts and equipment are used for lifting and manoeuvring glass from delivery vehicles to factory storage areas. • Maintain racks with unworn felt/rubber padding and set at the correct angle, i.e. 30.

[17] Writer, S. 2018. Reducing Waste Through Glass Manufacturing & Packaging. Thomas Insights. https://www.thomasnet.com/insights/reducing-waste-through-glass-manufacturing-packaging/

[18] Tangram Technology. 2015. Waste minimisation in glass processing. https://www.tangram.co.uk/TI-WasteMinimisation (Glass)-Tangram.PDF

3	Finding hidden costs	Estimate the 'true cost' of waste which is not only the cost of the raw materials but is also a function of how much-added value has been put into the product before it is lost from the production process. For example, if a product is broken in the goods-out department, causing it to be lost as waste, the true cost of that waste will be: The true cost of waste = *Cost of wasted raw materials + lost time + cost of utilities used + waste treatment + disposal costs.*
5	Production	• Plan production to minimise changeover losses. • Record glass utilisation wherever possible. Track, locate and reduce any variations.
6	Packaging waste	Re-use any packaging for products, where appropriate. Find ways of minimising packaging with both suppliers and customers. The packaging is paid for twice—once to buy it and again to dispose of it.
7	Cutting	• Set aggressive improvement targets for glass utilisation that are relevant to a business. • Fully optimise cutting to minimise waste—do not stop optimising at the first 'acceptable' result. • Check for any surface and edge defects before cutting. • Check the accuracy of the 'squareness' of cutting equipment. • Box in cutting tables so that cullet does not fall underneath them. • Contaminated cullet decreases in value and is often disposed of rather than recycled. • Catalogue and store significant off-cuts for future use.
8	Waste collection	• Optimise waste segregation and recycling to minimise the amount of waste requiring disposal. • Collect waste flat, float and clean glass separately from other glass types and contaminants (e.g. wood and metals) for recycling. • Collect coated, coloured and laminated glasses separately for recycling. • Make sure that ceramic, coloured or fire-retardant glass does not contaminate flat, float and clean glass forwarded for recycling. • Order replacement skips for cullet collection before the ones in use become full. This will avoid glass spilling on the ground and having to be disposed of to landfill because it is contaminated.
9	Maintenance	• Ensure that all machinery is well-maintained and clean to reduce mistakes, accidents and breakage. • Assign machines to operators to increase operator ownership. • Train staff to handle glass and end products correctly to avoid bruising, scratching and damage.
10	Site layout	Layout production areas to optimise material flow logistics. This reduces both the potential for breakage and the time taken to move the product.
11	Performance measure	• Production performance in the glass fabrication and the processing industry is often measured according to overall output and 'due date'. • Using performance measurements that relate directly to process efficiency will improve overall control and help you to develop good practice. • Examples of these measures include cutting yield, glass waste/tonne of saleable product and energy costs.

Source: Tangram Technology[18]

In addition to the general strategies presented in Table 9, there are specific opportunities to reduce waste in glass fabrication, focusing on the manufacture of sealed units and frames, and glass processing, which is concerned with activities such as laminating, toughening, bevelling and grinding (Table 10). These opportunities are identified by UK's Glass and Glazing Federation (2000).

Table 10. Opportunities to reduce waste in glass fabrications and processing

Good practice in glass fabrication	
Sealed units	• Check for waste at key points in the manufacturing process. Record the amounts and consider ways of eliminating or reducing this waste. • Collect steel and aluminium off-cuts separately for recycling or return to the engaged supplier. • Minimise desiccant use by calculating the exact amount required for the volume of the sealed unit. • Maintain the correct temperature for sealant storage and use to avoid wasting batches and to optimise sealant application. • Stagger breaks in production to avoid the need to purge sealant from machines before and after breaks. • Ensure that the optimum amount of sealant is used for a given gap between panes of glass by monitoring actual and target use. • Check the quality of two-part sealant mixes to ensure correct performance. • Store finished products in safe areas to minimise damage.
Fabrication of frames	• Check that the dimensions and quality of the profile material (e.g. look for rubs, marks and frames scratches) are acceptable to avoid subsequent wastage. • In sawing processes, minimise grip waste and, on mitres, cut to the width of the blade. • For PVC-u profiles: – order steel and aluminium reinforcement in pre-cut lengths to avoid on-site waste; – recycle waste PVC-u by regranulating and blending it into secondary profiles, i.e. not the all-weather sections but the secondary parts of the profile; and – sell PVC-u swarf from drilling/cutting and sprues from welding operations to a reprocessor. • If mistakes do occur: – recover fittings, hinges, handles, locks and glass in a material reclaim unit; – granulate uncontaminated PVC-u frames; and – recycle aluminium frames.
Good practice in glass processing	
Acid processes	• Use a high-quality sealing coating to avoid mistakes and thus minimise waste and rework.
Sandblasting	• Check the pattern cutting (the most critical stage) to ensure accurate sandblasting. This will avoid waste generation and the need for reworking. • Re-use grit and change it only when necessary. • Use the best quality sealing coating to avoid mistakes and thus minimise waste.
Drilling	• Cut a slot from the edge of the glass to reduce the incidence of breakage.
Laminating (resin)	• Before starting to laminate, ensure that the glass is clean and dry to avoid trapping moisture (resin). • Use demineralised water to avoid staining on internal surfaces. • Ensure that glass is securely clipped to avoid movement during processing. • Check that bubbles are not present in the resin before curing with ultraviolet light. • Use the correct cure time.
Laminating (pvb)	• Maintain suitable conditions for the storage and use of pvb laminate. This will avoid (pvb) deterioration of the laminate and ensure efficient application. • Keep the lamination equipment free of dust to avoid contaminating the product. • To guarantee accurate application, check that the lamination equipment is square to the laying table.

	• Inspect the laminated glass after autoclaving to ensure that downstream processes are not supplied with faulty material. • Trim the pvb overhang from laminated glass to avoid slippage and damage in subsequent processes, e.g. on double glazing lines. • Maintain autoclaves, cranes and hot air systems correctly to provide efficient and optimum operation. • Integrate driers with compressed air systems and autoclaves to avoid staining due to solid deposits, and the need for cleaning.
Bevelling and grinding	• Turn on the water supply to bevelling and grinding machines only when they are in use. • Turn off the water when the machines are not in use. • Recycle the water from bevelling and grinding machines to reduce water and effluent costs.
Bending	• Check moulds thoroughly to prevent quality problems. • To avoid unnecessary cracking, raise the oven hood at an appropriate speed and reduce the hood temperature correctly. • Utilise the bed space under the oven hood as much as possible to optimise production rates. • Operate the oven hood overnight when cheaper energy is available.
Toughening	• Plan work to maximise periods of continuous operation. This avoids start-up and shutdown, thus reducing energy use and other production costs. • To avoid rejects, check the glass for staining before processing. • Ensure that ovens and chillers are programmed accurately for each job to optimise heating/cooling time and to minimise the potential for breakage. • If a print is applied to the glass, place the print face-up to avoid damaging the rollers and having to stop the process to clean them. • Operate the toughener overnight when cheaper energy is available.

Source: UK's Glass and Glazing Federation (2000)

5.2 Waste reduction opportunities during the design, planning and contract

Proper design that guarantees the least variation and adjustment during construction leads to minimum waste generation. For instance, the design of custom glazing panels to use multiple replicates of the same size units wherever possible can assist with reducing glass waste. Arup's report on construction glass circularity provided some insight into the need for design with a view to recyclability[19].

The glass design equivalents would be to design out the use of laminate glass units or ceramic frit, which both currently makes glass recycling challenging or impossible. Ceramic fritted glass cannot be recycled, and the process of delamination crushes the glass in small particles—which cannot be used in the highest level of recycling—back into float glass. This means designers need to review the current trend of laminated double glazed units, which are often required to achieve the safety performance of the building façades. The other approach to address this challenge is to benefit from research and technical development to find a better way to delaminate glass, altering the interlayers or upgrading the delamination process.

[19] DeBrinca, G and E. Babic. 2013. Arup: Re-thinking the life-cycle of architectural glass. Construction flat glass recycling Viability study & value report.https://www.arup.com/perspectives/publications/research/section/re-thinking-the-life-cycle-of-architectural-glass

5.3 Reducing waste during the procurement

A significant challenge for the implementation of glass recycling on renovation and demolition projects is the existing procurement structure and processes used in the industry. In the early stages of renovation and demolition projects, clients and design teams should be defining the specification for the removal and recycling of building materials during the works. Knowledge of appropriate and available recycling methodologies needs to be disseminated to clients and specifiers to allow a greater uptake of recycling early in the life of a project, specifying the requirements to contractors prior to their engagement on the project. For instance, Arup has successfully specified the contractor's requirement to recycle glass at this high-level closed-loop process during renovation and glass replacement projects[19].

Defining standard clauses that can be included in contractual documents would assist the industry to adopt these requirements for recycling of building materials. Tender responses could require the contractors to state the level of recycled glass content from their supply chain and allow a measure between contractor returns. This could potentially have a positive effect on the promotion of increasing recycled content by the glass manufacturers, as they currently do not openly advertise this information. Commercial sensitivities of building product manufacturers may require some overcoming as we have found the glass manufacturers to be particularly secretive of their processes to maintain a competitive edge. Legislation may be required to make the release of this information compulsory for clarity on recycled content of products.

5.4 Reducing waste during transportation and delivery

The occurrence of glass wasted during transportation and delivery is common. One study in Hong Kong[14] reported that one of the two main reasons for glass waste generation is damages during transportation. Furthermore, the delivery of glass panes with large sizes increase the likelihood of glass waste, and hence there are restrictions from handling, processing and transportation that limit the use of larger glass sizes in the construction industry[19]. The other issue that arises during removal, storage and transportation is the contamination of glass waste. Minor contact with stainless steel can cause significant contamination that may cause critical inclusions[19]. Tangram Technology[1] report identified strategies to reduce glass wastage during delivery as follows

1. Use 'Just-In-Time' delivery to minimise storage time and damage;
2. Develop delivery quality checks to improve the quality of glass used and reduce defects/breakages; and
3. Measure all breakage in deliveries and chargeback to the supplier.

5.5 Reducing waste during construction

One study in Hong Kong[14] reported that the main reason for glass waste generation at a construction site is cutting to the required dimensions. Therefore, glass installation subcontractors have a pivotal role in reducing waste by having due diligence when cutting the glass delivered to a construction site. Tangram Technology[1] identified strategies to reduce waste during construction as follows:

1. Increase the stillage size to reduce space and number of glass lifts;
2. Maintain stillage's at an angle of 50 or 60;
3. Use battens to optimise storage conditions and avoid glass damage; and
4. Keep storage areas free of water leaks and dust to reduce staining.

5.6 Reducing waste during demolition and renovation

Glass emerged from demolition and renovation activities account for a large percentage of glass waste in the construction industry. For instance, renovation projects in the UK hold the majority of glass material for recycling, representing almost 85% of the glass quantity available for recycling[20]. While the recycling of waste glass is viable in refurbishment projects, the demolition projects present a bigger challenge.

However, with current demolition practises, it is likely to be economically challenging to recycle glass from demolition projects because it is often broken during demolition and mixed with other materials. Once mixed with foreign materials, it is very difficult to separate glass to the standard required by quality specifications for glass manufacturing. Therefore, as demonstrated by research[21] in Europe, most glass from demolition activities is mixed with a recycled hardcore to create an aggregate material that can be used for foundations.

The best opportunity with demolition projects is in the case of highrise buildings where for safety reasons demolition is controlled, and introducing measures to keep glass separated may not add significantly to the cost and time of the process. Research in the UK[19] demonstrated that the value of the cullet paid by the float manufacturers represents sufficient incentive to transport and deconstruct the materials in this way, using unskilled staff in the breakdown operations. It was found that moving the cullet following breakdown and bagging appears to be most cost-effective when the glass manufacturers backhaul the material on otherwise empty transportation following material deliveries in the local area of the recycling facilities.

Recycled glass generated from demolition and renovation projects is collected in two main different ways: mono-material collection (optionally with colour differentiation), or mixed with other dry recyclables (multi-material collection). Both options have advantages and disadvantages that are tabulated in Table 11:

[20] Hestin M., de Veron S., Burgos S., 2016. Economic study on recycling of building glass in Europe. Deloitte Sustainability.

[21] Glass fpr Europe, 2010. Recyclable waste flat glass in the context of the development of -end-of-waste criteria. Glass for Europe input to the study on recyclable waste glass.

Table 11. Characteristics of glass waste collection systems

	Disadvantages	Advantages
Mono-material system	• Requires existence of a reprocessor with adequate sorting technology within reasonable transport distance, otherwise, it is likely that the material will be used for open-loop recycling applications, such as aggregates, resulting in virtually no environmental benefits. • The additional stage of colour sorting may have a significant cost impact and even become economically not viable. • More demanding for consumers. • More costly in terms of collection than multi-material systems, especially if colour-separated.	• Normally results in higher quality. The amount of non-glass is significantly lower, making it easier to process and remove the lids, labels, foils, ceramics and any other impurities. • Cullet has higher quality, and it is thus fit for a larger range of glass recycling uses. This is especially valid if there is colour separation. • Increased added value over the recycling chain, also higher with colour separation. • Lower costs of reject disposal (non-glass material fraction) or bad quality cullet batch disposal. • In general, higher overall recycling rates (even though collection rates may not in all cases be higher). • Better image to the public, as the multi-material collection may result in the perception that glass is not being recycled • Avoidance of landfill levy for storage at material recovery facilities.
Multi-material system	• Higher reprocessing costs to achieve the same quality as mono-material collection, if at all achievable. • Lower recycling rates because of high contamination. • Higher glass loss during processing (typically 12-15% is wasted in material recovery facilities, compared to 1% for mono-material processing). • Cullet frequently not suitable for further reprocessing with the aim of re-melting in glass manufacturing facilities. Experts reported that even in some cases the cullet is not suitable for use as aggregates because of its high organic contamination. As a consequence, the cullet from multi-material systems is sometimes rejected by aggregate companies.	• Easier for construction and demolition companies, as less sorting space is needed. • Cheaper collection.

Source: Pharosproject (2005)[1]

5.7 Reducing waste through reusing

Most of the flat glass used in buildings could be dismantled and recycled in glass furnaces. However, reusing the unwanted or damaged glass products without processing is difficult. According to anecdotal evidence and some industry reports reusing glass waste and its derivatives in the fabrication of construction, the glass material is minimal. For instance, a sustainability study[20] in the UK showed that, despite its excessive recyclability, end-of-life glass is almost never recycled into new glass products. However, with technological advances, new techniques such as electrolysis, filtration, reverse osmosis, centrifugation emerged that through which reusing can be facilitated during glass manufacturing processes and construction activities[22]. In the UK, waste recovery services usually take a separated waste glass from site free of charge, or require the builder to pay transportation costs. From the builder's perspective, this is a saving, compared to the landfill tax (regardless of the landfill tax rate) and should be actively encouraged to support glass recycling. After the glass waste is processed at the glass recycling facility, which includes removal from frames and sorting into three categories of quality, they sell the cullet to float glass manufacturers. The following is a description of a case study in which the construction glass waste is reused.

A case study in the UK[23]: Lloyd's, Richard Rogers

In 2010, Lloyd's decided that it required more daylight and improved views from the iconic Richard Rogers designed building originally completed in 1987. Some of the original rolled sparkle glass panes were replaced with clear flat glass, and 123 t of the original glass was removed from the building and sent back to Saint Gobain in Eggborough for remelt back to float glass. Additionally, some of the sparkle glass was reused. The panels were cut into the new required size, and installed back or stored for any replacements required in the future (Figure 4). Some of the "off-cuts" were used in furniture designs for the building, such as tops for coffee tables. The work on Lloyd's demonstrates re-use and recycling of glass at the highest standard and with minimum environmental impact.

Figure 4. Lloyd building in London, UK. Source: **Lloyd's© Arup (2013)[23]**

[22] Lawson, E. 2018. 8 Effective Ways to Reduce Manufacturing Waste. Fishbowl. https://www.fishbowlinventory.com/blog/2018/01/31/8-effective-ways-to-reduce-manufacturing-waste/

[23] DeBrinca, G and E. Babic. 2013. Arup: Re-thinking the life-cycle of architectural glass. Construction flat glass recycling Viability study & value report.https://www.arup.com/perspectives/publications/research/section/re-thinking-the-life-cycle-of-architectural-glass

5.8 Waste recovery (recycling and upcycling)

Technically, glass can be recycled several times for use in different applications. However, due to the reasons stated earlier, in the real world, the reusability and recyclability of glass waste do not take place typically as high as it should. According to a study[24] on the extent of recycling of C&D based glass waste in five construction project case studies in Hong Kong, the average recycling rate was pretty low (29.6%) compared to other construction waste materials such as concrete, metal, timber, paper and plastic. One study in the EU[23] showed that, across the EU, the proper recycling of all building glass waste compared to the business-as-usual scenario could avoid 925,000 t of landfilled waste every year and could save around 1.23 Mt of natural materials annually (of which 873,000 t is sand) and reduce carbon emissions by in excess of 230,000 t annually.

In Australia, the latest glass waste statistics (Table 6) show that, except for NSW where 100% of glass waste generated in the C&D sector is recycled, other jurisdictions landfill their entire glass waste. However, the recycling rate for all waste streams is significantly higher, reaching 56.7% in Australia, and ranging from 36.7% (NT) to 81.7% (SA). One possible reason for these contradictory trends could be the negligible amount of waste generated during construction and demolition activities making less economic sense for construction firms to send it to recycling facilities. As a result, it seems that reducing waste and focusing on green building/infrastructure schemes can be sustainable solutions. The following is a description of the applications of recycled and upcycled glass waste.

One of the widely approved applications of glass waste-based materials in recent years is in the production of concrete. This application seems to be the most viable option in glass Due to excessive breakage in the collection and sorting, resulting in mixed colour glass cullet, which is unsuitable for recycling into containers. The finely ground (38–45lm) glass powder (GP) with high silica content (SiO_2> 70%), high surface area and amorphous nature suggest that GP could perform as an alternative supplementary cementitious material (ASCM) to replace cement in concrete partially[25].

The other application of glass waste is in building road pavement. The incorporation of glass in asphalt concrete, otherwise commonly known as glasphalt was first introduced into several international markets in the late 1960s[26]. When the glass is properly crushed, this material exhibits a coefficient of permeability similar to coarse sand. Also, the high angularity of this material, compared to rounded sand, may enhance the stability of asphalt mixes. In general, glass is known for its heat retention properties, which can help decrease the depth of frost penetration[6].

A report prepared by GHD[6] listed out the various applications of glass waste in the construction and other industries. These include:

- Aggregate in road base and sub-base
- Aggregate in asphalt, including 'glassphalt'
- Aggregate in tiles
- Aggregate in decorative concrete for architectural facades
- Alternative to mulch
- filtration material
- An alternative to sand in golf courses
- An alternative to fill and bedding material
- Aggregate in concrete and cement

[24] Tam, V.W., 2011. Rate of reusable and recyclable waste in construction. *Open Waste Management Journal*, 4(1), 28-32.

[25] Omran, A.F., Etienne, D., Harbec, D. and Tagnit-Hamou, A., 2017. Long-term performance of glass-powder concrete in large-scale field applications. *Construction and Building Materials*, 135, 43-58.

[26] Mohajerani, A., Vajna, J., Cheung, T.H.H., Kurmus, H., Arulrajah, A. and Horpibulsuk, S., 2017. Practical recycling applications of crushed waste glass in construction materials: A review. *Construction and Building Materials*, 156, 443-467.

Table 12 provides a summary of studies investigating the quality of glass waste recycling and upcycling.

Table 12. Summary of studies investigating the applications of glass waste

	Application	Summary of findings	Reference
Upcycling	Use of glass aggregate as a reflective agricultural mulch	Reflective mulches had an influence on aromatic profiles of the study grapes harvested without altering yield components or traditional harvest parameters. The effect was made through a change in soil and canopy environment conditions.	Mejias Barrera (2012)
	Use of glass cullet as a filter medium for swimming pool water treatment	Results show, that despite larger negative zeta potential of cullet particles, filtration efficiency was comparable and recycled glass can be a useful material for optional filtration medium.	Korkosz et al. (2012)
	Use of recycled glass as a growing medium component for turfgrass in golf course	The results of field experiments showed an equal performance of recycled glass to conventional quarried sand.	Philp (2011)
Recycling	Use of glass powder as a filler material in concrete production	Glass powder (3% passed through a 0.075 mm sieve) achieved the highest stability of the three fillers with an optimum of 7% for all types of filler.	Jony et al. (2011)
	Use of glass powder as a replacement of cement	It is found that glass powder can be used as cement replacement material up to particle size less than 75µm to prevent an alkali-silica reaction.	Vijayakumar et al. (2013)
	Use glass aggregate in road surface production	The test results reveal that glass waste is a viable material for asphalt concrete.	Su and Chen (2002)
	Use of unsorted recycled glass mix to create segmental retaining wall (SRW) brick	The durability of bricks made of optimum glass plastic mixture compared well with that for current SRW bricks in commercial use. The life cycle cost analysis suggested that the cost of manufacturing glass plastic bricks is much cheaper than the SRW bricks. Hence the outcome of this study is the production of a viable, superior and inexpensive SRW brick made from recyclable materials that are sent to landfills.	Meegoda (2011)
	Waste glass in fired clay brick production	Waste glass addition enhances the physical and mechanical properties of fired clay brick.	Phonphuak et al. (2016)
	Waste glass in the production of Gypsum Composites	Analysis comparing composites with glass waste content to reference gypsum showed that it is viable to prepare gypsum composites with the addition of glass waste to reduce water absorption by capillarity, improve mechanical strength, and increase surface hardness. The resultant composites comply with the minimum requirements set by regulations and can be applied in the manufacturing of prefabricated gypsum elements or as interior coatings requiring special surface hardness, improved water behaviour, and mechanical strength properties.	Villoria Sáez et al. (2018)

	Waste glass in the production of ceramic tile	The final products obtained using recycled glasses can be pro-posed in different fields: building materials, artistic ceramics, furniture industry and ceramic tiles. The products are distinguished from those already existing for the highest percentage of recycled glass used and for the versatility of forming shaping processes.	Andreola et al. (2016)
	Waste glass in the foam glass production	Since the glass foams used glass waste as a reactant, the results suggest the development of an alternative route for glass recycling.	Bento et al. (2013)

The use of recycled glass in road applications comes with a risk of leaching contaminants such as heavy metals into the groundwater table[27]. This risk has been proven to be negligible[28] and can meet the requirements of local road authorities and other environmental protection agencies such as EPA Victoria. The main strategies to mitigate environmental concerns are identified[27] to be:

- Application of appropriate design and methodology can mitigate the leaching of contaminants;
- Application of recycled glass in places with a sealed surface, for example, an asphalt paved surface, or in elevated grounds; and
- Appropriate processing of recycled glass prior to application to remove contaminants before they can harm the water table

A case study in the US: Trafalgar Park in Nelson City

The use of recycled glass in the landscape and horticulture industry has achieved some success. The examples of this application are the use of recycled glass as a reflective mulch (Philp, 2011) and growing medium (Table 12). An analysis of a golf course case (Trafalgar Park in Nelson City) upgrade in the US[29] showed that recycled glass aggregates have a satisfactory performance as quarried sand. The project manager of this project reported that the use of recycled glass could save $50,000 to $100,000 USD in production and transport costs than conventional quarried sand.

Figure 5 shows the growth of turf grass on a medium that is comprised of recycled grass in a golf course.

Figure 5. A cross-section showing established grass turf grown on a glass sand medium
Source: Opus International Consultants Ltd

[27] Mohajerani, A., Vajna, J., Cheung, T.H.H., Kurmus, H., Arulrajah, A. and Horpibulsuk, S., 2017. Practical recycling applications of crushed waste glass in construction materials: A review. *Construction and Building Materials*, 156, 443-467.

[28] Disfani, M.M., Arulrajah, A., Bo, M.W. and Sivakugan, N., 2012. Environmental risks of using recycled crushed glass in road applications. *Journal of Cleaner Production*, 20(1), 170-179.

[29] Philp, M., 2011. Spinning Glass into Grass. *Engineering Insight*, 12(4), 19-20.

Case study in Australia: Fletcher Insulation: recycling glass into an insulation[30]

Fletcher Insulation is a manufacturer and supplier of insulation materials for buildings in Australia. They use glass waste stream for the production of glass wool insulation. Up to 74% of the total raw materials input is from waste sources, such as C&D waste, off-cuts from the glass manufacturing industry and bottle glass from the packaging industry and recycling stream.

Fletcher Insulation has been refining their manufacturing process to be able to input as much recycled glass as possible. The production of glass wool insulation relies on a precise mix of inputs to create the correct conditions in the furnace. The formulation of the raw materials is critical and ultimately dictates the proportion of recycled input that the process will tolerate. It is estimated that the glass wool insulation industry in Australia produces 80 kt of insulation per year. Up to 70% of this can be recycled glass and, therefore, the industry has the capacity to recycle over 50kt of glass per year from the C&D waste stream, including bottle glass, scrap car-windscreen glass and glass industry production waste.

The main driver for re-use is economics—using post-consumer waste glass is less expensive than virgin glass material and has the added benefit of reducing the process energy for manufacturing glass wool insulation. The other benefits include social responsibility, the ability to deliver a product to the construction industry that is produced from a high proportion of post-consumer material, and process efficiency: the energy efficiency gained from the use of recycled glass reduces the energy required in the furnace. The production of glass from raw materials requires temperatures of 1600 °C. Cullet melts at 800–900 °C and is, therefore, less energy-intensive to use.

A case study in Australia: Waverley Council: recycled glass in NSW's roads[31]

In 2010, Waverley Council, in partnership with NSW Department of Environment, Climate Change and Water, NSW Roads and Traffic Authority, Institute of Public Works Engineering Australia and the Packaging Stewardship Forum, provided the first site within NSW to demonstrate an alternate use of crushed glass in pavement construction as an accepted product in New South Wales roads. Two 100-metre sections of pavement containing glass product were constructed. The first site at Blair Street, Bondi used glass product in asphalt and the second site at O'Brien Street, Bondi used glass product in concrete pavements. Use of recycled and re-used material Waverley Council substituted 15t of glass cullet into the road projects, 7.5t into the asphalt and 7.5 t into the concrete.

5.9 Illegal dumping and stockpiling

In the case of glass, illegal dumping and stockpiling is quite prevalent in Australia. There is a number of reasons for this trend. The majority of stockpiling occurs in recycling centres where facility owners believe that there is no viable market for recycled glass[32]. The other reason is related to the cost associated with creating glass products in Australia that is currently in favour of import. The local production of glass can absorb a portion of recycled waste. The situation has become tougher for recycling companies who need to deal with EPA regulations restricting large stockpiling one hand and long term contracts with councils to collect glass waste on the other hand.

[30] Edge Environment Pty Ltd. 2011. Construction and demolition waste guide - recycling and re-use across the supply chain.

[31] National Waste Policy. 2011. Case Study: Waverly Council: recycled glass in roads. https://www.environment.gov.au/system/files /pages/9014ac31-f832-48bd-85b9-f02d8ef70fbe/files/waverley-council.pdf

[32] Meldrum-Hanna, C., A. Davies and D. Richards. 2017. Recycling companies stockpiling thousands of tonnes of glass as cheap imports leave market in crisis. ABC News: https://www.abc.net.au/news/2017-08-07/recycling-companies-forced-to-stockpile-glass-industry-crisis/8778088

Figure 6 shows the situation of a recycling company warehouse with a large volume of glass waste being stockpiled. These giant bags of glass waste are regarded as almost worthless sources at the current market conditions. Unfortunately, not all glass waste dumped into recycling companies are stored. As shown in Figure 6, there are instances[32] of stockpiling activities outdoors where there is a risk of leaking into the ground.

Figure 6. Inside a recycling company's warehouse (Plytrade)
Source: Meldrum-Hanna (2017)[32]

In NSW, a report by the federal goverment[31] showed the estimations of glass waste stockpiled in this state. The estimations indicated that 60,000t of glass waste is stockpiled in Sydney. According to a report received by EPA NSW from industry, in 2017, the issue with stockpiling continued to present itself and it allegedly has reached the crisis point[32].

5.10 Landfill the waste

Despite a higher level of recycling of glass waste relative to landfilling in all waste streams, landfilling is prominent in the C&D waste stream. Glass waste landfilling coming from various streams. After recycling (56.7%), it is the major waste fate in all Australian jurisdictions, with a 43.3% ratio. According to the latest available data (2016-17)[15] on the annual volume of glass waste going to landfill (Table 6), 467,256t of glass waste was landfilled; of this figure, C&D waste stream had 1,531t or 32.7%. The average landfilling rate of glass waste in the C&D stream is 82.3%. Except for NSW, which experienced 100% recycling, the total waste generated in the C&D stream in 2016-17 was landfilled in all Australian jurisdictions.

In the same period, the degree of landfilling of all glass waste differed in the eight states and territories. The highest rank of glass waste landfilling is attributed to NT (60.3%), WA (58.3%) and Qld (55.5%). In the C&D sector, only NSW registered recycling activities for C&D based glass waste (Table 6). In NSW, a report, received by local EPA in 2017, revealed that, due to lack of viable market for recycled glass plus increasing freight costs, landfilling has become an attractive option for many regional/rural areas.

6 GLASS WASTE MARKET

The glass waste market is currently not as efficient as it could be due to the several reasons that are reviewed below. An economic analysis of using recycled glass with all the issues attached to it, including contamination and the undesirable marketability of recycled glass, reveals that, at the moment, there is not an economic incentive for recyclers as well as manufacturers. The main reason is the low-cost overseas outsourcing of glass materials. However, with promising results from new initiatives across Australia, it is likely that the current trends in the market will change for the better.

Estimations made in 2011[31] in Sydney indicated that if the concrete industry was to use the crushed glass fines, they would avoid using 75kt of natural sand at $30 per tonne. This would save them $2.25 m. This is a solution that not only provides economic benefits but also contributes to protecting the environment through reduced sand excavation activities. Research in the UK[19] demonstrated that the value of the cullet paid by the float manufacturers indicates sufficient incentive to transport and deconstruct the materials in this way, using unskilled staff in the breakdown operations. In WA, a recent field trial on a 250-metre road (Wanneroo Road, Flynn Drive realignment) with the usage of crushed glass waste[33] provided some insight into the economy of glass waste management. According to the work's contractor, the crushed glass waste used is cheaper than limestone; it uses up to 10% less water in order to achieve the same compaction levels as limestone. In Queensland, it was reported that 80% of recyclables, including glass waste fines, is sent to local processors and glass fines are used in Brisbane's asphalt production[34]. In NSW, in an insulation manufacturing company, up to 70% of the ingredient can be recycled glass using post-consumer waste glass. This material is less expensive than virgin glass material and has the added benefit of reducing the process of energy for manufacturing glass wool insulation[35].

6.1 Existing and future markets for glass waste

The *Handbook on Alternative Uses for Recycled Glass* divided the recycled glass market into two sections: established alternative markets and promising markets for which glass has yet to be fully accepted, or that still require additional study.[36] Under the established categories, the handbook outlined the following applications:

1. **Construction Aggregates**
   - A. Roadway construction
   - B. Paving Applications (Glass in asphalt)
   - C. Bedding & Backfill—(Pipe and utility trenches, retaining walls, foundations, embankments)
   - D. Drainage—(French drains)
   - E. Septic fields
   - F. Landfill cover
   - G. State Specifications and Guidelines

2. **Recycled Aggregate in Concrete**
   - A. Cement/Concrete Applications
   - B. Pavers, blocks, countertops, tiles, etc. a. "Glascrete" b. Binders c. Fused & Kiln Fired Tiles

[33] Bettini, L. 2019. Personal communications with WA's Main Roads.

[34] Environment and Communications References Committee. 2018. Never waste a crisis: the waste and recycling industry in Australia, 81.

[35] Edge Environment Pty Ltd. 2011. Construction and demolition waste guide - recycling and re-use across the supply chain.

[36] Andela, C. and E.V. Sorge. 2005. Handbook of Alternative Uses for Recycled Glass. https://wasteinitiatives.com.au/wp-content/uploads/2017/10/Glass-Uses-Handbook-Complete.pdf

3. **Decorative Landscaping Aggregate**
   A. Decorative coloured glass gravel—(Mulch, footpaths)
   B. Fountain and Aquarium gravel

4. **Abrasives**
   A. Blast media
   B. "Sand" paper
   C. Traction (Non-skid surfaces)
   D. State Specifications for Abrasives

5. **Filtration Media**
   A. Waste Water & Potable Water Treatment Systems
   B. Pool Filtration
   C. State Specifications for Filtration Media

Andela and Sorge (2005) reviewed several research projects to identify the new markets for recycled glass. However, some of these applications, 15 years after the publication of this reference, are already operationalised on a wide scale. Table 13 shows eleven applications for recycled glass in the construction and other industries that were deemed new at the time, including transport, medicine, landscape and horticulture:

Table 13. The future applications of recycled glass

Application	Description
Fillers	For glass to be employed as an industrial filler, it needs to be ground to a consistency of fine powder. At that point, it could be used to replace calcium carbonate in paints, as an additive to plastic lumber and in tyre production to replace a variety of clay fillers.
Hydroponics	In a study conducted by Clean Washington Centre (CWC)[37,38], researchers found no statistical difference between glass-grown basil and control-grown basil employing an expanded clay aggregate as the soil substrate.
Soil amendment	In another CWC study[39], topsoil replacing 60% of the sand with glass cullet produced plants of equal or greater growth size compared with plants grown in standard topsoil.
Foamed glass insulation	An inorganic insulator that does not burn, it has a low heat conductivity, exceptionally high strength, and tends to be water-insoluble and corrosion resistant in most acids[40].
Traction deicer	Michigan Technology University has incorporated glass, limestone waste and food waste into a new product called Trac-Deicer[41]. The mixture of crushed glass and CMA (calcium magnesium citrate) is proving as effective as salt for maintaining winter roads and appears to be much less corrosive on steel and road surfaces.
Glass cable	Replacing steel with glass fibres may extend the life of a typical bridge from 50 years to 200 years. Surprisingly, when woven, glass is stronger than steel[42].

[37] Clean Washington Center Report #GL 96-2, Testing the Use of Glass as a Hydroponic Rooting Medium.

[38] Hydroponics as a Hobby. http://www.ext.vt.edu

[39] Moller K. and Leger, S. 1998. Crushed Glass Cullet Replacement of Sand in Topsoil Mixes. CWC Report #GL97-10, 1998. http://www.cwc.org

[40] Foamed Glass http://www.permonline.ru

[41]Michigan Technology University, Researchers Seek Replacement of Road Salt, Technical Topics: 1997. http://whyfiles.org/shorties/nosalt.html

[42] Glass Bridges http://www.popularmechanics.com/science/transportation

Frictionator	Glass has been found to serve as a "frictionator" for lighting and firing in the production of matches, matchbook striker surfaces and ammunition[43].
Fluxing agent	Glass as a brick fluxing agent, reduces firing temperatures and firing time, leading to an increase in production capacity and reduced fuel consumption[44,45].
Medical uses	Micron-size ground glass serves as a fine abrasive in dentistry. Radiation housed in micro-spheres of glass bead is also being used to fight inoperable liver cancer. The US FDA recently approved glass' use in this application[46].
Insecticide	Terrestrial insects breathe through a complex network of air tubes called Trachea that open to the outside through a series of small, valved apertures (spiracles) along the sides of the body. Operators of fine grind facilities note that insects are seldom seen nearby, suggesting that fine, micron-size glass dust particles may clog the spiracles and cause suffocation.
Adsorbent and cation exchange material	Glass can substitute for zeolites (naturally-occurring compounds used to separate molecules based on differences in size, shape and polarity) or in ion exchange systems like water softeners that swap softer alkaline metals for "hard" calcium.

Source: Andela and Sorge (2005)

6.2 Integrated supply chain and glass lifecycle model

In this section, three specific supply chain models for glass material are presented: WRAP's model, the Scottish supply chain network and Sustainability Victoria's supply chain. Furthermore, the model for the supply chain that is based on the opportunities for minimising glass waste landfilling in this study is also presented.

6.2.1 WRAP's supply chain model[47]

This model, which underpins the Waste and Resources Action Programme (WRAP), a UK environmental agency, is based on the philosophy of the circular economy. It is driven by two sub-streams of glass waste: mixed cullet and clear cullet. The model showcases how glass waste recovery can take place in collaboration between manufacturers, builders and waste recycling facilities.

[43] Secondary Uses of Cullet: Frictionator http://www.gpi.org/cullet.html

[44] Fluxing Agent, Universal Ground Cullet, (216), 267-8057 Http://www.groundcullet.com/htdocs/applications.htm

[45] Fluxing Agent, PA DOT: Recyclable Materials Supply & Demand Workpaper, Alternative Uses. http://www.dep.state.pa.us

[46] University of Missouri-Rolla, Research News, Delbert Day Elected into the National Academy of Engineering for Cancer Research, 2/12/2004. http://www.umr.edu/index.php?id=1586&tt_news

[47] Waste and Resources Action Programme 2008.

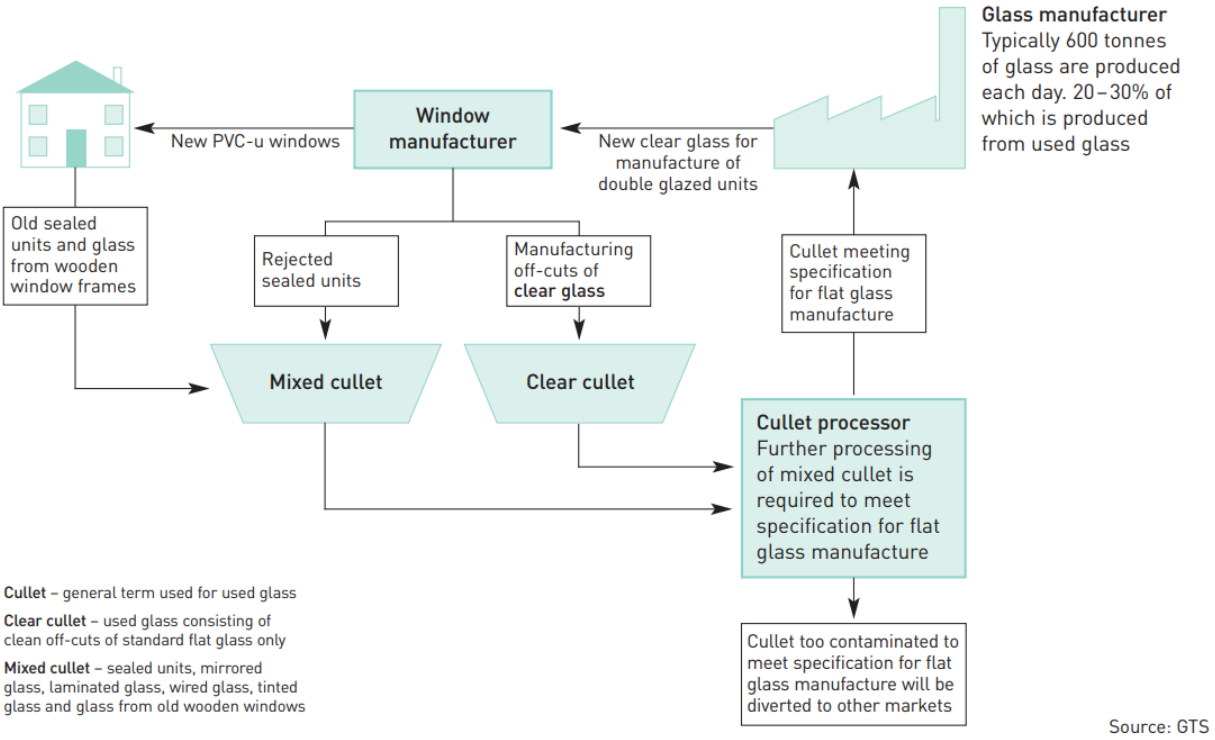

Figure 7. The flow of recovered flat glass for recycling
Source: UK's waste and Resources Action Programme

6.2.2 The Scottish supply chain network

The growth of the construction glass recycling industry requires a new network to develop. In Scotland, such a supply chain network is already naturally growing, which could be duplicated in Australia, creating a sustainable industry that can supply the demand of high-quality glass cullet to the glass float lines across Australia. A simplified model (Figure 8) of this Scottish network is suitable for universal adoption but based on local coordination. The developing network in the central belt of Scotland has several sites, which include building renovation and demolition projects from all sectors. Each of these includes a design team, contractor and client. A small number of collectors are active who are willing to collect and transport the glass units in the order of 80 km to break down the glazing units, removing frames and spacer bars for financial benefit.

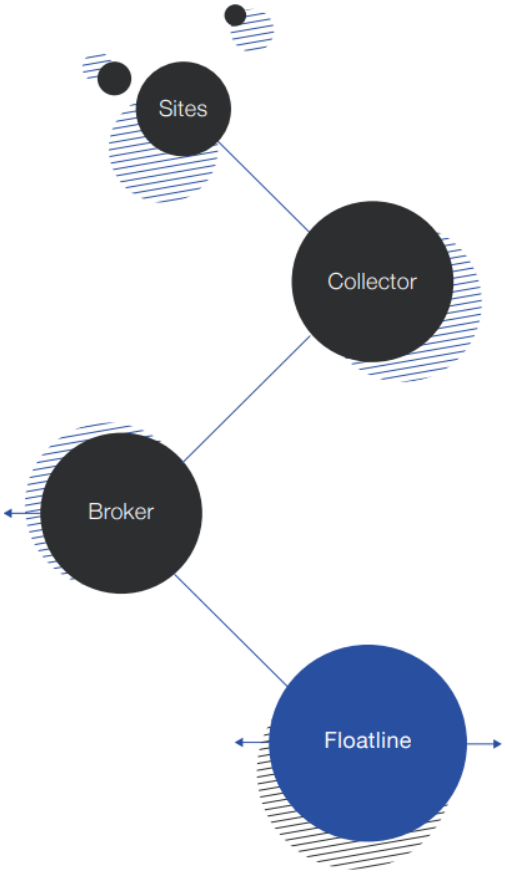

Figure 8. A simplified model of a new glass-recycling supply chain network
Source: DeBrinca and Babic (2013)[19]

A broker coordinates the cullet materials available from a number of small collectors; this broker has connections with the float glass manufacturers and the experience and business acumen to develop this relationship and gain the best financial rewards for larger quantities of high-quality cullet from a number of collectors. The broker can organise, arrange transportation and gain best economies by utilising backhaul opportunities from the float manufacturers glass delivery logistical systems. In the observed model, the transportation distance between the collector and float glass plant is in the order of 200 miles. The transportation distances between main populations and glass-manufacturing plants do not vary significantly across much of the developed world.

6.2.3 Sustainability Victoria's supply chain[48]

In Victoria, the glass waste supply chain is shared between the three main waste streams. Glass collected for recycling primarily comes from food and drink bottles and jars, and includes clear, green and amber glass (Figure 9). glass not suitable for recycling includes cookware glass, light globes, drinking glasses and C&D glass. These types of glass have different melting points compared to food and drink bottles and jars. Plate or window glass may be reprocessed in Australia into the insulation. However, this is not widespread, and a large quantity goes to landfill. Plate glass can also be used as

[48] Sustainability Victoria. 2015. Fact Sheet: Market summary – recycled glass. https://www.sustainability.vic.gov.au/~/media/resources/documents/publications%20and%20research/research/market%20analysis/market%20analysis%20glass%20sept%202014.pdf

aggregate and for blast cleaning. glass is typically sorted from mixed recycled waste at a Material Recovery Facility (MRF) and then further refined (beneficiated) to be suitable for reprocessing.

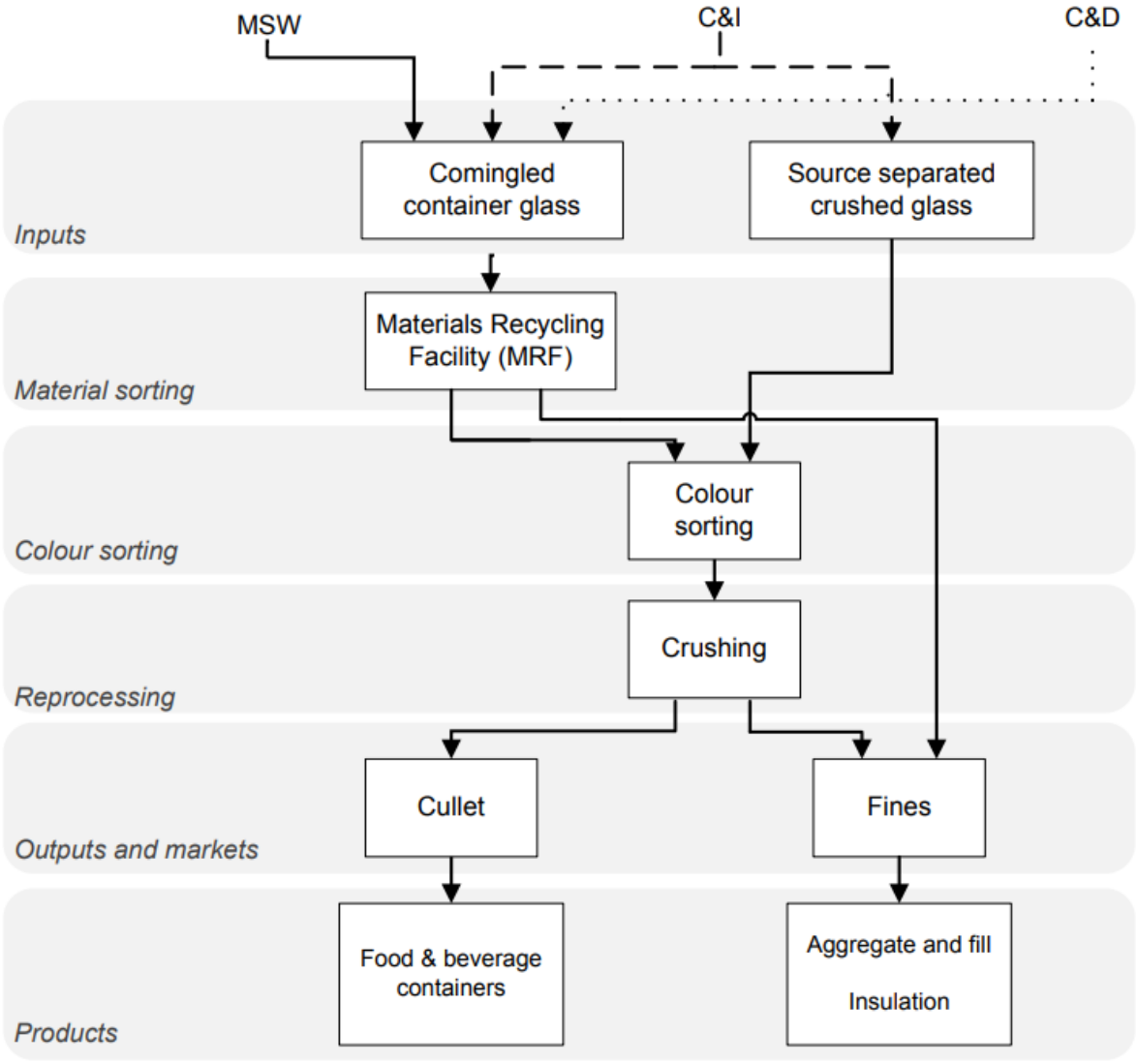

Figure 9. The flow of glass through the recycling chain
Source: Sustainability Victoria (2015)[48]

On-site bottle crushing equipment is used by some businesses in the hospitality sector for onsite bottle crushing, which allows for reduced transportation volumes, improved occupational health and safety standards and higher recycling yields. These machines reduce quantity to at least 80 per cent of the original bottle, but the cullet is still suitable for beneficiation and provides a cleaner stream than MRF recovered glass due to less contamination. Glass bottles and jars are separated by colour either by hand or using automated sorting equipment. glass can now be sorted down to 8 mm for use as cullet and fragments smaller than 8 mm are mixed together to produce glass fines for use in aggregate and abrasives. The colour-sorted glass is transferred to a beneficiation plant where contaminants are removed and glass is crushed to produce cullet, which is sorted by size.

6.2.4 Glass LowMor model

In this model, there are 11 points wherein glass waste can be efficiently managed. Figure 10 depicts these opportunities and the relationships between them.

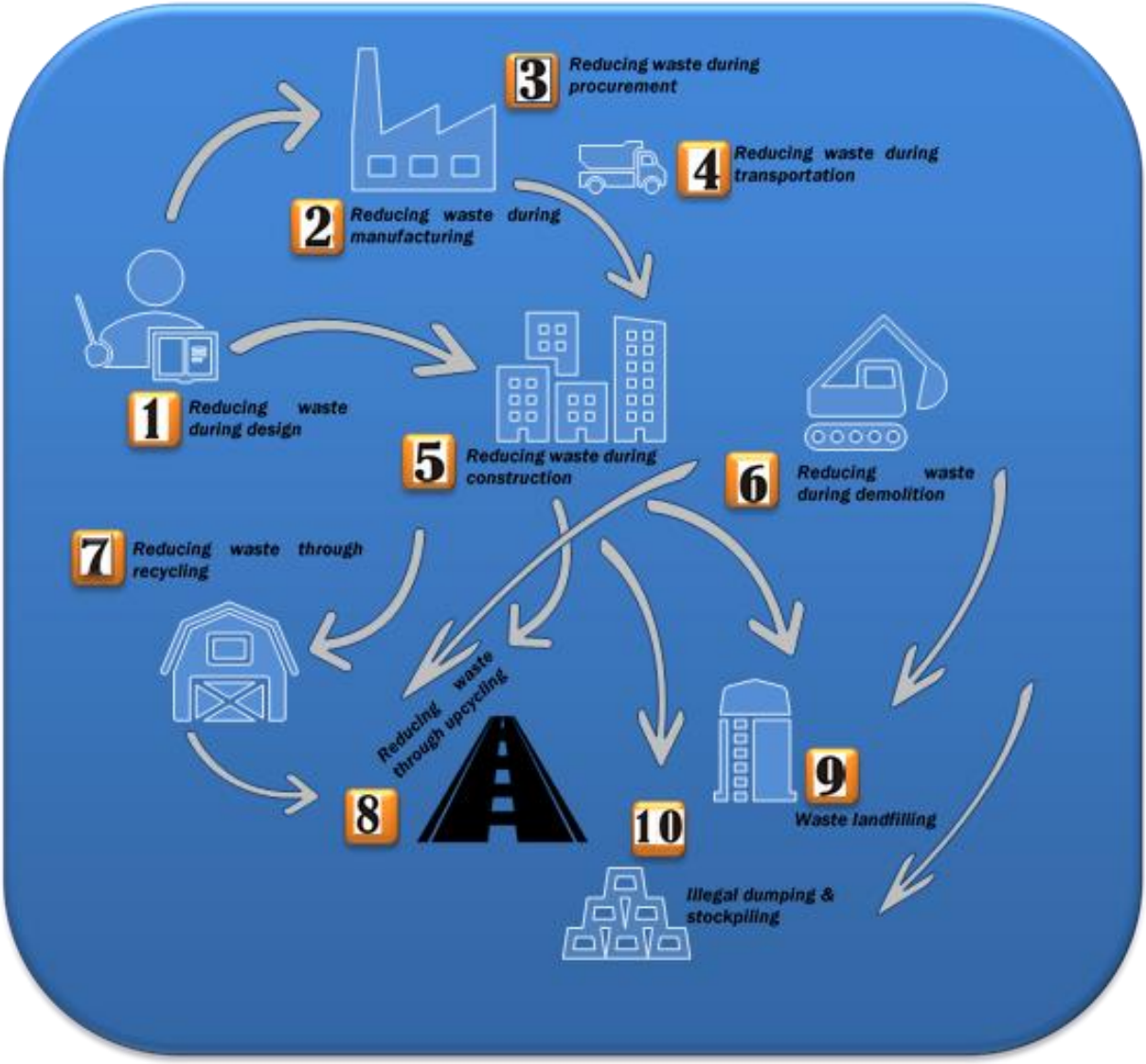

Figure 10. The integrated supply chain lifecycle model for glass waste

6.3 Barriers towards the establishment of a market for glass waste-based materials

The barriers to the effective establishment of a market for glass waste are numerous. Table 14 presents the main barriers that are outlined by a few organisations.

Table 14. Main barriers to market development for C&D based glass waste.

Reference	Strategies to remove barriers to market development for glass waste
ACT NoWaste (2018)[49]	• Low-value economics of recycled glass compared to imported glass, combined with contamination issues and limitations on the market to absorb recycled glass.
GHD (2008)[50]	• Limitations in glass crushing infrastructure, facilities Infrastructure and facilities for glass fines.
National Waste Policy (2014)[31]	• Reluctance by road engineers to move towards recycled glass as an alternative to virgin material in construing asphalt. • Shortage of tradespeople who are able to work with the inconsistencies of reclaimed and recycled materials.
Howling Pixel (2012)[51]	• A typical glass furnace holds hundreds of tonnes of molten glass, and so it is simply not practical to shut it down every night, or in fact in any period short of a month. Factories, therefore, run 24 hours a day 7 days a week. This means that there is little opportunity to either increase or decrease production rates by more than a few per cent. • New furnaces and forming machines cost tens of millions of dollars and require at least 18 months of planning. Given this fact, and the fact that there are usually more products than machine lines, products are sold from stock. • The marketing/production challenge is, therefore, to predict demand both in the short 4- to 12-week term and over the 24- to 48-month-long term. • Despite its positioning as a mature market product, glass does enjoy a high level of consumer acceptance and is perceived as a "premium" quality packaging format.
Sustainability Victoria (2015)[48]	• Markets for glass fines are likely to be characterised by a pattern of inconsistent demand (i.e. transactions will be large but irregular, often as a result of large civil infrastructure projects). • Increasing the production of cullet from glass waste will reduce the availability of glass fines. • Although cullet has higher value than fines, its recovery is likely to be more costly (as the cost of sorting technology, for example, must be considered). • Glass available for recycling currently exceeds the processing capacity of the recycling industry. However, capacity constraints in Victoria cannot be alleviated by exporting glass for reprocessing, as stakeholders note that the cost of transport will make reprocessing uneconomic. • The recycled glass market is typically very strong. However, the volume of reprocessing activity remains sensitive to price. When prices are low, it is common for materials to be stockpiled.

[49] ACT NoWaste. 2018. Waste Feasibility Study Roadmap and Recommendations. Discussion Paper. https://s3.ap-southeast-2.amazonaws.com/hdp.au.prod.app.act-yoursay.files/8615/2575/8129/WFS_roadmap.pdf

[50] GHD. 2008. Packaging Stewardship Forum, Australian Food and Grocery Council. The use of crushed glass as both an Aggregate Substitute in Road Base and in Asphalt in Australia Business Case.

[51] Howling Pixel.2012. Glass production. https://howlingpixel.com/i-en/Glass_production

6.4 Strategies towards the establishment of a market for glass waste-based materials

Together with the responses to the barriers identified above (Table 14), a number of strategies that can facilitate the establishment of a sustainable market for glass waste-based materials are presented in this section (Table 15).

Table 15. Strategies to boost the market for C&D waste materials

Reference	Strategies to remove barriers to market development for glass waste
ACT NoWaste[52]	• Establish Government 'buy-back' schemes for recycled products through procurement commitments, including road bases from crushing of inert waste and glass fines.
National Waste Policy (2014)[31]	• Use the potential of industry associations such as the Institute of Public Works Engineering Australia to create a course to educate road engineers as well as tradespeople in how to use alternative materials in construction projects.
Sustainability Victoria (2015)[39]	• To ensure continued access to high-quality glass cullet feedstock, stakeholders need to shift towards medium- to long-term contracts for supply in order to hedge against price volatility. • The concentration and size of these contracts mean that processor capacity must be adequate to meet both current and future demand.
ARUP (2013)[19]	• As the window frames and glass units need to be removed more carefully than during demolition, they are more likely to be stored separately, which makes it easier to collect the glass without contaminating it at source - a crucial enabler for recycling. • Opportunity and value is increased due to the viability of recycling the uPVC frames and other elements such as aluminium spacer bars from the window units. These replacement works are likely to be undertaken by a specialist window supply and installation company, often directly appointed by the building/homeowners or, for public housing, local authorities. • We have observed in our research a number of window companies actively seeking to improve their recycling process through their own initiatives. This is encouraging and should continue to be promoted. These companies utilise this process as part of their social corporate responsibility and promote their business activities as "green" or "sustainable" to potential customers. • A key driver for this move is growing consumer awareness and desire to buy "green" products and that such activity may win more work. Education of the public to grow awareness of the issues and accessibility to these companies will continue to promote these opportunities. • For public and social housing, legislation should be established that requires the contracts for window replacement to include recycling of all removed materials in closed-loop schemes so that the large opportunities and quantities of potential materials are not overlooked in this sector. Government Buying Standards (GBS) could be more ambitious to encourage further uptake of recycled content entering the supply to glass manufacturers

[52] ACT NoWaste. 2018. Waste Feasibility Study Roadmap and Recommendations. Discussion Paper. https://s3.ap-southeast-2.amazonaws.com/hdp.au.prod.app.act-yoursay.files/8615/2575/8129/WFS_roadmap.pdf

6.5 Economics of glass waste recovery in Australia

According to Sustainability Victoria[48], the average cost of collection, transport and recovery of C&I and MSW materials is in the region of $110 and $124 per tonne respectively. The price paid to reprocessors ranges between $0 to $49 per tonne. The market value of recycled glass product is not clear, as there is limited information available. Estimates are in the range of glass cullet: $100 and $149 per tonne delivered and glass fines: $0 to $49 per tonne delivered.

In the C&D waste sector, for either renovation or demolition activities, the glass is required to be deglazed from the framing system. Depending on the framing system employed, this may be undertaken on-site, such that only the glazing units are removed, for example in the refurbishment of curtain wall systems. Alternatively, the frame and glazing is removed in one unit, which may be appropriate for a residential window, and deglazing undertaken at ground level or in a factory environment. The costs associated with these activities will be project-specific and need to be considered when specifying glass recycling on a project[11]. The demolition or façade contractors would provide a price for undertaking these works as part of a tender process. The following table (Table 16) shows the costs associated with C&D based glass waste management and recovery.

Table 16. Cost estimation of C&D-based glass waste management and recovery

Company	Pricing mechanism	Waste fate
Bingo	$600 including dropping, renting and picking up a skip bin with a capacity of 6 tonnes of glass waste in Vic $150/tonnes to accept the waste at the facility	The acceptable waste is recycled, and the rest is sent to landfill

6.6 Relevant industry associations

In this section, the relevant industry associations that specifically work towards better management of glass and the waste associated with glass waste are identified. These associations are to collaborate with the public sector towards recognising opportunities for further reducing, reusing and recycling glass waste in Australia. Table 17 summarises the main industry associations with a focus on glass waste in Australia.

Table 17. Industry associations relevant to the management of glass waste

Associations	Vision	Website
The Australian Glass and Window Association (AGWA)	AGWA is the peak association representing over 1000 member companies covering window manufacturers, glass manufacturers, glass processors, merchants, glaziers and suppliers of supporting machinery, services and materials. We endorse compliant, sustainable and fit-for-purpose products and provide services to members that support their efforts to operate successfully.	https://www.agwa.com.au/
The Australian Glass & Glazing Association (AGGA)	AGGA is a peak industry body that brings together over 600 manufacturers, importers, processors, installers, glaziers and suppliers to the building and window industry, and promotes and encourages the trade and business interests of its members.	https://www.agwa.com.au/

Auto Glass Association (AGA)	AGA was formed in 2013 to give all sides of the automotive glass industry a unified voice, becoming a central conduit for communication, training and representation operating in the interest of the industry as a whole.	https://www.autoglass.org.au/The-AGA
O-I Australia	O-I Australia has four manufacturing plants, located in Brisbane, Sydney, Melbourne and Adelaide. They have a diverse product range, making glass packaging for Australia's world-renowned beverage and food brands.	https://recycleglass.com.au/
The Institute of Public Works Engineering Australasia (IPWEA)	IPWEA is the peak association for the professionals who deliver public works and engineering services to communities in Australia and New Zealand. IPWEA provides services to its members and advocacy on their behalf.	https://www.ipwea.org/about-ipwea/aboutipwea

6.7 Key stakeholder and their role in glass waste management

In this section, the role of the key stakeholders in effective market development for glass waste is provided (**Error! Reference source not found.**). The role of the stakeholders is reviewed in eleven stages with the view to reducing, recovering and diverting waste from landfilling.

Table 18. Role of various stakeholders in the reduction of glass waste

No.	Stage	Stakeholder(s)	Contributions
1	Design	Designers, construction firms, clients	• Design a new building to facilitate its re-use in the future • Consider building standardisation to improve buildability and reduce the number of off-cuts
2	Manufacturer	Manufacturers, recyclers, suppliers	• Develop an agreement where a contractor "sells back" the recycled waste from the original material supplier • Participate in the extended producer responsibility and product stewardship schemes
3	Procurement and contract	Construction firms, quantity surveyors, government	• Construction firms should order glass products more accurately using the best take-off practice. • Use other materials in substitute of glass;
4	Transportation & delivery	Construction firms, transporters, recycling companies	• Just-in-time delivery of materials to construction to avoid damage taking place due to insufficient space for proper storage and adverse weather conditions • Do due diligence and exercise standard work practices
5	Construction	Construction firms, sub-contractors, waste collectors, recyclers Universities and research centres	• Research and develop specifications for further testing to increase acceptance of the crushed glass product • Remove window frames and glass units separately in and more carefully to avoid contamination in renovation projects to encourage recycling

6	Demolition	Demolition contractors, waste collectors, recyclers	• Consider selective de-construction to maximising the reuse potential of its components
7	Reusing	Construction firms, state and territory governments, EPAs and other equivalent organisations, waste collectors	• Facilitate market development • Adjust specifications in favour of more usage of glass waste-based materials in new constructions projects
8	Recycling	Recyclers, construction firms, state and territory governments, EPAs and other equivalent organisations Training courses	• Facilitate market development • Fund the development of waste recovery infrastructure • Adjust specifications in favour of more usage of recycled glass waste in new constructions projects • The jurisdictional landfill levy regulations need to change in favour of glass recycling • Create a course to educate road engineers on how to use alternative materials in construction projects • Promote the usage of crushed glass in road projects such as asphalt and road base and subbase • Improve the purity of cullet and prevent colour contamination to increase the value and recyclability of cullet
9	Upcycling	Recyclers, construction firms, state and territory governments, EPAs and other equivalent organisations	• Facilitate market development • Adjust specifications in favour of more usage of glass waste-based materials in new constructions project • Facilitate market development • Fund the development of waste recovery infrastructure
10	Stopping illegal dumping and stockpiling	State and territory governments, EPAs and other equivalent organisations	• Reinforce activities that stop illegal dumping and stockpiling • Set stricter regulations with a higher rate of penalty fees to discourage illegal dumping and stockpiling • Strengthen controls over licensed landfill sites
11	Landfill	State and territory governments, EPAs and other equivalent organisations	• Design appropriate landfill levy schemes to discourage glass waste landfilling

7 RECOMMENDATIONS

The following are the recommendations to maximise the opportunities for reducing glass waste in various stages of construction and demolition activities.

1. Promote the use of glass aggregate in asphalt;
2. Change jurisdictional landfill levy regulations in favour of glass recycling;
3. Design a partial levy exemption for residual waste in the recycling industry;
4. Conduct more research projects to establish new applications for glass waste such as used in the landscape industry;
5. Grow consumer awareness and desire to buy “green” products—such activity may win more work;
6. Establish legislation for public and social housing that requires the contracts for window replacement to include recycling of all removed materials in closed-loop schemes so that the significant opportunities and quantities of potential materials are not overlooked in this sector; and
7. Improve the purity of cullet and prevent colour contamination to increase the value and recyclability of cullet.

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