Sustainable Communities and Waste

National Environmental Science Program

Current and Emerging Technological Recycling Solutions for Circular Economies in Regional and Remote Communities

IP2.02.02 Finding Fit for Purpose Technological Recycling Solutions for Regional and Remote Communities

UNSW Sydney · CSIRO · Monash University · Curtin University · University of Tasmania

Current and Emerging Technological Recycling Solutions for Circular Economies in Regional and Remote Communities

Revision 2.2

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The Sustainable Communities and Waste Hub acknowledges all Aboriginal and Torres Strait Islander Traditional Custodians of Country and recognises their continuing connection to land, sea, culture, and community. We pay our respects to Elders past, present, and emerging. We support Aboriginal and Torres Strait Islander peoples and their aspirations to maintain, protect and manage their culture, language, land and sea Country and heritage.

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Glossary of Terms

Term	Definition
SCaW Hub	Sustainable Communities and Waste Hub
NESP	National Environmental Science Program
UNSW	University of New South Wales
IP2	Impact priority 2
OECD	Organisation for Economic Co-operation and Development
ASGS	Australian Statistical Geography Standard
MRFs	Material Recovery Facilities
DCCEEW	Department of Climate Change, Energy, the Environment and Water
ISO	International Organisation for Standardisation
KPI	Key Performance Indicators
FAIR	Findable, Accessible, Interoperable, Reusable
ISO/TR	International Organisation for Standardisation \ Technical Reports
MSW	Municipal Solid Waste
C&D Waste	Construction and Demolition Waste
MRFs	Materials Recovery Facilities
IoT	Internet-of-Things
ACCC	Australian Competition and Consumer Commission
FOGO	Food Organics, Garden Organics
BIM	Building Information Modelling
2D	Two dimensional
3D	Three Dimensional
NIR	Near-infrared
LIBS	Laser-induced breakdown spectroscopy
PPL	Paper-Plastic Laminates
PET	Polyethylene terephthalate
PPE	Personal Protective Equipment
SMaRT Centre	Sustainable Material Research and Technology Centre

Introduction

This report aimed to provide accessible information regarding current and emerging technology that could enable a transition to a circular economy, particularly for "closing the loop" of end-of-life items in regional and remote communities. The Blue Environment report, Regional and Remote Australia Working Group and the Department of Climate Change, Energy, the Environment and Water (DCCEEW) have highlighted the lack of understandable or accessible expertise on science and technology solutions required to make well informed decisions by those working in the circular economy, including Site Managers, Sustainability Operations Coordinators and Environmental Officers. The technology in this report were categorised according to the key steps involved in creating a circular flow of resources.

This report built upon the previously published IP2 report by providing a comprehensive review of currently available technology as well as considering emerging technology relevant to regional and remote cases. While the previous report primarily focused on pre-processing technologies commonly used in Material Recovery Facilities (MRFs), the scope was expanded to include other steps involved in creating a circular flow of resources, from waste collection to recycling and remanufacturing. Additionally, the previous report discussed criteria for selecting technologies. This was not continued here as it was expected that through further co-design with project stakeholders, a more tailored evaluation tool would be developed.

This report was produced with funding from the National Environmental Science Program's Sustainable Communities and Waste Hub.

The Sustainable Communities and Waste Hub

The Sustainable Communities and Waste (SCaW) Hub was part of the Australian Government's National Environmental Science Program (NESP). NESP partnered scientists with Traditional Owners, government, community and industry to design projects for environment and climate research. It funded this research through four hubs, that being the SCaW Hub, Resilient Landscapes Hub, Marine and Coastal Hub, and Climate Systems Hub.

The SCaW Hub was hosted by the University of New South Wales (UNSW) and had 5 Impact Priority focused research areas. This report was an output of Impact Priority 2 (IP2) – Reduced impact of plastics and other materials as part of a project for finding "fit-for-purpose" technological recycling solutions for regional and remote communities.

In a media release in August of 2024 by the Minister for the Environment and Water, the government announced a new inquiry being led by the Productivity Commission to explore sustainable solutions that would help cut the amount of waste going to landfill and encourage more efficient use of virgin materials – boosting circularity in the Australian economy. In this release it was said, “Australia has the third highest material footprint per capita in the OECD,” and that, “The transition to a circular economy clearly requires economy wide changes, with innovative thinking and reforms from government and businesses.”

In 2022, 28 percent of Australia’s population lived in areas classified as regional or remote based on the 2021 Australian Statistical Geography Standard (ASGS) Remoteness Structure (Australian Institute of Health and Welfare, 2024). However, as demonstrated in Figure 1, the regional and remote population was spread over an incredibly wide and diverse area. More information on the remoteness classifications used in Australia can be found in a separate factsheet.

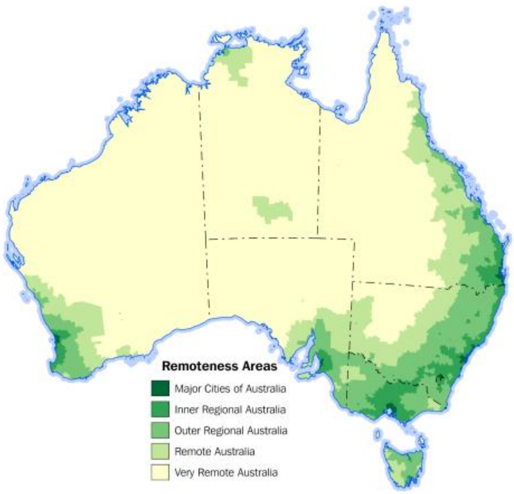

Figure 1. Map of the ASGS Remoteness Areas

With such a large area, each community faced unique challenges compared to major cities when it came to resource recovery and recycling. For example, waste transportation was a much more significant cost factor than in urban areas, a challenge compounded by sudden and destructive weather events, damaged roads and low overall resource recovery rates leading to low return on investment (Blue Environment, 2022). A report summarising regional and remote case studies explained that to overcome these challenges, regional and remote communities required tailored solutions to meet their circumstances (Regional and Remote Australia Working Group, 2013).

Methodology

In 2022, NESP started working with the Department of Agriculture, Water and the Environment to create a framework that captured the complexity of Circular Economy principles and identified gaps in knowledge regarding a transition to a circular economy for regional and remote communities. This began with a focus on the infrastructure for collection and processing waste streams like plastic, paper, mattresses and solar panels and identified specific concerns for waste management in regional and remote communities. It was recognised that there was a lack of clarity in the nuance and language used to describe the different stages in the material and technology cycle for a circular economy.

Through further industry and stakeholder engagement with organisations like Shoalhaven City Council, a framework was co-designed which portrayed the stages involved in closing the loop for end-of-life materials. In a workshop held in Dubbo in August 2024, a diagram of this framework formed the basis of an activity designed to allow engagement with the concepts of circular economy and identify opportunities to solve waste problems while creating value from items that would otherwise be destined for landfill. Feedback from this workshop, and other recent events, was used to make iterations to the framework which improved clarity and highlighted the different roles there are to facilitate a shift from linear to circular economy.

The framework itself focussed on the flow of physical materials within a circular economy and did not include sustainability steps in the waste hierarchy such as refuse or reduce. Finding technology-based solutions that engaged with how a user chose to use or not use items was considered beyond the scope of the current project as the goal was to target materials that had already entered the economy. The framework will continue to be co-designed and be presented in a future report.

Whilst the framework for this project was still under development, it helped in forming a structure for this report using certain terminology and their definitions as different steps in a circular economy. For each step, a general description was provided, drawing from the family of circular economy standards (ISO 59000). Material-specific processes were highlighted as different material properties would determine the selection of the most fit-for-purpose technology. The material categories chosen for this report aligned with the National Waste Report with tyres being included as its own category. Lastly, emerging technologies were listed with a brief explanation of their function and potential use.

The roadmap was developed through a combination of desktop-based research and through workshops and meetings with SCaW hub stakeholders. Whilst the desktop research was fundamental to discovering different technologies and finding definitions, it was equally critical to talk with the local communities, governments and industries to understand their unique challenges as regional and remote communities. It was also important to see how different groups had successfully engaged with the circular economy and what value potential research users could gain from reading this report.

In presenting different technologies, both established and emerging, the SCaW Hub did not aim to endorse specific brands or systems. What has been presented was a systematic list of technologies that may allow communities of any size to engage with the circular economy, with the hope that the users of this research may draw their own conclusions as to which technology avenue to invest into and to what scale. The SCaW hub and UNSW SMaRT Centre has not received any funding or specific directives for the promotion of any specific equipment or services.

It should also be noted that whilst many of the technologies discussed in this report could address some of the unique challenges of different regional remote communities, a more in-depth analysis of specific challenges and technological solutions will be conducted in future reporting as it was considered out of scope for this report. It was intended that the work on fit-for-purpose technologies would build on the circular economy foundations established in this and previous reports to provide context and broader insights for the research users.

ISO standards for circular economy

In May 2024, the International Organisation for Standardisation (ISO) released the IS0 59000 family of standards "designed to harmonise the understanding of the circular economy and to support its implementation and measurement".

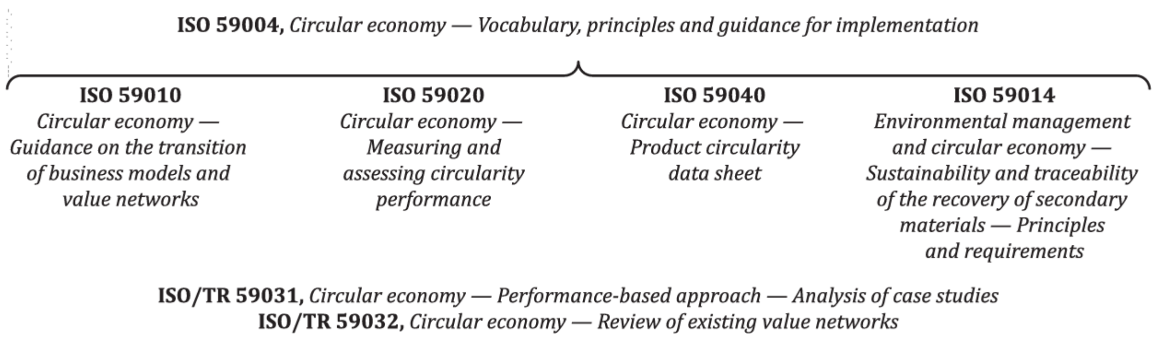

Figure 2. Structure of ISO 59000 family of standards

The standards could be summarised as follows:

- **ISO 59004** defined the vocabulary of circular economy, its principles and general guidance on how these principles could be implemented. This vocabulary formed the foundation for the entire family of standards.
- **ISO 59010** provided more business-oriented guidance on the transition from a linear to a circular economy. These businesses could be in the public or private sectors, with methods of assessing and enhancing their waste management processes.

- **ISO 59020** provided a structured approach in measuring and assessing circularity, performance and sustainability impacts. This included how to report on waste management activities and outcomes, how to engage with multiple stakeholders to plan and execute waste management initiatives and what key performance indicators (KPIs) to use to track progress and identify areas for improvement.
- **ISO 59040** included key considerations on the environmental, social and economic impacts when implementing waste management practices, aligning good practices with global sustainability objectives.
- **ISO 59014** presented guidelines for quantifying and reporting on waste generation and waste management. Data collection was considered key to a successful and sustainable waste management system and the standard provided advice on how to follow the FAIR data principles (Findable, Accessible, Interoperable, Reusable).
- **ISO/TR 59031** was still under development at the time of writing this report.
- **ISO/TR 59032** was a technical report highlighting the importance of transitioning from Value chains to Value networks, where manufacturers, wholesalers, collection services, recyclers etc each cooperated with one another as a network rather than just their immediate supplier and customer.

As was noted in the gaps identified through industry and stakeholder engagement, the vocabulary and understanding of the circular economy stages had yet to be standardised across the industry. With the introduction of the new family of circular economy standards, a defined vocabulary provided a clearer ‘voice’ to each stage of the process. Through the initial framework developed during the Dubbo workshop and this report, the ISO standards have been fundamental to providing the required definitions and framework of thinking to build a deeper analysis of the current circular economy landscape and available technologies.

The standards may also be beneficial for transitioning from economies of scale to economies of purpose using local supply chains through the provision of guidelines and frameworks that can improve existing processes across industry and government.

Important definitions from the ISO standards included:

Circular economy – economic system that uses a system approach to maintain a circular flow of resources by recovering, retaining or adding to their value while contributing to sustainable development.

Virgin resource – natural resource, or energy that is used as a resource, for the first time as input in a process or for creating a solution.

Waste – resource that is no longer considered to be an asset as it, at the time, provides insufficient value to the holder.

Reverse Logistics – process of managing, collecting and moving products from their current location after end of use for the purpose of recovering or retaining value through proper handling.

Material recovery – method of recapturing or reutilising recoverable resources specifically for re-use, refurbishing, remanufacturing, recycling or other methods that add or retain value of a resource.

Energy recovery – generation of useful energy through direct and controlled transformation of recovered resources.

Recycling – activities to obtain recovered resources for use in a process or product, excluding energy recovery.

Remanufacturing – industrial process by which an item is returned to a like-new condition from both a quality and performance perspective.

Cascade – Shift recovered materials from one loop to another to optimise feedstock flows through additional cycles.

Re-mine – Mining or extraction from landfills and waste plants can be possible in some cases if mining or extraction activities are sustainably managed.

Technical cycle – cycle(s) within the social system through which resources are used, recovered, restored and utilised within existing or new structures.

Biological cycle – cycles(s) through which biological nutrients are utilised by living organisms and subsequently restored into or within the biosphere in a way that rebuilds ecosystem resilience and natural capital and enables the regrowth of renewable resources.

Technology Forecast

1. Reverse Logistics

The definition for Reverse Logistics in ISO 59004 was an important distinction to waste management in that it implied an intent to keep the materials in use and divert from landfill. The role of waste management therefore was to minimise adverse impacts of residual waste on human health and the environment. The technology used in Reverse Logistics was further categorised into the roles of ‘Collection and Transport’ and ‘Storage’. The collection phase began with the methods that allowed the user to dispose of items in a manner that created a stream for material recovery. Material segregation at the disposal point could create waste streams that could be more efficiently processed. This waste stream was then transported to be further sorted, processed or safely stored until ready for recovery processes.

Storing waste material was challenging as improper storage could result in environmental damage from contamination of ground water, potential fire risks from exceeding waste pile limits, incur fines from environmental protection groups or socio-economic and health implications for local communities (Pilipenets, et al., 2024). Waste collection and waste storage became closely related as proper storage management and compactors helped to minimise the footprint of the stored waste whilst regular collection ensured that the waste was not stored for long in any one location. Pilipenets et al. highlighted that safe storage of waste depended on the storage being short-term to prevent leakage of potentially hazardous and toxic materials and stockpiling inefficiencies. Thus, technologies for monitoring how much waste was present and reducing the footprint of the waste become critical, especially when coupled with effective management procedures to ensure material was stored and transported in a timely manner.

Throughout the different steps in the circular material flow, there were technologies which were not directly involved in the processing stages but contributed to the overall quality of the product, efficiency of the process or improvement in aspects of safety. As such, these technologies have been included in a separate category ‘Product Improvement and Safety’.

1.1 Collection and Transport

General

Stationary container

Stationary container collection units were those that remained at the site of storage and were periodically collected by transferring into a collection vehicle. A common example of this was the wheelie bins used for kerbside collection of Municipal Solid Waste (MSW). Whilst it may seem trivial to discuss the humble wheelie bin, new technologies in how we collect waste may result in cleaner streams of waste or bring awareness to communities about how waste can be properly disposed and handled. It was often a challenge to balance the separation of waste streams with minimising the logistics and impact of having many different bins at a single location. Moreover, improvements have been made to the sustainability of these containers with a South Australian trial achieving 100% recycled content in their Mobile Garbage Bins (Green Industries SA).

One method was to use multiple similar containers placed together with variations in colour or shape to encourage the separation of material types at the point of disposal. The container volume and frequency of collection was chosen depending on the predicted volume of waste to be generated. The benefit of this method was that it allowed efficient, predictable collection for continuous waste streams and a relatively simple pre-sorting stage which could reduce comingling and contamination.

Figure 3 - Waste diversion products (Source Separation Systems)

Hauled container

Hauled container collection systems used larger volume bins temporarily placed at the site of disposal where they were later collected and transported with its contents. A common example was the skip bins used in the collection of construction and demolition waste (C&D waste), as this method was more suitable for bulky, heavy and high-volume waste items. These containers varied in design depending on the vehicle used for collection, such as hook bins or roll-off containers, and could also be incorporated into the collection vehicle itself.

In other cases, compactor bins have been deployed to reduce the frequency of collection by increasing how much waste could be store. Compactor bins were typically a type of hauled container fitted with a strong mechanism that could compress the waste within the vessel.

Drop-off site

Drop-off sites have been useful when the waste type was too bulky or hazardous for typical collection methods. Users could dispose of end-of-life items at a location or facility which could group similar items (e.g. batteries, automotive parts, appliances, etc.) to be collected as required. Key benefits included the collection of seasonal waste streams, improved material segregation, safe disposal systems for the community and minimising illegal dumping (Gallardo, et al., 2017) (Miftahadi, et al., 2024).

Reverse vending machines have seen growing success as automated drop-off sites for specific consumer waste types. These systems often used rebate schemes, such as the Container Deposit Scheme, to encourage the disposal of specific items (usually packaging waste such as beverage containers) at a central location. By using sensors and automation, these systems ensured that higher quality materials were accepted thus reducing the need for pre-sorting at Materials Recovery Facilities (MRFs).

Figure 4 – ‘Return and Earn’ point in NSW (TOMRA)

Due to the technologies employed to enable automated operation, remote monitoring, localised compacting and material segregation, these deposit schemes have been able to create a network of small-scale drop-off points to maximise convenience and efficiency. This in turn has led to an increase in recycling and waste diversion by managing the streams of waste and providing a reward for people who make the effort to recycle (Return and Earn, 2023).

Collection vehicle

Collection services filled in the gap where drop-off points were not practical or suitable, providing on demand collection for specific waste types from homes or businesses. These services were crucial for businesses who could not invest in technologies for collecting and transporting large volumes of their waste but still wished to avoid landfilling. Common services include tyre collection or textile collection, where the collection service provides a more direct link to the recycler or the waste management facilities.

Similarly, waste collection vehicles would transport waste as a service from the point of disposal, or storage, to the point of processing. These vehicles usually have a large vessel with a mechanical device that quickly emptied waste containers without requiring much physical labour. They often have compaction technology to increase efficiency and enable long collection routes. These vehicles enable the logistics of taking waste materials from many different sources to a facility where they could be processed at scale.

Figure 5 - Waste collection vehicle *(Veolia)*

Emerging technology

A clear challenge was in maintaining uncontaminated streams of waste when storing or collecting as it was far simpler to have a single stream where one container held all different kinds of waste mixed together. However, by using the same techniques of smaller, stationary container collection units, some industries have employed multiple skip bins, colour coding and on-site training to improve waste segregation at the source to improve material recovery rates (Sertyesilisik, et al., 2012).

Figure 6 – Colour Coded and Marked Skip bins and 660 L Bins for on-site waste segregation (Revert Group)

A technological improvement in waste disposal has been in equipping bins with sensors which measured the fill level of waste containers and delivered the data to waste management or reverse logistics companies. Using Internet-of-Things (IoT) technologies, these industries could monitor their bins, prevent overflows, plan efficient collection routines and forecast future waste generation whilst reducing costs and littering (Ali, et al., 2020). Ultrasonic sensors were often used in these application as they were low cost, reliable and readily available for fitting onto new or existing systems. An increasing number of bins have also been manufactured out of recycled or recyclable content, with the uptake of recycled plastics and metals.

Collection services have begun to access the growing alternative-fuel vehicle market, whether it be electric, renewable diesel or hydrogen (Cleanaway, 2024). Electric and hydrogen have seen added benefits of lower noise pollution and zero carbon emissions. Whilst applications requiring smaller vehicles have seen wider adoption for basic utility and cleaning, trials have begun with utilising electric waste collection trucks as a replacement for the typical diesel-powered vehicles, such as in the regional state of Shepparton, Victoria (ABC News, 2024).

Figure 7. Electric Garbage truck trialled in regional Victoria

1.2 Storage

General

Baler

Balers were commonly used machines which compacted waste into a standardised shape (e.g. cube) to be more efficiently stored and transported. Sometimes mixed waste was baled together but the value of the baled units became limited. Sorted and baled waste could often be fed straight into a material-specific process increasing efficiencies and the value of the product being supplied. Balers could have variations depending on the main material it was used for. There were two main types of balers; vertical and horizontal. Vertical balers compress downwards and were usually loaded and operated manually, typically taking up a small footprint. Horizontal balers could be automated or semi-automated and enabled continuous baling for faster and more efficient processes.

For some materials, particularly harder metal products, a specialised crusher was required as they could exert more force than standard crushers and balers. Similarly, bailers for tyre waste were often much larger to accommodate the volume of tyres and could exert the force required to crush the stiffer material. Thus, the selection of bailers and compactors was partially dependent on the material and flow of material in the facility to determine the required forces and volumes.

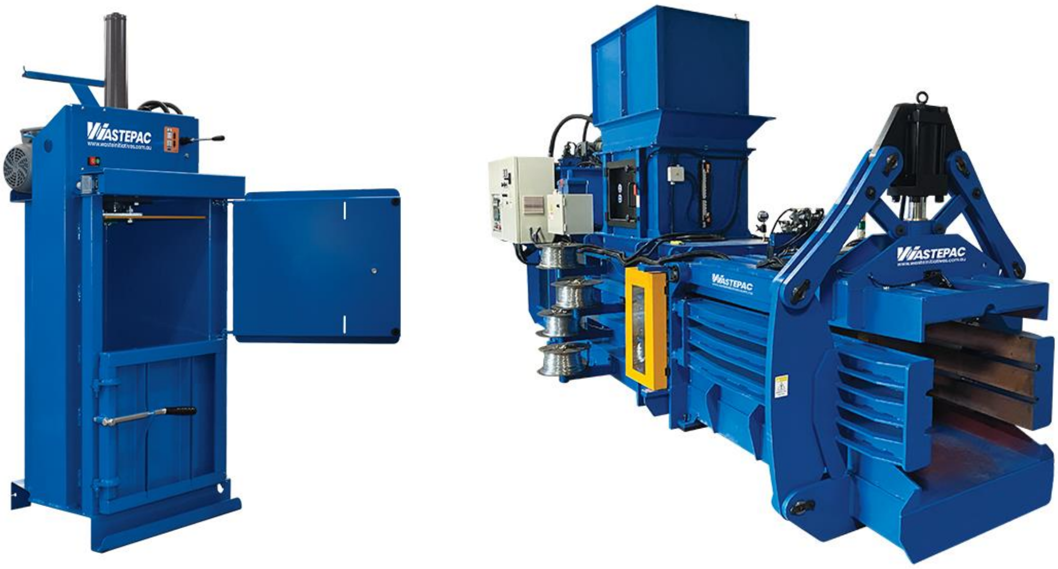

Figure 8 - Vertical baler (left) and horizontal baler (right) (Waste Initiatives)

Figure 9 – Material-specific balers: Metal drum baler (left), tyre baler (right) (Gradeall International Ltd)

Tyres

Tyre racks were uniform, stackable racks that could efficiently pack tyres for storage or within transport vehicles while limiting fire risks. Rubber tyres when alight were extremely difficult to extinguish and so facilities that have bulk tyre storage must follow Fire & Rescue NSW Fire Safety Guidelines. Furthermore, facilities with 500 tyres (or 5 tonnes) may need an Environment Protection License (NSW EPA, 2023).

Building and demolition materials

Compactors could also be fit onto existing storage systems to further maximise the capacities of the units and minimise the number of trips to collect the waste. These technologies may be a suitable solution for smaller sites with limited space for dedicated compaction units, construction sites collecting bulky waste materials or waste handlers with existing storage units looking to improve their current systems.

Product improvement and safety

General

Bin tipper

Bin tippers were mechanical devices used to empty smaller bins (e.g. wheelie bins) into larger bins eliminating several safety risks such as pinch points, debris exposure or injury while lifting.

Figure 10 - Bin compactors: Construction and demolition waste (left) (Bin Masters), Commercial waste (right)

Fire suppression

The storage and transportation of waste can introduce fire risks. Fire suppression technologies have been incorporated in some facilities to limit these risks. For example, FireRover used thermal cameras to detect temperature changes, and an automatic system to apply a biodegradable fire retardant. This technology will especially benefit facilities storing lithium batteries as they were a growing fire hazard as more and more technology became portable with integrated batteries. In 2023 alone, 272 lithium-ion battery-related fires were recorded, the equivalent of 5.2 incidents a week (Fire and Rescue NSW, 2024).

Storage of lithium-ion batteries was its own complex topic, as fires could spontaneously occur when the battery was compact, exposed to heat or moisture, punctured or otherwise abused (ACCC, 2023).The fires themselves were often intense and self-fuelling due to the chemicals present inside the battery. The Australian Competition and Consumer Commission (ACCC) noted that regulations were fragmented across different states, often focussing on appropriate warning labels and safe storage of devices containing lithium-ion batteries but not safe storage of the battery upon disposal for recycling. To improve the storage of used batteries, companies have developed storage systems that applied fire suppressing materials and specific packaging to protect the batteries from external forces.

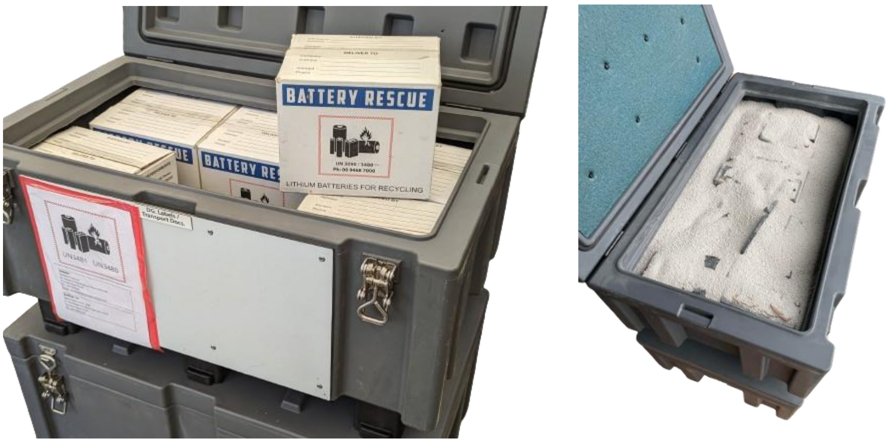

Figure 11. Lithium Battery Storage Box with labelled packaging and fire supressing granules (Uniseg)

Organics

Organic waste can leach substances which can be harmful to human health and the environment. The use of sealed containers during transportation and disposing the waste in bio-degradable or compostable bags can help contain the leachate. Odour control and biofilter technologies will be covered in later steps.

Signage and educational resources were also critical technologies in communicating the importance of waste segregations and encouraging community engagement with the circular economy. Randwick City Council reported that almost 40% of general waste produced was food (Randwick City Council, 2024). Promoting the separation of food waste and other organics from general waste increased Food Organics, Garden Organics (FOGO) recycling and prevented the production of methane in landfills as the waste decomposed. Therefore, as councils introduced more FOGO collection services, educational resources and instructions on what could be disposed led to increased recycling rates, reduced contamination and lower landfill emissions (Sandi, et al., 2024).

Emerging technology

Building Information Modelling (BIM) was an emerging software which was being incorporated in the planning and execution of construction and deconstruction. It was a parametric model of a building and digital representation of the physical and functional characteristics (Rajendran & Gomez, 2012) that could be used to create a chain tracking the physical assets of a building as well as minimising future waste in the design stage (Liu, et al., 2015).

2. Material Recovery

Recoverable resources collected from the various waste streams required further processes to obtain separated materials of desired size and free of contaminants. Material recovery technologies referred to those which pre-processed disposed products into a resource to be used in recycling or remanufacturing. This step was broken down into three stages.

1. Beneficiation, in this case, referred to processes which increased the concentration of the desired material within the overall waste fraction. This could be done by directly extracting the desired material from the waste flow or gradually redirecting or removing undesired materials. Therefore, this stage predominantly consisted of sorting technology.
2. Size reduction processes reduced the size of items through methods such as crushing or shredding, generally for easier processing. It was common for resources to undergo several stages of size reduction.
3. Homogenisation referred to processes that intended to make the resources more uniform whether it be in size, shape, colour, etc. While processes categorised under homogenisation may include the reduction in size of the substances, the distinction was made depending on whether the intended outcome was to create a more homogenous output or simply a smaller output. For example, shredding was classified as size reduction whereas granulating was considered homogenisation.

2.1 Beneficiation (sorting)

For waste streams where there was likely to be contamination of non-recoverable resources, the waste fraction passed through a system where obvious contaminants were removed by hand. This manual pre-sorting prevented these items from disrupting further sorting processes or damaging equipment. A common example of this was single-use plastic bags.

Once obvious contaminants were removed, co-mingled waste was separated into categories based on the material properties and size through a range of automatic sorting processes. This allowed for highly efficient, less labour-intensive material separation which could be customised depending on the desired material to be extracted.

General

Material feeder

Material feeders dispersed piles of waste to provide a constant flow (feed-rate) of material onto the conveyors. A flat, even flow of material improved the reliability of automatic sorting machines. The choice of feeder type and parameters was heavily dependent on the material and the state of the material being moved. For example, co-mingled waste required feeders that could handle bulky materials, heavy loads and non-uniform shapes. Shredded materials benefited from enclosed systems to prevent dust and microplastic exposure.

Figure 12 - Drum Feeder (Bollegraaf Recycling Solutions, n.d.)

Conveyor

Conveyor belts were used to move waste throughout an automatic material recovery system. Therefore, they were common in industrial facilities where large volumes of waste were processed. Conveyor belts could be tailored to their function. Common types were belt conveyors, cleated conveyors and screw conveyors. Bounce conveyors could be used to separate lights objects which would float on the conveyors while round or heavier objects would roll down.

Bales were often held together with wire which may interfere with material recovery machines. Wire cutters were used to remove this. Some machines were integrated into conveyor systems to automatically cut the bale wire.

Screens

Mechanical screens and classifiers were used to segregate resources based on their size, shape and material properties. The characteristics of the desired output determined which type of screen was used.

Roller screens used a series of rollers which accepted a throughfall (or “unders”) which fell between the rollers while large or bulky items which may disrupt further processes continued over the rollers ("overs") to a different location. Disc / star screens were similar to roller screens but had specifically designed discs on the rollers to carry light or flat (2D) items such as paper or plastic film while 3D items fall through. Trommel / drum screens were cylindrical, rotary screens with perforated holes of a certain diameter which would only accepted items small enough to fit through. These could be inclined with progressively increasing diameter to separate the resources based on the size distribution. Given glass was readily crushed, it was generally easy to separate from co-mingled waste early in the process through these types of screens. Efficiency of such screens could reach 95% (Cimpan, et al., 2015). These were just some examples of commonly used screens. There were many more types including ballistic separators and vibrating screens which used motion to assist in the separation.

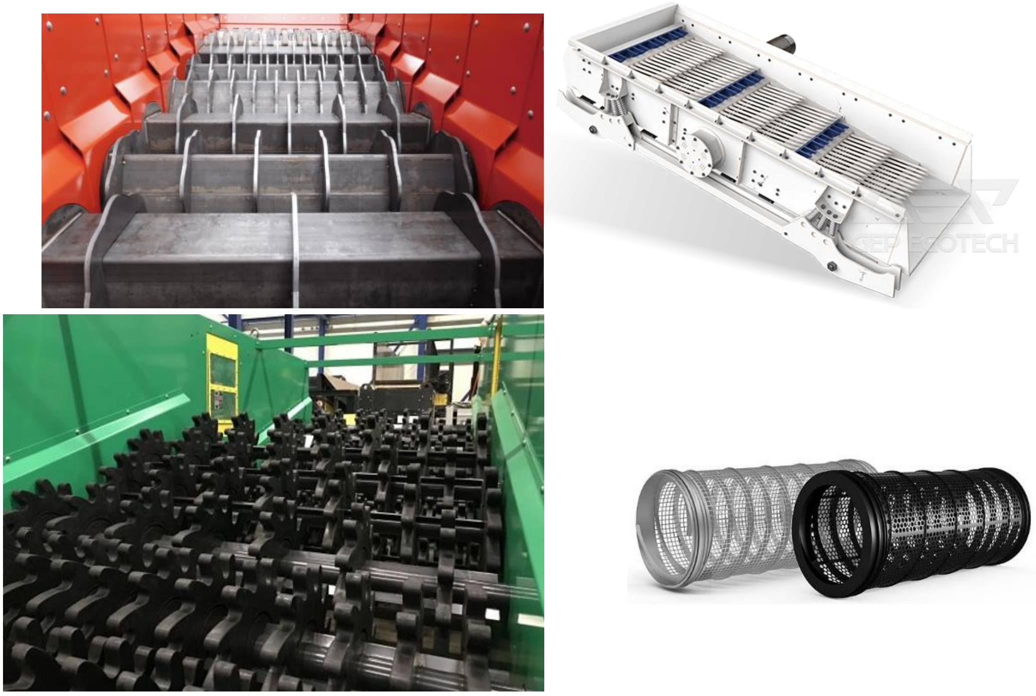

Figure 13 - Types of screens: roller (top left) (Rentec), star (bottom left) (Bollegraaf Recycling Solutions), vibrating (top right) (GEP Ecotech), trommel (bottom right) (Eggersmann Recycling Technology)

Magnetic separator

Magnetic separators utilised the ferromagnetic properties of certain metals to separate these materials from the bulk of the waste. Strong magnets could be placed above the conveyor to draw the items upwards and out of the material flow or within the end of the conveyor such that the metal fraction stays attached and fall into a container while the rest of the waste flow continued to the next stage. Magnetic filters could be used for powdered material to remove ferrous and weak magnetic materials.

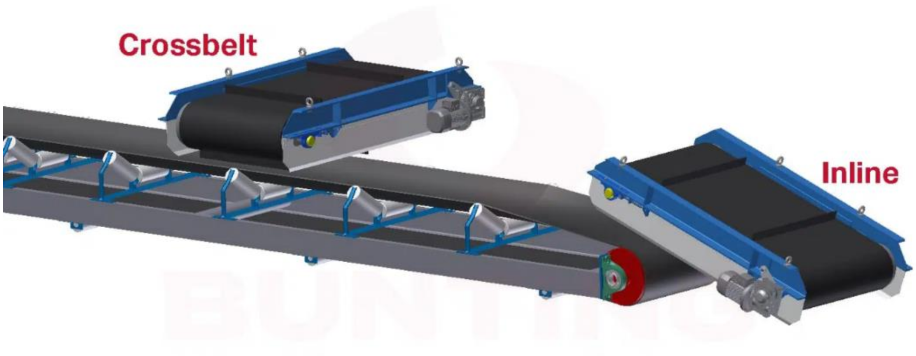

Figure 14 - Types of screens: roller (top left) (Rentec), star (bottom left) (Bollegraaf Recycling Solutions), vibrating (top right) (GEP Ecotech), trommel (bottom right) (Eggersmann Recycling Technology)

Eddy current separator

Eddy current separation was used to separate non-ferromagnetic materials. These machines created a rapidly changing magnetic field, inducing eddy currents in conductive materials, which produced an opposing magnetic field within the non-ferrous metals (e.g. aluminium, copper). The interaction between these fields created a repelling force which propelled the desired material beyond a divider which was placed such that the rest of the waste fell into a separate stream. These machines have been found to be highly efficient and environmentally friendly (Smith, et al., 2019).

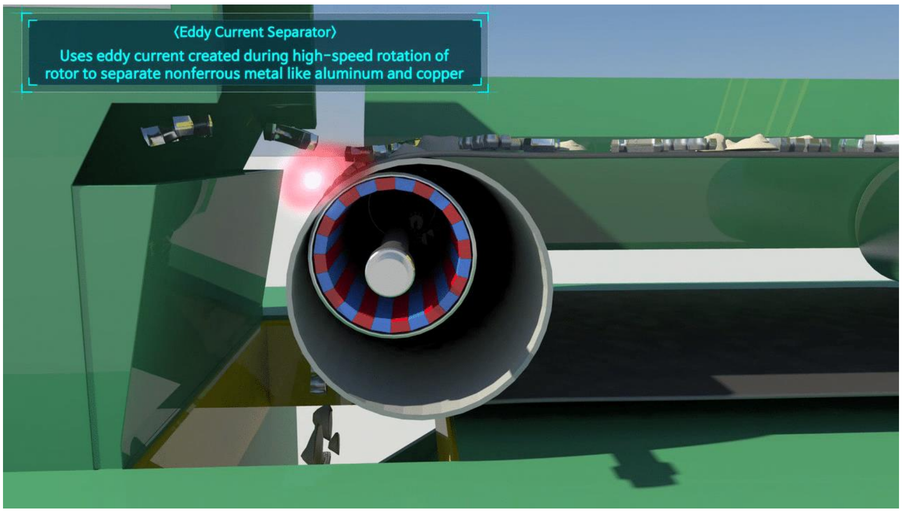

Figure 15 - Diagram of eddy current separator (MecBio)

NIR and optical sorter

Near-infrared (NIR) sensors operated on the principal that each material absorbed and reflected NIR light differently, creating a characteristic spectrum which could be used to identify materials. Machines equipped with NIR sensors rapidly examined the material composition of each item and, depending on the desired separation, used jets of air to propel these items across a divider. This method was particularly useful for separating different polymers and found applications in sorting textiles based on their fibre type.

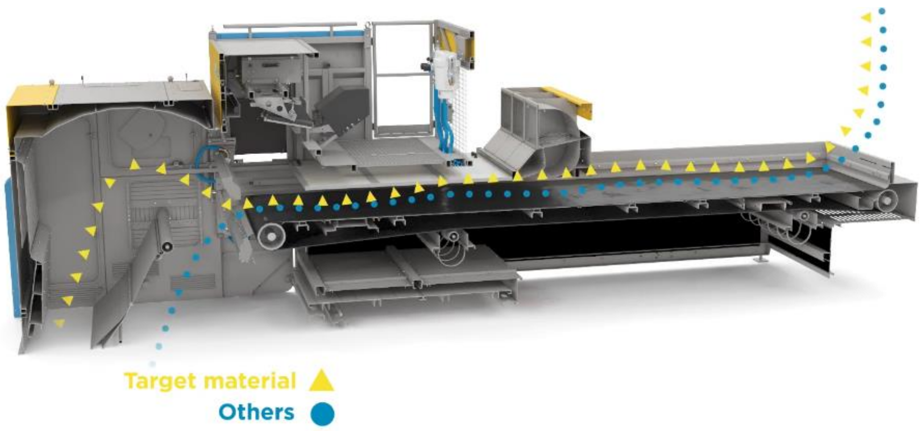

Figure 16 - Diagram of Near-infrared (NIR) sorter (Pellenc St)

Electrostatic separator

Electrostatic separators exposed items moving on a conveyor or drum to an electric field to make them electrically charged. However, conductive materials quickly lost the charge, and non-conductive materials retained the charge for longer causing them to remain attached to the drum. Dividers were used to separate the materials depending on the trajectory at which they became detached from the drum. A common application was the separation of mixed plastics (Higashiyama & Asano, 2007).

Density separator

Density separation or classification was a technique that relied on the differences in material density to sort items or remove contaminants. For general separation of light items from heavy in a mixed waste, stream air or water could be used. For precise separation, a medium of a specific density resulted in one fraction remaining on the surface of the medium while the other sank below. A 2018 paper found that sink-float separation in a cylindrical centrifugal force separator achieved the best results for separating post-consumer plastic (Bauer, et al., 2018).

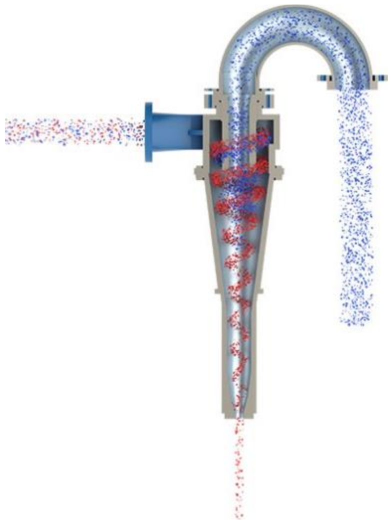

Figure 17 - Diagram of density separation using air (Pla.to Technology)

Glass

Automotive and commercial glass products consisted of layers of films which added certain properties to the glass. The non-glass components of glass composite items could be removed by delamination machines to create a clean glass fraction and a polymer fraction. A 2022 paper demonstrated an industrial-scale capable process for recovering 98.86% of polyvinyl butyral and 99.26% of glass with purity sufficient for remanufacturing (Swain, et al., 2022).

Metals

Metal made up major components of appliances (whitegoods), electronics and many other common items but were mixed with multiple other materials, requiring deconstruction into parts to recycle. The disassembly step allowed for the recovery of still functioning components and the separation of different material types contained within the item. Due to the complexity of modern devices, this was usually a manual, labour-intensive process that required specific tools and technology (e.g. fridges with cooling systems that needed to be safely disassembled). Because of this, it was common for facilities to shred entire items however disassembly prior to size reduction steps has been shown to improve the purity of valuable fractions removal toxic components (Johansson & Luttropp, 2009).

X-ray sorter

X-ray sorting systems operated like NIR systems but utilised x-ray fluorescence with high-speed data processing to differentiate between different metals based on the energy transmitted to a detector. Dual-emission x-ray was a development which used two beams of different wavelengths as materials of higher density would have more attenuation of the x-ray radiation (Gundupalli, et al., 2017).

Textiles

Before textile waste could be properly processed, parts such as zippers and buttons had to be removed. This was done manually or through shredding the entire item and using automatic sorting methods previously mentioned to remove the non-textile components.

Tyres

Tyre formulation, construction and size was tailored to the application (passenger, truck, off-road). Sorting based on these characteristics allowed different tyre types to be processed more efficiently. Additionally, dirt, sand, snow, stones, etc., could become embedded into the tyre surface which could cause additional wear on the shredder knives (Eldan Recycling). Washing systems have been used to prevent this.

Once disposed tyres have been shredded, materials within the tyre (metal, textile) could be removed through some of the automatic sorting methods mentioned above and sent to their respective recycling streams. Additionally, there were machines specific to tyre pre-processing such as wire liberators which extracted the metal fines or aspirators which separated the textile (and dust) from the rubber granules (Eldan Recycling).

Organics

Food wastes found stuck to the primary packaging must have this removed as non-biodegradable materials restricted the ability of microorganisms to process the organic material. Depackaging systems separated the packaging fraction from the organics fraction (substrate) allowing for high recovery and purity rates (Coker, 2021) however concerns have been raised about the existence of microplastics in the output with currently no solutions for this (Porterfield, et al., 2023).

Emerging technology

Laser-induced breakdown spectroscopy (LIBS) was an established laboratory technique for material characterising with growing industrial use in precise identification of metals, particularly aluminium alloys and precious metals (Legnaioli, et al., 2012). Machine learning has been applied with this technology to create an AI scrap sorting system (Diaz-Romero, et al., 2022).

REDWAVE Technology has implemented new software with proprietary cameras and lighting to improve the separation of glass, ceramics, stones and porcelains through a multi-stage process (Redwave Technology). The use of cameras for waste identification has been extended into the field of robotics, with researchers beginning to tackle the complexities of live image and pattern recognition, automated pathways and end effectors capable of picking up objects of different shapes and sizes (Wang, et al., 2020).

For composite recycling, innovations like Cupcyclng from James Cropper were being developed to improve the separation of paper-plastic laminates (PPL), such as those used in coffee cups, to enable recycling of these components (James Cropper).

Similarly, clothing made from blends of different fibre types could be difficult to recycle. Chemical separation technology from BlockTexx could separate textile products back into the individual raw materials without deterioration to any of the components (BlockTexx).

2.2 Size reduction

General

Crusher

Crushers used mechanical force between a hard surface to fracture the items into pieces. There were many different types of crushers based on the mechanism in which the size reduction occurred. Small scale crushers, such as BottleCycler, could be kept at the point of disposal to reduce the volume of the disposed material.

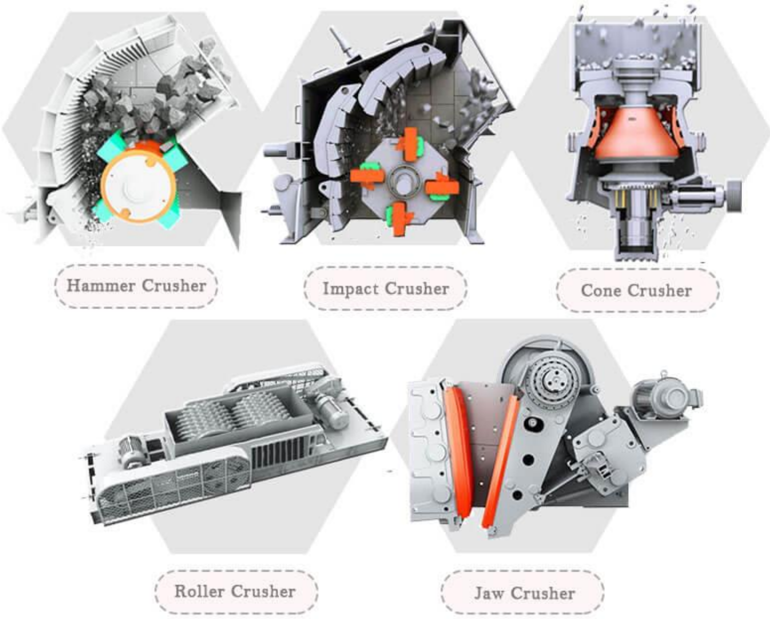

Figure 18 - Diagram of main crusher types (Agico Cement)

Shredder

Shredders operated by passing the waste flow through rotating, interlocking blades to shred the materials into smaller pieces. The shredded fraction was easier to store, transport and put through further processing. Shredders varied depending on the material and throughput it was used for.

Figure 19 - Shredders: single shaft (left) (Fordura), twin shaft (right) (Brentwood Recycling Systems)

Organics

For organic matter such as branches, leaves food scrap and other green waste, high speed shredders were used to create an output for mulching. Pulverisers, or grinders, transformed organic matter into a pulp which could be more easily pumped and used for further composting applications. For anaerobic digestion, a smaller particle size did not necessarily improve the performance and could even affect digestor performance (Zhang & Banks, 2012).

Building and demolition materials

For metal wires and cabling, specific machines like cable shears were required for shredding. Additionally, industrial shredders used for heavy duty applications such as scrap metal and other demolition debris were designed to be low-speed and high torque.

Figure 20 - Slow-speed shredder for heavy duty applications (CSS Equipment)

Emerging technology

SELFRAG was implemented as a lab technique used to fracture glass along phase boundaries in industrial applications such as recycling scrap metals. High voltage electrical pulses selectively fragmented solid composite materials, liberating contaminants and inclusions (SELFRAG).

Cryogenic gases have been used to cool materials to very low temperatures thus making them more brittle and easier to crush (Millennium Cryogenic Technologies). This was being tested in tyre recycling as a way to improve the output quality of the rubber, improve metal wire separation and consume less energy in the shredding / crushing process (STM Microtec, 2023) (Yerezhep, et al., 2021).

SmartCrusher has developed a crushing technology used for processing Construction and demolition waste which could identify the different components of debris to selectively crush cement while leaving the stone (Slimbreker).

2.3 Homogenisation

General

Granulator

Granulators were machines used to reduce materials into fine, uniform particles using rotor knives and sizing screens. This was a slower process to shredding and needed a more controlled feed rate. The outcome of this was that the more uniform output could be used as a feedstock with controlled and reliable properties. Some manufacturers offered shredder-granulator combinations which perform both functions.

Screens

Mechanical screens were described in more detail in 'Pre-processing' as they were one of the first processes used to sort mixed waste streams but could also be used to homogenise resources, such as glass cullet or tyre shred, based on the item size. For example, screens may only allow a certain size of shredded rubber to pass otherwise it would be diverted back to the feeding line to pass through the shredder again. These screens were more like sieves, where the output was of a specific mesh size.

Optical sorter

Similar to NIR, optical sensors detected visible spectra to separate materials based on their colour. Recent developments have improved the characterisation of dark items that have low reflectance and were previously hard to separate (Rozenstein, et al., 2017).

Cleaning

For materials with residual contaminants remaining on the surface, including a washing or cleaning process was sometimes necessary to improve the quality of recycled material. An example was PET flakes being washed in a cleaning solution to improve the quality of the recycled plastic product (Shen & Worrell, 2024). A drying step followed this as moisture removal improved further processing. For high purity requirements, separation tables could remove contaminants such as metal dust from a plastic fraction after metal separation.

Figure 21 – Water Separation Table (Eldan Recycling)

Figure 22 – Shredder-Granulator Combo (Genox)

Glass

Glass was usually separated into three colour categories: flint (clear), amber (brown) and green. This provided benefits to glass manufacturers who required a consistent colour from their products and was achieved using specific types of NIR and optical sorters as described above.

Paper and cardboard

To homogenise paper and cardboard resources, the materials entered a machine which circulated a fluid to break apart the fibres in a slurry. In this state, contaminants were more easily removed by passing the slurry (or 'pulp') through screens. To remove inks, adhesives, and other residues, the pulp underwent a de-inking process. This could involve washing, flotation, or chemical treatments to separate ink particles from the paper fibres. Enzymatic de-inking used enzymes to breakdown the inks and adhesives in paper products (Saxena & Chauhan, 2016). Furthermore, ultrasonic treatment could improve the quality of recycled pulp fibre (Tatsumi, et al., 2000).

Tyres

Most tyres were made of vulcanised rubber which used sulphur and heat to improve the hardness and durability of rubber tyres. Applications that required high-purity rubber products may need to undergo devulcanization to remove this component however this was not necessary for most applications (Markl & Lackner, 2020).

Once other components were removed, the remaining rubber underwent further shredding, milling, granulation, and pulverisation (comminution) steps to reduce rubber granules to particles of a desired size. The wire-free rubber crumb, granulate or powder could be used in many applications including the steel manufacturing industry.

Organics

Organic waste was decomposed by microorganisms. This could be done in the absence of oxygen (anaerobic digestion), which produced biogas and digestate, or in the presence of oxygen (aerobic composting) which produced fertiliser. Focussing on the latter process, the organic fraction must be periodically turned and aerated for an extended period. At an industrial scale, “windrows” of fertiliser could be aerated with fans or pipe systems or by using windrow / compost turners. However, there was increasing demand for smaller, modular (“in-vessel”) composting systems such as the one presented below.

Figure 23 – In-vessel composting machine (Green Mountain Technologies)

Digestate from anaerobic decomposition could undergo dehydration and then be mixed with waste fraction undergoing aerobic composting to produce more fertiliser. This way a byproduct of anaerobic decomposition was recovered.

Mesophilic digestion takes place at 30-40ºC but by using different bacteria a higher operating temperature of 50-60ºC could be achieved, resulting in a faster reaction rate (Singh, et al., 2023; Pham, et al., 2023). This was referred to as thermophilic anaerobic digestion.

Emerging technology

Ultrasonic baths were effective in removing surface contaminants to create a high purity item. This could also be useful when recovering precious metals such as gold from e-waste.

Product Improvement and Safety

General

Dust suppression

The pre-processing of materials could release dust particles into the environment. Not only can this buildup cause machinery damage but it also posed health risks to workers and the environment. As such, dust suppression and filtration were important considerations for pre-processing facilities. Wet suppression used water or other liquids to bind dust particles preventing them from becoming airborne. For example, misting cannons which sprayed water over a large area. Cemac Technologies have developed Pollutex which used a biodegradable foam which bound itself to dust and suspended particles (Cemac Technologies). Furthermore, ventilation systems and dry filtration created airflow and capture the airborne dust particles.

Figure 24 - Photographs capturing the effect of Pollutex (Cemac Technologies)

Noise suppression

Crushing and shredding can create harmful levels of noise. For this reason, machines were sometimes housed within sound-dampening enclosures. Additionally, walls or other physical sound barriers could be placed around the machines. Noise sensors helped determine areas at risk and inform where wearing personal protective equipment (PPE) was necessary.

Plastic

It has been well-reported in recent times the health risks associated with microplastic pollution for humans and the environment. The pre-processing of plastic can result in microplastics being created and entering the surrounding environment (Chen, et al., 2022). Enclosures have been used to prevent microplastics from dispersing. Vacuum conveyors and other forms of enclosed systems would be ideal to suppress microplastic exposure.

Organics

Before being released, odorous fumes produced from the decomposition of organic matter were pumped through a filter. Bio-filters made from woodchips or other organic materials can trap the sources of the odour before the air was released into the atmosphere.

Building and demolition materials

The size and weight of some resources made it difficult to move around pre-processing facilities and load into machines. To perform this, industrial machinery such as dozers and loaders were often used to manoeuvre large volumes of Construction and demolition waste.

3. Recycling & Remanufacturing

Recycling and remanufacturing were the final steps in the circular economy framework. It referred to processes that transformed the recovered, pre-processed materials through physical or chemical means into new resources which could then re-enter the manufacturing supply chain as a feedstock or be directly remanufactured into a new product. That is, recycling technologies were those through which a material that could be used as a feedstock in the place of virgin material were produced. For example, pelletising a polymer to be used for injection moulding. Remanufacturing technologies were more specifically those which used the pre-processed materials as the direct input for the production of new parts or products.

It should be noted these definitions did not directly align with the ISO standards in order to prioritise the aims of the framework. 'Recycling' as a term has been used to encompass all activities involved in keeping materials out of landfill, from collection to production. This framework applied a more limited but specific definition to tailor the meaning to the context of circularity in regional and remote areas and highlight steps which add value to the material streams and provide economic opportunities for these communities. Similarly, re-manufacturing has been defined as such to emphasise the potential for innovative processes that utilise local waste as a resource in new products thus creating environmentally and economically sustainable waste solutions – an objective identified by the Department early in the development of this project.

The use of recycled materials in the place of virgin materials had environmental, economic and social benefits. For example, producing recycled aluminium required 95% less energy than that needed to make new aluminium (The Aluminium Association). Identifying remanufacturing opportunities in regional and remote areas can reduce greenhouse gas emissions in this way as well as eliminating the need to transport waste to landfill. In the same media release mentioned above, the Minister stated that, "For every job in landfill, there are three jobs in recycling."

Plastics

Plastics were recycled in two ways; mechanical and chemical. Mechanical recycling was more common and produced an output with no significant changes to the materials' chemical structure. Chemical recycling, or advanced recycling, changed the chemical structure often back to the original monomers which were used to produce new plastics with properties comparable to the virgin material (Chemistry Australia).

For mechanical recycling, pelletising was the predominant process, particularly for PET, as pellets had great utility as a feedstock that could be used in a large variety of manufacturing operations (Ragaert, et al., 2017). To perform this, the pre-processed polymer, usually in the form of shredded flake, was heated to a flowable state. Extruders then pushed the molten polymer through a die (cross-section of the final product) of desired diameter. To pelletise, the extruded plastic could be chopped before or after cooling. Strand pelletising cooled a long, continuous filament by pulling it through a liquid bath. The strand was dried before being chopped into a pellet desired length. Hot die pelletising cut the filament as it exited the die. The pellet then fell into a bath where it was cooled and solidified. This eliminated the chance of the filament breaking during cooling (Case, et al., 2018).

A novel technology called Resin8 has been developed for the construction industry which accepts all plastic waste types and converts the resources into an aggregate to be incorporated into concrete products (CRDC Global, n.d.).

Figure 25 - Pelletisers: strand (left), hot-die (right) (NGR Plastic Recycling Technologies)

Other products included fibres which used an array of small holes (spinnerets) through which the polymer was extruded into threads and then spun into a yarn, or films through blown film or cast film processing. Alternatively, cold pressing granulated PP and ABS has been able to produce sheets which were then used to make various items.

Figure 26 - Cold presses sheets (Image provided by Salamander Bay Recycling)

Chemical recycling covered a set of technologies (pyrolysis, gasification, hydro-cracking, depolymerisation) that converted polymers back into the chemical building blocks (monomers, oligomers, hydrocarbons, etc.) (King, et al., 2021). An exception to this was purification, or solvent-based recycling, which separated the polymer chains from additives and contaminants by first dissolving in a solvent and then later precipitating it back out (CreaSolv). The benefit of these technologies was that new materials could be created with properties equivalent to virgin material. Additionally, mechanical recycling was generally only suitable for thermoplastic polymers and degraded the quality of the material over successive cycles whereas chemical recycling processes could process complex polymer types albeit at a greater cost (Ragaert, et al., 2017).

Glass

Glass had a long-established history of recycling as due to the reversible glass transition phenomenon it can be infinitely recycled without any loss in properties (Lebullenger & Mear, 2019). Glass cullet was simply remelted to a molten state and reformed into the desired shape by blowing, moulding, pressing or even spun into fibreglass to be used as insulation. One non-conventional application was the use of small, glass beads in road markings and signs, utilising its reflective properties (Dyer, 2014). However, this still required cullet free from contaminants and of a certain colour and other applications may have quality requirements which prevented the use of recycled glass.

Foamed glass was a porous, strong and light-weight product with thermal and chemical properties that made it extremely useful for insulating and fire-proofing applications (Smiljanic, et al., 2023) (Vancea & Lazau, 2014) and could include up to 98% recycled cullet (Dyer, 2014).


Figure 27 - Close-up photograph of foam glass (FOAMGLAS)

Alternative applications of recovered glass that did not require remelting were as a replacement for sand in concrete as well as an aggregate in asphalt and roads such as Reconophalt (Downer Group). Although this diverted a large volume of glass waste from landfill, it did not provide much material value return. Milling glass into a fine powder generated upcycling opportunities such as water filtration mediums (Evans, et al., 2002) (Soyer & Akgiray, 2010) or sandblasting.

Metals

In Australia, the resource recovery rate for metals in 2020-21 was 87% (Blue Environment, 2022). Similar to glass, metal could be infinitely recycled, at least in theory, by smelting the recovered metal in a furnace, casting the molten metal into a mould and then cooling to let it solidify in this shape. A challenge for metal recycling was the recovery of precious and specialty metals which are used in small quantities in complex applications (Reck & Graedel, 2012). It was common for most metals to be reformed into ingots, rods or billets which, like pellets, were sent to manufacturers for a range of uses.

For smelting, furnaces can vary depending on the volume and material being processed. For example, Tenova manufactured twin-chamber melting furnaces which operated at an industrial scale and can use contaminated scrap (grease, oil, lacquer) without the need for pre-treatment (Tenova). SiroSmelt was a cost-effective, environmentally sensitive process which has been used for recycling scrap metal, e-waste, lead batteries and other wastes (CSIRO). Plasma arc heating systems were an alternative way to melt metals which demonstrated a purification effect on the extraction of metal from metal-containing wastes like printed circuit boards (Changming & Chao, 2018).

Another stream for recovered metal resources was in additive manufacturing (Nascimento, et al., 2022). Some technologies currently in use in the construction and automotive industries were selective laser sintering and binder jet printing (Buchanon & Gardner, 2019). Both of these required the metal to be in powder form with precise dimensions and properties. This has been done through physical (e.g.

ball milling) and thermal (e.g. atomization) means (Zhang, et al., 2017) (Hoizon Technology, 2020). Commonly used metals for these processes have been titanium, aluminium and stainless steel (Lodha, et al., 2023).

Figure 28 - Examples of metal products made from Additive Manufacturing (Continuum Powders)

Paper and cardboard

The “very significant majority” of paper was recycled back into other grades of paper with the most common product being corrugated cartons however virgin fibres are required for most products as the fibre properties deteriorate with each cycle (Industry Edge, 2019). The general process of papermaking included de-inking and screening the recycled-paper slurry, adding virgin fibres and thickening the pulp, then pouring this pulp over a moving mesh which caught the fibres but let much of the water fall through. This continuous stream of paper travelled through a series of rollers (calender) which both removed the excess moisture and pressed the fibres together, flattening and strengthening the sheet. Depending on the final use, the sheet underwent further processes such as brightening, coating or corrugating.

For small scale operations, scrap cardboard could be turned directly into packaging materials using technology such as the Recycle Pack. This used a machine to cut the cardboard into a pattern which made it flexible and a suitable replacement for plastic packaging materials (Recycle Pack).

Figure 29 – RecyclePack (Recycle Pack)

An emerging use for wastepaper sludge has been the production of bacterial cellulose for use in the textile industry. A chemical process using a combination of acidic hydrolysis and bacterial fermentation has been shown to produce a new source of fibre which can be spun through a Lyocell process (Ngo, et al., 2023) (Silva, et al., 2023).

Textiles

Perhaps due to clothing being classed as a basic human need, there was a strong societal push to re-use clothing perhaps more than any other material type. However once these products did reach end-of-life, the options were usually limited to downcycling into products like rags, energy recovering or landfilling (Piribauer & Bartl, 2019). The pre-processed fibres were usually too short to allow for respinning back into yarns and the increasing prevalence of mixed-fibre clothing made from both natural and man-made fibres made recycling even more complex.

In recent years, more research has gone into fibre-to-fibre recycling to overcome these challenges. Dissolution recycling was similar to the chemical recycling processes described in 'Plastics' and involved putting polymer fibres into a solvent which separated contaminants and cellulose fibres making it particularly useful for polycotton textile blends. A cost-effective solution that can be scaled commercially was currently being developed and showed 20% reduction in energy use and a 99% recycling rate for the solvents used (Mu, et al., 2023). Furthermore, a microwave-assisted glycolysis process has been shown to depolymerise polyester and spandex (Andini, et al., 2024).

An alternative solution was to use the recovered textile fraction in products that are not disadvantaged by the short fibres. This has been seen in insulation and cushioning applications, ceramic products from Kandui Technologies described below and decorative bricks (FabBRICK).

Figure 30 - Display of FabBRICK applications

Tyres

Once tyres had been pre-processed and the metals recovered for scrap metal recycling, the remaining rubber crumb was used in asphalt for the construction of road surfaces to extend the life of the roads and reduce noise (Tyrecycle, 2024) or as filler material to replace fine ground limestone used in asphalt (Alex Fraser Group, 2023). In other applications, rubber crumb was used in concrete slabs, playground flooring, athletic tracks, shock absorbing mats, landscaping, patio tiles or roofing material (Maga, et al., 2023).

Organics

When looking at the material cycle of organics, farming can be seen as the recycling and remanufacturing stage of the closed-loop system. The recovered resources, in the form of fertilizer, provided the nutrients to produce new products to be consumed. Given the vast nature of the agriculture industry, farming technologies are not discussed in this report.

More immediate recycling technologies for organics include mulching and waste rendering. Mulching used specific chipper-shredders to turn wood chips, leaves and similar materials into a substance which protected the soil surface. Rendering technology applied heat and pressure to animal by-products and other organics. After the removal of water and fat, the solid fraction was ground with a hammermill to produce a high-protein bone meal feed (MecBio).

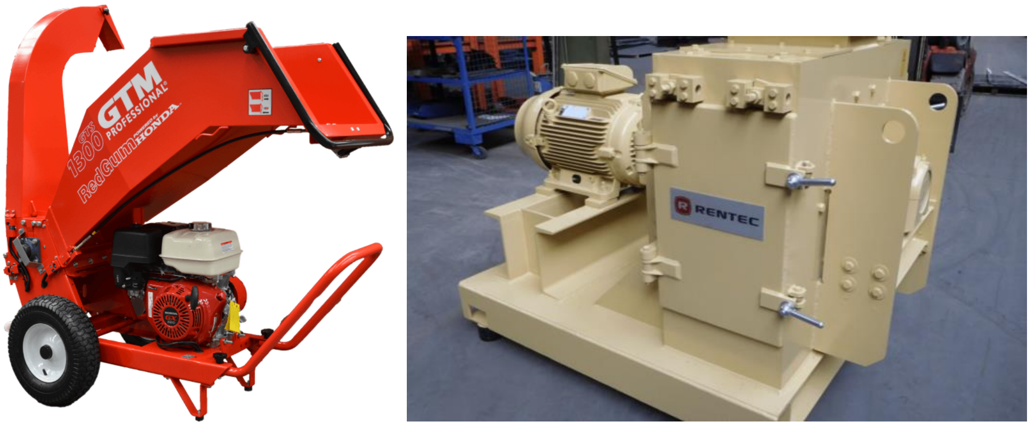

Figure 31 - Wood chipper for mulching (left) (RedGum Products) and Hammermill for organic wastes (right) (MecBio)

Another source of animal feed using organic waste can be made through an emerging process called bioconversion. Organic residues (crops, animal manure, compost) are used to feed black soldier fly larvae – a harmless and non-invasive species (DiGiacomo, 2023). After growing, the grubs are dried and processed to create a fat and protein rich food source for farmed animals, including fish (Veolia Group).

Building and demolition materials

Building and demolition waste was commonly converted into aggregates or sand for non-structural applications once the metals had been removed. These products would be used in concrete, asphalt, low-strength bricks and other built-environment applications to replace the typical materials used from virgin sources (Ma, et al., 2024). When compared to Australian quarried aggregates, recycled aggregates had a 57% reduced carbon footprint whilst transport costs were also reduced when comparing the journey to and from a landfill versus a quarry (Oteng, et al., 2024).

In Europe, the types of C&D recycling plants considered were either stationary or mobile (Ulubeyli, et al., 2017), where stationary plants could process 100-350 tons per hour whilst mobile plants could deal with up to 100 tons per hour. These mobile sites were ideal in locations where larger, more permanent processing sites were not available but where the waste needed to be compacted and/or classified to reduce landfill space and increase transportation efficiencies.

To obtain high-quality aggregates for the construction industry, the waste first had to be pre-processed to achieve a smaller particle size and remove contamination such as reinforcement, wood, plastics and metals (Behera, et al., 2014). On-site pre-processing techniques such as crushing led on to washing, screening, sludge treatment and water treatment, with more advanced processes incorporating nitric acid dissolution, pre-soaking treatments, freeze-thaw treatments, microwave heating, ultrasonic agitation and more.

Figure 32. C&D Waste Before (Left) and After (Right) (CDE Group, 2014)

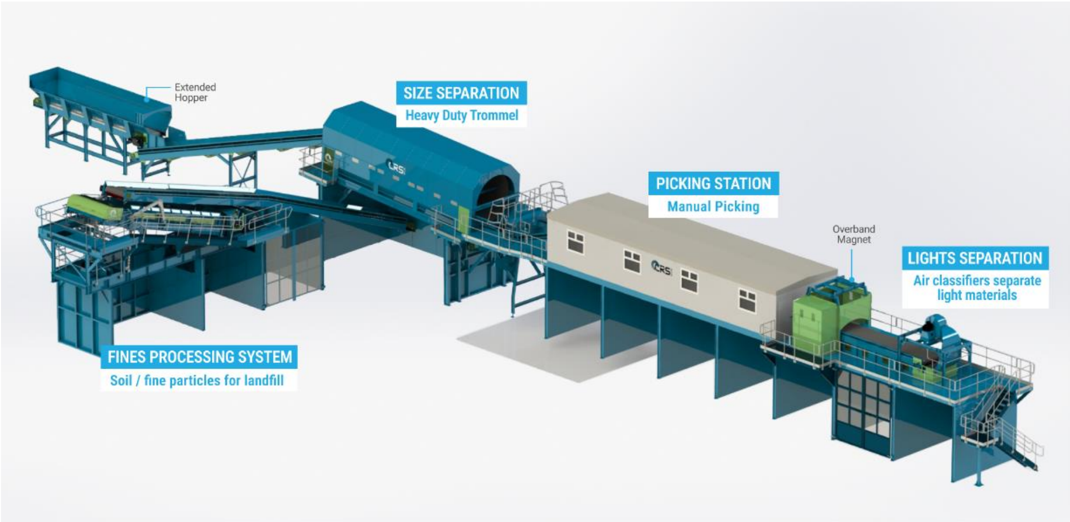

Figure 33. Integrated C&D Waste Recycling System Diagram (Waste Initiatives)

Emerging Technology

One of the challenges with recycling rubber tyres into a higher-value product was the vulcanising process that made the rubber highly durable but difficult to heat and melt. Waste rubber tyres have been introduced into injection moulding as a partial filler, combining post-consumer recycled plastics and car tires to replace virgin plastics (plascon plastics, 2024). Rubber tyres have also been introduced into steel manufacturing through the SMaRT Centre's polymer injection technology (UNSW SMaRT Centre, 2024). By injecting the rubber crumb as a replacement for coke in electric arc furnaces, the rubber became a source of carbon for remanufacturing steel.

Material recycling lines for processing C&D waste have seen advancements made in smaller-scale operational models to compliment the turn-key solutions that required far larger investment and energy. These systems were often a compact version of the more complex recycling plants or mobile versions of each module that could be brought on-site and quickly set-up.

Figure 34. Wet processing of soil waste (left) (CDE Group) (CDE Group, 2024) and mobile picking stations (right) (Waste Initiatives)

The Shoalhaven Green Ceramic MICROfactorie™ was built and operated in a partnership model between the UNSW SMaRT Centre, Shoalhaven City Council and Kandui Technologies. The facility was able to remanufacture ceramic products using waste glass and waste textiles from local waste sources, including the Shoalhaven landfill on which the MICROfactorie™ was built. The use of glass instead of virgin quartz reduced the impact of quarrying and international transportation whilst removing the silicosis concerns when handling typical stone products.

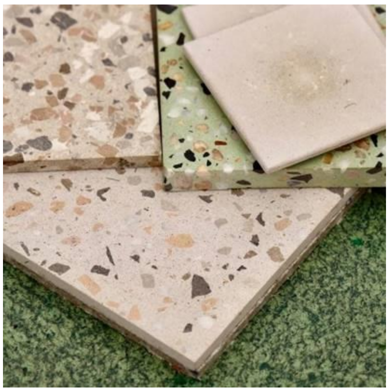

Figure 35. Ceramic products remanufactured from local waste streams.

Using the MICROfactorie as a short case study on a Circular Economy in action, it began to show the network of collaborations that made an effective remanufacturing process. Shoalhaven council collected and stored the glass waste through yellow recycling bins that were kerb-side collected using collection trucks. Those were then pre-processed through crushers, washers and classifiers to obtain the raw crushed glass material for remanufacturing. The textile waste stream was collected through reverse logistics networks before being pre-processed by Kandui’s own shredding processes. Finally, Kandui collected the processed glass and textile waste and remanufactures the material into the final product where they are packaged, distributed and installed. At the end of their life, the tiles could then be collected by reverse logistics during demolition for further remanufacturing in the future.

Figure 36. Example of a Circular Economy network, using Green Ceramic remanufacturing as a case study

Future Work

The SCaW Hub has been developing a comprehensive list of different technologies categorised using the circular economy framework presented in the technology roadmap. This will be further expanded upon and developed into a webtool enabling regional and remote communities to search for different technologies relevant to their circumstance. The aim will be to allow different communities to have a broader view of the circular economy, enhancing overall community engagement and knowledge sharing, and learn from innovative solutions which utilised current or emerging technologies to shift from a linear to a circular economy.

Research into technologies will also be expanded into identifying mobile or modular solutions that may find applications in remote and very remote communities where the challenge of distance and access to facilities were further amplified. Further work will be conducted on researching and presenting case studies where technologies have been utilised successfully by various regional and remote councils. It may be appropriate to incorporate a system for councils and private businesses to leave a review or evaluation on the webtool to share their own solutions and challenges for each technology.

A key step for building on the current list of technologies will be a system for assessing or indicating their readiness for adoption in regional and remote communities. Some features of this indicator could include:

- whether the technology has been proven or was still experimental
- ease of deployment in regional and remote locations
- relative costs per tonne of product
- requirements for operator training
- power requirements
- carbon abatement opportunities
- repairability
- human and environmental health impacts.

Conclusion

In developing a circular economy framework with stakeholders from regional and remote communities, the scope for the steps involved in closing the loop for end-of-life materials was broadened. The goal was to capture the roles different organisations could play at every stage of a material or products' life when shifting from a linear to a circular economy. Each technology was selected to build a network of technologies that could be operated by a network of local businesses to divert materials from landfill and achieve greater sustainability. By providing an update on current and emerging technologies, it was anticipated that this would allow users to identify what opportunities for value creation would fit their own unique circumstance without the pressure of attempting to solve every problem and invest in every single technology themselves.

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