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Advanced recycling technologies to address Australia's plastic waste

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Contents

Figures

Tables

Glossary

TERM	DESCRIPTION
ABS	Acrylonitrile butadiene styrene
Advanced recycling	Conversion to monomer or production of new raw materials by changing the chemical structure of a material or substance through cracking, gasification or depolymerisation, excluding energy recovery and incineration.
APCO	Australian Packaging Covenant Organisation
ARENA	Australian Renewable Energy Agency
ASA	Acrylonitrile styrene acrylate
Ash	The powdery residue left at the end of a decomposition process.
atm	Atmospheres (unit of pressure)
Carbon black	Any group of intensely black finely divided forms of amorphous carbon, usually obtained from the partial combustion of hydrocarbons.
Cat-HTR™	Licella's catalytic hydrothermal reactor technology that uses supercritical water to convert a variety of waste feedstocks into bio-crude.
Char	The remaining carbonaceous solid residue remaining from conversion of plastics.
Chemical recycling	See Advanced recycling
Chemolysis	The breakdown of a large molecule to smaller building blocks using chemicals.
Downcycling	Where recycled material is of lower quality than the original material.
Enzymolysis	The splitting or cleaving of a substance into smaller parts by action of an enzyme.
EPS	Expanded polystyrene
ERA	Environmentally relevant activity
Feedstock recycling	See Advanced recycling
FMCG	Fast moving consumer goods
Gasification	Waste materials are heated to very high temperatures (e.g. 1,000–1,500°C) with some oxygen or steam that breaks down the molecules into a syngas.
HBCD	Hexabromocyclododecane
HDPE	High-density polyethylene
Hydrocracking	The addition of hydrogen to hydrocarbon molecules to break them down into simpler molecules, often done with a catalyst and under pressure.
Hydrogenation	The chemical reaction between molecular hydrogen and another compound, usually in the presence of a catalyst.
Hydrothermal treatment	Reaction of compounds with water molecules at high temperatures (160–450°C) at a pressure that maintains water in the liquid state.
ISCC	International Sustainable Carbon Certification
LCA	Life cycle assessment
LDPE	Low-density polyethylene
LLDPE	Linear low-density polyethylene
LPG	Liquified petroleum gas
Materials recycling facility (MRF)	A specialised plant that receives, separates, and prepares recyclable materials for marketing to end-user manufacturers.
Molecular recycling	Another name for feedstock recycling, returning polymers to small molecules.

TERM	DESCRIPTION
Monomers	A molecule that that can react with other monomer molecules to form a very large molecule, a polymer.
MSW	Municipal solid waste
PA	Nylon
PB	Polybutylene
PC	Polycarbonate
PE	Polyethylene
PET or PETE	Polyethylene terephthalate
Plastics-to-chemicals	Conversion of plastic material into useful chemicals.
Plastics-to-fuels	Conversion of plastic material into fuels for vehicles, boilers, generators, etc.
Plastics-to-plastics	Conversion of plastic material into new useful plastics.
PMMA	Poly(methyl methacrylate)
Polyolefins	Large molecules formed by the polymerisation of olefin (or alkene) monomer units consisting of carbon and hydrogen only. Polyethylene and polypropylene are polyolefins.
PP	Polypropylene
PRF	Plastic recovery facility
PS	Polystyrene
PU	Polyurethane
PVC	Polyvinyl chloride
Pyrolysis	The treatment of materials with heat in the absence of oxygen, with or without catalysts. Usually conducted between 400 and 1,000°C.
RMF	Recycling Modernisation Fund
RPO	Recycled polymer oil
SAN	Styrene acrylonitrile
Solvolysis	A generic term for processes where a material reacts with a solvent to break into smaller components (e.g. hydrolysis, methanolysis, aminolysis, glycolysis).
Thermal cracking	The use of heat and pressure to break large molecules into smaller molecules.
Thermolysis	The use of heat to break down materials.
Thermoplastics	Materials that soften (become plastic) on heating and harden on cooling and are able to repeat this process.
Thermoset polymers	A polymer that irreversibly becomes rigid when heated.
Upcycling	The transformation of unwanted products into new materials perceived to be of greater value.
Virgin material	Material that has been sourced through primary resource extraction, often referred to as primary materials.
WEEE	Waste electrical and electronic equipment
WtE	Waste to energy – the generation of energy from the treatment of waste.

Executive summary

Australia intends to significantly improve waste recovery for plastics. One mechanism to achieve that is through increased recycling, including the use of advanced recycling technologies. New policies, such as the plastic waste export ban for mixed plastics (commenced 1 July 2021), 70% of plastic packaging recycled or composted by 2025 and the national action plan of 80% resource recovery rate from all waste streams by 2030 mean Australia must innovate to realise a circular economy for plastics. Despite international investment and application at commercial scale, advanced recycling for the recovery of waste plastic is not yet part of Australia's recycling strategy and lexicon, but it could be.

"Advanced recycling is the conversion to monomer or production of new raw materials by changing the chemical structure of a material or substance through cracking, gasification or depolymerisation, excluding energy recovery and incineration"[1].

Advanced recycling is also referred to as chemical, molecular or feedstock recycling. These terms can sometimes be used interchangeably. Advanced recycling is complementary to mechanical recycling. It can assist with diverting mixed, flexible and contaminated waste plastics that are not able to be mechanically recycled economically and would otherwise go to landfill.
This report describes three major advanced recycling processes, purification, depolymerisation and conversion technologies, to produce intermediate products (light and heavy oil, gas, char). These products can be further processed into recycled polymers that are able to be manufactured into new products with recycled content, represented in Figure 1. A summary of these technologies is provided in Table 1 with the preferred polymers and summary of typical outputs or products.

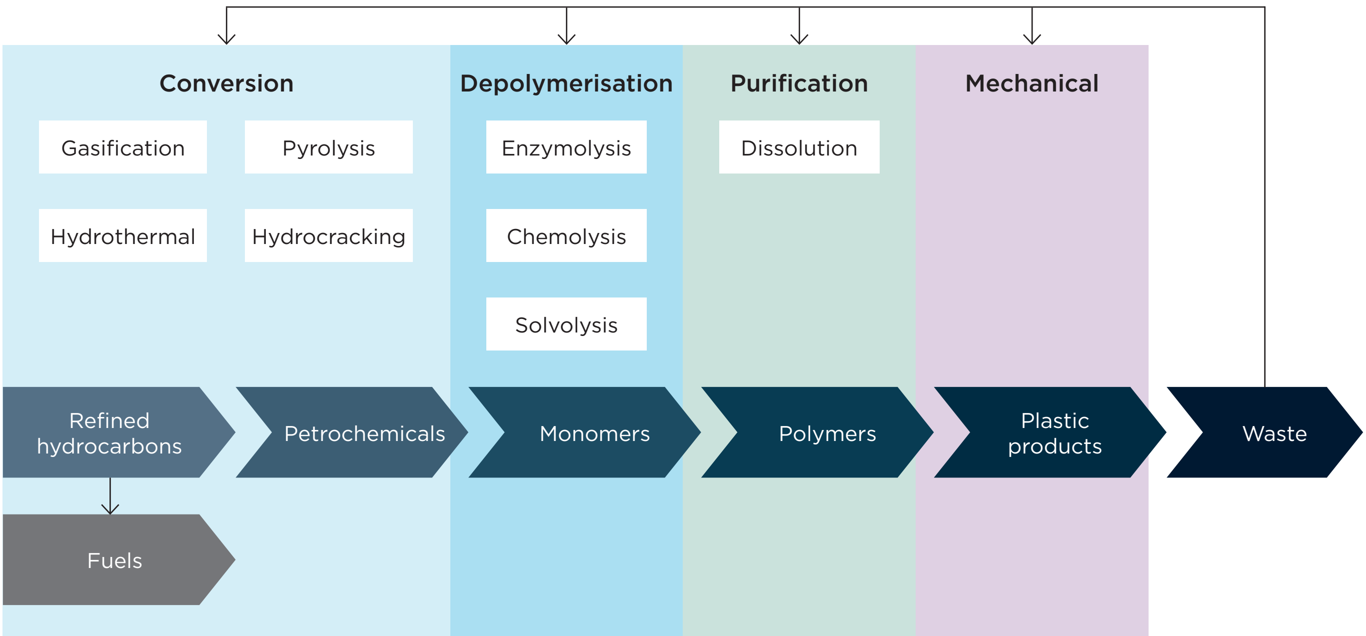

Figure 1: Summary of advanced recycling technologies and their products

Derived from Closed Loop Partners 2019

1 https://www.iso.org/obp/ui/#iso:std:iso:15270:ed-2:v1:en

Plastics are a highly valuable feedstock for waste-to-energy plants due to their high calorific value but may instead be processed by advanced recycling technologies which specifically focus on waste plastics. Advanced recycling conversion technologies can convert plastic waste to oil (not including gasification where the typical output is syngas). This oil may be further processed and used as a fuel. This is depicted in Figure 2 as a 'plastic-to-fuel' pathway. However, advanced recycling also provides an opportunity to further process that oil with an outcome that is more beneficial for the waste hierarchy than the creation of fuel. The same plastic waste to oil pathway must be followed by any advanced recycling technology that might want to convert 'plastic-to-plastic', by cracking the oil (the process of breaking the chemical bonds of long chain hydrocarbons to smaller units) to produce a monomer (the building block of polymers) which can be further processed to a plastic. This is a desirable circular economy proposition as the plastic waste has been recycled, back to plastics.

In this report we consider major plastic polymer types, their generation as waste streams, polymer interactions within processes, and barriers to the application of technology for the treatment of plastic waste in Australia. International industry examples are used to illustrate the economic and environmental implications of plastic waste recycling by various technologies. Through direct industry engagement, we also report major factors influencing the adoption of advanced recycling in Australia.

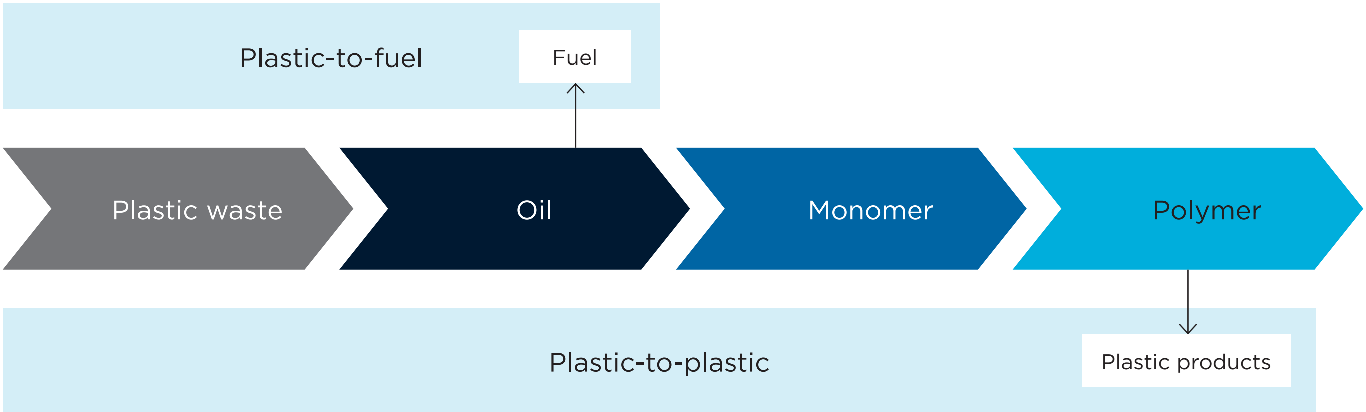

Figure 2: Plastic to fuel compared to plastic to plastic pathways for advanced recycling

Australia has all the critical elements necessary to launch a new industry of advanced recycling for plastics, which supports greater recovery, recycling and reuse of materials consistent with improved circularity and sustainable economic development. Three major report highlights are:

1 Advanced recycling will increase Australia's recovery of plastics

Advanced recycling is highly complementary to mechanical recycling as it provides a pathway for problematic wastes, such as mixed, flexible and contaminated plastic wastes that might otherwise go to landfill. Australia needs multiple options to improve recovery and recycling of waste plastics to meet national recovery (80% average recovery by 2030) and packaging (50% average recycled content, and 70% plastic packaging recycled by 2025) targets. Given Australia's current low rate of plastic recovery, it is unclear how these targets will be met with the current technology options. Advanced recycling technologies exist to repurpose plastics into valuable materials that might otherwise go to landfill.

2 Advanced recycling will generate new markets for products in Australia, including monomers, recycled polymers and fuels

There is increasing global and local market demand for recycled polymers. Domestic demand is sometimes being met by imported material. A new domestic advanced recycling industry has the potential to meet domestic demand and export high-value products to meet global demand. Advanced recycling produces food contact compliant recycled polymer, which has advantages compared to mechanical recycling. Independently verified mass balance certification provides the necessary chain of custody and traceability of recycled polymer.

3 Australia has the critical elements to adopt advanced recycling for plastic waste

Australia has major infrastructure (refinery, steam cracker) and polymer manufacturing skills and capability (plastics supply chain), which are essential for processing recycled hydrocarbon intermediate outputs that can be further manufactured into recycled plastics. Technologies at different scales are currently available in Australia. Collaboration across the supply chain is essential and has been demonstrated at pilot scale to work effectively.

Following industry engagement and assessment of themes through the PESTLE framework (political, economic, social, technological, legislative and environmental), the pathway for establishing an advanced recycling industry for plastics in Australia requires the following for success:

- A national discussion about advanced recycling to improve awareness of the range of technologies available, and to facilitate an understanding of where it sits in the waste hierarchy.
- An innovation approach to support pilots, trials with plastic wastes, collaboration across the supply chain and an innovation network to support scale up coordinated, for example, with a national centre.
- Harmonisation of government definitions, policy and approvals to support greater adoption of advanced recycling.
- Government support and engagement, which is essential for launching a new advanced recycling industry.
- Greater differentiation between advanced recycling of plastics and waste-to-energy technologies.
- Full collaboration across the entire supply chain, including waste managers, technology providers, polymer manufacturers, refinery operators, plastics manufacturers/recyclers and brand owners, to match demand with supply of recycled polymers.
- Techno-economic and life cycle assessment (LCA) studies to provide further evidence that technologies are commercially and environmentally sound.
- Adoption of globally recognised certification processes that exist to provide chain of custody verification and market confidence for recycled polymers and plastics that were processed through advanced recycling technologies.

Highlights

- The total Australian consumption of plastics in 2018–19 was just over 3.4 million tonnes with 2.54 million tonnes of plastic waste generated. Currently, Australia recovers 393,800 tonnes per year, which is 11.5% of consumption.
- From 1 July 2021 a total of 149,695 tonnes of mixed plastics is no longer able to be exported and is unlikely to be suitable for mechanical recycling without additional sorting. There is a risk this material will be stockpiled or sent to landfill.
- Advanced recycling can assist Australia to meet the national target of 80% resource recovery rate from all waste streams by 2030 and 70% of plastic packaging recycled or composted by 2025.
- Advanced recycling is complementary to mechanical recycling and accepts mixed, multi-layer, flexible and contaminated waste plastics that might otherwise go to landfill.
- Advanced recycling may be suitable for product steward schemes to address and recover plastic waste, such as almost 100,000 tonnes of agricultural plastics and over 800,000 tonnes of food plastic packaging. It is highly suited to the recovery of 300,000 tonnes of flexible plastic packaging.
- Advanced recycling is positioned above waste-to-energy on the waste hierarchy.
- Advanced recycling encourages pathways that are circular, rather than linear, by retaining material in the economy as part of a transition away from non-renewable and non-recyclable resources.
- Australia has unique technical expertise that would be suited to launching an advanced recycling industry for waste plastics, leveraging existing infrastructure (e.g. refineries and crackers) to recycle plastic wastes. Australia's polymer and plastics manufacturing supply chain is essential to realising benefits of advanced recycling and improved recycling rates of plastics.
- Advanced recycling technologies have a $120 billion annual addressable market in North America (Closed Loop Partners 2019).
- Global market demand for recycled plastics will continue to grow. Top global brands (representing 20% of all global packaging) average 6.2% recycled plastics in packaging where most have targets of 25% (and greater) to reach by 2025.
- Advanced recycling of mixed plastic waste by pyrolysis has a 50% lower climate change impact and energy use than energy recovery by incineration. Its carbon dioxide emissions are comparable to mechanical recycling (Jeswani et al. 2021).
- Technologies are available (four examples described in this report) and the Australian-invented Licella Cat-HTR™ technology converts 85% of plastic mass to hydrocarbon products.
- Advanced recycling produces food contact grade recycled plastics and can be certified with international standards using a mass balance approach.

Advanced recycling in Australia could utilise existing manufacturing infrastructure.
Image credit: Qenos

Table 1: Summary of advanced recycling technologies, polymer feedstocks and outputs

TECHNOLOGY	DESCRIPTION	PREFERRED POLYMERS	OUTPUTS
Purification	Purification technologies produce a polymer so are not generally considered advanced recycling technologies. However, because they use chemicals (solvents) as part of their process they are included for completeness.	3,5,6 – PVC, PP, PS	Polymers
Depolymerisation	Depolymerisation technologies convert plastics back to a monomer. These technologies are commonly applied to PET and may use an enzyme, chemical and/or solvent. It requires a clean stream of material such as plastic bottles (PET).	1,3,6 – PET, PVC PS, nylon and other polymers	Monomers
Conversion	**The following conversion technologies are named as such because they 'convert' plastics back to original chemical building blocks required to manufacture new plastics.**		
Gasification	Feedstock containing carbon is heated and reacted at high temperatures (>750°C) with a controlled amount of oxygen and/or steam to produce energy and a gas called syngas.	2,4,5,6 – HDPE, LDPE, PP, PS	Energy, syngas, ash
Pyrolysis	The thermal degradation of materials in the absence of oxygen. It may be conducted at low or high temperatures generally in the range 400–1,000°C. Pyrolysis may include a catalyst and additives such as hydrogen (known as hydrocracking or hydrogenation), which makes the conversion process more efficient and improves the quality of the oils produced.	2,4,5,6 – HDPE, LDPE, PP, PS	Heavy oil, naphtha (light oil), syngas (and/or other gases) and char
Hydrothermal	Use of high-pressure water as a reaction medium to crack polymer bonds and produce hydrocarbon products. Temperatures may be 250–500°C.	2,4,5,6 – HDPE, LDPE, PP, PS	Heavy oil, naphtha (light oil), syngas (and/or other gases) and char

Note: PVC = polyvinyl chloride; PP = polypropylene; PS = polystyrene; PET = polyethylene terephthalate; HDPE = high-density polyethylene; LDPE = low-density polyethylene

1 Introduction

Globally, there is a plastic waste crisis and the world is looking for innovative circular solutions to minimise plastic waste generation and increase recycling and reuse. The challenge to recover plastic waste is clear. It is estimated that by 2050, our oceans will contain more plastics (by weight) than fish (Ellen MacArthur Foundation 2016), and research has also shown that 95% of seabirds may have ingested plastic waste in their lifetimes (Hardesty et al. 2014). Global scenarios to 2050 show that 60% of plastics produced might be derived from reused or recycled plastics (Hundertmark et al. 2018), with an Australian scenario estimating that by 2030, 50% of plastics might be recycled, based on achieving an 80% average recovery rate (Schandl et al. 2021).

The recycling of plastics is critical to recovering material, adding value and reducing litter. Recycling is a major contributor to realising a circular economy for plastics (see Figure 3). However, there is more than one process for recycling plastics. Mechanical recycling pathways are suitable for well-sorted, single-polymer waste streams – particularly the higher value polymer streams of PET (polyethylene terephthalate) and HDPE (high-density polyethylene). Mechanical recycling produces a clean resin for reuse or an extruded product. Advanced recycling can accept multiple polymer types with a degree of contamination. Technologies convert plastics back into chemical building blocks that are then further processed to produce polymer resins. Advanced recycling can accept mixed, multilayer, flexible or contaminated plastics that mechanical recycling cannot. Further down the waste hierarchy is waste-to-energy where plastics are valued for their high calorific value, however, they are incinerated, which results in the plastics being lost from the economy for future reuse.

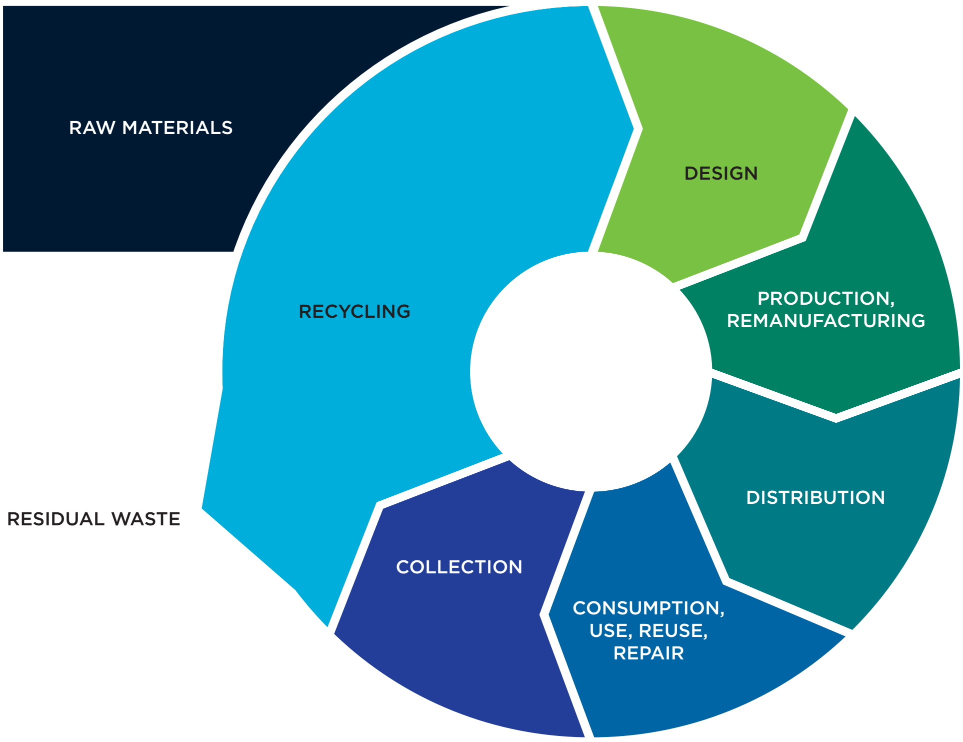

Figure 3: Circular economy

Adapted from image source: Australian Government 2019

Advanced recycling technologies have potential to assist in the recovery of plastics in Australia. It is estimated that feedstock technologies have a $120 billion annual addressable market in North America (Closed Loop Partners 2019). The benefits of advanced recycling are that it is complementary with mechanical recycling and overcomes some of the constraints of polymer degradation found in mechanical recycling. For example, thermo-oxidative degradation that occurs when plastics are melted down, which can make it difficult to continually produce a recycled plastic with the same physical properties as virgin plastics. Advanced recycling thus promotes circularity by improving the recovery and retention of plastic materials in the economy.

The lack of awareness of advanced recycling for plastics represents a risk to Australia in developing a circular economy in relation to plastics and achieving improved plastics recovery outcomes in support of the National Waste Policy Action Plan, National Plastics Plan, and the United Nations Sustainable Development Goals (particularly Goal 12 – Responsible Consumption and Production).

The purpose of this report is to investigate the applicability of advanced recycling to Australia to add value to end-of-life plastics that are not suitable for mechanical recycling pathways, as part of an integrated approach, consistent with the waste hierarchy. By doing so, we aim to address a knowledge gap for plastics recycling in Australia and identify key priorities that support innovation in the plastics manufacturing and recycling industries. This report aims to launch a national discussion on advanced recycling for plastics in Australia.

This report:

- Provides a credible, layperson's reference and guide to advanced recycling for plastics
- Aims to reduce confusion, and increase clarity, consistency and confidence around language and technologies
- Describes polymer types and plastic waste streams and their suitability for advanced recycling
- Describes the relevant factors for Australia in adopting advanced recycling.

Advanced recycling technologies will help address Australia's plastic waste challenge. Currently, each Australian generates an average of 101 kilograms of plastic waste per year, including 59 kilograms of single-use plastic waste (Pickin et al. 2020). An estimated 130,000 tonnes of plastic waste leaks into the Australian environment each year (WWF 2020). The decision by China and other South-East Asian countries to ban the importation of wastes, including plastics, is driving a need for Australia to develop domestic solutions for waste processing and recycling of these wastes, including increasing our waste processing capacity. Following these restrictions, Australia has announced plastic waste export bans, which commenced in July 2021 for mixed plastics and 2022 for unprocessed, single-polymer type plastics. Based on 2018–19 data Australia exported 149,695 tonnes of mixed plastics and 37,695 tonnes of single-polymer type plastics (COAG 2020). In addition, the national packaging targets aim for 100% of packaging (including plastics) to be reusable, recyclable or compostable by 2025, with a 50% average recycled content in packaging, and 70% of plastic packaging to be recycled or composted (APCO 2020).

The total Australian consumption of plastics in 2018–19 was just over 3.4 million tonnes. Of this, consumption can be divided into predominantly single-use applications (33%), long-life plastics (24%) and other/unidentified (34%). Australia's national waste policy action plan, target 3, sets a goal of an 80% average resource recovery rate from all waste streams by 2030 (Australian Government 2019). The Australian national waste report states 2.54 million tonnes of plastic waste was generated in 2018–19 (Pickin et al. 2020), which equates to 74% of consumption. Note that not all plastics consumed each year will reach end of life as some plastics contribute to products in long-lived applications such as buildings, electrical goods or vehicles. Currently, Australia recovers 393,800 tonnes per year, which is 11.5% of consumption.

To provide an estimate of Australia moving towards the national target of 80% average resource recovery for plastics based on available data, an additional 1.6 million tonnes of plastics will need to be recovered. Figure 4 shows the data for 2018–19 consumption and recovery compared to an estimated 80% of end-of-life plastics (just over 2 million tonnes). Note that this is an estimate, (not including any consumption increase) but demonstrates the scale of the plastic waste challenge. This requires significant infrastructure, commitment, and multiple options for processing plastics in Australia. There is a significant challenge for Australia to pivot from disposing of plastics, to collecting and processing waste plastics.

Compounding this challenge is that there is not a single type of 'plastic' and there are different polymers, each with different properties. Plastic products also contain additives and may comprise more than one polymer type. Moreover, there are two types of plastics, thermoplastics (such as PET, PE [polyethylene] and PP [polypropylene]) and thermoset plastics. Thermoplastics are suitable for mechanical recycling. The latter, thermoset plastics, are permanently crosslinked during manufacture and cannot be melted and reformed. Therefore thermoset plastics such as unsaturated polyester or epoxy resins are not suitable for mechanical recycling, other than being pulverised to a fine particle or powder (Hopewell, Dvorak & Kosior 2009).

A summary of different polymer types, their use and recyclability, is provided in Table 2.

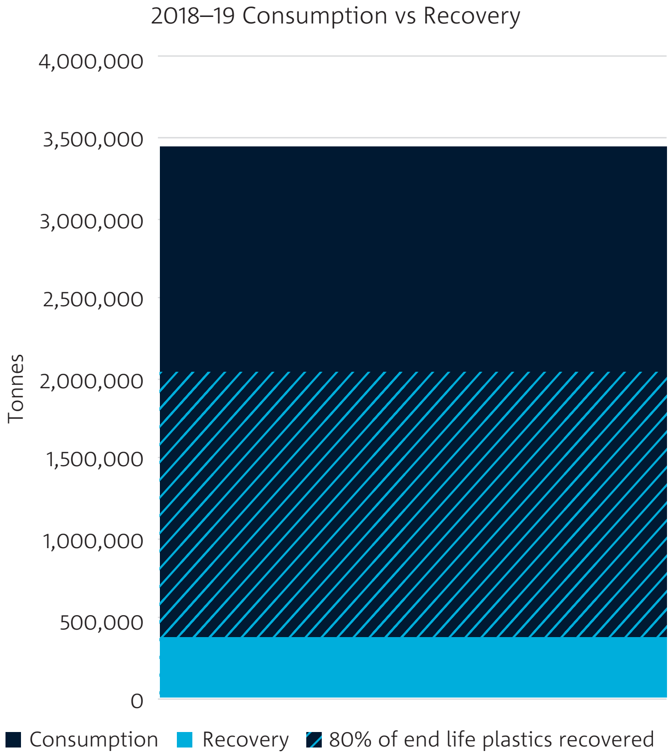

Figure 4: Comparison of current (2018–19) and estimates of future (2030) recovery demand of plastics, in line with national targets

Table 2: Polymer types, use, recovery and recyclability

CODE	NAME	USE	RECOVERY RATE 2018–19	RECYCLABILITY IN AUSTRALIA
1 PET	Polyethylene terephthalate (PET or PETE)	Consumer drink packaging, medicine bottles	21%	Packaging captured in container deposit schemes, existing recycling PET facilities. Good polymer for mechanical recycling pathways. An ideal polymer for depolymerisation.
2 HDPE	High-density polyethylene (HDPE)	Durable containers: detergent, bleach, shampoo, motor oil, milk bottles Cereal box liners, retail bags	19.7%	Municipal waste collection via MRF facilitates. Considered a good polymer for mechanical recycling pathways. When mechanical is not possible, best suited for conversion technologies.
3 PVC	Polyvinyl chloride (PVC)	Packaging: rigid bottles, blister packs Medical: bedding, shrink wrap, tubes, fluid bags Carpet backing, coated fabrics and flooring Construction: ducting, pipes	2%	Collection scheme for some medical plastics. Considered contamination in municipal plastics collections. Opportunities for greater collection in building and construction sector. Undesirable for conversion technologies. Best suited for purification technologies.
4 LDPE	Low-density polyethylene (LDPE)	Bags, film wrap, sealants, wire cable covering	17.3%	Consumer packaging wrap collected by REDcycle in Australian supermarkets. Clean post-industrial film suitable for mechanical recycling. Also suitable for conversion technologies.
5 PP	Polypropylene (PP)	Packaging containers, bottle caps, carpets, flexible packaging	8.9%	Low recycling rate in Australia. Suitable for either conversion or purification technologies.
6 PS	Polystyrene (PS) and Expanded polystyrene (EPS)	Packaging peanuts, Styrofoam, protective foam, insulation, yoghurt pots	11.5%	Growing focus to reduce PS in packaging to meet recovery targets. EPS packaging collected at transfer stations. There is some recycling into the built environment. The majority of what is collected is currently exported. Excellent candidate for purification technologies. Also good for conversion and depolymerisation technologies.
7 Other	A mixture of polymer types: ABS/SAN/ASA, PU, nylon, bioplastic and other aggregated or unknown polymer types	Multilayer barrier films, toothbrushes, some food containers, tyres, waste electrical and electronic equipment (WEEE), etc.	5%	Low recyclability, niche collection and recycling of different polymer types.

Recovery rate data source: O'Farrell 2019

Advanced recycling is suitable for face masks and other soft plastics.

The method for developing this report is based on a literature review of academic, peer-reviewed and grey literature (non-academic reports, e.g. government, not-for-profit, industry reports, working papers, etc.). Report authors also hosted a workshop with 36 industry participants to secure input to relevant factors for advanced recycling in Australia.

This report commences with an overview of plastics recycling pathways, and defines and describes the different advanced recycling technologies. The report then describes the suitability of polymers for different technologies and examples of plastic wastes and volumes (where possible) that are suitable for advanced recycling technologies. Finally, to evaluate the potential application of advanced recycling to the Australian context we present a range of factors (policy, economic, social, technology, legislation and environmental) for consideration. This report concludes with a summary of challenges and opportunities.

Advanced recycling technologies can leverage polymer manufacturing infrastructure.
Image credit: Qenos

2 What is advanced recycling?

Advanced recycling of plastic wastes is also referred to as feedstock, molecular or chemical recycling and encompasses a range of technologies that may involve chemical, thermal or biological processes to convert waste plastics into chemical building blocks. We apply the term 'advanced' to refer to a family of technologies that modify the chemical structure of waste plastics. Generally, advanced recycling converts waste polymers into their original monomers, oligomers, hydrocarbons, or other valuable chemicals, such as energy and fuels, which can be reused as raw materials for the production of new plastics.

A definition of advanced (feedstock) recycling from the ISO Standard (15270:2008) on 'Plastics guidelines for recovery' defines it as:

> Conversion to monomer or production of new raw materials by changing the chemical structure of a material or substance through cracking, gasification or depolymerisation, excluding energy recovery and incineration.[2]

Figure 5 shows the relevant stages of the plastics life cycle (indicated by the arrows at the base), the different types of recycling processes for plastics (e.g. conversion, depolymerisation, purification and mechanical), and technology examples for each recycling process. Lastly, it shows the recycling processes that are included in the advanced (feedstock) recycling standard definition, namely conversion and depolymerisation technologies.

The purification stage has the potential to be considered 'mechanical recycling' (Crippa et al. 2019) as the resulting product is a polymer. However, the primary method for purification uses chemicals (solvents), and as advanced and chemical recycling terms are often used interchangeably, purification is sometimes included as an advanced recycling approach. We have shown it as a separate technology in this report because the production of a polymer does not fit with the definition of an advanced recycling technology, as provided in Figure 5. However, we do describe purification technology as it is part of the broader family of technologies that sit beyond mechanical recycling.

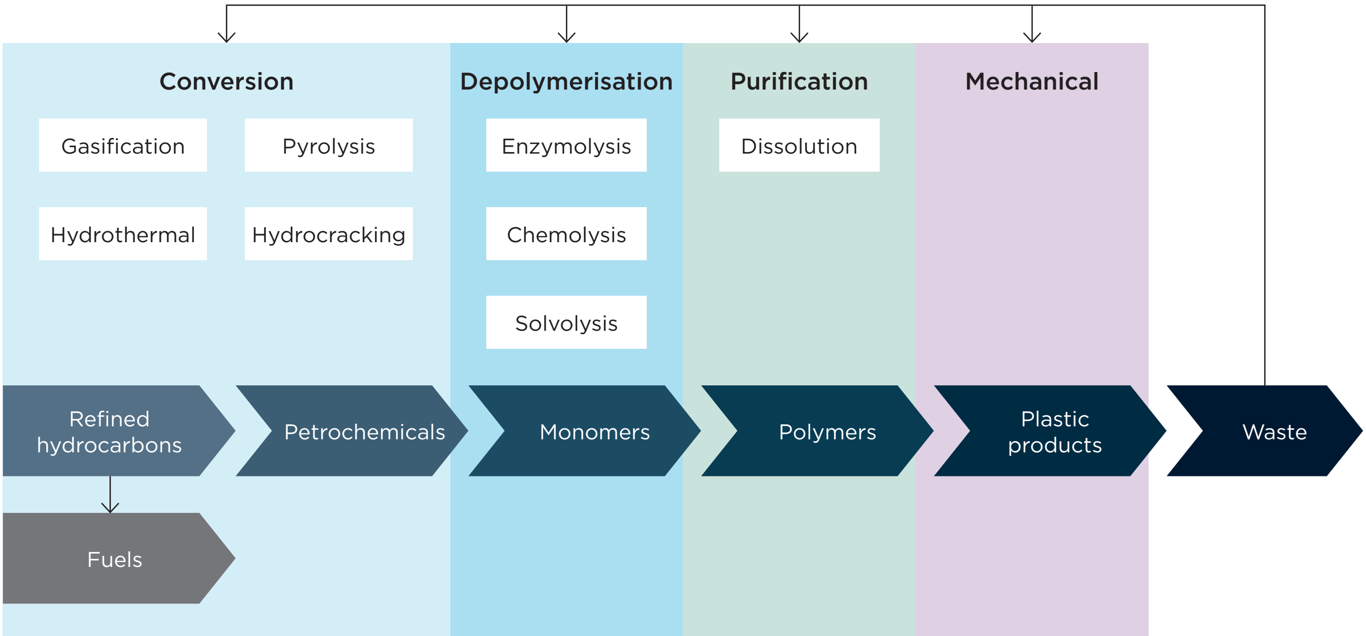

Figure 5: Summary of advanced recycling technologies and their products

Derived from Closed Loop Partners 2019

2 https://www.iso.org/obp/ui/#iso:std:iso:15270:ed-2:v1:en

Another important consideration is the resulting products of these technologies. From conversion technologies, there are three main pathways – waste plastics-to-fuels, waste plastics-to-plastics and waste plastics-to-chemicals. Any technology that converts waste into fuel may be considered waste-to-energy technology (Parliament of Australia 2020). This is an important consideration as pyrolysis may produce a liquid oil and whether it is considered advanced recycling or waste-to-energy depends upon which market or supply chain those products become part of. Any kind of energy consumption is no longer part of a circular material loop and therefore is not considered part of a circular economy (Ellen MacArthur Foundation 2020a). To be considered advanced recycling, a conversion technology should integrate with existing infrastructure for the manufacture of chemicals to produce polymers. This topic is discussed further in Section 4.6.4 Plastics-to-fuels.

The structure of this section is to describe each of the recycling stages presented in Figure 5, commencing with mechanical recycling (which is not considered part of advanced recycling but included here for completeness and comparison).

2.1 Mechanical recycling

Mechanical recycling is a very well-established, mature technology. It is best suited to thermoplastic materials such as PET, HDPE, LDPE, LLDPE (linear low-density polyethylene), PP and PVC and is not generally suitable for thermoset polymers or laminates. Thermoplastics can be continually softened, melted, reshaped and recycled. Typically, waste thermoplastics are sorted by polymer type, chopped, washed, and melted into granulates before being extruded into new plastic products. Europe uses mechanical recycling to recycle approximately 5 million tonnes of waste plastic material per year (Qureshi et al. 2020). Mechanical recycling is most efficient when the waste is pre-sorted by plastics type, and process efficiency and product quality is reduced if mixed plastic wastes are introduced into processing. Polymer degradation also occurs during the recycling of thermoplastics due to the chemical and physical forces exerted during extrusion (Rahimi & Garciá 2017). Mechanical recycling often decreases the tensile strength and elongation at break of rPP[3], the tensile strength for rHDPE, elongation at break for rLLDPE, impact strength of rPP, and causes a multitude of issues for rPET (Schyns & Shaver 2021). Polyethylene has a high thermal stability, which allows it to undergo multiple melt-and-remould cycles in mechanical recycling processes. It has been found that LDPE can be extruded up to 100 times at 240°C, although performance is reduced after 40 extrusions, with significant changes in processability and mechanical properties observed (Rahimi & Garciá 2017). Locally, a trial has shown minimal deterioration in properties of HDPE for milk bottles when mechanically recycled 6 times and 10 times with pure HDPE incorporated at 50% and 70%, respectively (Davies et al. 2021).

Mechanical recycling does not remove all of the colourants or odours from waste plastics. There are mechanical recycling technologies to remove odours including filtration and vacuum extraction of odoriferous compounds during extrusion, washing with surfactants or addition of odour capturing materials, but these add an extra cost to the process (Schyns & Shaver 2021). Generally, the products of mechanical recycling do not meet the requirements for food contact compliant applications. Colours, odours and reduced physical properties ultimately lead to a downgraded product, sometimes referred to as 'downcycling'. Downcycling is mitigated by stringent sorting processes at the front end to ensure coloured or poor-quality plastic waste is removed prior to processing. Despite the limitations, mechanical recycling is an excellent way to recycle high-quality, clean, post-industrial waste and cleaned post-consumer waste to ensure that materials are retained in the market.

Mechanical recycling technologies are a key part of Australia realising a circular economy for plastics, with seven new or upgraded recycling facilities (mostly for rPET) with 145,000 tonnes a year of mechanical processing potential coming online in the next 1–3 years (Envisage Works 2020). One of these recent projects is the collaboration between Pact Group, Cleanaway, Asahi and the NSW Government in Albury, NSW to produce rPET and associated products from high-quality waste PET streams. When considering appropriate recycling technologies for mixed plastic waste, mechanical recycling and advanced recycling complement each other, whereby the polymer and product types more suited to mechanical recovery are avoided for use in advanced technologies.

3 Note: r=recycled

2.2 Purification

Purification technologies take waste plastics and dissolve them in a suitable solvent, followed by a series of steps that remove additives and contaminants before solvent removal (Vollmer et al. 2020). The output is pure precipitated polymer pellets that are largely undegraded by the process and can be reformulated into products. Purification technologies have been used successfully for homogenous waste streams of PS, PE, PVC, PC (polycarbonate) and PP, and for more heterogeneous complex mixtures containing laminates or electric and electronic waste plastics. Technically this is not a chemical recycling process as generally no bonds are cleaved but it is a system that requires the use of solvent chemicals and a deep understanding of chemistry to be successful.

Purification processes use solvents to dissolve a plastic material, with immiscible solvents used to then extract the additives, leaving a purified polymer for recovery. The purification process includes pre-treatment, dissolution of the target polymer at elevated temperatures, filtration of undissolved solid materials, solvent extraction of impurities (such as dyes and flame retardants), reprecipitation and finally, solvent removal (drying or vacuum to recover the solvent). The recovered polymers are then extruded into pellets (Zhao, Lv & Ni 2018). An increasing number of purification-based recycling plants for the treatment of plastic waste are being commercially developed (Closed Loop Partners 2019).

PS is highly soluble in a range of solvents, and this flexibility makes it an excellent candidate for recycling by purification processes. There is an opportunity for PS collection stations to operate small-scale purification processes on-site to reduce the impact of storing collected EPS foam, which can consume a high volume of storage and transportation space. Purification processes for the recycling of PS also enable the removal of common contaminants, such as flame retardants and dyes from PS wastes, not only resulting in a purified rPS stream, but also reducing the impacts associated with improper treatment of these contaminants. Polystyvert Inc. in Canada recycles PS into clean rPS polymer pellets that can then be used to make new PS products (Polystyvet 2020). Dissolution has also been applied to recover PS from construction and demolition wastes using the CreaSolv® process developed by Fraunhofer (Germany). PolyStyreneLoop uses this technology in the Netherlands to recover PS and the banned flame-retardant hexabromocyclododecane (HBCD) (PolyStyreneLoop 2021).

Like PS, the use of purification methods to recycle PP waste has also been demonstrated commercially (Closed Loop Partners 2019). PP wastes are amenable to purification processes for recycling because a selective solvent has been identified that enables impurities to be extracted. PureCycle Technologies in the US uses supercritical butane to dissolve and purify post-consumer PP waste (PureCycle 2021). The technology was originally developed by The Procter & Gamble Company as part of their commitment to reduce the impact of their products on the environment. It is reported that the process produces rPP with the same properties as virgin material. PureCycle plans to be in production by late 2022 with a plant being constructed in Ohio, US, which will have a processing capacity of 48,000 tonnes a year. There are plans for the construction of larger plants in Europe (Acquisition 2020).

PET can be dissolved using a number of solvents and this has been used to recover it from packaging and mixed textile products. Worn Again Technologies uses purification technology to purify PET. Dyes are removed in the first stage, which is done by swelling the plastic, the plastic is then dissolved and filtered to remove any insoluble impurities (Sherwood 2020). While the PET does not acquire any damage to the polymer bonds during the process it does lose some crystallinity which lowers its toughness, stiffness and resistance to solvents (Sherwood 2020).

PVC waste streams have been purified by VinyLoop®, a Solvay (Belgium) technology (Sherwood 2020). PVC was selectively dissolved in an organic solvent then precipitated by steam-driven evaporation of the solvent, which itself was recycled. The process took PVC streams often contaminated with textiles and other materials and produced PVC that was said to be of the same quality as the original material. VinyLoop® was commercialised as a joint venture in 2002 and ran until 2018. The plant in Ferrara, Italy was established to recycle up to 10,000 tonnes of waste a year, primarily cable insulation. Unfortunately, the economics were not viable, largely because the plasticisers in the PVC were not removed in the process. Initially this was thought to be an advantage as the PVC could be used for the same products, but the plasticisers used were subsequently banned by the European Chemicals Agency (Plasteurope 2018).

Purification technology has been applied to separate films containing PE/PP/aluminium foil and recover PC from waste electrical and electronic equipment (Vollmer et al. 2020). APK uses their Newcycling® process in its commercial plant located in Germany to separate films and can process 8,000 million tonnes per year (Vollmer et al. 2020). Waste electrical and electronic equipment has a high proportion of PC that can be extracted using a mixture of acetonitrile and dichloromethane in high yield (>95%) with similar purity and quality to virgin PC (Weeden, Soepriatna & Wang 2015). This method uses 84% less energy and costs less than 30% of the cost of producing PC from petroleum (Vollmer et al. 2020).

Many polymers do not dissolve completely due to their high molecular weight and cross linking. Instead, they soften to allow the infiltration of solvent molecules to dissolve the impurities. In Australia, the organisation PVC Separation has developed a solvent process that can separate laminates and multilayer films but does not require full dissolution of the polymers (Vollmer et al. 2020). In the process a plastic laminate material is infiltrated but not dissolved by a low boiling point solvent. It is then heated rapidly to above the solvent boiling point and the action of the flash evaporation causes the layers to separate. Utilising a similar technology, Saperatec in Germany plans to have a plant (18,000 tonnes a year) operational by the end of 2021 that will separate PET, PE and aluminium foil in laminate materials (Vollmer et al. 2020; Saperatec 2020).

Some of the challenges for purification technologies include the identification of optimum solvents and conditions, the processes associated with safe use of hazardous solvents, and the difficulty in removing the solvent at the end of the process resulting in cost increases and lower quality material. The ideal solvents are environmentally benign, easily recovered and have a high dissolution capacity (Goldberg, Haig & McKinlay 2019). Disposing of the extracted contaminants also requires consideration.

Like mechanical recycling, the product of purification technologies are polymeric material and a small amount of degradation of properties (depending on the process) is often observed. While purification technologies often have limited input streams, they do offer a purer and less degraded product than mechanical recycling. This is because any contaminants are chemically removed. Purification technologies also offer the highest carbon dioxide savings of the various advanced recycling methods because no chemical bonds are broken (Vollmer et al. 2020).

2.3 Depolymerisation processes

Depolymerisation processes for recycling of plastic waste involve breaking down the polymer to constituent monomers or small groups of monomers. These chemicals can then be used to make the same plastic material again, making the manufacture of these products a circular process. Depolymerisation is achieved using chemical (chemolysis/solvolysis), thermal (thermolysis) or biological (enzymolysis) processes. It is most efficient for polycondensate polymers including PET, PA (nylon) and PU (polyurethane). Depolymerisation of polyolefins (PE and PP) is limited due to the presence of strong carbon–carbon bonds, making the application of depolymerisation processes for monomer recovery more energy intensive with a wide range of products for polyolefin polymers (Vollmer et al. 2020).

PET depolymerisation is the most widely used in the plastics recycling industry, and is achieved using a number of different methods (Table 3) (Closed Loop Partners 2019). The simplest method is glycolysis, which converts PET to bis 2-hydroxyethylphthalate and other specialised polyols that can be used to make other polymers (Ragaert, Delva & Van Geem 2017). Coloured PET can still be challenging as the monomers produced can be discoloured and require further clean-up (Rahimi & Garciá 2017). Loop™ Industries takes PET and uses catalytic thermolysis at low temperatures to return it to monomers that can be used to make new PET (Loop Industries 2021).

Enzymatic treatment (enzymolysis) of PET plastics and fibres can convert them back to their original monomers. Carbios (France) has recently announced that they are also able to convert polyester textile waste back to monomers and then into bottles using their scalable PETase technology (Carbios 2020). Textiles to bottles is not possible using mechanical recycling methods. CSIRO has also developed a PETase enzyme that can efficiently break down PET to its original monomers. Enzymolysis can be slow compared to chemical techniques and enzymes may be sensitive to conditions and impurities.

Depolymerisation is an interesting recycling option for PU as it cannot be mechanically recycled (Vollmer et al. 2020). PU has been successfully depolymerised to mixtures of polyols that can be repolymerised to good quality PU by mixing with virgin feedstocks (Sheel & Pant 2018). PU can be depolymerised by hydrolysis and glycolysis (Rane et al. 2015). There are a number of pilot scale plants for the depolymerisation of PU under construction in Germany (Lardiés 2020).

PS can be depolymerised using thermal catalytic methods in the presence of oxygen to produce the monomer styrene. PS can also be depolymerised using high-power microwave technology, and this is in early commercial development with Pyrowave, a Canadian-based enterprise (Pyrowave 2021). This process uses 15 times less energy than manufacturing styrene from virgin resources and offers high yields (95%), with a processing capacity of approximately 750 tonnes a year.

PC can be depolymerised by a number of different chemolysis methods to provide monomers that can be made back into PC or used in other production streams (Emami & Alavi Nikje 2019). Hydrolysis, glycolysis, methanolysis and aminolysis can all be used to depolymerise PC (Antonakou & Achilias 2013). Most of these methods lead back to bisphenol-A, which unfortunately has limited commercial value. It is usually converted to other compounds with greater value during the degradation process. The depolymerisation is complicated by the fact that PC often contains high concentrations of additives (Antonakou & Achilias 2013).

While depolymerisation of PVC is technically possible, the value of the products formed is low and it is not currently economically worthwhile when compared to the manufacture of virgin PVC (Rubio 2021). It can be achieved by thermal degradation in a two-step process, including a low temperature (250–320°C) dehydrochlorination reaction to remove chlorine from the material, followed by higher temperature processing to yield toluene and/or benzene (Yu et al. 2016).

One drawback of depolymerisation as a recycling process is that most methods require a relatively pure input stream of polymer to produce a high-quality product. Other issues include separating the chemical cleavage agent and by-products (an issue for both purity of products and recovery and reuse of reagents), achieving good contact area between the cleavage agent and the solid polymer and recovering dissolved catalysts (Vollmer et al. 2020). Depolymerisation processes will also have unreacted material and other solids that may contain hazardous or toxic residues that will require disposal (Goldberg, Haig & McKinlay 2019).

Table 3: Depolymerisation of common plastics

INPUT POLYMER	PROCESS	OUTPUT	OUTPUT USE
PET (textiles/bottles)	Enzymatic degradation	Terephthalic acid Ethylene glycol	New PET
PET	Hydrolysis	Terephthalic acid	New PET
PET/textiles	Chemical glycolysis	Bis 2-hydroxyethyl terephthalate Polyols	New PET Epoxy, PU, acrylic, etc.
PET	Methanolysis	Dimethyl terephthalate	New PET
PET	Aminolysis	Diamides of terephthalic acid	New chemicals
PS	Microwave degradation	Styrene	New PS
PVC	Thermal	Hydrogen chloride, benzene (<300°C) Toluene (>300°C)	Input chemical industry
PA	Thermal hydrolysis	Caprolactam	New PA
PA	Methanolysis	Caprolactam	New PA
PU	Glycolysis/hydrolysis	Polyols	New PU
PMMA	Thermal	Methyl methacrylate	New PMMA
PC	Alkaline hydrolysis	Bisphenol A	New PC

2.4 Conversion technologies

Conversion processes take waste materials and convert them into much smaller molecules that can be used to make new polymers, new chemicals or fuels. The technologies discussed here include gasification, pyrolysis and hydrothermal processes. The products are separated by boiling point ranges and are either used directly as fuels or processed further before use. This processing can involve refinery processes including distillation, olefins cracking and other petrochemical conversion to produce monomers and other small molecules for plastics, chemicals or fuels.

2.4.1 Gasification

Gasification is a process whereby a feedstock containing carbon is heated and reacted at high temperatures, typically greater than 750°C, with a controlled amount of oxygen and/or steam to produce energy and a gas called syngas. Syngas is rich in carbon monoxide and hydrogen and contains some short hydrocarbons. Small amounts of solid char and tars (often defined as hydrocarbons with a molecular weight greater than benzene) may also be produced. The syngas can be combusted to produce electricity (waste-to-energy) or used as a feedstock for the production of chemicals.

The technology for gasification is well established for processing coal, biomass and to a lesser extent municipal solid waste (MSW). Gasification is usually performed in fixed bed reactors, fluidised bed reactors or entrained flow reactors, which have been designed for specific requirements (e.g. feed material and scale of operation). Plasma gasification is another route for producing syngas. Plasmas generate very high temperatures, which result in high gas yields, very little tar formation and the elimination of toxic compounds.

The input gases (steam, air, oxygen and/or nitrogen) in gasification systems have a significant effect on the syngas produced. Air gasification is the simplest technology as the reaction is self-sustaining, with the energy required being offset by the energy released by reaction of the oxygen in the air and the organics in the feed. The syngas formed contains nitrogen, which makes it more amenable for power generation than chemical manufacture. Gasification with oxygen instead of air produces a higher calorific value syngas free of nitrogen. However, an air separation plant is required, which increases the cost of the process. Steam gasification of waste plastics also generates syngas without nitrogen and maximises the production of hydrogen. However, the process is endothermic, requiring an external heat source to heat the gasifier.

Waste plastics have different properties and are highly heterogenous compared with other feedstocks, which means they can't be processed in conventional gasifiers. The Texaco gasification process is the most well-known for gasification of plastic wastes. It is a two-step process where the plastic is first liquefied to a synthetic heavy oil followed by processing in an entrained gasifier (Ragaert et al. 2020). A major challenge with gasification of waste plastics compared with other feedstocks is the generation of a higher proportion of tars. The tars need to be removed before the syngas can be used. Tar removal can be achieved through additional thermal or catalytic breakdown of the hot tars, or cooling and separation of the condensed tars. All plastics can be processed by gasification. However, due to the chlorine content, PVC can only be processed if the gasifier is constructed of corrosion resistant materials and is fitted with a suitable scrubbing technology to remove the hydrogen chloride produced from the gas. Issues experienced when gasifying waste plastics are generally ameliorated by blending them with biomass or MSW. Co-gasification of waste plastic or refuse-derived fuel from MSW with biomass improves the process because of the synergistic effects of the two different feeds leading to reduction of the sticky ash/tar formed (Yang et al. 2021).

Gasification for processing waste plastics has been demonstrated at commercial scale. EBARA developed a commercial-scale process in 2003 that processes 70,000 tonnes a year of waste plastic at Showa Denko's site in Kawasaki (JGC Holdings Corporation 2020). The technology incorporates a pressurised twin internally circulating fluidised bed gasifier with oxygen and steam injection. The hydrogen and carbon dioxide produced through processing waste plastics is used to produce ammonia for fertiliser production and for products such as dry ice and carbonated drinks, respectively. Powerhouse Energy Group are constructing a waste plastics gasification facility in the UK to generate electricity and hydrogen using steam injection into a rotating drum gasifier (Powerhouse Energy Group 2021). The plant is proposed to have the capacity to process 12,600 tonnes a year of plastic waste. Enerkem has been operating an oxygen/steam fluidised bed gasifier in Edmonton, Canada since 2011 that processes 100,000 tonnes a year dried MSW and converts it into ethanol and methanol (Butler, Devlin & McDonnell 2011).

The gasification industry has seen many abandoned projects due to technical challenges and lack of government support (World Waste to Energy 2020). The main technical challenges for large-scale plastic waste gasification are the large energy requirements, managing the waste tar and ash formed in the process and maximising heat transfer through the reactor.

2.4.2 Pyrolysis

Pyrolysis is the thermal degradation of materials in the absence of oxygen, with or without catalysts. Pyrolysis is usually conducted between 400 and 1,000°C (Goldberg, Haig & McKinlay 2019). It is a mature technology that enables the processing of biomass or waste plastics. There are commercial plants already operating around the world, and industrial and pilot-scale plants are in development in many countries (Qureshi et al. 2020). The pyrolysis plants that are coming on stream currently range in size substantially depending on local need. There are many technologies that are modular and relatively small scale (0.5–10 tonnes a day), such as those developed by Blest, PlastOil, IQ Energy Australia and Plastic2Oil (Closed Loop Partners 2019; Qureshi et al. 2020). Larger systems are also operating with more under development that can process 10–500 tonnes a day. Some of the companies involved include Agilyx (US), which has more than 50 projects in development, and Oursun Resources (China), which has a number of facilities running and is an exporter of pyrolysis technology (Closed Loop Partners 2019).

Plastics pyrolysis involves the degradation of long polymer chains to form a mixture of smaller hydrocarbon molecules. The three major products from pyrolysis are oil, syngas (pyrolysis gas) and char. The oil is often collected in two fractions with different boiling point ranges, namely heavy oil (similar to diesel) and light oil, also known as naphtha (more like gasoline). The oil fraction produced can sometimes be used directly by a furnace, diesel engine, turbine or boiler without further treatment. These products can be combusted for heat production for the pyrolysis system itself.

An issue for the pyrolysis of mixed plastic wastes is the complexity of reactions that occur, especially where they lead to the formation of large complex molecules (Sharuddin et al. 2016). Distillation of the resultant oils will afford a number of fractions; however, sophisticated separation technologies are required to produce pure chemical feedstocks. The oils can be used as a feedstock for refinery industries or olefin (steam) crackers for further conversion and separation into chemicals or fuels displacing natural gas and crude oil as feedstock.

The process of pyrolysis is highly flexible as the operating conditions can be optimised to deal with different input materials and to alter the yield of the various outputs (Sharuddin et al. 2016). Temperature, reactor type, residence time, flow rate, catalyst and type of fluidising gas are all parameters that can be manipulated. What is critical, and perhaps most challenging, is matching the plastics input supply and polymer mixtures with operating conditions and desired outputs. Due to the technical flexibility of processing, pyrolysis can be used to recycle a range of waste plastics, including single-polymer plastic wastes, mixed plastic wastes, plastic wastes contaminated with harmful chemicals and additives, and those that can no longer be mechanically recycled. Elevated pressures lead to increased coke formation and heavy fractions of oil where catalysts are not used (Vollmer et al. 2020). Catalysts result in higher amounts of smaller hydrocarbons and lower liquid yields. One of the benefits of pyrolysis technologies for waste plastics is that they do not cause water contamination like mechanical recycling. By using pyrolysis to convert plastics that are not suitable for mechanical recycling into fuel or feedstocks for refineries there are savings in greenhouse gas emissions, water consumption and energy use compared to using fossilised sources of crude oil (Qureshi et al. 2020).

Though pyrolysis can be useful for recycling a range of mixed and contaminated plastic waste streams, the efficiency of processing, and purity and quality of end products is impacted by the presence of contaminants and purity of inputs for processing (Butler, Devlin & McDonnell 2011). Contaminants such as antioxidants and flame retardants in some plastics will also lead to traces of sulfur, chlorine, bromine, nitrogen and other elements that will impact the purity of the products formed. Thermally degraded materials that contain these elements are more likely to produce molecules that react with each other, reducing process efficiency and leading to the formation of large complex molecules (Butler, Devlin & McDonnell 2011). The resultant end products are usually lower quality and will require further refining using catalytic conversion and/or separation processes.

Pyrolysis is particularly useful for polyolefin recycling, as these plastics are not amenable to depolymerisation processing due to the unreactive nature of the polymer chains. Pyrolysis of polymers such as PE, PP, polybutylene (PB) and PS result in the formation of a range of basic hydrocarbon products that can be further processed into useful materials (Sharuddin et al. 2016). For polyolefins, there is some laboratory-scale research suggesting that pyrolysis processes could produce a feedstock very high in monomers and oligomers that could be used directly to synthesise more plastic material (Donaj et al. 2012). However, it is challenging to produce high yields of single monomer types due to the chemistry of the breakdown of the polymer chains, which is why most pyrolysis processes do not aim to produce these monomers as products (Vollmer et al. 2020).

While PVC plastics are useful for their fire-resistant properties and are found in many products such as cables, hoses and medical bags, they are particularly problematic for pyrolysis processes as they release hydrogen chloride gas, which is both hazardous to the environment and highly corrosive for equipment. The resulting pyrolysis liquid will also contain chlorinated materials, which prevents its use as a fuel or petrochemical feedstock (Ragaert et al. 2020). Pyrolysis can only be achieved once the PVC material goes through a dechlorination step, which adds additional cost to the process. Given the corrosive and toxic nature and low yields of the products, PVC is not considered a desirable polymer for pyrolysis, and only very low contamination levels (0.1–1%) of PVC can be tolerated in pyrolysis of mixed plastics before the outputs are impacted (Miskolczi, Bartha & Angyal 2009). Plasma pyrolysis is robust enough to process complex mixtures containing PVC and produce a syngas that is low in tar and has a high heating value (Solis & Silveira 2020). The technology is robust enough to process complex mixtures, including PVC. The high temperatures limit the formation of free chlorine gas from hydrogen chloride, thus reducing the formation of organochlorines and associated emissions.

As well as PVC, contamination of the plastic feedstock by PET also impacts pyrolysis due to the formation of organic acids, which are corrosive and possess high boiling/sublimation temperatures. The formation of organic acids can lead to equipment contamination and damage and the formation of low-quality oils with high viscosity, high acidity and low calorific values (Jia et al. 2020).

To produce outputs that are higher in quality, the pyrolysis system can include catalysts and/or hydrogen. The pyrolysis reactor system also has a large impact on the nature of the outputs and some common systems are discussed later.

Brightmark

Brightmark is a San Francisco, USA-based company founded in 2016, that develops, owns and operates waste to energy projects employing technology solutions including advanced plastic recycling (or plastic renewal). Brightmark is commissioning a plastics renewal facility in Ashley, Indiana, USA. It will divert 100,000 tonnes of plastic waste each year from landfills and incinerators, converting it into 18 million gallons of ultra-low sulfur diesel fuel and naphtha blend stocks and 6 million gallons of wax. Brightmark is also constructing a 400,000 tonnes per year facility in Macon, Georgia, USA.

Brightmark's plastic renewal facilities take co-mingled plastic waste in single stream, with the ability to renew all recyclable plastics classified as 1–7, including the difficult to recycle plastic types 3–7, especially the single use and multi-layer plastics that are commonly used in consumer packaging. Plastic waste is collected, prepped for conversion by shredding, removing metals, drying, and pelletising. Pellets are then extruded and fed into pyrolysis vessel(s) continuously, and once inside the vessel, the pelletised plastic material is then heated and vaporised in an oxygen starved environment. The vapor is captured, and cooled into a hydrocarbon liquid, which is refined into fuel products (ultra-low sulfur diesel) and paraffin wax. The naphtha and hydrocarbon liquid itself can serve as feedstock for virgin polymers.

PlastOil modular pyrolysis

PlastOil uses pyrolysis technology from Biofabrik (Germany) in their modular plastic processing WASTX system. The compact and fully automated system can convert up to one tonne of plastic per day. The system is designed to offer a decentralised option to plastic waste treatment and produce outputs that can be used locally. The oil produced can be used for combustion engines to generate energy or can potentially be fed into chemical production. The technology was developed in Germany and is currently being tested in locations around the world, including Melbourne.

The pyrolysis system converts plastics (HDPE, LDPE, PP and PS) into a high-quality oil that can be directly used in industry and the community. The system can tolerate small amounts of PET, paper and food contamination, but PVC must be removed. The WASTX Plastic technology modular system takes chopped dried plastic waste with a small amount of catalyst and compacts it using a tamping screw feed to compress the input material, remove air and preheat it. The temperature is then increased up to 500°C with nitrogen gas to break down the material into gas (12%), pyrolysis oil (85%) and carbon black (3%). The system can utilise the pyrolysis gas as a feed material for a generator that can provide up to 70% of the power required by the process.

In Australia, PlastOil is working with the University of Melbourne, RMIT and CSIRO in collaboration with Australian Paper Recovery to identify research needs that support scale up of this technology. Commercial arrangements are currently under discussion and will be unveiled in the coming months.

PlastOil's modular plastic recycling technology, the WASTX Plastic System.
Image credit: PlastOil

IQ Energy Australia

IQ Energy is developing a modular, scalable and containerised advanced recycling unit that will recycle dirty and mixed plastics back into a plastic-derived crude oil or gas that can be further refined into a variety of consumer or industrial products, including virgin plastics. The units are fully automated and containerised and this enables them to be decentralised and replicable so that they can be installed in a range of locations large or small, urban or regional, and regulated or less regulated waste management contexts (e.g. in some areas of South-East Asia).

The plant contains four modules: a thermal dryer, gasifer, thermolyser and pyrolyser. The modules come in two sizes that can be chosen depending on the volume of waste to be processed: 2,500 tonnes a year and 8,000 tonnes a year. The pyrolysis module can be used to convert all plastic types into oil and gas products. Modules can be added to increase the volume of waste that can be processed.

The technology can generate its own renewable energy by utilising the organic matter of feedstock to heat and power the pyrolysis process and consequently increase the yield of 'plastic molecules' available for recycling. The company has a focus on minimising its emissions to the environment. Problematic waste streams can be converted to useful materials, with air emissions such as nitrogen oxides, sulfur oxides and hydrogen chloride converted to salts and solids, which are captured and reused, and work is progressing on carbon dioxide capture. Manufacture of the first project for Canada is imminent with the intent of being operational by the end of 2021.

Catalytic cracking

Catalytic cracking in pyrolysis uses a suitable catalyst to lower the temperature and time required to complete the breakdown of the plastic polymer materials, which can make processing more economically viable (Panda, Singh & Mishra 2010). Catalysts can have many functions that will improve the stability and quality of the end products and process efficiency including hydrogenation of the alkenes, isomerisation of formation products, and removal of heteroatoms (e.g. oxygen, nitrogen and halogens). Catalysts can also reduce the degradation temperature of the polymers (Grause et al. 2011). The type of catalyst chosen will significantly influence the products formed during the process and can generate higher quality products with properties similar to diesel or petrol often with lower molecular weights compared with thermal pyrolysis (Sharuddin et al. 2016). These products are more acceptable to be used directly as fuels.

Catalytic pyrolysis of polyolefins (PE, PP) offers the best results during pyrolysis because the processes used are similar to those in the petrochemical industry. Catalysts are well developed as they are the same or similar to those used in the petrochemical refining sector (Butler, Devlin & McDonnell 2011).

The most common catalysts for pyrolysis are made from silica-alumina, zeolites, clays (montmorillonite, saponite), activated carbon, metal oxides and alkali and alkaline metal carbonates (Panda, Singh & Mishra 2010). Heterogenous catalysts are used most frequently for catalytic pyrolysis. Heterogenous catalysts are in a different phase to the reaction materials, usually in solid form, mixed with gas or liquid.

Poisoning of the catalyst is a significant problem for catalytic cracking. Carbonaceous deposits on heterogenous catalysts often require catalyst regeneration at high temperature (Butler, Devlin & McDonnell 2011). Inorganic materials, heteroatoms (nitrogen, oxygen) and halogens found in PET, nylon, PVC and other difficult polymers, can contaminate the catalyst leading to poor outcomes and high expense. If PET, nylon, PVC or other polymers are to be pyrolysed then the choice of catalyst is very important. PET needs a catalyst that acts to decarboxylate the ester group, releasing carbon dioxide and leaving hydrocarbon rich material (Panda, Singh & Mishra 2010).

Pyrolysis with inline catalytic reforming is often used to decompose unwanted products such as terephthalic acid from PET (Jia et al. 2020). The liquid or gaseous products from pyrolysis are passed over a catalyst bed and as such, the impurities in the plastic waste remain in the reactor, avoiding deactivation of the catalyst (Solis & Silveira 2020). This type of system generates high-quality hydrogen with lower costs than gasification (Lopez et al. 2017).

Hydrocracking

Hydrocracking (hydrogenation) is pyrolysis that uses hydrogen gas in the catalytic cracking process to produce high-quality hydrocarbons with very low levels of toxic by-products such as dioxins (Butler, Devlin & McDonnell 2011). It is usually a two-step process where the pyrolysis step produces an oil or gas that is then passed over a catalyst bed with hydrogen gas. Hydropyrolysis reactors use a fluidised bed reactor containing catalyst and hydrogen gas is fed into the same reactor (Vollmer et al. 2020).

Hydrocracking offers advantages where the output from pyrolysis is required to be a stable product that can be stored with low contamination. Hydrogen is added to the thermal degradation products of polyolefins, which are often unstable, to convert them to more saturated products, alkanes rather than alkenes (Butler, Devlin & McDonnell 2011). The addition of hydrogen reduces the amount of char produced in the pyrolysis system by reacting with the precursors of char formation (Vollmer et al. 2020). Hydrocracking deoxygenates the pyrolysis products so that the system can handle polyolefin material contaminated with some PET (oxygen containing). They also generate iso-paraffins, which are branched hydrocarbons that offer a higher quality fuel product more similar to what you would expect from a refinery fuel (Butler, Devlin & McDonnell 2011). Iso-paraffins are not suitable as input material for crackers that feed into HDPE or PP production as these polymers are straight chains. Disadvantages of hydrocracking are that it often happens at high pressures (70 atm) and can be expensive due to the cost of hydrogen and the equipment required. PVC contamination is a significant problem as its chlorinated by-products deactivate the catalysts used.

Pyrolysis reactor types

There are many different reactor types and these are summarised in Table 4, with an associated summary that compares reactor types and their operational features. Gasification technologies also use similar types of reactors to process waste plastic materials.

Extruders can be used as a pre-treatment that can feed into other reactors. Material passes through an externally heated screw/auger. This has the advantage of removing air and ensuring that the material is well heated and mixed.

Fixed bed reactors are the oldest type of pyrolyser. Reaction occurs in a steel vessel with a fixed bed of material where the products flow out as they heat up and expand and the char remains in the reactor.

Fluidised bed reactors offer excellent temperature control and have excellent heat and mass transfer and can be used with or without catalysts. A gas or liquid stream is used to fluidise the bed material which facilitates the heat and mass transfer and prevents the formation of hot spots. Catalysts can be added to the bed material or in a second reactor to react with the vapours produced. They use heat to vapourise the melt polymer feed while simultaneously cracking the hydrocarbons formed in a continuous system. Drawbacks include the added requirement of an inert fluidising gas, long residence times for mixing, lost bed materials and the necessity for catalyst to be topped up. In addition, scale up presents challenges, and it often provides low liquid yields due to over cracking (Panda, Singh & Mishra 2010).

Bubbling fluidised bed reactors have waste material fed into a bubbling bed of hot sand. The bed is fluidised using an inert gas to give intense mixing and ensure good temperature control and heat transfer.

Circulated fluidised bed reactors work on the same principle as the bubbling fluidised bed, but the bed is highly expanded and solids continuously cycle around an external loop comprising a cyclone and loop seal. Temperature control is very good and solid products are easily removed.

Rotary kiln reactors have been used extensively to pyrolyse waste. The waste material is fed into a rotating vessel where ceramic or metal balls are used to mix the material to avoid char build-up. The heat is supplied via externally heated walls. Rapid heating and short residence time can be achieved. The scale is limited due to the difficulty in heat transfer as the diameter of the vessel increases.

Vacuum pyrolysis reactors pass waste material from top to bottom of the system on a series of heated plates that increase in temperature. Limitations of vacuum pyrolysis include regular fouling of the vacuum pump, challenges with heat transfer and low yields of liquids.

Melting vessels or stirred tank reactors are commonly used to produce chemicals but they have been used to pyrolyse plastic waste. They involve in situ heating by an oil or vapour and use of a catalyst. They suffer from poor heat transfer and require big infrastructure and frequent maintenance.

Table 4: Reactor comparison for pyrolysis of plastic waste

	Temperature control	Heat transfer	Particle size flexibility	Process flexibility	Value of obtained products	Scale up flexibility	Economic feasibility
Fixed bed	Poor	Poor	Satisfactory	Poor	Good	Poor	Satisfactory
Bubbling fluidised bed	Satisfactory	Good	Satisfactory	Good	Good	Satisfactory	Satisfactory
Circulated fluidised bed	Satisfactory	Good	Satisfactory	Good	Good	Satisfactory	Poor
Rotary kiln	Poor	Poor	Good	Good	Satisfactory	Satisfactory	Satisfactory
Vacuum pyrolysis	Satisfactory	Satisfactory	Good	Good	Satisfactory	Satisfactory	Satisfactory
Melting vessel	Poor	Poor	Satisfactory	Satisfactory	Satisfactory	Satisfactory	Satisfactory

Good Satisfactory Poor

Adapted from Qureshi et al. 2020

2.4.3 Hydrothermal processes

Hydrothermal processes are similar to pyrolysis technologies, but these processes operate with the addition of water and are more flexible regarding plastic feedstock compositions. Hydrothermal processes use hot compressed water as a reaction medium to convert complex organic compounds into smaller and simpler products (Qureshi et al. 2020). These conditions make the water a good solvent for dissolving organic compounds, although co-solvents and other materials such as biomass and catalysts are often added to improve the process. Most of the research into this process has centred on biomass biological inputs, but hydrothermal processing has been identified as a promising option for plastics recycling due to the ability to process mixed plastic wastes (Shen 2020). Contamination from glass, metal, grit and stones must be removed, but in contrast to other processes, the plastic wastes do not need to be dried before processing, which can improve process economics (Qureshi et al. 2020). Hydrothermal processing is suitable for complex mixed wastes and hard to recycle plastics, including contaminated PET, carbon fibre reinforced plastics, printed circuit boards, polycarbonate, styrene-butadiene, polylactic acid and nylon. It can also tolerate other organic materials such as paper and food wastes. Processing wastes in the presence of water also stops unwanted side reactions, leading to high yields of stable hydrocarbon liquids with low gas formation (Chen, Jin & Wang 2019). The water also dissolves unwanted side products such as hydrogen chloride and oxygen containing materials. However, the processes are quite energy intensive, and the main output is a complex synthetic oil that usually needs to be upgraded by standard refinery operations before it can feed into production of chemicals again.

Hydrothermal processing is particularly suitable for condensation polymers such as polyesters, polyethers, polycarbonates and polyamides that are also suitable for depolymerisation processes, due to their susceptibility to react with water under thermal and/or catalytic conditions (Pedersen, Thomas & Conti 2017). The recovery of monomers from polycarbonate and styrene-butadiene using hydrothermal processing, has been demonstrated at a laboratory scale (Pedersen, Thomas & Conti 2017). In addition, oil products that are very similar to naphtha and have excellent heating values (48–49 million joules per kilogram) have been recovered from PP using hydrothermal processing (Chen, Jin & Wang 2019).

Hydrothermal processing of PVC, particularly medical wastes, has been successful when a source of lignin is added. The lignin derived from materials such as woodchips prevents agglomeration of hydrochar and assists the dechlorination reaction (Shen et al. 2016). The end product of hydrothermal processing of PVC in the presence of lignin is predominantly hydrochar, with little chlorine contamination, and is therefore suitable for use as solid fuel.

The leading hydrothermal processing technology is the Licella Cat-HTR™ process (Licella Holdings, Australia), which has been demonstrated in pilot scale for processing mixed plastic wastes to recover a synthetic crude oil. This process is scaling up globally and will be adopted to process mixed plastic waste in the UK. Licella can add a distillation fractionation process to their recycled polymer oil (RPO), which will produce high-quality intermediate products (e.g. an ultra low-sulfur heavy oil and naphtha) and intermediate products with minimal contaminants (such as chlorine).

In summary, some of the key advantages of Licella technology are that it:

- has efficient heat transfer and operates at a comparatively low temperature, 450°C, which is associated with producing lower char than other processes
- accepts PET (which can clog pipes and contaminate products in pyrolysis processes)
- is tolerant of contamination (e.g. paper, cardboard) and is therefore good for processing multilayer plastics packaging
- can process thermoset plastics
- is tolerant of some chlorine (from PVC), which washes out with water as a salt.

Licella and CAT-HTR™ technology

Licella Holdings, an Australian-based company, has developed Cat-HTR™, a continuous flow catalytic hydrothermal liquefaction process. Licella uses supercritical water (high pressure and temperature) to break down a range of polymers into light hydrocarbon gases and a liquid product that resembles a high-quality, ultra-low sulfur synthetic 'Plasti-crude' that can be used to make new plastics, chemicals, fuels or road products in the same way as fossil crude. The process feedstock consists of mixed plastic waste including composite polymers, and multilayer, flexible and rigid plastics. The process is not impacted by the presence of contamination from non-plastic materials, such as paper and other organic matter.

Shredded plastic waste is heated and compressed, then combined with supercritical water and the temperature increased. In a separate reactor (the Cat-HTR™), the supercritical water acts to break down the bonds holding the polymers together to create useful short-chain, stable hydrocarbons. At the end of the process, during the depressurisation step, the Plasti-crude can be used as is and co-processed in existing refineries or separated into different outputs such as a naphtha fraction – for new plastics, fuels – diesel and fuel oil – and waxes and residue for use in chemical or road applications. These products can be stored and purchased for application in other industries. While the operating conditions of the technology can be modified to deliver varying output fractions, a general midpoint is a production of 85% liquid, 12% gas and 3% ash.

A number of different scale pilot plants in NSW have trialled and upscaled the technology over the past 13 years. In the UK the first licensee, ReNew ELP, in collaboration with Dow (polymer manufacturer), established the first commercial facility for this technology in Teesside, England. The facility is planned to process up to 80,000 tonnes of mixed end-of-life plastics.

Amcor, Coles, Nestlé and Licella are working with LyondellBasell and iQ Renew to assess the feasibility of a commercial-scale Cat-HTR™ plant in Victoria. It is planned that the plant will process a variety of end-of-life plastics and convert them to oil, which will be used to manufacture new soft packaging materials (ELP 2020).

2.4.4 Conversion technology outputs

The outputs (products) obtained from advanced recycling methods will depend on a number of factors, the most important being the method used, plastic inputs, process temperature, heating rate, catalyst use and other process additives (hydrogen, steam, water). Contamination of the input materials with PVC and plastics containing oxygen, nitrogen or other heteroatoms with affect the quality of all of the output materials.

Figure 6 shows some of the possible pathways for recycling mixed plastic waste by conversion processes. From left to right the diagram shows three different conversion technologies, each of which produce different outputs. These are termed 'intermediate products' as they generally all require further processing (shown in the next stage) before they become final products. The diagram uses purple arrows for products most likely to become fuels, and black arrows for intermediate products heading to a refinery pathway. There are multiple pathways and options, therefore this diagram is a simplification. For example, the syngas product arising from pyrolysis and hydrothermal processes may also include more hydrocarbon gases than is typical for syngas. Note also that syngas produced from gasification may also follow the same path as syngas from pyrolysis and hydrothermal technologies and go directly to a steam cracker to form monomers.

As shown in Figure 6, the main product from gasification of plastic wastes is syngas, and this can be recovered to make useful materials including hydrogen, methanol, ammonia, naptha (light oil) and waxes. It can also be combusted in a plastics-to-fuels pathway. The solid material produced from the processes, such as ash and char, may have useful applications but will most likely need to be upgraded before being a useful material.

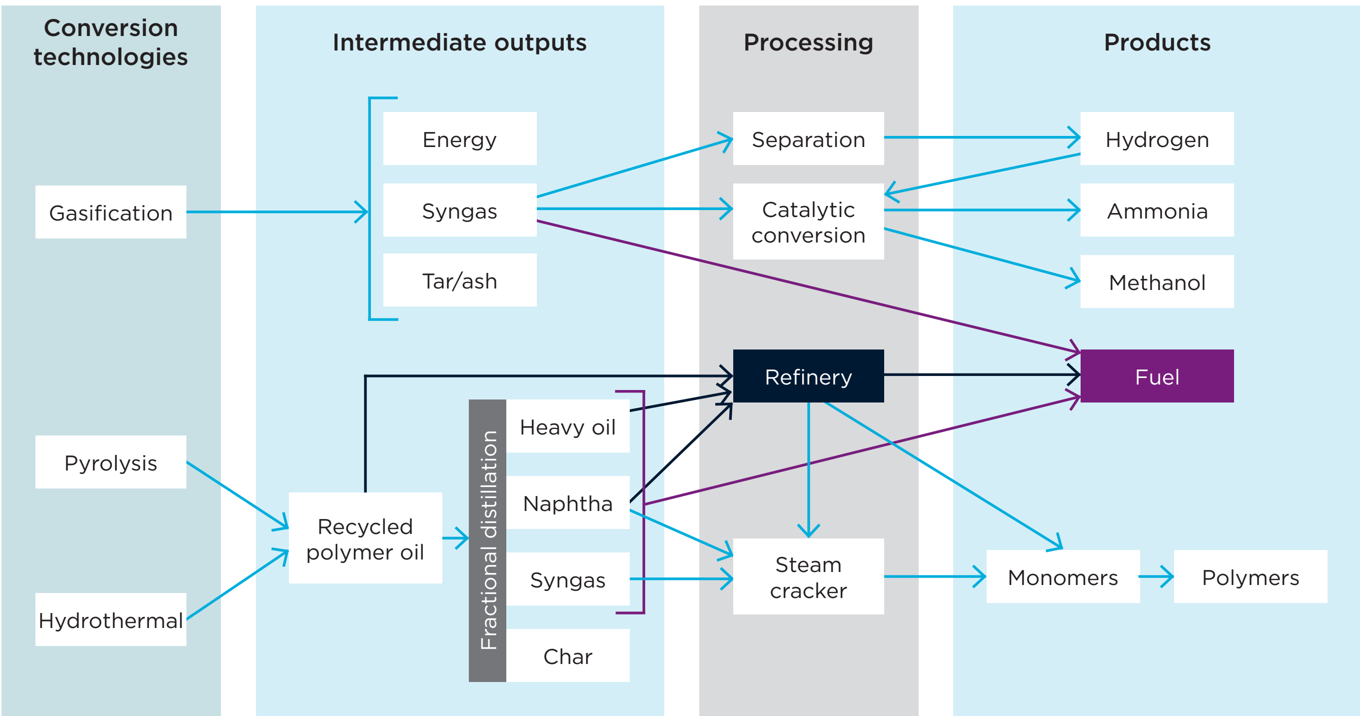

Figure 6: Outputs arising from conversion processes, showing additional processing options and downstream products

The products from pyrolysis and hydrothermal processing are similar, although their actual composition will vary greatly depending on operating conditions, reagents and input materials. The liquid hydrocarbon outputs generated by pyrolysis and hydrothermal conversion processes can be used as fuel, or as reagents to make new polymers. Refineries can incorporate crude naptha or heavy oil from advanced recycling with crude oil and process it to afford chemicals and fuels. Similarly, a steam cracker can take small molecular weight hydrocarbons and, using steam cracking technology, make monomers that can be used to manufacture new PE and PP, respectively. The steam cracker will work most efficiently with input materials that are high in straight chain hydrocarbons and less efficiently with high levels of aromatics and branched hydrocarbons.

Hydrothermal processing produces mainly solid and liquid materials, with more solid material produced at lower temperatures. Continuous hydrothermal processing produces a RPO (recycled polymer oil, sometimes also referred to as 'plasti-crude') that has a wide boiling range. This can be separated by fractional distillation into naphtha and oil fractions. The highest boiling fraction can be used in bitumen or processed by a refinery. The naptha is similar to a petrol fraction and has a number of possible pathways as shown in Figure 6.

Figure 7 gives an indication of the proportions of solid, liquid and gaseous products from gasification, high and low temperature pyrolysis, catalytic pyrolysis and hydrothermal processing of plastic wastes. Generally, low temperature pyrolysis without catalysts leads to formation of (comparatively) a large amount of solid char, a medium quantity of liquid products and a small amount of gaseous products. High temperature pyrolysis produces much less char, with a higher proportion of gases formed. When a catalyst is added to a pyrolysis system, catalytic pyrolysis, it significantly reduces the volume of char produced as there are fewer side reactions. The liquid product produced also increases as does the gaseous component due the more extensive breakdown of the materials. The hydrocarbons formed are more uniform in composition. In comparison, hydrothermal processing of plastic waste material produces low levels of gaseous products and solid char with excellent yields of stable RPO (liquid) produced.

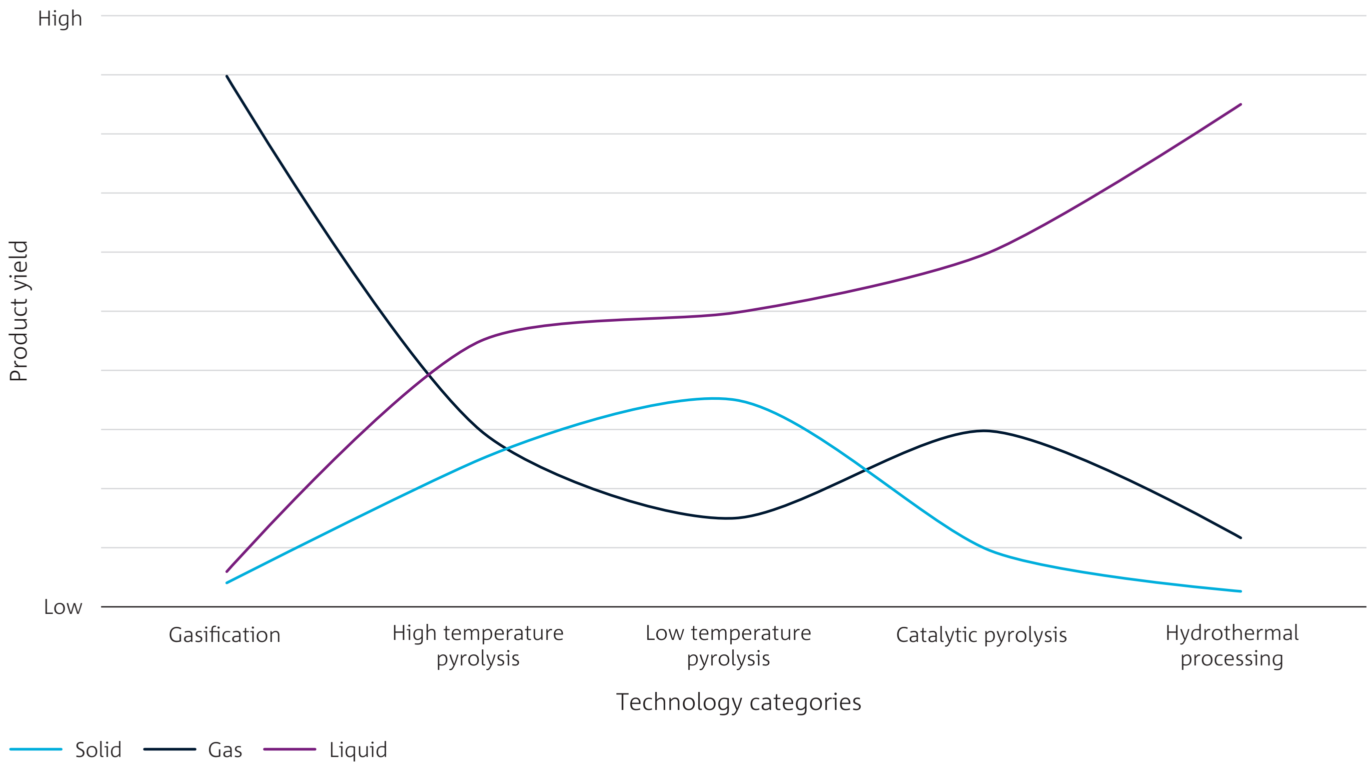

Figure 7: State and indicative yield from various advanced recycling methods

Advanced recycling technologies could generate new opportunities for Australia's manufacturing industry.
Image credit: Qenos

Syngas

Syngas (synthetic gas) is the gas produced from pyrolysis and gasification of carbonaceous material (natural gas, coal, biomass, organic wastes, plastic material). It is a mix of hydrogen, carbon monoxide, carbon dioxide and some short hydrocarbons (Goldberg, Haig & McKinlay 2019). Generally, the higher the temperature of the process the higher the proportion of gases produced. Gasification produces syngas as the major product. The syngas from pyrolysis will contain more light hydrocarbons than gasification and is usually a significantly smaller proportion of the outputs. Catalytic pyrolysis with reforming in its last stage can produce excellent quality syngas too (Solis & Silveira 2020).

Syngas is an important resource for the production of hydrogen, ammonia, methanol and synthetic fuels. Syngas is difficult to sell into the natural gas market as most companies will not want to risk degrading the quality of their product and as such needs further refining (TyreStewardship Australia, Sustainability Victoria & Department of the Environment and Science 2018). Syngas can be burned to provide heat energy to the pyrolysis system or to generate electricity in a gas turbine combined system (Erdogan 2020). The hydrocarbon portion of the syngas can also potentially feed into an olefins steam cracker to lead straight back to PE production. Eastman uses the resulting carbon monoxide and hydrogen from gasification of combined mixed plastics and coal to make acetyl-based products such as cellulose acetate (Tullo 2020).

Hydrogen

Hydrogen gas is produced predominantly from gasification of plastic wastes, although pyrolysis systems can be tailored to produce higher quantities. The hydrogen is separated from syngas using a selective membrane or pressure swing adsorption (Marcantonio et al. 2019). Hydrogen is an excellent energy carrier and its energy can be released as heat through combustion or as electricity using fuel cells. It is used in refining processes to hydrogenate hydrocarbons and increase the energy density of fuels or to produce specific chemicals. It is also used to make ammonia for fertiliser.

Methanol

Syngas from waste plastic gasification can be used to produce methanol. Syngas, hydrogen and carbon dioxide are reacted in a fixed bed tubular reactor at high temperature and pressure using a catalyst to produce methanol (Giuliano, Freda & Catizzone 2020). Methanol is a critical feedstock for the manufacture of other chemical products including formaldehyde, acetic acid and plastics, with approximately 100 million tonnes (~US$32 billion) produced globally each year (International Renewable Energy Agency & Methanol Institute 2021). The methanol-to-olefins process is used extensively to produce PE, particularly in China. Methanol is used directly as fuel for vehicles and boilers, and blended with gasoline. It is a convenient product to transport as it is a liquid and it is able to use infrastructure that other fuels use. It is currently largely produced from fossil fuels, and demand for it has increased substantially since the mid-2000s. The most of the world's methanol comes from syngas produced from the steam reforming of natural gas.

Char

Char is the solid residue left after the pyrolysis or hydrothermal processing of materials that are high in carbon. Char from plastic pyrolysis is often low or negative in value and will generally need to be further treated to form useful products. The quantity and quality of the char from plastic waste will depend on the input materials, and the process variables such as temperature, residence time, heating rate, reactor type and catalyst (Saptoadi, Rohmat & Sutoyo 2016). When heating rates are high, the liquid yield is higher, and the char yield decreases. The quantity of char produced during pyrolysis and gasification is generally low (1–3%) but can be as high as 20% if there are heat transfer challenges with the system (Miandad et al. 2016; Wyss et al. 2021). The char produced in hydrothermal processing is more variable. When polyolefins are the main input to hydrothermal processes, the solid yield is low.

The char will contain some carbon and complex hydrocarbons due to reactions between products and ash. When volatile hydrocarbons have a longer residence time in the reactor and they can repolymerise to form high molecular weight char. Often inorganic fillers are added to polymers to improve the moldability and stability of plastics, particularly in more rigid and complex materials. These inorganic materials will remain and become part of the recovered char/ash. If input materials are contaminated with dirt (likely from agricultural plastics), metals from foils and dyes, or other additives, these contaminants will also be present in the char.

Depending on the quality, the char can be briquetted and used for heating or to adsorb heavy metals and toxic gases in water or air filtration systems. Char can also be used as an additive to asphalt or as a colourant for plastic materials including tyres. A recent publication has shown that flash joule heating of pyrolysis ash from waste PP can produce excellent yields of high-quality turbostratic graphene in the laboratory (Wyss et al. 2021). When added, the turbostratic graphene improved the performance of cement and polymers.

If pyrolysis is efficient and the plastic input is low in contaminants, carbon black will be the main component of the char recovered. Carbon black has a value of approximately $900–$1,000 per tonne (Randell, Baker & O'Farrell 2020). Carbon black is mainly carbon in para-crystalline form that has a high surface area to volume ratio. It is widely used as a pigment in tyres, where it acts to increase thermal and abrasion resistance to extend their life. Carbon black is also used in other non-tyre rubber goods including as an additive to PP where it acts as an ultraviolet stabiliser.

Heavy and light oils, and waxes

The oil from the advanced recycling of plastic waste is often collected in two different boiling point ranges, with a heavy oil fraction (hydrocarbons with greater than 12 carbon atoms; comparable to diesel) recovered between 150 and 380°C and a lighter oil or naphtha (hydrocarbons with 4–12 carbon atoms; more comparable to gasoline or naphtha) recovered between 35 and 200°C (Vollmer et al. 2020). Heavy oil varies in composition depending on the process, conditions used and input material. It is often comparable in properties to a conventional diesel and can be used as an energy source for boilers and furnaces.

The oil from pyrolysis may contain chlorine, moisture, organic acids, sulfur and solid residues. Further purification will be necessary to produce a high-grade fuel if these are present. Where contamination is minor it can be blended with diesel fuel. The analysis of various blends from different pyrolysis oils has consistently shown positive results, with lower carbon dioxide emissions from the blends than diesel alone (Erdogan 2020). However, there was a general increase in nitrogen oxide and carbon monoxide emission with increasing plastic oil in blends.

Naphtha (light oil) is similar in properties and composition to petroleum fuel. Recovered naptha is often blended with crude oil and processed in a refinery or used directly as a fuel. Where the naptha has a higher proportion of smaller straight chain hydrocarbons it would be a useful input for an olefins steam cracking system. Octane numbers for the light oil fraction are generally lower than for conventional gasoline because of the large amounts of straight chain paraffins present. It is more beneficial to have branched paraffins and aromatics for combustion in vehicles (Ragaert, Delva & Van Geem 2017).

Waxes form a large part of the products of PE and PP recycled by low temperature thermal pyrolysis without a catalyst present (Arabiourrutia et al. 2012). They are also a product of hydrothermal processing. The waxes are typically high molecular weight hydrocarbons with boiling points in the range of 343 and 525°C, and these can be used to produce lubricants and coatings. To return it as a feedstock for plastic materials, waxes can be catalytically reformed and separated in the same manner as crude oil or fed back into the process to break them down into smaller molecules.

Undesirable by-products

A clear understanding of feedstock materials is required to monitor and mitigate environmental and human health risk from advanced recycling. All advanced recycling plants will have to consider how to capture gas and liquid emissions as both are potentially harmful to human health and the environment (TyreStewardship Australia, Sustainability Victoria & Department of the Environment and Science 2018). Some of the gases may be produced in the conversion process or when combusting the gases for energy include sulfur dioxide, nitrogen oxides, hydrogen sulfide, ammonia, dioxins and furans, hydrocarbon gases, carbon dioxide, carbon monoxide, formaldehyde and hydrogen cyanide as well as particulate matter (TyreStewardship Australia, Sustainability Victoria & Department of Environment and Science 2018).

Dioxins and other toxic heteroatom containing by-products (e.g. containing oxygen, nitrogen, sulfur) can be removed from oil products by hydrocracking after the pyrolysis step. If PVC is included in the recycling process, a pre-treatment step to remove the hydrochloric acid will be required and systems to manage the resultant acidic gas, including scrubbing with a basic chemical solution, will need to be installed. Although the hydrochloric acid captured by the scrubbing system can be recovered, it will be contaminated by some light hydrocarbons and is unlikely to be able to be reused. Scrubbing systems to remove hydrogen sulphide may also need to be considered.

Often systems are designed to use the gas produced in pyrolysis to power a generator to provide heat energy for the process, which will reduce gas emissions. If not consumed in the process, to control air pollution, a thermal oxidiser (after burner) can be used to decompose gaseous air pollutants through chemical oxidation. Gasification and pyrolysis produce less direct air emissions and residues than incineration (Demetrious & Crossin 2019).

The char can be contaminated with inorganic materials, ash, aluminium from foil and possibly heavy metals from dyes and glues used in plastic products (Goldberg, Haig & McKinlay 2019). To mitigate the contamination the system can preferentially use plastic materials that are rich in soft plastics and transparent polyolefins that are low in these materials. Float sink techniques can be used to separate char and ash but the char may need to be disposed of in landfill.

If the naptha or heavy oil are to be used as fuels there are limits for certain contaminants. The regulations are far more restrictive for gasoline than for diesel. Polyaromatic hydrocarbons are a common side product from pyrolysis reactions. These are required to be less than 8% of diesel fuel in Europe, and while usually lower proportions are formed during pyrolysis this will need to be monitored (Gala et al. 2020). There are also limits on moisture and benzene (<1%) and the acidic components that may come from PET.

2.5 Waste-to-energy

Incineration and thermal technologies that produce energy as their primary product are common in Europe. Annually, waste-to-energy plants in Europe contribute 39 terawatt hours and 90 terawatt hours of electricity and heat, respectively, and are estimated to prevent about 50 million tonnes of carbon dioxide emissions that would otherwise be generated by fossil fuel production (Levaggi et al. 2020).

Waste-to-energy is considered a recovery process, and as such falls second to last on the waste hierarchy (recover) before disposal (landfill). Waste-to-energy technologies are not considered as truly circular, given that they follow a linear path, resulting in the downgrading and/or permanent loss of materials from the economy. However, it is argued that in creating energy and fuel by-products, waste-to-energy may contribute to circularity through production of new materials. There are substantial environmental and economic burdens, with waste-to-energy processes producing significant environmental emissions and chemical wastes. Waste-to-energy processes are energy intensive, with high capital and operating costs. Incineration of plastic materials generates substantially less energy then the energy conserved by recycling (Rahimi & Garciá 2017).

Waste-to-energy processes accept gross MSW (municipal solid waste) diverted from landfill, of which plastic waste can be a subset component. The presence of plastic waste in the input feed of waste-to-energy processes can be useful, due to their high calorific value, which allows the processes to operate with a stable calorific intake and maintain process efficiency. However, these processes are generally unable to process single waste streams. As such they are a solution for highly mixed and low-quality waste streams that cannot otherwise be upgraded or recycled, and for wastes that are not suitable for mechanical or advanced recycling.

In late 2020, it was reported that the Australian Renewable Energy Agency (ARENA) invested $98 million in 25 waste-to-energy projects across Australia (Parliament of Australia 2020). Australia's first large-scale thermal waste-to-energy plant is under construction in Kwinana, WA (Avertas Energy), with completion due late 2021. The facility is proposed to divert 25% of Perth's post-recycling waste from landfill and to generate 36 million watts of baseload electricity for the grid (ARENA 2020a). A second thermal waste-to-energy plant has been approved in WA (Acciona and Hitachi Zosen Inova), which will increase the WA waste-to-energy capacity further, diverting another 300,000 tonnes of MSW from landfill, and generating 29 million watts of power (ARENA 2020b, 2020a). There are other projects in the pipeline for other states such as QLD (ARENA 2020a).

Though waste-to-energy processes have a role to play in the recovery of energy, fuels and other value adding by-products, it is largely accepted by the Australian federal and state governments that waste-to-energy processes should complement other material recovery and recycling processes, with the goal of more broadly improving waste management outcomes in Australia (Parliament of Australia 2020). As such, WA, Victoria, NSW, SA and QLD all have policies and position statements addressing the use and targets associated with waste treatment by waste-to-energy processes, and there are moves to harmonise these policies across jurisdictions. In 2020, the Victorian Government announced that it would cap waste-to-energy for 1 million tonnes of MSW per year to 2040, with significant investment made for innovations in waste management that complement energy recovery processes (DELWP 2020).

Gasification technologies can be used to produce useful products that can be converted into new chemical products or used as waste-to-energy processes. Gasification technologies can be used to process waste plastics exclusively, or are more commonly applied to MSW (containing waste plastic) as waste-to-energy technology. Seven Thermoselect gasification plants have been operating in Japan since the mid-2000s processing unsorted MSW at throughputs of up to 100,000 tonnes a year (Yamada, Shimizu & Miyoshi 2004). Many gasification systems worldwide are now moving towards the production of useful products, including hydrogen, rather than just energy generation.


Alpina
Vit.C
Coca-Cola

3 Plastic waste supply for advanced recycling

Advanced recycling technologies require a plastic waste supply. The quality of outputs depends on the polymer type or plastic waste being processed, along with technology type and operating conditions. Advanced recycling in Australia requires a clear understanding of the production, consumption and generation of plastic wastes, and the suitability of these wastes for the conversion processes of pyrolysis and depolymerisation.

This section commences with a description of the types of polymers available and their suitability for different technology options. It next describes the segments of the plastic waste market (e.g. mixed plastics, soft/flexible plastics) that may be more suitable for advanced recycling. Advanced recycling is ideal for plastics that do not already have a mechanical recycling pathway. In this sense, it is highly complementary, and not competitive, with mechanical recycling. Plastics that are difficult to mechanically recycle include plastics degraded by environmental conditions, thermoset plastics and plastics with high levels of additives. Also, mixed plastics, laminate materials, and dirty or contaminated plastics are difficult to mechanically recycle. In general, plastics degrade over time and by exposure to heat, light and chemicals. Plastics also contain fillers, such as calcium carbonate, silica, carbon black or metal oxides (for colour). These minerals are insoluble and create issues for mechanical recycling.

3.1 PET (Polyethylene terephthalate)

PET is one of the most widely used plastics for packaging due to its intrinsic properties, colourlessness, heat and cold stability, and durability. PET is a condensation polymer that contains oxygen. It is widely used in packaging foods and beverages, especially soft drinks and juices. PET is also used in clothing, films and moulded parts for automotive and electronic applications. To produce a high-quality mechanically recycled output the plastic needs to be sorted by colour and graded. Often PET bottles are recycled into lower grade thermoforms or fibre (downcycling) because it is challenging to maintain the physical properties and avoid discolouration in mechanical recycling.

PET has existing mechanical recycling pathways in Australia and clean collection systems such as container deposit schemes. The value for clean PET bales has ranged from $400 a tonne (2019) to $230 a tonne (2020) on the local and export market. This compares to a value of virgin PET resin of around $1,400 a tonne (Envisage Works 2020).

PET can be a problematic feedstock for pyrolysis as it decomposes to phthalic acids, which deteriorate the quality of the oil produced and can lead to clogging of the pipes in the system (Qureshi et al. 2020). PET pyrolysis oil contains benzoic acid, which results in lower calorific value of the oil (30 million joules per kilogram), making it a less desirable polymer type (Sharuddin et al. 2016). The use of catalysts and hydrocracking can improve the quality of the products obtained from PET, but it would be best if the system was designed around PET waste material. The products formed would be largely gaseous in a successful pyrolysis system for PET due to the conditions needed to minimise the deleterious products (Sharuddin et al. 2016).

Hydrothermal processing would be an excellent option for conversion of PET to hydrocarbon products, particularly with mixed waste systems. In a typical hydrothermal system, the water acts as a hydrogen donor and increases the amount of hydrogen in the product while also reducing the oxygen content. The oxygen in PET is able to be reduced in hydrothermal systems (Seshasayee & Savage 2020).

The most desirable chemical recycling option for PET is depolymerisation as it requires less energy and returns PET to its monomers. This can be achieved with biological degradation using PETase technology to depolymerise the PET back to monomers for manufacture back into PET. PET is readily converted back into its monomers or similar building blocks for other chemicals by chemical depolymerisation reactions (Closed Loop Partners 2019). The most advanced depolymerisation recycling processes have been developed for PET because the market is predominantly in food packaging, which has stringent quality requirements (Goldberg, Haig & McKinlay 2019). A number of commercial plants currently use these technologies to provide feedstocks for the production of new PET.

3.2 HDPE (High-density polyethylene)

HDPE forms a large part of municipal plastic wastes. It has high strength and is used widely in detergent bottles, oil containers, toys and many more products. HDPE is a polyolefin with long straight chains with very little branching and is well suited to conversion technologies. The price for washed and flaked HDPE has fluctuated from $400 to $650 a tonne. The price for virgin resin is around $1,400 a tonne, as at October 2020 (Envisage Works 2020). Mechanical recycling pathways are possible for PE products, which generally involve downcycling to materials that are not food contact compliant (laundry detergent bottles, pipes, benches, etc.). In Europe, technology has been developed to take waste rigid HDPE (milk bottles) and mechanically recycle it into new food contact compliant materials with two plants currently supplying the dairy industry in the UK (Goldberg, Haig & McKinlay 2019). Currently the best way to make recycled material from HDPE food contact compliant (US Food and Drug Administration approved) is via advanced recycling.

The pyrolysis of HDPE has been studied extensively and it produces excellent oils when pyrolysed at reasonably high temperatures (550°C). Catalysts are preferred in the pyrolysis as they lower the temperature required and produce liquid materials that are easy to handle. As the temperature increases above 550°C then the proportion of gaseous products increases steadily. Fuels obtained from pyrolysis of HDPE tend have good calorific values (42.9 million joules per kilogram) comparable to gasoline (43–46 million joules per kilogram) and are generally suitable to be used without much upgrading (Kumar & Singh 2011). HDPE is also well suited to gasification as it produces relatively clean gaseous products with low tar production. Hydrothermal processing will also effectively convert waste HDPE into oils.

3.3 PVC (Polyvinyl chloride)

PVC is widely used in the construction industry as it is inexpensive, rigid and durable with high environmental resistance. However, due to the chloride in its polymeric structure, recycling at high temperature results in the release of free hydrogen chloride gas, which is corrosive to plant and contaminates the end products (Rahimi & Garciá 2017). In addition, PVC often contains plasticisers, fillers and dyes, which make it a difficult waste to recycle due to technical limitations (contamination) and environmental restrictions (emissions). In 2018–19, PVC formed 11% of plastic consumed in Australia (O'Farrell 2019). The extensive use of PVC in the community causes issues with the contamination of plastic streams that are co-collected for recycling, especially if the recycling process is based on thermal conversion. For these processes, the tolerance to PVC contamination is very low (0.1–1%) (Miskolczi, Bartha & Angyal 2009). Even PET mechanical recycling tolerates less than 50 parts per million PVC as the acids formed during extrusion cause the rPET to be brittle and yellowish (ASG 2021).

There is a need for conversion technologies to pre-sort their mixed plastic input to ensure there are very low levels of PVC. Waste reprocessors are concerned that PVC packaging is a continuing issue in recycling streams as it causes problems in both rigid and flexible packaging recycling (O'Farrell 2019). PVC packaging has been banned in Canada, Spain, South Korea and the Czech Republic, with other countries limiting its use (Center for Health 2021). Australia will phase out PVC packaging labels by December 2022 (Pickin et al. 2020). It is well known that chlorinated compounds, including PVC, are harmful and undesired in recycling systems, as they cause corrosion and poison catalysts. A pyrolysis study conducted with PE, PP and PS with 0–3.0% PVC examined the effects of increasing concentration of PVC (Miskolczi, Bartha & Angyal 2009). They found that chlorine was found in all products and levels increased with the amount of PVC pyrolysed.

Given the challenges with thermal processing of waste PVC, mechanical recycling is a good option. However, due to the high level of additives and contaminants care should be taken to sort it and process it with only like materials, so as not to contaminate secondary products. In addition, purification can be used to recycle PVC as it is soluble in certain solvents, although it is technically challenging to separate out the plasticising agents and this makes reuse difficult. VinyLoop®, a PVC waste recycling purification plant in Italy, used butanol as a solvent and steam as an anti-solvent to recycle PVC from flexible cables to produce rPVC that would be suitable for the same use (Plasteurope 2018).

3.4 LDPE (Low-density polyethylene)

Like HDPE, LDPE is made from ethylene but with more branched molecules, which reduces the density of the plastic. In comparison, LLDPE is a substantially linear polymer that has frequent short branches. LDPE and LLDPE are used in rigid containers including bottles, containers and lids and as flexible materials such as films, plastic wrap, pouches, bags and cable covering. Australia uses around 400,000 tonnes a year of LDPE and LLDPE plastics and around 17% of this is recovered (O'Farrell 2019).

LDPE/LLDPE are suitable for mechanical recycling and the material can be processed many times without noticeable loss in properties (Rahimi & Garciá 2017). However, it is often used in laminate materials, where it is difficult to separate from other materials via mechanical recycling. Solvent-based purification technologies are available for LDPE/LLDPE (Vollmer et al. 2020). LDPE behaves in much the same way as HDPE when it is treated using advanced recycling methods, affording high-quality hydrocarbon liquids (see Section 3.2).

3.5 PP (Polypropylene)

Polypropylene (PP) is a versatile polymer, with a high melting point and high durability, and is resistant to acids and bases. It is used in robust products from car bumpers, rigid food packaging, polymer bank notes and face masks. Australian consumption of PP is around 500,000 tonnes a year, of which around 45,000 tonnes a year is recovered for recycling here or internationally (O'Farrell 2019). Municipal PP will often end up in mixed plastic bales when sorted in Australian materials recycling facilities (MRFs).

PP is suitable for mechanical recycling as it is a thermoplastic polymer. It is often coloured and has additives incorporated to enhance its properties like other plastics, which makes thorough separation important before recycling.

As with other polyolefins, PP is readily converted to hydrocarbon materials by conversion technologies, although it often contains more fillers and as such more ash will result when it is pyrolysed or gasified (Sharuddin et al. 2016). Purification is an excellent option for PP to remove dyes and additives and return excellent raw material using supercritical butane (PureCycle 2021).

3.6 PS (Polystyrene)

While PS and EPS (expanded polystyrene) are used less in Australia than other plastic materials, their use is increasing. In 2018–19, 77,000 tonnes a year of PS was consumed in Australia with a very low recovery rate of 11.6% (O'Farrell 2019), and there are not current markets for recycling of rigid polystyrene (APCO 2020).

EPS is lightweight, durable and an insulator and used extensively for protecting fragile items in transport and for extending the shelf life of fruit, vegetables and seafood. The collection of expanded polystyrene is challenging as it is not collected in kerbside bins due to its likelihood to break up into many pieces. Its large volume means that it takes up considerable space and while it can be collected at transfer stations it often ends up in landfill. While there are challenges with collection of polystyrene it is possible to use a variety of advanced recycling methods to recycle it.

PS and EPS are excellent candidates for purification technologies in all its forms due to their high solubility in a range of solvents. An excellent solvent for PS is cymene, a natural terpene-based solvent, which has been successfully used to dissolve PS. In Canada, collection stations immerse expanded polystyrene straight into cymene to dissolve it on site, substantially concentrating its volume and making transport significantly easier (Polystyvet 2020).

PS offers greater flexibility than other polyolefins in its conversion as it can be pyrolysed in controlled conditions to produce monomers (Crippa et al. 2019a). PS degrades at the lowest temperature of all plastics, and when a pure stream of PS is pyrolysed the monomers toluene, ethylbenzene and styrene are produced (Muhammad, Onwudili & Williams 2015). It is suitable for pyrolysis with other plastics and will increase the proportion of aromatic hydrocarbons in the recovered oils, increasing their suitability as fuels.

3.7 Mixed municipal plastics

After kerbside collection, municipal waste is sorted and separated out into materials including paper, steel, aluminium, cardboard, glass and plastic at a MRF. The plastic waste stream is then further sorted to recover PET and HDPE and a residual fraction, which is known as mixed municipal plastics. The mixed municipal plastic waste fraction usually contains code 3–7 plastics (Table 2), with residual quantities of PET and HDPE (Envisage Works 2020). Mixed municipal plastic waste that was recovered at MRFs was baled and exported overseas for treatment.

In 2018–19, Australia exported almost 150,000 tonnes of mixed plastics, which comprised 80% of the value of all waste plastics exports ($43 million) (DEE 2019). However, the China National Sword Policy, and the newly established Australian ban on the export of mixed plastic waste (commenced 1 July 2021) is driving a shift for Australia to recycle and recover our own wastes. Concurrently, the establishment of the Recycling Modernisation Fund (RMF) has the goal of developing new recycling infrastructure to increase local recycling and waste treatment capacity (Table 5). The RMF funding is provided to state and territory governments, who are primarily responsible for managing the collection and disposal of waste in Australia.

The National Waste and Recycling Industry Council reports that there is a 80,000–90,000 tonne shortfall in Australia's ability to locally process mixed plastic waste that is now diverted from export pathways (Read 2021). Despite there being established recycling pathways for some plastic waste streams via mechanical recycling in Australia, baled mixed plastic wastes are not always suitable for mechanical recycling due to the presence of polymer mixtures and other contamination. While mixed waste exports decreased by around 50% in 2019–20, advanced recycling can offer a pathway for the recovery of value from mixed plastic waste and contribute to achieving resource recovery targets set by the Australian Government.

Table 5: Exported mixed plastics compared to RMF infrastructure investment

JURISDICTION	MIXED PLASTICS EXPORTS 2018–19 (TONNES)	RMF PROJECTS PROCESSING CAPACITY (AS AT 31 MARCH 2021) (TONNES)
NSW	68,878	16,000 (Suez) + grant process underway
Victoria	58,500	20,000 (Cleanaway)
WA	11,897	35,000 (3 projects)
QLD	8,131	Nil
SA	2,041	Grant process underway
ACT	1,771	1,800 (MRF upgrade)
Tasmania	170	Grant process underway
NT	20	Nil
Total	**149,695**	**61,800**

Source: COAG 2020 and Read 2021

Mixed plastic wastes are more complicated to process by advanced recycling methods than pure streams of plastics. For efficient processing by advanced recycling it is likely that mixed plastic wastes would need sorting and cleaning to remove contaminants such as organics, PVC, textiles or residual metals. The addition of pre-sorting processes will increase the costs of production of raw materials and appropriate techno-economic assessments would be required to quantify the viability of processing mixed plastic wastes via advanced recycling. Mixed wastes cannot be processed using depolymerisation or purification technologies due to their different compositions and solubilities.

For recycling plastic mixtures, it is important to consider the plastic inputs into the advanced recycling system as each plastic has optimum degradation temperatures and conditions (Grause et al. 2011). There are complex interactions between products formed and this is increased when more complex mixtures are used as inputs. The most suitable technologies for mixed plastic waste are gasification, catalytic pyrolysis and hydrothermal processing (Solis & Silveira 2020). For all technology used for recycling of mixed plastic wastes, a clear understanding of the composition of the input materials is required to ensure process optimisation and efficiency, and to determine the quality of end products.

Gasification is generally less sensitive to PVC and PET contamination that may occur in mixed plastic waste inputs. However, the tar generated by processing mixed plastic wastes would be more complex, and pathways for recovery and reuse of these residuals may be more complicated (Ragaert, Delva & Van Geem 2017). As with the processing of pure plastic waste streams, the formation products are mainly gaseous (hydrogen gas, carbon dioxide and small hydrocarbons), and these can be separated by conventional technologies developed for existing gasification technologies.

In contrast to gasification, pyrolysis of mixed plastic wastes is more challenging. When working with mixtures, it is necessary to operate at temperatures higher than that of the highest melting plastic, which is more energy intensive when compared to processing single stream wastes. Although, higher liquid material recovery is achieved when using higher temperatures; this can lead to side reactions that may increase the char produced (Ragaert, Delva & Van Geem 2017; Solis & Silveira 2020). Pyrolysis systems for mixed plastic waste work best with combinations of polyolefins (PE, PP) and PS and generally tolerate only low levels of contamination from PVC, PET and other oxygen and nitrogen containing polymers. The input material also needs to be dry before it can be processed, which adds an energy cost. The addition of a catalyst during the process or as a separate cracking step can help the system to produce useful materials. A hydrocracking system where hydrogen is added can also manage oxygen and nitrogen containing plastic contamination (e.g. nylon, PET).

Hydrothermal processing does not require a drying step and can deal with low levels of contamination from PVC, rigid plastics, laminates and organic material. As such, it is the most flexible and tolerant technology for accepting mixed plastic wastes. When processing mixed plastic wastes, hydrothermal processing produces stable liquid hydrocarbons that can be stored and transported. Hydrothermal processing can also process MSW in conjunction with plastic waste.

3.8 Plastic packaging

Plastic packaging offers one of the best targets for advanced recycling, once pure polymer streams more suited to mechanical recycling have been removed. This is partly due to the national targets for recovery, particularly 70% recycled or composted by 2025, and that packaging currently has the greatest recovery rates compared to other application areas (O'Farrell 2019). Table 6 shows the 2018–19 plastic packaging consumption and recovery data (O'Farrell 2019). Based on the national target of achieving an average of 70% of packaging recycled by 2025, this shows an estimated increase of 474,240 tonnes of plastic packaging for Australia's recycling system (assuming all packaging is single use). A very small proportion might be met by organic recycling (composting) and some of this increase can be met by mechanical recycling. The implementation of new container deposit schemes in Victoria and Tasmania are important for securing pure polymer streams for those states. However, not all of the increased recovery will be suitable for mechanical recycling. This is where advanced recycling to a purified polymer, monomer or basic chemicals may be preferable.

Table 6: Tonnes of plastic packaging including consumption and recovery in 2018–19 and recycling targets to 2025

	PLASTICS RECYCLING DATA 2018–19		NATIONAL TARGET
Plastic packaging	Consumption	Recovery	By 2025 (70%)
Consumer	895,500	228,600	626,850
Commercial and industrial	183,800	52,600	128,590
Total	**1,079,300**	**281,200 (26%)**	**755,440 (70%)**
Increased recovery to 2025			474,240

3.9 Soft/flexible plastics

The term 'soft plastics', also known as flexible plastics, generally refers to plastics that can be scrunched into a ball and includes a range of polymer types, such as LDPE, LLDPE, HDPE and PP (APCO 2019). Soft plastics often contain multilayer, laminated materials, which make mechanical recycling challenging. The amount of soft plastics consumed and waste generated in Australia is difficult to calculate, but is estimated to be approximately 300,000 tonnes per year (APCO 2019). Soft plastics are used extensively and in many industry sectors, and have a number of collection systems in place in Australia (Table 7).

Soft plastics are frequently added to municipal recycling bins and cause problems with contamination at MRFs. The soft plastics mimic paper and become tangled in the equipment. The presence of soft plastics often means that large proportions of collected kerbside recycling end up being dumped in landfill.

Table 7 provides a summary of soft plastics consumed by industry sector, including polymer types available and current collection systems.

Current mechanical recycling of soft plastics in Australia typically involves the production of material and products for civil infrastructure (e.g. railway sleepers, highway sound barriers, bollards and park seating), road base and outdoor furniture. These reuse markets have the ability to grow but will not cope with the increased collection of soft plastic wastes, and as a result, other resource recovery processes need to be considered. Advanced recycling is the only option for recycling these plastics for reuse, and it generates output materials that are food contact compliant.

Recently, the consortium of Licella, Coles, Nestlé, LyondellBasell, VIVA Energy Australia, Taghleef Industries, REDcycle, iQ Renew and Amcor demonstrated the use of waste soft plastics to make a new candy bar wrapper (AM News 2021). They are currently conducting a feasibility study on the construction of a plant in Victoria that would be capable of producing 17,000 tonnes of soft plastic each year (Powell 2021). The use of feedstock could help brand owners source local content recycled packaging to meet the national packaging targets, which requires the industry to use 50% recycled content in packaging by 2025.

Table 7: Types of soft plastics by industry sector and collection systems

INDUSTRY SECTOR	PRODUCT DESCRIPTION	POLYMER TYPES	COLLECTION SYSTEM(S)
Municipal/ household	Mixed film packaging including retail bags, produce bags, consumer bags – pouches and film. Moderate contamination from glass, hard plastics, aluminium cans and residual food waste.	LDPE, HDPE, mixed other, PVC, PET, PP	Council trials of 'bag in a bag' collection of soft plastics; Melbourne and Central Coast councils have reported low contamination rates from trials. REDcycle drop-off points at retailers (grocery stores).
Commercial	Mixed film including shrink wrap, courier packs, food packaging and retail bags. Low contamination from hard plastics, paper.	LLDPE, HDPE, mixed other	Individual arrangements with contractors.
Industrial	Packaging offcuts, redundant packaging, plastic bags, bulk bags. High contamination with product residue, cardboard, gloves, general waste.	LDPE, PP, HDPE, mixed other	Collection and processing (e.g. Plastic Forests).
Agricultural	Bale wrap, grain bags, mulch film, baling twine. Can be highly contaminated with soil and residues.	LLDPE, LDPE, mixed other (e.g. woven PP, PVC)	Dairy Australia has a product stewardship grant to develop a regional and possibly national collection of silage wrap. The Plasback scheme operates in NZ (used to be in AUS). Plastic Forests accepts some agricultural wastes. Some councils have drop-off services (cost or free).

Adapted from: APCO 2019

3.10 Tyres

Australia produced 56 million waste tyres (465,000 tonnes) in 2018–19 (TyreStewardship Australia, Sustainability Victoria & Department of Environment and Science 2018; Randell, Baker & O'Farrell 2020). As there are no tyre manufacturers in Australia, there are no current product stewardship or take back schemes in place for tyres, and waste tyres are usually sent to landfill (licensed and unlicensed), stockpiled or illegally dumped (Schandl et al. 2021). There are a number of markets for products produced through the mechanical recycling of waste tyres including road surfacing, playground surfacing and explosives. However, these reuse activities do not deal with the total volume of waste tyres produced, and additional recycling processes are required to promote the recovery of resources from these materials.

Tyres are predominantly composed of steel wire, synthetic rubber (styrene-butadiene), natural rubber, carbon black, silica, nylon and polyester (Randell, Baker & O'Farrell 2020). Tyres are good candidate input materials for pyrolysis and gasification (Schandl et al. 2021) because they break down at relatively low temperatures and produce usable outputs. Although gasification and co-gasification of tyres with biomass have been extensively studied, there are few commercial-scale tyre gasification plants globally (Oboirien & North 2017).

When recycled by pyrolysis the tyres are first shredded and the metals are recovered. Typically, pyrolysis of tyres produces char (30%), steel (15%), oil (45%) and syngas (10%). The char is refined into carbon black. The oil can be used as a fuel for furnaces and the like but would need to be upgraded for use in vehicles. The syngas is best used as fuel for electricity generation on site.

There are a few tyre pyrolysis plants in operation in Australia and most are pilot or demonstration scale (TyreStewardship Australia, Sustainability Victoria & Department of Environment and Science 2018). The only plant that processes significant quantities of tyres is located in Queensland, Pearl Global, and processes 16,000 tonnes a year. BASF (Germany) uses its ChemCycling™ technology to co-pyrolyse end-of-life tyres with plastic waste to provide a naphtha feedstock for their steam cracker, the products of which they use to make a number of polymers (Sphera Solutions 2020).

Another pathway for recycling of waste tyres is devulcanisation, which converts them back to a material with similar properties to those of virgin rubber. Devulcanisation breaks the carbon–sulfur bonds that cross link the polymer, but it is not yet an economical process (Shulman 2019).

The challenges for pyrolysis in Australia include the high cost of plant, distributed input material, lack of consolidated markets to support economies of scale, limited successful plants to base the process on, distance from supply and end-markets, and a lack of extended producer responsibility. Plants have been successful in Europe where extended producer responsibility has underpinned the business case for construction of commercially viable plants and they have stable supplies and end-markets for the outputs (TyreStewardship Australia, Sustainability Victoria & Department of Environment and Science 2018).

3.11 Marine or plastic litter collections

There is potential for using marine debris or plastic litter collected from regionally isolated areas in advanced recycling technologies. The high cost of transportation of recyclable plastics often makes it uneconomic for remote communities to transport their waste or collect marine plastic debris, which leads to incineration or landfill options. Volumes and composition will vary significantly across locations. The important factors for successful advanced recycling technology for marine plastics or litter is robustness to contamination, modularity, ease of operation and ability to produce materials that can be used locally. The primary output is likely to be fuel for generators or boilers.

This waste stream will be composed of a wide range of plastics that will be degraded due to environmental factors including light and heat and will be unsuitable for mechanical recycling. While pyrolysis would be an option for these waste plastics, one of the main problems for processing would be separation of contamination from soil, salt, unsuitable plastics (PVC and PET), paper, glass and wood. Gasification processes operate at high temperatures, typically over 700°C, and are usually relatively large pieces of equipment that operate continuously. Gasification is not likely to be a suitable advanced recycling process for remote use. Hydrothermal processing is the least sensitive to contamination and would most likely offer the best solution in remote locations.

3.12 Thermoset plastics

Thermoset plastics are materials that have been irreversibly crosslinked to form a permanent solid material during their manufacture. Thermoset plastics are scratch resistant, and do not melt, deform or lose shape when heated or in extreme cold. Due to these excellent properties thermoset plastics form a large proportion of engineering and automotive plastics. Some examples of thermoset plastics and their uses include epoxy resins (carbon fibre reinforced products), silicone (adhesive, cooking utensils), phenolic resins (Bakelite), polybenzoxazine (coatings for circuit boards), vinyl esters (car parts) and polyurethanes (moulded furniture). Their properties are often enhanced by the addition of inorganic materials and fillers such as carbon or glass fibre and calcium carbonate. As thermosets are often used for engineering and electronic applications, they often contain flame retardants and toxic additives (Qureshi et al. 2020). Thermoset polymers are generally just contaminants in kerbside recycling bins as most of the products are in use for many years.

Thermosets cannot be recycled for the same purpose using mechanical recycling and can only be used as powdered or fibrous fillers (Devasahayam, Bhaskar Raju & Mustansar Hussain 2019). Thermal processes offer the best opportunity to recycle these polymers. Gasification, pyrolysis and hydrothermal processing are all applicable. However, pyrolysis and gasification systems need to use specific catalysts to effectively break down the polymers due to the high level of oxygen, nitrogen and other contaminants in thermoset polymers. As hydrothermal processing uses water to break down the polymers it is well suited to break down thermosets but may require the addition of basic chemicals (e.g. calcium carbonate) to assist. The presence of flame retardants and other fillers leads to the formation of toxic and halogenated by-products during thermal processing. Hydrothermal processing is able to remove chlorine and bromine in the water fraction. Thermosets lead to formation of more char than thermoplastic materials when thermally processed as they contain more fillers and have a higher proportion of oxygen or nitrogen. Whichever advanced recycling process is chosen, the best results will be obtained when thermosets form a small proportion of the total waste processed.

3.13 Summary

Based on the information presented in this section, Table 8 presents polymer types that are most suited to each advanced recycling option. Some polymer types appear more than once.

Table 8: Summary of preferred options for advanced recycling by polymer

PURIFICATION	DEPOLYMERISATION	CONVERSION
3 5 6	1 3 6	2 4 5 6

The following tables summarise suitability of polymers for each technology type (Table 9), and for waste plastics (Table 10).

Table 9: Summary on suitability of each polymer type for mechanical and advanced recycling technologies

POLYMER	MECHANICAL	PURIFICATION	DEPOLYMERISATION	CONVERSION
PET	Highly suitable when sorted.		Highly effective and commercially available.	Pyrolysis oil has organic acids – poor-quality oils and clogging of equipment. Hydrothermal processing works well.
HDPE	A good option but often results in downcycling.			Catalytic pyrolysis excellent option. Hydrothermal processing works well.
PVC	Possible but different materials may contain undesirable additives. Need to sort materials to ensure similar additives before processing.	Purification possible but may not be cost effective.	Hydrogen chloride produced when heated, which contaminates all processes.	
LDPE/LLDPE	Possible for clean material.			Catalytic pyrolysis excellent option. Hydrothermal processing works well.
PP	Suitable, but not generally separated and often included in mixed plastics.	Purification possible, pilot scale ventures coming on line internationally.		Pyrolysis and gasification good options. Hydrothermal processing works well. High levels of additives create more char/ash.
PS	Collection is challenging for EPS.	Purification excellent and pilot scale ventures running internationally. No styrene manufacturing in Australia.	Depolymerisation possible.	Pyrolysis and gasification work well.

Table 10: Summary on suitability of each plastic waste for mechanical and conversion technologies

PLASTIC	MECHANICAL	CONVERSION
Mixed municipal plastics	Undesirable	Gasification works best with PE, PP and PS. Can tolerate small amounts of PVC and PET. Pyrolysis works best with PE, PP and PS, no PVC or PET. Hydrothermal processing gives good products from complex wastes including laminates, thermosets, PET and nylon, and tolerates contamination from cellulosics.
Soft/flexible plastics (mixture of LDPE/LLDPE/ HDPE/PP – multilayer, laminate)	Mechanical downcycling to furniture, etc.	Suitable for all conversion technologies. (Purification is also possible.)
Tyres	Mechanical recycling a good option.	Pyrolysis is a good option with examples of technology operating in Australia.
Marine litter (highly degraded and contaminated wastes)	Undesirable	Pyrolysis possible fuel for generators. Hydrothermal processing possible.
Thermoset plastics (cannot be melted and reformed)	Mechanical grinding for use as fillers in composites	Conversion technologies best option. Pyrolysis challenged by oxygen, nitrogen and other contamination. Hydrothermal can cope with thermosets mixed with other waste.


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4 Factors influencing adoption of advanced recycling technology in Australia

This report describes technologies that have the potential to support Australia's waste management and plastics recovery goals but do not yet exist at scale. Therefore, when launching a new industry, it is useful to take a systems-based perspective of how Australia might adopt these new technologies. The following section summarises the relevant factors into six areas: political, economic, social, technological, legislative and environmental. Known as a PESTLE framework, it provides a broad perspective of the conditions that are relevant to a new technology and how it relates to the Australian context. The following section was developed based on peer-reviewed data and grey literature (media articles, company reports) and complemented by an Australian industry consultation workshop. Therefore, the factors described here provide an industry perspective of the key issues. A list of organisations that were consulted is provided at the end of this report.

4.1 Political

The policies of federal, state and territory governments have a large role in either enabling or discouraging industry investment into advanced recycling technologies. Local governments are also relevant as they are at the front line of balancing economic developments that benefit households and industry in local communities and regions. One of the most important points that was raised by industry was the number of difficulties encountered for industry (and consumers) when government policy is not harmonised. Australia's adoption of advanced recycling technologies would benefit from a national approach that seeks consistency across jurisdictions, while catering for regional differences.

4.1.1 Current Australian policy context

Australia has a strong commitment to improving the collection and domestic processing and use of waste plastics. This is evidenced by the recently released National Plastics Plan, and the 2019 National Waste Policy Action Plan, and is supported by national packaging targets established by the Australian Packaging Covenant Organisation (APCO) (Australian Government 2021; Ritchie 2019; APCO 2020). Australia has exported mixed plastic wastes to China and South-East Asia for many years. A portion of this waste has leaked into the environment and oceans due to poor storage where it is stockpiled, poor-quality material, lack of environmental controls and lack of trading options (Retamal et al. 2020). The Australian Government signalled an end to plastic waste exports and these will be implemented in 2021 for mixed plastics, and 2022 for unprocessed, single-type plastics. Each of these packages of domestic policy are consistent with the UN Sustainable Development Goals, in particular SDG 12 – Responsible Consumption and Production. The Australian Government, along with state and territory governments, has invested millions of dollars in supporting waste and resource recovery infrastructure. Various states and territories are introducing single-use plastic bans. It is important that advanced recycling is recognised in Australia's policy landscape due to the important role it can play in recycling plastics that are unsuitable for mechanical recycling and might otherwise be disposed of and lost to our economy.

4.1.2 Product stewardship schemes

The Australian Government has established a National Product Stewardship Investment Fund which recently funded over $10 million worth of projects, of which just over $5 million are plastics-related projects. In 2021, a Product Stewardship Centre of Excellence was launched to support best-practice product stewardship schemes in Australia.[4]

4 www.stewardshipexcellence.com.au

Three of the national product stewardship projects funded by the federal government target soft/flexible plastics in Australia. Two of these address agricultural plastics and one targets food packaging (see Table 11). According to the project descriptions, they target almost 920,000 tonnes per year of plastics that are currently not being collected (DAWE 2021). These plastics are likely to be suitable for advanced recycling due to having some degree of contamination (soil or food), possibly multiple layers and mixed plastics. Farm plastics, unless non-contaminated, are likely to be good candidates for advanced recycling. Regarding food packaging, these plastics may be appropriate for mechanical recycling if they able to be sorted to a single polymer type and importantly, have a domestic market. Alternatively, material currently going to landfill may be suitable for pyrolysis, gasification or hydrothermal technologies. As these product stewardship projects are ongoing, it would be useful for these schemes to include consideration of advanced recycling technologies in addition to mechanical. Trials of plastic waste material may be required to ascertain their suitability for different technologies and what outputs different plastic waste combinations might deliver.

Table 11: Three product stewardship projects that are potential candidates for advanced recycling processes

PROJECT TITLE	AVAILABLE PLASTIC WASTE	GRANT AMOUNT
Recycling farm plastics	8,000 tonnes/year waste farm plastics, silage wrap	$965,400
Recycling non-packaging agri-plastics	90,000 tonnes/year	$893, 866
Recovering food packaging	1 million tonnes/year plastic packaging waste (820,000 tonnes/year going to landfill)	$985,866

Source: Department of Agriculture Water and Environment 2021

4.1.3 Innovation policy and governance

New technologies can offer significant benefits but mechanisms to support their adoption and launch a new industry requires a combination of industry and innovation policy. The European Commission report ‘A circular economy for plastics’ presents a framework for the governance of sustainable transitions through a socio-technical landscape (Crippa et al. 2019).

Figure 8 shows the transition over time of an innovation from niche to mainstream using three analytical levels. The niche innovation is the location of experimental or novel innovation. Innovations must break through to the socio-technical regime where established rules, such as industry practices, market preferences, policy and cultural norms are a stable influence. The landscape level represents external societal factors such as public demand for greater recycling. The regime influences an innovation and, should an innovation break through, is influenced by the emerging niche. The arrows in Figure 8 show the relationships and forces applied to each level (niche, regime and landscape) over time, as a niche innovation emerges (Geels 2011).

Niche innovations underpin long-term transitions and are similar to pilots, demonstrations, or experimental innovations. The concept of niche innovation applies to advanced recycling technologies as they are novel (different from the prevailing technology), complex (require multiple stakeholders) and can support a transition to circular economy. Niche innovations depend on three elements to emerge – a shared vision, innovation network and shared learnings.

An example of generating momentum for niche innovation is from Germany where the Fraunhofer Institute launched a national network for chemical recycling and the circular economy.[5] A similar approach adopted in Australia would provide the three essential key elements required by niche innovations to create long term change. A national network facilitates a shared vision for scaling up and implementing advanced recycling for plastics. A network approach is important as the success of advanced recycling depends upon integration and collaborations across the entire supply chain. Lastly, it is important that progress of different technologies is shared amongst the industry and innovation system. Sharing lessons learned will highlight key success factors and ensure mistakes are not repeated, which accelerates the adoption of new technologies. A national network combining industry and stakeholders from the innovation system will facilitate adoption of these technologies in a timelier fashion compared to a piecemeal approach. In Germany it was proposed that reference sites be implemented for the trial and scale up of technology, which would be useful in removing barriers to engaging in technology. These would be supported by funding, subsidies and regulatory frameworks (Lee, Tschoepe & Voss 2021).

5 www.enfrecycling.com/directory/plastic-mrf/Australia

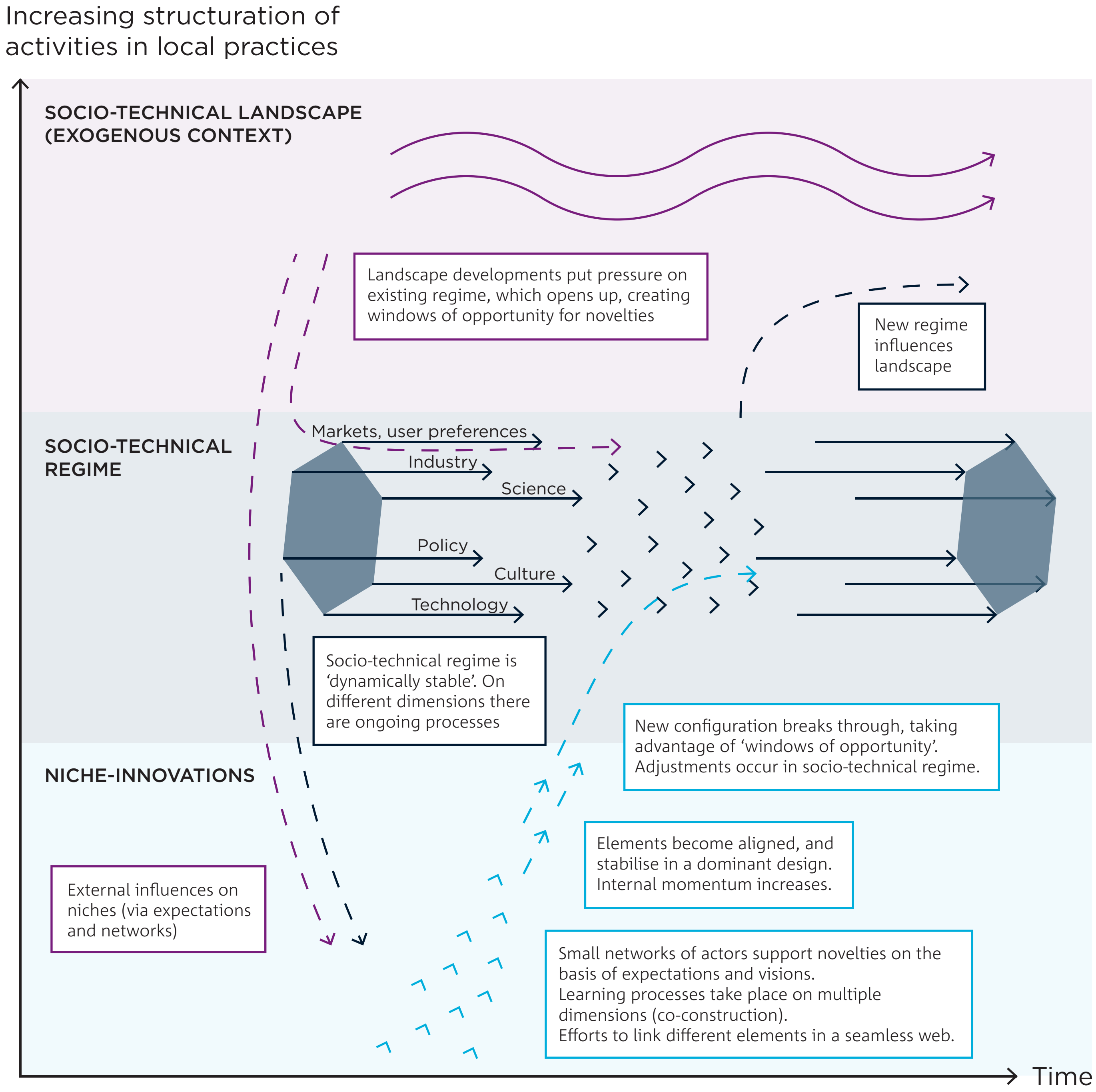

Figure 8: Multi-level perspective of socio-technical transitions

Adapted from source: Geels 2011

4.2 Economic

From an industry perspective, economic factors are the leading factor influencing advanced technology adoption in Australia. Landfill gate fees are important in determining if advanced recycling is cost competitive. Transport costs and distance of plastic wastes to processing are important. The scale of plant, additional sorting, cost of virgin material compared to recovered material, and the price of oil and energy costs – these all affect the economic viability of advanced technologies. For example, gasification facilities must offset capital costs with product revenues and tipping fees. The amount of fuels, chemicals or energy produced per tonne is affected by the management of the heat produced by the gasification process and whether it is captured or used at the facility to provide heat or energy to the system (Gershman & Bratton 2013).

The potential and size of market, noting again that these technologies complement rather than compete with mechanical recycling, is large. The North American market is estimated as a $120 billion opportunity (Closed Loop Partners 2019). However, many technologies are at an early stage. The early stage of development was noted by Closed Loop Partners who researched 60 global technology providers, and found many at lab scale but with the ability, or plans to scale up in the next 2 years (Closed Loop Partners 2019). There are several pilot plants operating in Europe, with some that have scaled up to an industrial scale (Recycling Technologies 2021).

Competition with waste incineration plants has contributed to gasification plants closing down in Germany (Lee, Tschoepe & Voss 2021) and Australian industry has raised competition with waste-to-energy plants as an emerging issue. Germany was a pioneer in the industrial-scale implementation of advanced technologies with advanced recycling centres in Berrenrath and Sekundärrohstoff-Verwertungs-zentrum Schwarze Pumpe (SVZ Schwarze Pumpe). Both plants were using gasification technologies to convert different types and mixtures of carbonaceous waste (e.g. unsorted MSW, plastic waste, tar and oil residues, waste wood, sewage sludges) mixed with coal into syngas and then producing methanol (~300 tonnes a day). Both plants were closed, the last in 2007, due to a range of factors including high operating costs, expenses maintaining the complex plant, low methanol prices and competition with waste incineration plants (Lee, Tschoepe & Voss 2021).

Clearly, market conditions have changed since 2007 and there are many examples of projects commencing around the world. However, in order to be competitive, recycled polymer will need to address economic drivers as they will typically have a higher price than virgin material (Goldberg, Haig & McKinlay 2019). An additional factor to consider is transport costs. It may be more efficient to process plastic waste into liquid intermediate products, rather than transport plastic waste. This is particularly relevant for regionally distributed cities and towns and where modular conversion technologies may be well suited.

4.2.1 Economic viability of advanced recycling technologies

Advanced recycling needs to compete with the low price of petrochemical feedstock. It has been said that this factor alone makes advanced recycling uneconomic without significant subsidies (Hopewell, Dvorak & Kosior 2009). However, despite the early stage of many technology solutions, there is evidence that advanced technologies can be profitable. An economic analysis of PP waste from New York, processed using pyrolysis (with a catalyst) and gasification was found to be profitable with a net present value of USD$149 million and USD$96 million, respectively. The key factors influencing economic performance were the discount rate applied, the price of waste PP and plant life (Bora, Wang & You 2020). Depolymerisation technologies have the potential for profitability as they avoid capital investments for petrochemical infrastructure and plants that manufacture PET. It has been estimated that a PET chemolysis facility requires 15,000 tonnes per year in order to be economically viable (George & Kurian 2014). By comparison pyrolysis, where outputs become cracker feedstocks, is estimated to be profitable down to $50 a barrel and as a technology, is generally more resilient to lower oil prices (Hundertmark et al. 2018). Another factor for consideration is the willingness of the public to pay a premium for recycled content.

However, these technologies are not without risks and there are examples of companies that have ceased operation. For example, VinyLoop®, a PVC waste recycling purification plant in Italy that used butanol as a solvent and steam as an anti-solvent, was shut down after more than 15 years of operation because the process was not effective enough to remove additives, such as plasticisers (Plasteurope 2018).

While PS is an excellent candidate for depolymerisation technologies there are no styrene producers in Australia therefore there is no connection with product outputs and a domestic manufacturing sector. PS is also an excellent polymer for pyrolysis systems as it breaks down at low temperatures and will provide aromatic compounds, which are particularly valuable if the output is to be a fuel (Erdogan 2020).

Each of the advanced recycling processes have an energy cost. Pyrolysis and gasification use high temperatures to break the chemical bonds and are energy intensive (Goldberg, Haig & McKinlay 2019). Depolymerisation and dissolution are also often carried out at temperatures over 80°C. Although many processes will use part of the outputs (oil or gas) to provide the heat energy required, there may still be an additional energy requirement and this needs to be factored into implementation.

4.2.2 Technology business models

A key economic challenge is maintaining security of supply and a consistent feedstock (Qureshi et al. 2020). This can be overcome by developing supply relationships with waste managers and additional pre-sorting of plastics. In fact, the business models for these technologies are likely to involve waste managers.

Large-scale commercial plants are likely to be sized at 30,000–200,000 tonnes a year. It is sensible to also offer recycling as a service where the plant receives waste, generates outputs and offers them for sale to the chemical sector (Recycling Technologies 2021). A second business model is likely to exist for small, modular units with capacity for processing 1,000–10,000 tonnes a year. Companies with plant that support distributed models of waste processing are more likely to offer the technology for sale. These modular units are suitable for regional or remote waste management. They may also be combined in series. They will require operation by suitably qualified waste handlers. While the technology provider secures revenue directly from the sale of technology, the operator of the unit will need to develop contracts with the chemical sector for the sale of product outputs (Recycling Technologies 2021). The business model for the collection of waste is also a key factor for consideration. This is where product stewardship schemes can provide a steady stream of plastic waste.

4.2.3 Licella Cat-HTR™ in Victoria

A feasibility study is looking at a potential site in Victoria for an advanced recycling facility using the Cat-HTR™ hydrothermal processing technology developed by Licella (Section 2.4.3) in a bid to tackle the growing issue of plastic waste (Licella Holdings 2021). The study is a collaboration between technology provider Licella, recycler iQ Renew, Coles, polymer manufacturer LyondellBasell and Nestlé to determine the technical, economic and environmental benefit of a Victorian advanced recycling industry. The study will build on the demonstration of making the Kit-Kat wrapper from soft plastics unveiled in 2021 (AM News 2021). The consortium acknowledges that without the input and cooperation from the whole value chain it won't be possible to implement the changes required bring about the industry.

4.2.4 Industry collaboration

For advanced recycling to be economically viable, there is a need for supply chain collaboration between manufactures, waste managers, advanced recycling technology owners and operators (Figure 9). In particular, there is a need for collaborative supply chain partnerships to be established with refinery or chemical manufacturing companies, as pursuing a plastics-to-plastics pathway depends on access to existing infrastructure to process the oil or gas outputs from advanced technologies. An example of the circular plastics-to-plastics supply chain stakeholders is provided below.

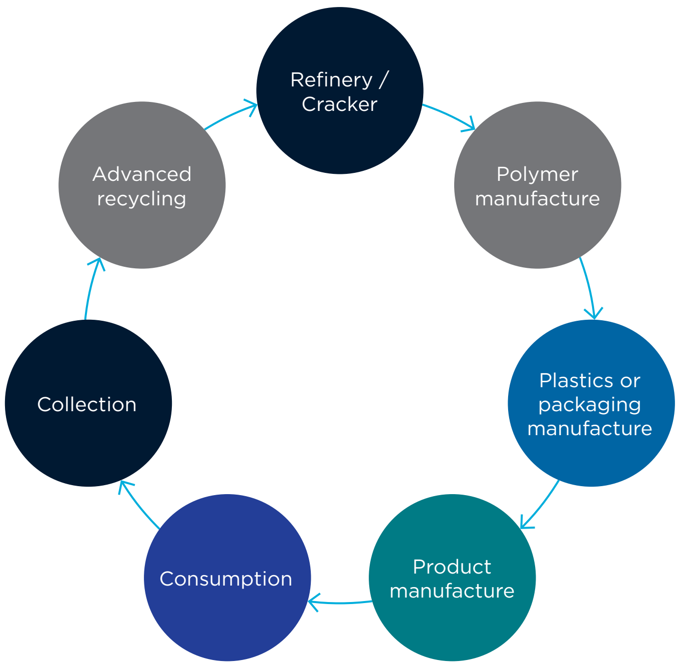

Figure 9: Circular industrial supply chain for advanced recycling of waste plastics back into plastic

Global brands are beginning to invest in advanced recycling technologies to ensure access to the limited supply of recycled plastics (Phipps 2019). These brands include Adidas, Unilever, P&G, Danone and Interface, which have all signed offtake agreements with a number of chemical recycling start-ups to support their growth. Plastics manufacturers Indorama and SABIC have also made strategic investments in Plastic Energy, Loop Industries and Ioniqa, and chemicals companies including BASF, Eastman Chemicals and LyondellBasell have integrated chemical recycling technologies in their own manufacturing and supply chains (Phipps 2019).

4.2.5 Advanced manufacturing export/import opportunities

The Ellen MacArthur Foundation Global Commitment unites businesses behind a common vision for a circular economy for plastics. The 2020 report includes more than 250 businesses and major multinational brand owners, representing 20% of all global packaging. These companies have on average 6.2% recycled content in plastic packaging. This constitutes a 22% increase year on year (Ellen MacArthur Foundation 2020b). Many major brands have targets to substantially increase their recycled content. A summary of the status of the top 10 fast moving consumer goods (FMCG) companies compared to 2025 targets is shown (Table 12). Four companies are not signatories to the Global Commitment, therefore data is not reported. These data show that while excellent progress has been made, there will be market demand for recycled plastics for global and domestic companies to meet their 2025 goals for recycled content in plastics packaging. This provides Australia with the potential to leverage existing infrastructure (refinery and crackers) to develop certified recycled chemicals (from waste plastics) for export. This means advanced recycling technologies could play a role in developing new, advanced manufacturing export opportunities.

Australia's major polymer manufacturing infrastructure may play a regional role by importing waste plastics processed by advanced recycling technologies from Asia-Pacific countries, such as New Zealand, for processing.

Table 12: Progress towards recycled plastic content for top 10 FMCG brands

		RECYCLED CONTENT IN PLASTICS (% BY WEIGHT)		TOTAL VOLUME OF PLASTIC PACKAGING (MILLION TONNES PER YEAR)
Top 10 FMCG Companies		Current (2019)	2025 target	
1	Nestlé	2	30	1,524,000
2	Procter & Gamble	n/a		
3	PepsiCo	4	25	2,300,000
4	AB InBev	n/a		
5	Unilever	5	25	700,000
6	JBS	n/a		
7	Tyson Foods	n/a		
8	The Coca-Cola Company	9.7	25	2,981,421
9	Mars, Incorporated	0	30	191,217
10	L'Oreal	6.9	50	137,280

Source: Ellen MacArthur Foundation 2020b

4.3 Social

The social dimension includes community education and awareness, stakeholder engagement, industry capability and securing social licence to operate. Industry feedback highlighted the importance of household education for the separation of plastics to reduce contamination and the need for increased community and government engagement on the role and environmental impact of advanced technologies. Industry also noted the importance of chemical engineering skills to be retained and developed in the manufacturing sector. The role of independent, trusted advisers such as CSIRO were noted by industry as having an important role in developing and communicating evidence-based information.

4.3.1 Community education on the value of plastics and recycling options

Australians consider plastics a serious environmental problem and there is data to show that plastic packaging is losing its social licence to operate (Dilkes-Hoffman et al. 2019). However, this is contrary to evidence that shows plastics to be preferable to paper and that plastics extend the life of food products, which prevents food waste. A recent study showed that plastics were considered the least favourable of food packaging options by Danish consumers, although they were actually the most environmentally preferred solution based on a life cycle assessment (LCA) (Boesen, Bey & Niero 2019). In addition to consumer education on the positive benefits of plastics packaging there is a need for increased consumer education on labelling that indicates the recyclability of products and harmonised municipal recycling messaging for households (Schandl et al. 2021).

The public has several misconceptions about plastic recycling. There is a view that all plastics are able to be recycled if they have the recycling code triangle on them. This is being addressed by the Australasian Recycling Label to be implemented for approximately 80% of supermarket items by 2023 (Australian Government 2021). Many people mistakenly believe that mechanical recycling is endlessly possible and an option for all plastic waste and as such do not understand how advanced recycling complements the recycling system. There are also misconceptions about the difficulties, cost and importance of separation of mixed plastic waste, resulting in high levels of contamination in MRFs.

4.3.2 Industry engagement

In a survey run in Germany, industry participants from diverse sectors (chemical, energy, non-government organisations, science) confirmed that their main concerns with advanced recycling were environmental impacts and uncertainty about the LCA impacts associated with chemical production (Lee, Tschoepe & Voss 2021). The main challenges identified to the implementation of technology in Germany were the high investment costs, high energy requirements and uncertainty around availability of waste as an input (Lee, Tschoepe & Voss 2021). The overall findings from the participant study in Germany were that there was a lack of quantitative data to evaluate the (positive and negative) benefits of advanced recycling. There is a need for evaluation studies and research and development to support establishment of reference sites. Supportive regulation to assist advanced recycling technology to compete against well-established waste-to-energy technologies will also be necessary.

4.3.3 Community acceptance and awareness (social licence to operate)

Social licence to operate is based on trust and can be withdrawn at any time. To build trust in advanced recycling with any group, the community must understand the perceived impacts and benefits, the governance, and have knowledge of the process, and this is achieved through strong relationships (Sustainability Victoria 2021).

There is confusion around the terminology for advanced recycling; it is also known as chemical, feedstock or molecular recycling. Also, there is a lack of clarity on inputs and targeted product outputs from advanced recycling (Lee, Tschoepe & Voss 2021). The public has very little understanding of advanced recycling. Most Australians understand the waste-to-energy incineration models and are concerned about loss of useful plastic material and greenhouse gas emissions from incineration. Advanced recycling needs a similar level of understanding amongst the community.

Lack of social licence was observed when two pyrolysis plants were recently proposed in Australia. Despite facilities like the proposed pyrolysis plant by Foyson Resources in NSW showing that they would take plastics that were not suitable for mechanical recycling, community groups such as the Total Environment Centre were concerned that recyclable plastic was to be burned as fuel (Vince 2015). Foyson Resources had communicated that their products were going to meet Australian standards, their plant would produce little noise and their emissions were a natural gas that they planned to use for energy and a non-hazardous ash waste. The NSW Environment Protection Authority rejected the proposal stipulating that it did not meet NSW's energy-from-waste policy (Burgess 2018). Likewise, a plant planned for Hume in the ACT that proposed to turn PE, PP and PS non-recyclable plastics into petrol, diesel and LPG via pyrolysis was stopped as a health panel decided that there was not enough evidence to prove the facility could be safe as it was a new technology (Burgess 2018). The community was concerned about emissions despite detailed information supplied by the company about the level of expected particulate and gaseous emissions. Foyson Resources detailed that its process would remove ash, and would deal with hydrocarbon contaminants, impurities and waste gas for heating by burning off gas at a high temperature to destroy noxious compounds. These recent examples show there is much to do to secure a social licence to operate for advanced recycling technologies. This can be achieved through the provision of credible, evidence-based information to government and community stakeholders.

4.4 Technology

This technology section includes factors that are necessary for plant scale up and implementation, such as access to existing cracker or refinery infrastructure. There is a need to understand the differences between technologies, the combinations of plastic waste inputs, operating processes and conditions, and the quality and yield of outputs.

4.4.1 Connection to existing refinery and polymer manufacturing infrastructure

The economics of some large-scale advanced recycling technologies is contingent on connecting with existing refinery or polymer cracking infrastructure to further separate molecules, so they are suitable for chemical processing. Australia currently has two polymer manufacturers, Qenos (PE) and LyondellBasell (PP). Without the presence of these manufacturers', conversion-based technologies Australia would only have a plastics-to-fuels pathway. Maintaining critical polymer manufacture infrastructure is essential to the viability of advanced recycling in Australia. As described further below, the State of Victoria holds critical pieces of infrastructure: a refinery, steam cracker and polymer manufacturing capability. It is in an ideal position to capitalise on these assets.

Around 20 years ago (2001), Australia had eight operating refineries that met almost all domestic fuel demand. Today, Australian refineries compete against larger and more efficient refineries in the Asia region. Australia currently has two refineries, one in Geelong (Viva Energy Australia) and one in Lytton, Queensland (Ampol). BP Australia announced in October 2020 that the Kwinana refinery would close and be converted to a fuel import terminal. ExxonMobil announced in February 2021 that their Altona refinery would close (ABC News 2021). The impact of the Altona closure is that Qenos will close and mothball one of its two ethylene-producing steam crackers, which will result in a 15% reduction in the production of PE and a reported loss of around 150 jobs (Macdonald-Smith 2021). The Qenos cracking facility takes ethane gas or liquid petroleum gas and produces ethylene to make HDPE and propylene that is supplied to LyondellBasell to make PP.

When high-quality ethane is fed to the steam cracker a high yield (80%) of ethylene and propylene is produced that can be used to make PE and PP products. The yield of ethylene and propylene from naphtha is lower (40% to 50%) depending on the quality of the feed and the configuration of the cracker. Methane and hydrogen (15%) are also produced and may be consumed as fuel in the process. The cracker can work well with small (two to five carbon) straight chain hydrocarbons to produce ethylene and propylene. One of the two Altona crackers previously processed much heavier oils, a capability that could be reinstated if it was economical.

Generally, the gases and naphtha produced from plastics pyrolysis and gasification contain a higher proportion of olefinic, isomeric and aromatic hydrocarbons. Such materials are well suited to a refinery processes and fuel applications. Without further treatment they provide low yields of ethylene if used directly as an input to a steam cracker. Steam crackers such as the Qenos Altona plant require a purified polyolefin input stream, free of oxygen, nitrogen and chlorine as these elements cause corrosion problems and can poison the various catalysts. Post-treatment processes have been developed to hydrogenate and purify the products of a suitably designed pyrolysis process, enabling the creation of a high-quality cracker feed. Any oxygen, nitrogen and chlorine contaminants can also be troublesome for the zeolite catalysts employed in a refinery fluidised catalytic cracker; however, the dilution into the much larger refinery fuel stream may make this workable.

While both refinery and polymer steam cracker paths can be used to process recycled polymer oil, steam crackers have the potential to produce ethylene and propylene that can be used to make new plastic materials whereas refineries will convert the majority of the product into fuel (gasoline and diesel).

A further risk identified by industry was, if Australia does not include advanced recycling alongside mechanical recovery to meet recycled content targets, then packaging capability may go offshore to achieve those targets. If packaging capability is lost to Australia, then the product manufacturing capability, technology and jobs will also be lost, resulting in Australia importing packaged finished goods.

4.4.2 Production of food contact compliant plastics

Most of the polymer manufactured in Australia meets food contact compliant plastics standards. Achieving a food contact compliant standard is a major consideration for recycled polymers. There is infrastructure to mechanically recycle PET suitable for food contact. PET has a high melting point so clean post-consumer PET from food applications is sterilised during the extrusion process. The plastic products produced meet US Food and Drug Administration guidelines. A big advantage of advanced recycling is that outputs can be fed back into the plastic production system for food contact compliant plastics, as they are the same as the raw materials. Thus, polymers other than PET can be recycled back into food contact grade plastics.

4.4.3 Technology scale up and research

One challenge for the collection of technologies that fit into the category of advanced recycling is that they are yet to be implemented at commercial scale for plastics recovery (Rahimi & Garciá 2017). There are, however, many that are on the verge of scale up in coming years and large-scale pyrolysis facilities might range from 30,000 to 100,000 tonnes per year with small-scale, modular units with up to 3,000 tonnes per year (Hundertmark et al. 2018). In the past, pyrolysis plants have faced market challenges; however, there are a range of technology providers emerging with modular technologies that are well suited to a distributed collection and recycling system (Crippa et al. 2019). It is estimated that the efficiency of pyrolysis is 71% but will increase with future development (Jeswani et al. 2021). Another relevant economic factor is that the heating energy required for pyrolysis is between 5% and 20% of the calorific value of the inputs, although ongoing improvements and catalytic cracking are improving outputs and reducing energy demand (Crippa et al. 2019).

An example of international investment is Plastic Energy, which is a Spanish company that has a commercial plastic waste conversion process using pyrolysis with two plants running in Spain (Sparrow 2020). They partnered with SABIC, a Saudi petrochemical company, to start the engineering and construction of a new advanced recycling system that will be in Geleen, the Netherlands, announced January 2021 (Plastic Energy 2021). They have also announced a collaboration with ExxonMobil to construct a plant in France capable of processing 25,000 tonnes a year and with Nestlé to create a recycling facility in the UK. The process uses predominately HDPE and LDPE, PS and PP that can no longer be mechanically recycled. Each tonne of plastic waste produces 850 litres of TACOIL (Sparrow 2020).

The polymer types of PET, PE, PP, PPMA (acrylic) and PS comprise 70% of global production. Currently there is little evidence that dissolution and depolymerisation technologies are economically viable at current market conditions. This is mainly due to the price competition with virgin materials. These technologies require greater research investment at lab and pilot scale to improve yield and energy efficiency (Crippa et al. 2019).

Research institutes have an important role in collaborating with industry for lab to pilot scale up. In addition, they have an important role in researching and providing evidence-based information to community and government stakeholders. The role of CSIRO in this regard was highlighted by industry participants during an advanced recycling workshop. Research institutes are part of the innovation system (as described in Section 4.1.3) and can assist in connecting industry supply chains under a vision of growing the advanced recycling network and shared learnings. Critical chemical and engineering research expertise can also be applied to the challenge of managing mixed polymer waste inputs to deliver ideal output yields.

4.4.4 Plastic waste supply – collection and sorting infrastructure

The quality of input material and sorting steps have a significant contribution to the final yield of advanced technologies (Jeswani et al. 2021). Industry participants provided very strong feedback that a major challenge for advanced recycling are issues with waste contamination (e.g. with PVC or non-plastics materials). New collection schemes for flexibles and greater aggregation of plastic wastes are needed to achieve high volumes of plastics suitable for advanced recycling. Current plastic separation technologies are not sufficient to produce high-quality (low contamination) inputs for advanced recycling. Australia needs investment in plastic recovery facilities (PRF) such as the example in Laverton, Victoria, by Cleanaway that operates alongside a materials recycling facility (MRF). There is a lack of readily available information at national or state and territory level about the processing capacities of plastics. This information is essential for policy and investment planning, particularly as facilities vary in their capability – tonnes per year, single vs multiple polymer types, municipal and/or commercial waste streams. However, there is a directory for Australian facilities available[5] (although it lacks information on tonnes processed per year and an easy to view measure of the polymer types accepted). The national plastics recycling survey has data on the number of waste processing facilities in each state by polymer type (O'Farrell 2019). Lastly, there is some data available on industry upgrade plans (Read 2021; Envisage Works 2020). Combining these data into a state or national perspective would provide a clear vision of gaps.

4.5 Legislation (and standards)

Implementation of legislation can be an enabler or barrier for supporting increased production of recycled plastics. The same legislation can be viewed by different stakeholders, positively or negatively. Given a general lack of awareness of advanced recycling technologies, some regulators consider them in the same category as waste-to-energy. Consideration should be given to technologies that exclusively process plastics for the purpose of deriving intermediate products, rather than electricity generation. The topic of standards and certification is highly relevant to advanced recycling technologies and is also reviewed in this section. It is useful to start by briefly mentioning recent legislation examples from the UK and US.

4.5.1 UK plastics tax

The UK will implement a plastics tax of £200 per tonne of packaging that does not reach a threshold of 30% recycled plastic. This tax commences from 1 April 2022 and it is intended to provide economic incentives for companies to include recycled content in packaging and to generate demand for recycled material and improve collection and diversion rates away from landfill and incineration (UK Government 2021). As Australia is integrated into global markets this tax will have a flow-on impact to some Australian companies.

4.5.2 US proposed *Break Free from Plastic Pollution Act 2021*

In March 2021, the US Congress evaluated the *Break Free from Plastic Pollution Act 2021*. This proposed act could place a three-year, temporary pause on permitting new or expanded plastics facilities and chemical/advanced recycling is no longer considered 'recycling'. Any pause in permits for these facilities (which includes all types of technologies discuss in this report) is so that regulations that prevent air and water pollution can be updated. The primary concern is to limit impacts on community health arising from the operation of plastics production facilities (Staub 2021).

4.5.3 Legislative factors for advanced recycling plants

A major constraint for the development of advanced recycling industrial processes is the large number of differences in policy and regulation across Australia. These make it challenging for companies to operate in the national market as they must meet the requirements for every state. Existing policies and guidelines have limited application to emerging technologies. Specifically, the eligibility of plastic as an input for pyrolysis is not clearly defined in legislature. It is best determined using the states' energy-from-waste policies and guidelines, as shown in Table 13.

The Queensland Energy from Waste Policy 2020 differentiates between waste to energy and waste to fuel. It places fuel recovery as one position higher than energy in the waste hierarchy. This is shown in Figure 10.

The regulatory pressures have driven Australian developments overseas. In NSW, Licella's joint venture with iQ Renew has been restricted by the NSW Environment Protection Authority, reportedly because of its energy-from-waste policy, and Licella has now set up a ReNew ELP venture in the UK (Hannam 2019; ELP 2020). Likewise, Foyson Resources was planning a plastics-to-fuel plant in Hume, ACT. As it was a new technology it was determined by a health panel that there was too much risk. Foyson Resources has merged with Integrated Green Energy Solutions in the Netherlands and will be shipping their facility to Amsterdam. Renewology announced plans for a facility in Victoria in 2017 but reportedly did not receive government support and finance (Khadem 2017).

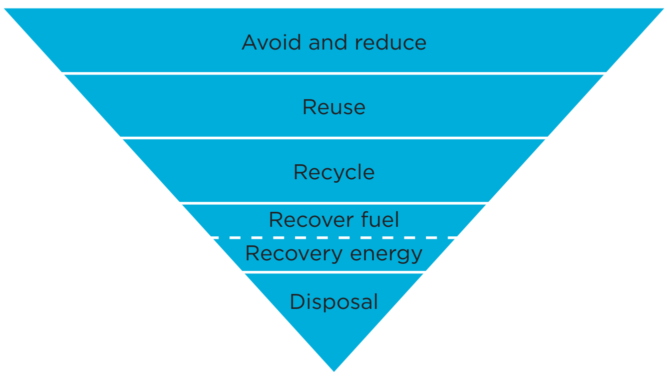

Figure 10: Queensland waste hierarchy considering energy from waste

Table 13: National and state-based energy from waste policy and guidelines that may affect advanced recycling for plastics operations

STATE	KEY POLICY	REQUIREMENTS
National	Parliament of Australia, inquiry into Australia's waste and recycling industries – 'From Rubbish to Resources: Building a Circular Economy' (2020)	Waste to energy refers to a range of technologies that convert waste to electricity, heat and fuel.
National	National Plastics Plan (2021)	The Australian government supports new technologies focused on reducing plastic waste and improving recycling. This includes chemical recycling.
VIC	Recycling Victoria – a New Economy (2020) Environmental Protection Act (1970)	Limit of 1 million tonnes/year until 2040. Plastic not specifically listed as an eligible feedstock, and is considered residual waste, which may be eligible for thermal treatment if it is assessed as the best alternative to landfill.
NSW	NSW Energy from Waste Policy Statement (2020)	Gasification and pyrolysis considered thermal treatment however energy from waste policy excludes thermal treatment where a transport fuel is produced. Does not recognise plastic as an eligible waste to use as input for thermal treatment. Does accept tyres for use in cement kiln.
QLD	Energy from Waste Policy (2020) *Planning Act 2016* Environmental Protection Regulation (2008) *Environmental Protection Act 1994*	Plastic not specifically mentioned other than, energy produced from fossil-derived plastics does not count as renewable energy. An environment relevant activity (ERA) approval is required, with ERA 61: *Thermal waste reprocessing and treatment* the most relevant for pyrolysis, with consideration to: • risk level – plastic is likely classed as Category 2 (moderate risk) • scale of operations.
WA	Waste to Energy Position Statement (2013) *Planning and Development Act 2005* Section 16e of the Environmental Protection Act 1986	Development approval is required under the *Planning and Development Act 2005.* Must be sited in industrial and appropriately distanced from sensitive land. Consistency with waste hierarchy: residual waste otherwise landfilled.

Mechanical recycling, as pictured, is a common process to recycle plastics, particularly for plastics used for food packaging. Advanced recycling complements existing mechanical technologies in Australia

4.5.4 Mass balance method for plastics-to-plastics

For technologies that process waste plastics into chemicals there is no way to distinguish recycled chemical feedstocks from non-renewable feedstocks. It is impossible to track chemicals from recycled feedstocks once they enter existing infrastructure where they are mixed in a continuous process, at a molecular level. Chemical plants are often linked directly together through logistical systems such as pipelines or transport linkages. This interconnectedness supports the use of a by-product from one system being used in another downstream process.

The Ellen MacArthur Foundation published a report on a 'mass balance' approach, which is a chain of custody method, to account for recycling of plastics back into chemicals when it is implemented at scale, and in conjunction with existing infrastructure. A chain of custody method is also applied to global resources such as timber, palm oil and cotton. A mass balance approach applies a bookkeeping method for ensuring that any certified recycled output does not exceed the input, minus any production or conversion losses. For example, pyrolysis and gasification processes are likely to achieve about 30–40% conversion to polymer (Goldberg, Haig & McKinlay 2019). The bookkeeping method requires a defined reconciliation period (Ellen MacArthur Foundation 2020a).

4.5.5 International certification

Using the mass balance approach, it is possible to achieve certification for recycled polymers processed through advanced recycling technologies. There are two options: International Sustainable Carbon Certification (ISCC) and REDcert2. Certification is important as claims of recycled plastics content should be verifiable. Certification processes track chain of custody through the supply chain, with some customers requiring certification. A certification process may also offer the potential to secure carbon credits.

Certification is increasingly important as it is possible for some manufacturers to mix virgin and post-consumer recycled plastic and market the product as 100% recycled. Given major multinational brand owners are committing to increased recycled content in packaging, the demand for recycled polymer will increase. The price of recycled PET has been US$1,000 a tonne compared to virgin PET at US$600 a tonne (Hicks 2020). For these reasons, certification of recycled polymer is important so that claims are verifiable and transparent.

4.6 Environmental

Environmental factors are a key element in securing social licence to operate alongside demonstrating technology meets environmental regulations. While recycling is often mentioned as a key part of ensuring plastics continue in a circular economy, the role of advanced recycling is often neglected. It is assumed that mechanical recycling is the only option, however it is not suitable for some plastics. Both mechanical and advanced recycling retain plastics materials in the economy. Advanced recycling technologies are part of a transition to a reduced dependency on non-renewable resources. This section addresses environmental concerns and impacts of these technologies.

4.6.1 Emissions from advanced technologies

Advanced recycling technologies all have some degree of emissions. In addition, dissolution and depolymerisation will have undissolved potentially hazardous material that will require disposal (Goldberg, Haig & McKinlay 2019). The solvents used in depolymerisation and purification technologies will need to be recovered and purified to keep emissions and costs low. Pyrolysis and gasification produce char (or ash) that may contain some useful material but will need some level of disposal of material contaminated with hazardous residues. Pyrolysis and gasification also generate toxic vapours that will need to be treated before emission to the atmosphere.

4.6.2 Life cycle assessment

The environmental impact of advanced recycling is an important consideration. A reliable life cycle assessment (LCA) provides transparency for the environmental and social impacts of processes. A LCA should be clear about its scope (what it includes or excludes), any comparison scenarios and impact measurements. As noted earlier, many advanced technologies are in an early stage of development. As they scale up to commercial levels, it is important that environmental impacts are monitored, so industry, government and the community have confidence that advanced recycling pathways are indeed a sustainable alternative to other treatment or disposal methods (Ellen MacArthur Foundation 2020a; Crippa et al. 2019).

There are a few studies on advanced recycling of plastics that have been completed using LCA methods. An academic study found that advanced recycling of mixed plastic waste by pyrolysis has a 50% lower climate change impact and energy use then energy recovery by incineration (Jeswani et al. 2021). There is also a significantly lower climate change impact comparing mixed plastic waste recycled from pyrolysis compared to plastics made from virgin resources (Jeswani et al. 2021). Another peer reviewed study found pyrolysis and gasification of PP plastic waste had lower greenhouse gas emissions than landfill or incineration alternatives (Bora et al 2020). ReNew ELP have reported that an independent LCA showed a 70% greenhouse gas emission saving compared to the production of hydrocarbons from fossil sources (ELP 2020). Using the Licella, Cat-HTR™ technology ReNew ELP convert over 85% of the plastic mass to hydrocarbon product that can be used to make new plastic or other hydrocarbon products.

A LCA was commissioned by BASF on their ChemCycling™ process, a pyrolysis-based advanced recycling system where the products are used to make new plastic products. This found that pyrolysis of mixed plastic waste emits 50% less carbon dioxide than incineration. Also that advanced recycling was comparable to mechanical recycling for carbon dioxide emissions (Sphera 2020).

Overall results showed that pyrolysis was preferred to incineration for mixed plastic waste. LDPE produced from pyrolysis oil (using the mass balance method described earlier) has significant climate change benefits compared to production from fossil-based naphtha but fewer benefits for the impact factors of acidification, eutrophication and photochemical ozone formation. An energy mix comprised of greater renewables was even more favourable to pyrolysis compared to incineration technologies for climate change values. This is relevant to developed countries such as Australia. However, for acidification and eutrophication impact categories, pyrolysis was not as preferable to incineration (Krüger 2020).

A recent Australian LCA, applied to the Victorian geographic context, found mixed plastics were best managed in landfill rather than incineration or gasification (the primary output is syngas) based on environmental impacts including acidification, climate change, photochemical oxidation and eutrophication potentials (Demetrious & Crossin 2019). This finding is significant as it does not accord with waste hierarchy conventions where energy is one step above (preferred to) disposal.

Overall, these data show that based on environmental life cycle assessments available in the public domain, advanced recycling has some advantages compared to alternatives for processing plastic waste. Any emissions from advanced recycling technologies need to be managed to reduce impact in other areas. However, there is a recognised need for LCA data relevant to the Australian context. Credible LCA studies will support government and community stakeholders with their concerns over environmental impacts of these technologies.

4.6.3 Non-government organisations and environmental group concerns

Some environmentalists suggest the plastics industry is disingenuous about its promotion of advanced recycling and attempting to placate criticism so it can go on increasing plastic production. To them, advanced recycling is a classic greenwashing scheme. Environmentalists maintain that advanced recycling consumes a lot of energy (Tullo 2020).

Advanced recycling in the US has been criticised by two environmental groups, Greenpeace and Global Alliance for Incinerator Alternatives. Two chief criticisms from both organisations are that many projects are not commercially viable and plastics-to-fuels should not be considered recycling (Greenpeace 2020; Patel et al. 2020). Given the early stage of the many technologies grouped under 'advanced' recycling, the first point is consistent with the early stage of development of many advanced technologies for plastics. The early stage of development was noted by Closed Loop Partners, who researched over 60 global technology providers and found many at lab scale but with the ability, or plans, to scale up in the next two years (Closed Loop Partners 2019).

The second criticism explores an important consideration regarding the end products developed from advanced technologies. Ideally, the goal is to upcycle plastics using advanced technologies into the chemical building blocks for manufacturing of new monomers and polymers. Sending products to a one-way use, such as diesel, results in products having a one-way, linear path, and this is inconsistent with the goals of a circular economy. This is addressed in the following section.

4.6.4 Plastics-to-fuels

One of the main outputs of conversion technologies, including pyrolysis, is a heavy oil fraction, which is a type of crude diesel. One viable market for that product is to sell that output as a fuel. This commits the pyrolysis output into a plastics-to-fuels path, which is undesirable if the goal is to transition to a circular economy. This market preference for fuel has been referred to as a 'linear lock-in' (Crippa et al. 2019). This issue is complex, however. Emerging pyrolysis technologies are small scale and there may be difficulties in selling their small volume outputs to the petrochemical industry, which operates on vastly different scales. There may be economic or market limitations for these small-scale operators to accessing refinery infrastructure or chemical industry supply chain partners (Lee, Tschoepe & Voss 2021).

However, there is a trade-off to be considered regarding the issue of plastics-to-fuels in Australia. If technologies that convert waste plastics-to-fuels are penalised to the extent that they are unable to operate, the alternative pathway for those materials might be landfill or a waste-to-energy plant. This limits potential future flexibility of options for outputs from advanced recycling infrastructure for use as a fuel or as a petrochemical feedstock. Of course, a domestic plastics-to-plastics pathway is only possible if Australia has refinery or polymer manufacturing infrastructure. A similar non-linear argument may be levelled against gasification technologies that produce ammonia for production of fertiliser and, of course, waste-to-energy technology. Therefore, it is important to note that conversion technologies may result in plastics-to-plastics or plastics-to-fuels products, or a combination of both. While plastics-to-fuels might be considered non-circular, whether this is an issue depends on the perspective of if that is considered a worse option than Australia's current paradigm of sending plastics to landfill. According to the waste hierarchy, waste-to-energy is preferred to disposal.

4.7 Summary

The industry perspective on each of these PESTLE areas is summarised in the following sections. More generally, industry reported that advanced recycling was not well understood, and it was important to clarify the different technologies. There should be greater recognition that multiple technologies are needed, and advanced recycling has an important role to play in Australia's greater recovery of plastic waste. Australia has the solutions, technology and very capable scientists and engineers.

Politically there is an opportunity for advanced recycling to be recognised as supporting Australia's waste policy action plan and plastics recovery targets to 2030. Advanced recycling is part of an advanced manufacturing sector and government support is likely to be necessary for launching a new advanced recycling industry. The economic factors are essential for commercially viable technology. Australia has smaller, modular technologies available and the potential for larger scale technologies. There was recognition by industry that economic benefits must flow across the supply chain and collaboration was essential. Recycling of plastics does cost more than virgin polymer, so incentives are needed alongside consumer recognition that recycled polymer is a premium product. Industry understands the only way these technologies can operate is by securing a social licence to operate. This requires increased community engagement with evidence-based facts about the environmental impact of these technologies. Household education is essential to improve collection and reduce contamination of plastic wastes.

For the technology factors, industry saw a need to differentiate advanced technologies from waste-to-energy plants. There is emerging competition for plastic waste from waste-to-energy technologies. Advanced recycling results in food contact grade plastics that can't be achieved through mechanical recycling. There is a need for investment in innovative technologies to ensure Australia does not lag behind Europe and North America.

Legislation was combined with the important topic of standards. Mass balance certification is available for product processed by a refinery or steam cracker. Certification provides consumer and market confidence that any recycled polymer can be verified. Some industry members attending the consultation suggested a tax on virgin resin and others, an excise exemption for polymer-derived recycled fuels as mechanisms to improve adoption of advanced recycling. The harmonisation of definitions and approaches to advanced recycling of plastics would reduce confusion. Life cycle assessment was viewed by industry as important for providing evidence-based information on environmental impact. Comparisons to mechanical, waste-to-energy and landfill would be beneficial. The lack of LCA studies relevant to the Australian context is an information gap. The role of other third parties was viewed as important to provide credibility to any definitive information about advanced recycling.

Summary of industry feedback on PESTLE factors for establishing an advanced recycling industry for plastics in Australia

Political

Lack of awareness and understanding of technology leads to industry challenges with policy development and approvals.

Recognition that advanced recycling supports Australian national plastics recovery targets and processes plastics unsuitable for mechanical recycling.

Government support and engagement is essential for launching a new industry.

Manufacturing could benefit from a more progressive image and approach from policymakers. It must be valued to survive and provide economic development benefits to Australia.

Recognition that advanced recycling is different to waste-to-energy (may even compete with) and material processed should be counted in recycling rates.

Industry needs a consistent policy approach across jurisdictions.

Economic

Economic benefits must flow across the entire value chain for advanced recycling to be successful and greater collaboration across the supply chain is needed.

There is emerging competition with waste-to-energy for plastic waste.

Plastics circularity may cost more for consumers and the business case is contingent on securing a premium for recycled polymers over virgin.

Economic viability should be supported by extended producer responsibility schemes, incentives and policy changes.

Mass balance certification can provide carbon offsets for plastics oil and this is a financial incentive for refinery/cracking processing.

Advanced recycling needs risk takers, scale and security of upstream supply and downstream processing.

Market demand can be improved by government commitment to purchase recycled content.

Social

Need greater commitment by government stakeholders (e.g. councils) for household education to reduce littering, improve sorting and reduce contamination.

Secure social licence to operate with increased community engagement about the role of advanced recycling in reducing plastic waste.

Address community concerns with evidence-based facts about the environmental impact.

There is a role for trusted advisers such as CSIRO to explain this complex topic and undertake evidence-based research.

Increase adoption and awareness of recycled content labels.

It is essential to maintain and develop industry expertise in chemistry and chemical engineering.

Technology

Improved waste collection, separation and aggregation will be needed to achieve required volumes of input materials.

Contamination and inconsistency of plastic waste supply puts the technology at risk.

Greater investment is needed or Australia will get left behind by investments in Europe and North America.

Existing polymer manufacturing and refinery infrastructure is essential to creating circular outputs from waste plastics.

Technology options (small and large scale) are available now in Australia.

Need to understand the difference between technologies (e.g. pyrolysis, gasification, hydrothermal) and how they are different from waste-to-energy plants.

Need recognition that advanced recycling produces food contact grade plastics.

It is important to understand yields and outputs based on different technologies and plastics inputs.

Legislation

Industry needs a consistent approach across jurisdictions (states, territory, and local government areas).

Traceability and certification ensure material claimed as recycled is credible and verifiable.

Mass balance certification should be advocated by government and industry.

Definitions of advanced recycling are important.

ISCC Plus certification is emerging as a leading standard and could be adopted in Australia.

Tax virgin resin to incentivise use of recycled material.

Mandate levels of post-consumer recycled content.

Introduce container deposit scheme collection for waste plastics.

Recognise advanced recycling as part of Australian plastics recycling.

Environmental

Life cycle assessments (LCAs) are an essential evidence-based approach to quantify the environmental impact of advanced recycling compared with mechanical recycling, waste-to-energy, and landfill.

CSIRO and other third parties are important to combat scepticism in the community about plastics.

Lack of harmonisation across environment protection authorities is a major barrier for industry.

Advanced recycling can prevent post-consumer soft plastics from going to landfill.

There is a need for technology with low emissions.

Need greater clarity on plastics-to-fuels (energy) vs plastics-to-plastics (chemicals) and how these are treated compared to waste-to-energy.

5 Conclusion

Plastic waste is a critical issue for waste management and resource recovery in Australia. Recycling of end-of-life and mixed plastic waste will be needed to help meet resource recovery targets set by the Australian Government. Mixed plastic wastes are typically complex, consisting of numerous polymer types at varying composition. The complexity and variability of feedstocks makes these wastes unsuitable for established plastics recycling pathways in Australia. Traditionally, these plastic wastes have been exported for processing. From 1 July 2021 a total of 149,695 tonnes of mixed plastics is no longer able to be exported and is unlikely to be suitable for mechanical recycling. Without additional onshore sorting and processing, there is a risk this material will be stockpiled or sent to landfill.

Plastics that are not suitable for mechanical recycling are able to be processed with advanced recycling (also known as chemical or feedstock recycling) technologies. The recovery of intermediate output such as oils and gases that can be converted to recycled polymers represent a significant economic opportunity. Advanced recycling of plastic wastes will create new markets within the Australian economy, and potentially for export, that support circularity and sustainability in the production and consumption of materials.

This report describes the opportunity of advanced recycling for improving recycling of plastic wastes produced in Australia and identifies opportunities for new markets for recovered products. We described the main types of technology (purification, depolymerisation and conversion) and identified secondary products and market pathways for these products. We described the interaction of polymers with advanced recycling technologies and potential plastic waste streams that might be suitable for processing with these technologies. Through direct engagement, the industry perspective of gaps, barriers and enablers for establishing an advanced recycling industry in Australia is captured and presented with the PESTLE framework.

The key findings of this report are:

- Advanced recycling can assist Australia to meet the national target of recovering an average of 80% plastics by 2030.
- Advanced recycling is suitable for mixed, multi-layer, flexible and contaminated waste plastics that cannot be processed by other means, such as mechanical recycling.
- Advanced recycling may be suitable for product steward schemes to address plastic waste, such as almost 100,000 tonnes of agricultural plastics and over 800,000 tonnes of food plastic packaging. It is highly suited to the recovery of 300,000 tonnes of flexible plastic packaging.
- The use of advanced recycling encourages pathways that are circular, rather than linear, by retaining material in the economy as part of a transition away from non-renewable resources.
- Advanced recycling can produce a range of high-quality recycled polymers for reuse, including food contact compliant plastics, as well as a range of secondary products that can enter markets in place of virgin materials.
- There is increasing global and local demand for recycled polymers. Global market demand for recycled plastics will continue to grow. Top global brands (representing 20% of all global packaging) average 6.2% recycled plastics in packaging where most have targets of 25% (and greater) to reach by 2025.
- Australia has unique technical expertise that would be suited to launching an advanced recycling industry for waste plastics, leveraging existing infrastructure (e.g. refineries or steam crackers) to recycle plastic wastes. Australia's polymer and plastics manufacturing supply chain is essential to realising benefits of advanced recycling and improved recycling rates of plastics.
- Technology for advanced recycling of plastic wastes exists at various scales in Australia, with four examples provided in this report.

Following industry engagement and assessment of themes through the PESTLE framework, the pathway for establishing an advanced recycling industry for plastics in Australia requires the following for success:

- A national discussion about advanced recycling to improve awareness of the range of technologies available, and to facilitate an understanding of the advantages and the differences to waste-to-energy technologies.
- An innovation approach to support pilots, trials with plastic wastes, collaboration across the supply chain and an innovation network to support scale up coordinated, for example, with a national centre.
- Harmonisation of government definitions, policy and approvals to support greater adoption of advanced recycling.
- Government support and engagement, which is essential for launching a new advanced recycling industry.
- Greater differentiation between advanced recycling of plastics and waste-to-energy technologies.
- Full collaboration across the entire supply chain, including waste managers, technology providers, polymer manufacturers, refinery operators, plastics manufacturers/recyclers and brand owners, to match demand with supply of recycled polymers.
- Techno-economic and LCA studies to provide further evidence that technologies are commercially and environmentally sound.
- Adoption of globally recognised certification processes to provide chain of custody verification and market confidence for recycled polymers and plastics that were processed through advanced recycling technologies.

To develop an advanced recycling industry for plastics in Australia and achieve Australia's resource recovery targets by 2025, it is important to establish a collective and clear vision that promotes research, development, innovation, scale up, collaboration and appropriate policy design. Australia has all the critical elements necessary to launch a new industry of advanced recycling for plastics, which supports greater recovery, recycling and reuse of materials consistent with improved circularity and sustainable economic development.

List of organisations consulted

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- Australian Food and Grocery Council
- Australian Paper Recovery
- BASF
- Brightmark
- Chemistry Australia
- Cleanaway
- Dow Chemical (Australia)
- Integrated Recycling
- IQ Energy Australia
- Licella
- LyondellBasell
- Nestlé
- Pact Group
- Plastic Energy
- Plastic Forests
- Plastoil
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