Carbon emissions assessment of Australian plastics consumption – Project report

Version 3

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Executive summary

The Australian Marine Conservation Society (AMCS) and World Wide Fund for Nature Australia (WWF) commissioned this study to quantity the carbon emissions of Australia's plastics consumption and end-of-life (waste) management, and then quantify the potential carbon emissions of a range of possible system change scenarios.

There are two key aspects to this study, which are:

- **Quantify the carbon emissions of current and potential future plastics use in Australia**
- **Assess the carbon impacts of a range of policy setting related scenarios.**

The primary goal of the study is to estimate the aggregated carbon emissions of plastics use in Australia, across the period of 2020 to 2050, with comparison of various scenarios across hydrocarbon sources into new plastic products, and pathways for the end-of-life management of used plastic products.

The system change scenarios assessed in this study are outlined in Table E-1. These scenarios have been selected to explore the emissions landscape in relation to changes in consumption quantities and material sources, recovery and energy sources. The scenarios are not forecasts or predictions. The consumption reduction related scenarios assume that substitution with other materials or services is not required.

Table E-1 System change scenarios assessed in this study

Scenario	Description
Scenario 1 – Business-as-usual	Current consumption and EoL generation projections to 2050.
Scenario 2a – Flat consumption to 2050	Flat consumption and recovery relative to 2019–20.
Scenario 2b – 10% consumption fall by 2050	10% reduction in consumption relative to 2019–20.
Scenario 2c – 40% consumption fall by 2050	40% reduction in consumption relative to 2019–20.
Scenario 2d – 60% consumption fall by 2050	60% reduction in consumption relative to 2019–20.
Scenario 3a – 50% recovery by 2050	50% recycling rate by 2050.
Scenario 3b – 100% recovery by 2050	100% recycling rate by 2050.
Scenario 4 – 100% renewable energy	100% renewable energy globally by 2050.
Scenario 5a – Combined scenario 1	10% reduction in consumption relative to 2019–20 / 100% recovery rate by 2050 / 100% renewable energy by 2050.
Scenario 5b – Combined scenario 2	100% recovery rate by 2050 / 100% renewable energy by 2050 / 100% biobased or CO_2 based by 2050.
Scenario 5c – Combined scenario 3	10% reduction in consumption relative to 2019–20 / 100% recovery rate by 2050 / 100% renewable energy by 2050 / 100% biobased or CO_2 based by 2050.

Presented in Figures E-1 and E-1 are the system change scenario modelling results on a global warming potential (GWP) 100 year and GWP 20 year basis respectively.

On both a GWP 100 year and GWP 20 year basis, the scenario that provides for the greatest reduction in carbon emissions is Scenario 5c. This is followed by either Scenario 5b (GWP 100 basis) or Scenario 5a (GWP 20 basis).

The summary results are:

- **GWP 100 year basis** – Scenarios 5c and 5b provide reductions from the BAU carbon emissions (Scenario 1) of 72% and 64% respectively.
- **GWP 20 year basis** – Scenarios 5c and 5a provide reductions from the BAU carbon emissions (Scenario 1) of 71% and 64% respectively.

Figure E-1 System change scenario results for all plastics – 2020 to 2050 – GWP 100 year basis

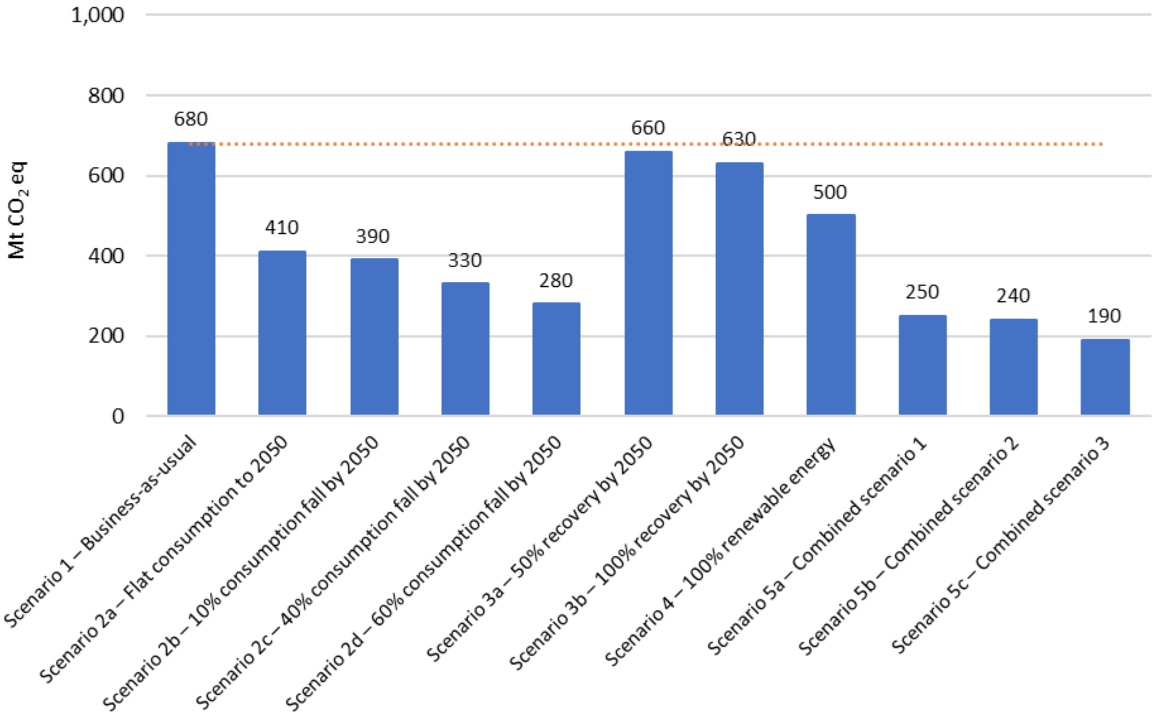
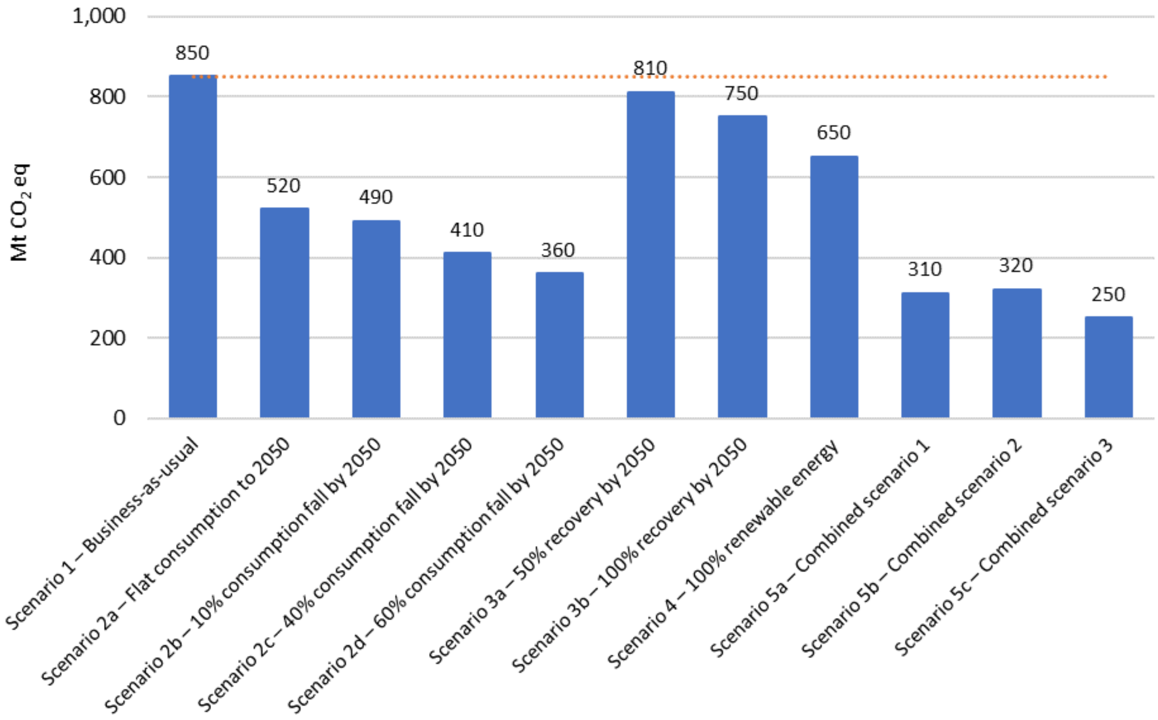
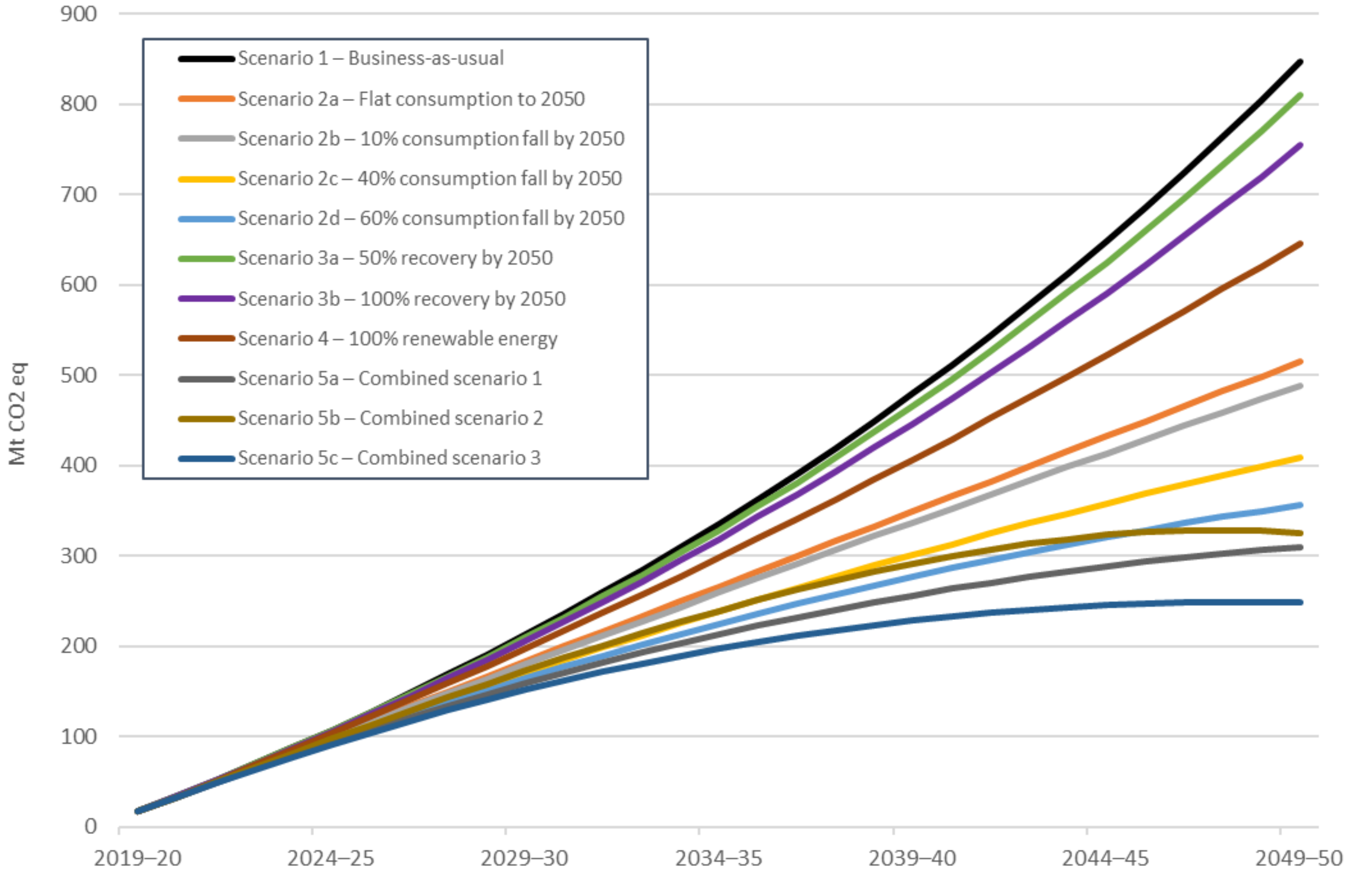


Figure E-2   System change scenario results for all plastics – 2020 to 2050 – GWP 20 year basis



Provided in Figure E-3 are the estimated annual accumulated carbon emissions by scenario on a GWP 20 year basis, from 2019–20 to 2049–50.

Figure E-3 Annual accumulated carbon emissions by scenario, from 2019–20 to 2049–50 – GWP 20 year basis



Scenarios that solely rely on reductions in consumption perform well. The achievement of flat consumption (scenario 2a) as an outcome between 2019–20 and 2049–50 results in nearly a 40% fall in carbon emissions relative to BAU.

Scenario 4 (100% renewable energy by 2049–50) performs moderately well as a single system change, and is a key contributor to the combined scenarios that achieve high reductions in carbon emissions relative to BAU.

Scenarios that solely rely on dramatic increases in recycling rates perform only marginally better than BAU by 2049–50.

Overall, the study findings strongly indicate that multiple complementary system level changes are required to significantly reduce the carbon emissions relating to plastics use. These changes include reductions in plastics use, decoupling polymer production from fossil hydrocarbons, decarbonising energy systems globally, and significantly increasing recycling rates.

The recommendations arising from the findings of this study are:

1. Reduce growth in plastics consumption dramatically within the next 10 years, through a combination of approaches such as avoiding unnecessary plastics use, redesigning products and packaging, shifting from single-use to reusable packaging systems, and consumer behaviour change.
2. Decouple plastics production entirely from fossil carbon dependency as the carbon source in the plastic. The preferred additional carbon source, within the scope coverage of this study, is generally CO_2.
3. Shift to a 100% renewable energy system for both stationary energy and transport, and electrify plastics production, product manufacture, product use and product EoL management.
4. Maximise product EoL recycling, with a strong preference for mechanical recycling where feasible.
5. Avoid the EoL management of plastics via energy recovery or incineration, which in a future state with an otherwise fully renewable energy system, have effectively the same carbon emissions averaged across all plastics.

A key limitation to this study is that while carbon emissions are an important environmental aspect of the life cycle of a product impacting climate change, a product's life cycle can have impacts related to other areas of concern (e.g. resource depletion, air, water, soil and ecosystems health). In some cases, actions to minimise a single environmental impact can result in greater impacts arising from other environmental aspects (e.g. the use of biomass to reduce emissions can negatively affect biodiversity).

Decisions about product impacts that are only based on a single environmental issue can be in conflict with goals and objectives related to other environmental issues. Carbon emissions should not be the sole component of a decision-making process.

1. Introduction

1.1 Project background

The Australian Marine Conservation Society (AMCS) and World Wide Fund for Nature Australia (WWF) have commissioned this project to quantity the carbon emissions of Australia's plastics consumption and end-of-life (waste) management, and then assess the potential carbon emissions of a range of possible system change scenarios.

This study comes at a key turning point in time, as UN member states negotiate international legally binding instrument on plastic pollution, including in the marine environment, over the period 2023–24.

There are two key aspects to the study, which are:

- **Quantify the carbon emissions of current and potential future plastics use in Australia**
- **Assess the carbon emission impacts of a range of policy setting related scenarios.**

There is growing evidence that the carbon emissions related to plastic production and end-of-life (EoL management, whether synthesised locally or overseas, are potentially understated in much of the existing life cycle assessment (LCA) literature. This is due to the following factors:

1. The growing proportion of the use of fossil gas as a feedstock into plastics production with the growth in gas production internationally, and related to this, the growing evidence base identifying significant understatements of the quantities of upstream (production related) fossil gas emissions to the atmosphere.

   Here in Australia the fossil gas production industry typically uses a 0.5% assumed methane emission rate (loss to atmosphere) which is then reported in official estimates (MEI, 2016, p. 5). This is a factor based estimate and is not based on regularly updated real-world measurements.

   However, more recent aircraft and satellite based measurements suggests that for both conventional and unconventional gas production this is an underestimation, conceivably by a factor of 4–28 (MEI, 2016, p. 65; Baillie, et al., 2019, p. 9; Zhang, et al., 2022, p. 4), with estimates typically towards the middle and upper-end of this large range.

   If this is the case then the carbon impacts associated with methane emissions, could actually be significantly larger than the CO_2 emissions resulting from gas being combusted as a fuel.

   It is also noted that unconventional gas production, with growing evidence of its relatively large gas emissions, is a relatively new technology, and post-dates much of the circulating LCA literature calculating the carbon emissions associated with plastics production.

2. The common use of 100-year time horizon global warming potentials (GWPs) in the existing life-cycle literature, when determining the carbon emissions of plastics, is arguably less appropriate than a 20-year time horizon.

   Given the accelerating impacts of climate change, and the international movement towards carbon neutrality by 2050, a 100-year planning horizon is no longer appropriate. It is more appropriate that the modelling has a primary focus on 20-year GWPs, with 100-year GWPs a secondary focus. For reference the 20-year and 100-year GWPs were 83 and 30 in the IPCC 6th assessment report AR6 (IPCC, 2021, p. 1017), nearly a factor of 3 difference.

This is particularly the case due to the short residence time of CH_4 (methane) in the atmosphere, which is around 12 years, compared with over 100 years for CO_2. With a heavily 'methane' exposed material group such as plastic polymers, defraying the climate change impact over 100 years is too long, as the fossil gas production carbon emissions related to methane emissions are almost entirely incurred during the first 20 years from the time of fossil gas extraction.

However, it is important make the general point that reductions in methane emissions need to be seen as a complementary strategy to CO_2 emissions reductions, not an alternative.

3. At the point of disposal plastic products in Australia have historically been sent to landfill, with much lower quantities (typically around 10–15% of end-of-life generation) sent to recycling (usually from a limited range of rigid plastic packaging).

   This picture is now changing, with growing quantities of end-of-life plastics being sent (or planned to be sent) to energy recovery related fates nationally, with the related release of the carbon in the plastics to the atmosphere as CO_2.

   The plastics fraction of the waste is considered an important contributor to the energy content of the incoming feedstock fuel. This plastic would previously have been landfilled and the carbon largely sequestered in landfills around the country.

   With the introduction of waste-to-energy facilities the fossil carbon in the combusted plastics will be released to the atmosphere, contributing to the carbon emissions of plastics use in Australia.

   The carbon impact of plastics combustion will be offset by the avoided use of fossil fuels to generate electricity and heat. However, as electricity grids continue decarbonising nationally, electricity generated through the combustion of waste plastics will become more and more carbon intensive relative to the competing (increasingly renewable) electricity generators.

Plastics are regularly promoted as being less greenhouse gas intensive than competing materials. However, the actual climate change impacts associated with plastics use may be regularly understated by a significant margin.

It is important to note that the carbon emissions of products and services is only one of many environmental indicators that can be quantified through the application of LCA. This carbon emissions study does not provide information on the overall environmental preferability of differing scenarios of plastics use, with respect to environmental impacts beyond climate change.

1.2 About this study

This is a study on the carbon emissions of plastics use in Australia, across the period of 2019–20 to 2049–50. However, it is based on and guided by more fundamental life cycle assessment (LCA) principles. LCA is one of the methods that have been development to better comprehend and compare the environmental impacts of product manufacture, consumption and end-of-life management.

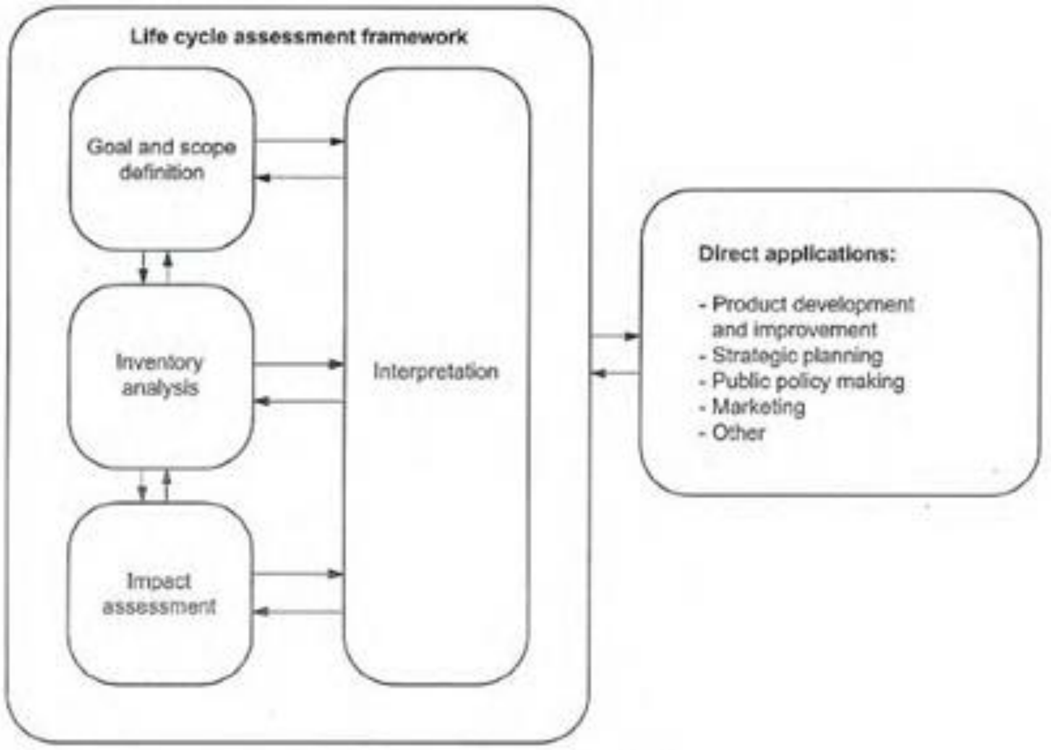
LCA is a technique for assessing the environmental aspects and potential impacts associated with a product or service by:

- Compiling an inventory of relevant inputs and outputs of the product or service system.
- Evaluating the potential environmental impacts associated with those inputs and outputs. For this study only carbon emissions are evaluated.

- Interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study.

LCA models the environmental impacts from each stage of a lifecycle across raw materials acquisition, manufacture, use and end-of-life. It incorporates the stages outlined in Figure 1.

Figure 1 Stages of an LCA (ISO, 2006a)



The goal, scope, and interpretation phases of life cycle assessment frame the study, while the inventory analysis and impact assessment phases produce information on the modelled system.

Life cycle assessment can potentially quantify numerous types of environmental impact category. However, the impact category that is the subject of this study is climate change (carbon emissions) only.

1.3 Reference standards

The two key reference standards that have been used to frame this carbon emissions study are:

- ISO, 2018. *International Standard ISO 14067:2018 Greenhouse gases - Carbon footprint of products - Requirements and guidelines for quantification*, Geneva: International Organization for Standardization.
- WRI & WBCSC, 2011a. *GHG Protocol – Product Life Cycle Accounting and Reporting Standard*, Washington: World Resources Institute (WRI) and World Business Council for Sustainable Development (WBCSD).

The ISO (2018) and WRI & WBCSC (2011a) standards are largely interchangable, but as ISO (2018) is the more recent, it has been adopted as the 'base' standard for this study. The WRI & WBCSC (2011a) standard does provide more detail in some respects than ISO (2018), and has been drawn on where this additional detail is required.

The more general standards that underpin both ISO (2018) and WRI & WBCSC (2011a) are:

- ISO, 2006a. *International Standard ISO 14040:2006 Environmental management - Life cycle assessment - Principles and framework*, Geneva: International Organization for Standardization.
- ISO, 2006b. *International Standard ISO 14044:2006 Environmental management - Life cycle assessment - Requirements and guidelines*, Geneva: International Organization for Standardization.

These two (more general) standards have only been drawn upon for this study as required by ISO 14067 (2018).

1.4 Critical review

This carbon emissions study has been critically reviewed by a panel of 3 independent and qualified reviewers, and has undergone 3 review rounds by the panel.

Refer to Appendix A for the critical review statement for this study

2 Goal of the study

2.1 Goal and intended application of the study

The key purpose of this project is to assist in building the evidence base for evaluating the most effective policy solutions for reducing the climate change impacts of plastics.

The primary goal of the project is to estimate the aggregated carbon emissions of plastics use in Australia, across the period of 2020 to 2050, with comparison of various scenarios across hydrocarbon sources into new plastic products, and pathways for the end-of-life management of used plastic products. The system change scenarios assessed in this study are outlined in Section 5.2.2.

The intended application of the study is to inform consideration of the major existing or prospective approaches that are available to minimise the carbon emissions of future plastics use in Australia, using currently available projections of plastics use and EoL generation to 2050.

The study is intended to support and inform the Australian Government's engagement in negotiations towards a legally binding instrument on plastic pollution, currently being negotiated by UN member states. This will be a two year process during which time addressing existing research gaps will be particularly critical.

The wider application of the study is to support evidence-based advocacy for policy options that value a circular economy, eliminate unnecessary and problematic plastics, and drive the plastic policy agenda with a strong understanding of the emission profile of plastics. It will also inform a wide range of stakeholders on the carbon emissions of plastics use and pollution.

This report has undergone a critical review by a panel of reviewers, and is considered suitable for public communications in relation to the stated goals of the study.

2.2 Reasons for carrying out the study

The reasons for carrying out the study are to:

- Drive the plastics policy agenda and better understand the emissions profile of plastics.
- Inform evidence-based policy and advocacy work by any interested parties, particularly during the draft time period of the UN Environment Assembly resolution to End plastic pollution.
- Provide updated and peer reviewed information into the public domain on the carbon emissions of plastics, incorporating the latest data on the upstream and downstream emissions associated with plastics manufacturing and EoL management respectively.
- Investigate potential implications of changes in plastics consumption on climate policy.
- Inform considerations of the threat to marine health of plastic use (e.g. through acidification and temperature increases).
- Build the evidence base for the most effective policy solutions for use in advocacy, for example; Container Deposit Schemes (CDSs), levies on the use of plastics in packaging (not covered under CDSs) and non-packaging products, phasing out of single use plastics, and pricing schemes for virgin plastics.
- Inform assessments of future investments in plastics – both in infrastructure and policy solutions.
- Investigate emerging pathways and emissions implications of new technologies.

2.3 Intended audience of the study

The intended audience for this study consists of:

- AMCS and WWF
- government policy makers
- decision makers in industry
- the general community.

3 Scope of the study

3.1 The system under study and its functions

The system under study for this project is polymer (plastic) production, product manufacture, product use and end-of-life management, as it relates to plastic products used in Australia.

The polymer types selected for direct carbon emissions modelling are:

- polyethylene terephthalate (PET)
- high density polyethylene (HDPE)
- polyvinyl chloride (PVC)
- polypropylene (PP)
- polylactic acid (PLA).

Section 3.3.2 of this report provides further details on the rationale for selecting these polymer types for inclusion in the modelling. The 5 polymers that have been directly modelled represent **54.2% of Australian plastics consumption in 2019–20**.

Section 3.3.2 also details how the emissions for polymers that have not been directly modelled ('All other polymers') to determine polymer specific life cycle emission factors, have been incorporated into the system change scenarios. As some polymers have been modelled using proxy emission factors the modelled emissions for these polymers may not reflect the actual emissions as quantified in the system change scenario modelling undertaken by this study.

It is important to note that the carbon emissions quantification exercise undertaken in this study differs from how carbon footprinting and LCA studies are typically framed, which is in relation to a specific product or service, or the comparison of two or more different products or services delivering the same function.

This study is instead focussed on comparing the same polymer against different production and end-of-life management processes over time periods to 2049–50.

The scope of the system for this study includes all the major life cycle stages (with significant exclusions in relation to the use stage, see Section 3.3.5 for further detail), but converts flows to a mass basis (tonnes), rather than a unit plastic product basis. This approach has been taken for the following reasons:

- To provide approximations of the carbon emissions of plastics use in Australia that are not linked to any specific plastic product, and so are potentially more suitable for communicating the carbon emissions of plastics on average, without reference to any specific product type.
- To quantify the carbon emissions of plastics use in terms of mass, which typically has more generalised utility than per unit product quantifications.
- To support the national level system change scenario analysis that has been undertaken as part of this carbon emissions study.

In Table 1 2019–20 data on the sources of modelled and all other polymers is presented. In 2019–20 a total of 86.4% of plastics use was based on resin production undertaken overseas, which was almost entirely virgin resin. Of this, 60.5% was imported as finished and semi-finished goods. Only 8.8% of plastics use in Australia was based on virgin resin manufactured in Australia. The remaining 4.9% of consumption in 2019–20 was sourced from locally recycled plastics.

The 'All other polymers' quantities in the table do not include the 570 kt of rubber (mostly synthetic) and other plastics in tyres imported in 2019–20. Tyres have been entirely manufactured overseas since April 2010.

Table 1 Australian polymer sources into use in 2019–20

Polymer	Imported resin	Imported goods[1]	Local resin – virgin	Local resin – recycled	Total	
	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(%)
PET	114,600	214,900	0	25,000	**354,500**	**10.2%**
HDPE and PP[2]	323,300	515,500	204,400	81,200	**1,124,400**	**32.5%**
PVC	212,800	172,100	0	5,200	**390,000**	**11.3%**
PLA[3]	1,900	6,500	0	100	**8,500**	**0.2%**
All other polymers[4]	242,900	1,184,700	99,600	57,100	**1,584,300**	**45.8%**
Total (tonnes)	**895,500**	**2,093,600**	**303,900**	**168,600**	**3,461,700**	-
Total (%)	**25.9%**	**60.5%**	**8.8%**	**4.9%**	-	**100%**

1. Includes imports of plastics in finished and semi-finished goods. Examples of semi-finished goods include products such as large format rolls of plastic packaging films that are locally converted into packs.

2. HDPE and PP combined in the table for data confidentiality reasons.

3. PLA data is for all bioplastics consumption in Australia.

4. These polymers have not been directly modelled to determine polymer specific life cycle emission factors. However, proxy values have been adopted for each polymer in the scenario analysis, to support the estimation of indicative carbon emissions for all polymers under each scenario. See Table 4 on page 18 for more details.

Source: Envisage Works (2021).

Australian production of virgin fossil carbon based plastics accounts for less than 10% of all plastic consumed in Australia. For this reason, and to simplify the overall modelling requirement, the carbon emissions of fossil carbon based plastics synthesised in Australia have been included in the study using the global emission factors that have been estimated (to the out-going gate of the production facility). The global emission factors are considered likely to be reasonable proxies for Australian production of the same plastic types.

It is also worth noting that the longer-term future of the local resin manufacturing sector is uncertain. Effort spent on quantifying the 2019–20 baseline carbon emissions of the two remaining resin manufacturers (Qenos and Viva Energy Polymers) may be irrelevant or superseded within the next few years. The reasons for this include significant changes in feedstock sources (which will be difficult to predict and thus model), or business exits from Australia for commercial reasons.

In Table 2 2019–20 data on the end-of-life (EoL) generation and fates of directly modelled and all other polymers is presented.

Including landfill, an estimated 93.7% of Australian EoL plastics had a local fate, of which 87.0% was sent to landfill and 6.7% was recovered and remanufactured locally. The other 6.3% was exported, either in reprocessed forms (e.g. flake or pellets) or directly (sorted but not reprocessed).

Note that from July 2022 unprocessed scrap (waste) plastics could no longer be exported from Australia, and all exported scrap plastics must be reprocessed locally prior to export.

Table 2 Australian polymer EoL generation and fates in 2019–20

Polymer	EoL generation	Recovery[1]					Landfill	
		Locally reprocessed to local use	Locally reprocessed to export	Direct to overseas	Total			
	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(%)	(tonnes)	(%)
PET	313,400	25,000	5,700	35,900	**66,600**	**20.4%**	246,800	11.3%
HDPE	496,900	45,000	11,100	23,000	**79,100**	**24.2%**	417,800	19.1%
PVC	204,500	5,200	100	1,100	**6,400**	**2.0%**	198,100	9.0%
PP	402,600	36,200	2,400	7,300	**45,900**	**14.1%**	356,700	16.3%
PLA[2]	6,400	100	0	0	**100**	**0.0%**	6,300	0.3%
All other polymers	1,092,200	57,100	12,400	59,000	**128,500**	**39.3%**	963,700	44.0%
Total (tonnes)	**2,516,000**	**168,600**	**31,700**	**126,300**	**326,600**	**-**	**2,189,400**	**-**
Total (%)	**100.0%**	**6.7%**	**1.3%**	**5.0%**	**13.0%**	**100.0%**	**87.0%**	**0.0%**

1. Recovery includes plastics to energy recovery, which is modelled as a separate EoL management fate.

2. PLA recovery estimate is to composting only in 2019–20.

Source: Envisage Works (2021).

3.2 Functional unit and reference flow

3.2.1 Is a functional unit or a declared unit the appropriate unit for this study?

There is a terminology related question in relation to the scoping of this study, which is whether a 'functional unit' or 'declared unit' is the most appropriate term to adopt. The international standard ISO 14067 (2018, p. 15) states that:

> *A CFP [carbon footprint of products] study shall clearly specify the functional or declared unit of the system under study. The functional or declared unit shall be consistent with the goal and scope of the CFP study. The primary purpose of a functional or declared unit Is to provide a reference to which the inputs and outputs are related. Therefore, the functional or declared unit shall be clearly defined and measurable.*
>
> *The declared unit shall only be used in a partial CFP.*

The consideration is whether the scope is better described as a full or partial carbon footprint of products (CFP). The scope of the study includes all life cycle stages, including generic allowances for the conversion of polymer into products. However, it does largely exclude the use stage, but this is identical for each polymer type once converted into products. It is considered reasonable practice to exclude the use stage from 'full' LCAs, if the use stage is identical for product system that are to be compared.

This study does involve the comparison of different product systems, but the comparison is only within each polymer type, with respect to the differing scenarios for hydrocarbon sources and end-of-life management fates. Comparisons are not valid or undertaken between each of the polymer types, as the functionality and substitutability between the polymer types is not necessarily equivalent, particularly once polymer to product conversion inputs/outputs are considered.

What this means in relation to the scope of this study, and the type of comparisons between product systems that are undertaken, is that, to err on the side of caution, the use of the term 'declared unit' is considered the most appropriate, and has been adopted in this study as needed.

3.2.2 Declared unit

The primary purpose of the declared unit is to provide a reference to which the inputs and outputs of a product system are related. Where product systems are to be compared the declared unit must provide the same function or service for each of the compared systems. The ISO standard 14044 (ISO, 2006b, p. 8) provides more detail on the definition, purpose and requirements of a declared unit:

> *The scope of LCA [or carbon footprint] shall clearly specify the functions (performance characteristics) of the system being studied. The functional unit [or declared unit] shall be consistent with the goal and scope of the study. One of the primary purposes of a functional unit is to provide a reference to which the input and output data are normalized (in a mathematical sense). Therefore the functional unit shall be clearly defined and measurable.*

For the purposes of this study, and in particular to assist with supporting the system change scenario analysis that is informed by the modelling outputs, the study has been undertaken using five mass based declared units (in tonnes terms), which while framed in terms of the polymer type (rather than specific plastic product types), also incorporate allowances for the plastic product manufacturing stage.

The primary declared unit is:

> *The delivery of the product service provided by Australian PET, HDPE, PVC, PP or PLA plastics use on an annual basis between 2020 to 2050, under various scenarios for plastic production, product manufacture and end-of-life management.*

The 5 secondary declared units that have been adopted in the modelling to support the determination of the primary declared unit are:

> *Plastic production, (product) manufacture, and end-of-life management of 1 tonne of plastic products made from x (where x is PET, HDPE, PVC, PP or PLA).*

It is worth noting that while it is often the case that the 5 polymers are used interchangeably for many applications, with a similar mass of each polymer required, that the results of this study do not support such comparisons.

It is important to note that this study is a generalised carbon emission quantification of plastic products use, and it is not specific to a particular product (e.g. PET beverage bottles) as is typically the case for these types of studies. Due to this, the results are more macro-level and indicative than is usually the case for carbon footprint studies.

3.2.3 Reference flow

The reference flow is a concept that is closely linked to the declared unit, and it only requires a general definition, not a study specific definition as is required for the declared unit.

The reference flow is the quantification of all the outputs from processes in a given product system, required to deliver the function expressed by the declared unit.

3.3 Scope of plastics flows

3.3.1 Summary of modelled systems

Each of the 5 modelled plastic types have had foreground processes created to model carbon emissions across the 4 generalised life cycle stages of:

- polymer production
- product manufacture
- product use
- product EoL.

In total, 56 foreground processes have been created to build the required modelling framework. The following table provides a more detailed outline of the modelled systems.

Table 3 Summary of modelled systems

Polymer production	Product manufacture	Product use	Product EoL
The modelled plastic production pathways are: • Virgin plastic (fossil carbon based) • Mechanically or chemically recycled plastic • Biobased plastic • CO_2 and H_2 based plastic Also included are transport and various other inputs.	The production manufacturing inputs are polymer dependent across: • Blow moulding • Extrusion - film • Extrusion - profile • Fibre production • Injection moulding • Sheet calendering • Thermoforming Also included are transport and various other inputs.	Minor transport to end-user allowances only.	The modelled product EoL pathways are: • Mechanical recycling • Chemical recycling • Composting (PLA only) • Waste-to-energy • Incineration • Landfill Also included are transport and various other inputs.

With respect to energy inputs, two versions of each of the foreground processes (and relevant background processes) have been modelled, which are:

- **Current energy** – The current energy supply is based on the available pre-existing data in the ecoinvent LCI database (v3.8) for international inputs, and 2021 data for Australian electricity inputs. The current energy supply is a mix of coal, oil, fossil gas, nuclear (overseas processes) and renewables. Variable timeframes across the 2010–2021 time period (with some exceptions).
- **Renewable energy** – Assumed 100% energy supplied through the generation of renewable energy. The 100% renewably generated energy supply is effectively assumed to entail the electrification of all energy supply, applied from the point of the plastic synthesis facility, but not upstream from that activity.

  This assumption (of including the plastic synthesis facility, but not upstream) has particular implications for fossil fuel refineries. The available data indicates that refineries currently source (US data) an average of only 4% of offsite energy supply from electricity imports (Energetics, 2012, p. 73). It is considered highly unlikely that existing or new fossil fuel configured refineries would materially shift from using incoming fossil hydrocarbons to renewable electricity (or similar) as the energy source, so this has been assumed not to take place when modelling 100% renewable energy supply.

  The renewable electricity supply is estimated assuming a 1:1 ratio between photovoltaic (PV) and wind generation, which was the approximate ratio of these two sources in Australia in 2020–21 (DCCEEW, 2023).

There may be other renewable electricity sources in the future (e.g. biomass) but these are assumed to either not have a noteworthy market share in electricity generation, industrial heat generation or transport (with the possible exception of international sea freight), or if they do, to have similar low carbon emissions to PV and wind.

A carbon emission ratio 0.05 was calculated based on the proportion of carbon emissions of 2019–20 Australian grid average electricity end-use supply (0.80 kg CO_2e/kWh)(AusLCI v1.40), and an estimate of carbon emissions for renewable supply (0.042 kg CO_2e/kWh)(Blue Environment estimate based on ecoinvent 3.8 published data). The following context and caveats around the adoption of this ratio are provided:

- Where the energy requirement is for electricity the adopted ratio should provide a reasonable estimate of the emissions ratio related to the completion of the shift from mostly fossil fuels based electricity to 100% renewable electricity.
- Where the energy requirement is for heat the adopted ratio will provide a reasonable estimate of the emissions ratio of the change from fossil fuels to renewable electricity.
- Where the energy requirement is for combustion engines, with their large associated energy losses to heat, the ratio of 0.05 will likely overstate the renewable electricity carbon emissions by a significant margin, as heat losses from electric motors are much lower. However, as the ratio is only 0.05 and only relates to transport, which is a relatively minor contributor to the overall life cycle emissions of plastics, this potential overstatement in the carbon emissions associated with the use of renewable energy based transport is assumed well below the 1% cut-off.

3.3.2 Polymer types

The potential polymer types for direct life cycle carbon emissions modelling for the project are outlined in Table 4, and brief reasons for inclusion/exclusion are provided. In summary, the modelled polymer types are:

- Polyethylene terephthalate (PET)
- High density polyethylene (HDPE)
- Polyvinyl chloride (PVC)
- Polypropylene (PP)
- Polylactic acid (PLA)

Ideally all the polymer types listed in Table 4 would have had life cycle carbon emissions modelling undertaken, noting that HDPE and LDPE (which was not modelled) are very similar. However, it was beyond the resources available for this study to model all the major polymer types across the processes summarised in Table 3. So for the purposes of the scenario analyses undertaken for this study, the closest match modelled carbon emission factors, have been assigned to the polymer types that have not been modelled. The rationales for selecting the modelled polymer types, and for assigning the proxy emission factor values to those polymers types that have not been modelled, are outlined in Table 4.

It is important to note that as a number of polymers have been modelled using proxy emission factors the modelled emissions for these polymers may not reflect the actual emissions as quantified in the system change scenario modelling undertaken by this study.

In Table 4 polymer types have been screened for modelling principally on the basis of % carbon and quantity onto the market each year in Australia. The % carbon value is used as a proxy for the fossil hydrocarbon exposure for each polymer type.

Table 4 Polymer scope coverage and key characteristics

Polymer	PIC[1]	Formula	% carbon	% C onto market 2019–20	Directly modelled	Adopted emission factors	Comments
Polyethylene terephthalate (PET)	1	$-(C_{10}H_8O_4)_n-$	62.5%	8.7%	Yes	PET	Major polymer type, with medium % carbon, so useful to model for comparison with polymers that have high and low % carbon levels.
High density polyethylene (HDPE)	2	$-(CH_2)_n-$	85.6%	21.6%	Yes	HDPE	Major polymer type, with high % carbon, so useful to model for comparison with polymers that have medium and low % carbon levels.
Polyvinyl chloride (PVC)	3	$-(C_2H_3Cl)_n-$	38.4%	5.9%	Yes	PVC	Major polymer type, with low % carbon, so useful to model for comparison with polymers that have high and medium % carbon levels.
Low density polyethylene (LDPE)	4	$-(CH_2)n-$	85.6%	12.5%	No	HDPE factors	Major polymer type, but with the same formula as HDPE so life cycle emission factors will be similar. HDPE emission factors adopted in the scenario analysis as the best available proxy values.
Polypropylene (PP)	5	$-(C_3H_6)n-$	85.6%	16.2%	Yes	PP	Major polymer type, but with the same (effective) formula as HDPE so production related carbon emissions will be similar, so reduced value in modelling separately. However, PP is largest quantity polymer manufactured globally. Included in scope because of large global production quantity.
Polystyrene (PS) and Expanded polystyrene (EPS)	6	$-(C_8H_8)n-$	92.3%	5.2%	No	HDPE factors	Less major polymer type, with high % carbon, but similar enough to HDPE for likely reduced value in modelling separately. HDPE emission factors adopted in the scenario analysis as the best available proxy values.
Acrylonitrile butadiene styrene / styrene acrylonitrile / acrylonitrile styrene acrylate (ABS/SAN/ASA)	7	$-(C_{15}H_{17}N)n-$ (ABS formula / group is diverse)	85.3%	2.9%	No	HDPE factors	Less major polymer type, with high % carbon, but similar enough to HDPE for likely reduced value in modelling separately. HDPE emission factors adopted in the scenario analysis as the best available proxy values.
Polyurethanes (PUR)	7	$-(C_3H_8N_2O)n-$ (ethylurea formula / PURs are diverse)	40.9%	1.4%	No	PET factors	Major group of polymers, with typically low % carbon. Similar % carbon to PVC, but substantially different structure. Value in modelling separately but excluded to keep scope manageable in size. PET emission factors adopted in the scenario analysis as the best available proxy values.
Polyamides (PA) (nylons)	7	$-(C_6H_{11}NO)n-$ (nylon 6 formula / PAs are diverse)	63.7%	2.6%	No	PET factors	Major group of polymers, with typically medium % carbon. Similar % carbon to PET, but substantially different structure. Value in modelling separately but excluded to keep scope manageable in size. PET emission factors adopted in the scenario analysis as the best available proxy values.
Polylactic acid (PLA)	7	$-(C_3H_4O_2)n-$	50.0%	0.2%	Yes	PLA	Not a major polymer type overall, but is of interest as it is a major biodegradable polymer type that is fast growing in use, and is made from biogenic carbon. Included in scope to provide an example of a compostable polymer in the analysis.
Other (7) / Unknown polymer	7	Diverse	73.6%[2]	22.9%	No	PET/HDPE factors	The plastic resin types which make up most of the 'other' category are various acrylics, acetals, polyethylene oxide, polyisobutylene and other. Simple average of PET and HDPE emission factors adopted in the scenario analysis as the best available proxy values.

1. PIC – Plastic identification code.
2. Other (7) and unknown polymer % carbon is an estimate based on the weighted average of the other polymers.

The modelled polymers represent approximately 53% (1,340 kt C) of 2,550 kt C of the embodied carbon in plastics, onto the Australian market in 2019–20. LDPE (4) was the most significant polymer in terms of embodied carbon that was not directly modelled, excluding the 'Other (7) / Unknown polymer' grouping.

It is worth noting that as of 2019–20 there was no Australian manufacture of most plastics from precursor chemical requiring a significant level of transformation. The exceptions to this are HDPE, LDPE and PP, which are manufactured by Qenos (HDPE/LDPE) and Viva Energy Polymers (PP).

Major plastics types that are not made in Australia include PET, PVC, PS, polyurethanes and polyamides (nylons).

3.3.3 Polymer consumption and production

Plastics consumption in Australia

Australian plastics consumption data, for the 2019–20 financial year, and projections to 2049–50, have been drawn from the annual Australian Plastics Flows and Fates study (Envisage Works, 2021).

Plastics production modelling outline

There are 4 plastic production pathways that have been modelled, which are:

- Fossil carbon based plastic.
- Recycled plastic (either mechanically or chemically recycled).
- Biobased plastic.
- CO_2 and H_2 based plastic.

CO_2 and H_2 based plastics production has been included in the scope of the study as it is an area of growing interest internationally (PlasticsEurope, 2022). While this is still a theoretical production pathway, it appears to have promise, particularly as supply of H_2 increases and the cost decreases, and as the cost of CO_2 emissions increases over coming decades.

Examples of the (simplified) chemical reaction pathways that can produce precursor hydrocarbons for major plastic types include:

- $CO_2 + 4H_2 \rightarrow CH_4$ (methanation/Sabatier reaction) $\rightarrow C_nH_{2n}$ (electrochemical oxidation)
- $CO_2 + H_2 \rightarrow CO + H_2O$ (water–gas shift reaction) $\rightarrow CO + 2H_2 \rightarrow CH_3OH$ (hydrogenation) $\rightarrow C_nH_{2n}$ (methanol-to-olefins)
- $CO_2 + H_2 \rightarrow CO + H_2O$ (water–gas shift reaction) $\rightarrow C_nH_{2n+2}$ (Fischer–Tropsch process)

The specific CO_2 and H_2 to polymer production pathways that have been modelled in this study are detailed in the following 5 tables (Table 5–Table 9).

PET production pathways

The modelled polymer production pathways for PET are outlined in Table 5.

Table 5 Modelled polymer production pathways, by carbon source – PET

Carbon source	Precursors 1	Precursors 2	Precursors 3	Precursors 4[a]	Comments
Fossil	Terephthalic acid	Para-xylene	Toluene	Oil	It is unlikely that significant quantities of toluene are made from CG or UG. Ethane is primarily sourced from natural gas but is also a co-product from oil refining. PET production data is global average data (Hischier, 2007a). sourced from the ecoinvent LCI database (v3.8).
	Ethylene glycol	Ethene	Ethane or naphtha	CG / UG / Oil	
Recycled	Mechanically recycled PET	–	–	–	The production inputs for recycled polymer production are relatively minor, and are for transport from the outgoing gate of the recycling facility (either mechanical or chemical), which is the outgoing boundary of the product EoL process, to a local or overseas warehouse. The adoption of the outgoing gate of the recycling facility as the outgoing boundary of the product EoL process is in line with the adoption of the closed-loop allocation procedure (see Section 3.7.2) and the guidance provided in ISO 14067 (2018, p. 39).
	Chemically recycled PET	–	–	–	
Biobased	Terephthalic acid (TA)	Para-xylene	Biobased oil	Wood chips	There is currently negligible commercial production of TA from any biobased sources. The theoretical production pathway adopted for this study is the conversion of wood chips to a biobased crude oil equivalent liquid, followed by conversion to para-xylene and then TA (Chen, et al., 2016, p. 9; Walker & Rothman, 2020, p. 3).
	Ethylene glycol (EG)	Ethylene oxide	Ethanol to ethene	Sugarcane	There is currently some minor commercial production of EG from biobased ethanol sources. The production pathway adopted for this study is the fermentation of sugars to ethanol, the dehydration of ethanol to ethene (Mohsenzadeh, et al., 2017, p. 80), followed by conversion to ethylene oxide and then EG. Removals of atmospheric CO_2 are allocated to the biobased polymer production stage.
CO_2 based	Terephthalic acid (TA)	Para-xylene	Methane	CO_2 and H_2	There is currently no commercial production of TA from CO_2 and H_2. The theoretical production pathway adopted for this study is the capture of CO_2 from cement kiln flue gas (~20% CO_2) using the average technology mix as assessed in Voldsund, et al. (2019), which is reacted with renewable H_2 to form CH_4 (Sabatier reaction), followed by conversion to para-xylene (Niziolek, et al., 2015) and then TA.
	Ethylene glycol (EG)	Ethene to ethylene oxide	Methane	CO_2 and H_2	There is currently no commercial production of EG from CO_2 and H_2. The theoretical production pathway adopted for this study is the capture of CO_2 from cement kiln flue gas (~20% CO_2) using the average technology mix as assessed in Voldsund, et al. (2019), which is reacted with renewable H_2 to form CH_4 (Sabatier reaction), followed by conversion to ethene (Zhu, et al., 2019) and then EG via ethylene oxide.

a) Potential fossil hydrocarbon raw material supply options are; conventional gas (CG), unconventional gas (UG)(including coal seam gas, shale gas and tight gas), oil and coal.

HDPE production pathways

The modelled polymer production pathways for HDPE are outlined in Table 6.

Table 6 Modelled polymer production pathways, by carbon source – HDPE

Carbon source	Precursors 1	Precursors 2	Precursors 3	Precursors 4[a]	Comments
Fossil	Ethene	Ethane or naphtha	Fossil gas or crude oil	–	Ethane is primarily sourced from fossil gas but is also a co-product from oil refining. Naphtha is sourced from oil. HDPE production data is global average data (PlasticsEurope, 2016a) sourced from the ecoinvent LCI database (v3.8).
Recycled	Mechanically recycled HDPE	–	–	–	The production inputs for recycled polymer production are relatively minor, and are for transport from the outgoing gate of the recycling facility (either mechanical or chemical), which is the outgoing boundary of the product EoL process, to a local or overseas warehouse. The adoption of the outgoing gate of the recycling facility as the outgoing boundary of the product EoL process is in line with the adoption of the closed-loop allocation procedure (see Section 3.7.2) and the guidance provided in ISO 14067 (2018, p. 39).
	Chemically recycled HDPE	–	–	–	
Biobased	Ethene	Ethanol	Sugarcane	–	There are currently relatively small quantities of HDPE production globally from biobased sources. The largest producer globally is *Braskem*, which manufactures ethene from ethanol sourced from the fermentation of sugars obtained from sugarcane. HDPE production data is global average data (PlasticsEurope, 2016a) sourced from the ecoinvent LCI database (v3.8), modified to substitute the input of fossil based ethene with the supply of biobased ethene based on the process described in Mohsenzadeh, et al. (2017, p. 80). Removals of atmospheric CO_2 are allocated to the biobased polymer production stage.
CO_2 based	Ethene	Methane	CO_2 and H_2	–	There is currently no commercial production of ethene from CO_2 and H_2. The theoretical production pathway adopted for this study is the capture of CO_2 from cement kiln flue gas (~20% CO_2) using the average technology mix as assessed in Voldsund, et al. (2019), which is reacted with renewable H_2 to form CH_4 (Sabatier reaction), followed by conversion to ethene (Zhu, et al., 2019) and then to HDPE.

PVC production pathways

The modelled polymer production pathways for PVC are outlined in Table 7.

Table 7 Modelled polymer production pathways, by carbon source – PVC

Carbon source	Precursors 1	Precursors 2	Precursors 3	Precursors 4[a]	Comments
Fossil	Vinyl chloride	Ethene	Ethane or naphtha	Fossil gas or crude oil	Ethane is primarily sourced from fossil gas but is also a co-product from oil refining. Naphtha is sourced from oil. Sodium chloride is sourced from mineral ore (rock salt), sea water or salt lakes. PVC production data is global average data (PlasticsEurope, 2016b) sourced from the ecoinvent LCI database (v3.8).
		Chlorine	Sodium chloride	–	
Recycled	Mechanically recycled PVC	–	–	–	The production inputs for recycled polymer production are relatively minor, and are for transport from the outgoing gate of the recycling facility (either mechanical or chemical), which is the outgoing boundary of the product EoL process, to a local or overseas warehouse. The adoption of the outgoing gate of the recycling facility as the outgoing boundary of the product EoL process is in line with the adoption of the closed-loop allocation procedure (see Section 3.7.2) and the guidance provided in ISO 14067 (2018, p. 39).
	Chemically recycled PVC	–	–	–	
Biobased	Vinyl chloride	Ethene	Ethanol	Sugarcane	There are currently relatively small quantities of ethene production globally from biobased sources. The largest producer globally is *Braskem*. PVC production data is global average data (PlasticsEurope, 2016b) sourced from the ecoinvent LCI database (v3.8), modified to substitute the input of fossil based ethene with the supply of biobased ethene based on the process described in Mohsenzadeh, et al. (2017, p. 80). Bio-ethene has been substituted in both the VCM input and the dichloroethane input. Removals of atmospheric CO_2 are allocated to the biobased polymer production stage.
		Chlorine	Sodium chloride	–	Sodium chloride is sourced from mineral ore (rock salt), sea water or salt lakes.
CO_2 based	Vinyl chloride	Ethene	Methane	CO_2 and H_2	There is currently no commercial production of methane from CO_2 and H_2. The theoretical production pathway adopted for this study is the capture of CO_2 from cement kiln flue gas (~20% CO_2) using the average technology mix as assessed in Voldsund, et al. (2019), which is reacted with renewable H_2 to form CH_4 (Sabatier reaction), followed by conversion to ethene (Zhu, et al., 2019) and then vinyl chloride monomer (VCM).
		Chlorine	Sodium chloride	–	Sodium chloride is sourced from mineral ore (rock salt), sea water or salt lakes.

PP production pathways

The modelled polymer production pathways for PP are outlined in Table 8.

Table 8 Modelled polymer production pathways, by carbon source – PP

Carbon source	Precursors 1	Precursors 2	Precursors 3	Precursors 4[a]	Comments
Fossil	Propene	Propane or naphtha	Fossil gas or crude oil	–	Propane is primarily sourced from fossil gas but is also a co-product from oil refining. Naphtha is sourced from oil. PP production data is global average data (PlasticsEurope, 2016c) sourced from the ecoinvent LCI database (v3.8).
Recycled	Mechanically recycled PP	–	–	–	The production inputs for recycled polymer production are relatively minor, and are for transport from the outgoing gate of the recycling facility (either mechanical or chemical), which is the outgoing boundary of the product EoL process, to a local or overseas warehouse. The adoption of the outgoing gate of the recycling facility as the outgoing boundary of the product EoL process is in line with the adoption of the closed-loop allocation procedure (see Section 3.7.2) and the guidance provided in ISO 14067 (2018, p. 39).
	Chemically recycled PP	–	–	–	
Biobased	Propene	Butene	Ethene	Ethanol (from sugarcane sourced sugars fermentation)	There are currently very small quantities of PP production globally from biobased sources. The largest producer globally is possibly *Braskem*, although this bio-PP production activity may still be at pilot scale. The modelled production pathway is an idealised conversion of ethanol to propene, which is highly approximated and uncertain due to the unavailability of information on the small number of existing (pilot) commercial processes. This overall process entails the conversion of ethanol to ethene, followed by the conversion of ethene to butene. Ethene and butene are then reacted together to form propene. This pathway is based on the little available published information on the Braskem process that could be identified (Gotro, 2013), and many process assumptions. Removals of atmospheric CO_2 are allocated to the biobased polymer production stage.
CO_2 based	Propene	Ethene and butene	Methane	CO_2 and H_2	There is currently no commercial production of propene from CO_2 and H_2. The theoretical production pathway adopted for this study is the capture of CO_2 from cement kiln flue gas (~20% CO_2) using the average technology mix as assessed in Voldsund, et al. (2019), which is reacted with renewable H_2 to form CH_4 (Sabatier reaction), followed by conversion to ethene, which then follows the same reaction pathway as biobased PP above.

PLA production pathways

The modelled polymer production pathways for PLA are outlined in Table 9.

Table 9 Modelled polymer production pathways, by carbon source – PLA

Carbon source	Precursors 1	Precursors 2	Precursors 3	Precursors 4	Comments
Fossil	Acetaldehyde	Ethene	Ethane or naphtha	Fossil gas or crude oil	PLA is commercially produced from fossil hydrocarbons. However, this production pathway has a significantly lower market share relative to production from biogenic sources. In this process acetaldehyde is reacted with NaCN or KCN. PLA production data is global average data (Althaus, et al., 2007) sourced from the ecoinvent LCI database (v3.8), modified to substitute the biobased maize grain related inputs with fossil hydrocarbon based acetaldehyde.
Recycled	Mechanically recycled PP	–	–	–	The production inputs for recycled polymer production are relatively minor, and are for transport from the outgoing gate of the recycling facility (either mechanical or chemical), which is the outgoing boundary of the product EoL process, to a local or overseas warehouse. The adoption of the outgoing gate of the recycling facility as the outgoing boundary of the product EoL process is in line with the adoption of the closed-loop allocation procedure (see Section 3.7.2) and the guidance provided in ISO 14067 (2018, p. 39).
	Chemically recycled PP	–	–	–	
Biobased	Lactide	Lactic acid	Maize starch	–	Maize sourced starch is fermented to produce lactic acid, which is then converted to lactide. The lactide is then polymerised to produce PLA. PLA production data is global average data (Althaus, et al., 2007) sourced from the ecoinvent LCI database (v3.8).
CO_2 based	Lactide	Lactic acid	CO_2 and H_2	–	There is currently no commercial production of PLA from CO_2 and H_2. The theoretical production pathway adopted for this study is the capture of CO_2 from cement kiln flue gas (~20% CO_2) using the average technology mix as assessed in Voldsund, et al. (2019), which is reacted with renewable H_2 to form lactic acid (bacterial mediated process) (Mook, et al., 2022). The lactide is then polymerised to produce PLA.

Allowance for additional upstream fossil methane production emissions

The life cycle inventory databases drawn on for this study do include allowances for upstream fossil gas emissions. However, there is increasing evidence generated by relatively recent aircraft and satellite based atmospheric methane monitoring that methane emissions from natural gas extraction and processing are notably larger than those included in the existing LCI database sources (with the possible exception of CarbonMinds (2023) LCA database, which due to cost was not available for review for this study).

The literature review undertaken for this study found that atmospheric methane concentration and rate of growth are significantly higher than expected, and that there are "*Large discrepancies between atmospheric inversions, bottom-up inventories and biogeochemical models*" (Lauvaux, et al., 2022, p. 2).

This finding is supported by a numerous and growing list of other published literature (Ehret, et al., 2022; Hmiel, et al., 2020; Lafleur, et al., 2016; Zhang, et al., 2022). For example, Hmiel, et al. (2020, p. 411) stated that "*bottom-up inventories strongly underestimate CH_4 emissions from fossil fuel extraction, distribution and use*". The International Energy Agency recently published the 2022 update of its *Global Methane Tracker* (IEA, 2023), which found that global methane emissions "*are about 70% greater than the sum of estimates submitted by national governments*". This includes methane emissions across gas, oil and coal.

The likelihood of the systematic understatement of natural gas and oil extraction and production emissions globally is so great that it is a requirement of ISO 14067 to account for these, if possible, in this study.

There is a growing dataset of satellite based methane monitoring that would ideally be used to resolve this issue. However, the collection and interpretation of this dataset is developing space, and no literature could be identified, based on these direct, regular and global atmospheric measurements, that was suitable to correct the available published data for understatements in fossil methane emissions. Instead, the Hmiel, et al. (2020) paper published in Nature was used to provide approximations of the required real-world emission correction.

The Hmiel, et al. (2020) paper adopted a carbon isotope mass balance approach, using measured methane concentrations in the atmosphere, to determine a range on the underestimation of overall anthropogenic fossil methane emissions. The paper found that fossil CH_4 emissions are understated by 25%–40% by bottom-up inventory based estimates, as typically adopted by governments internationally. This estimate relates to all anthropogenic fossil CH_4 emissions, across gas, oil and coal. However, it has been adopted here as being reasonably indicative of the proportional (separate) contributions of each of the fossil hydrocarbon feedstocks to these emissions. This is substantially less than the Global Methane Tracker (IEA, 2023) published data, but has been adopted in this study as it was available at the time of modelling.

The Hmiel, et al. (2020) data range (mid-point of 32.5%) was used to approximate a correction for the required additional upstream natural gas extraction and production methane emissions in the life cycle inventory data incorporated into this study (primarily drawn from the ecoinvent LCI database v3.8).

Polymer production transport

The other type of inputs into the polymer production processes are transport inputs. The modelled foreground transport parameters are summarised in the following two tables. There are no foreground transport inputs for fossil polymer production, and the inputs substantially relate to transporting recycled polymer from the reprocessing facility gate to an overseas warehouse, at which point the material becomes available to overseas product manufacturers.

Table 10 Transport inputs – Polymer production – Recycled

Parameter description	Value	Unit	Data sources / comments
Proportion of recycled plastics to export	0.50	Proportion	Proportion of recycled plastics sold to overseas buyers, based on the ratio (around 1:1) for 2019–20 (Envisage Works, 2021).
Transport – articulated truck – recycling facility to port	100	km	Road freight transport allowance from the location of recycling to port, for the proportion of recycled plastics sold into overseas markets (Blue Environment, 2023).
Transport – sea – Australia to China	8,600	km	Approximation of the Australian weighted average transport distance for reprocessed plastics from the nearest Australian port to China, which is the adopted proxy location for the remanufacture of the recycled plastics into new products (Sea-Distances.org, 2023; Blue Environment, 2023).
Transport – articulated truck – from overseas port to overseas warehouse	50	km	Road freight transport allowance from the overseas port to an overseas warehouse, for the proportion of recycled plastics sold into overseas markets (Blue Environment, 2023).
Transport – articulated truck – from recycling to Australian warehouse	50	km	Road freight transport allowance from the location of recycling to an Australian warehouse, for the proportion of recycled plastics sold into Australian markets (Blue Environment, 2023).

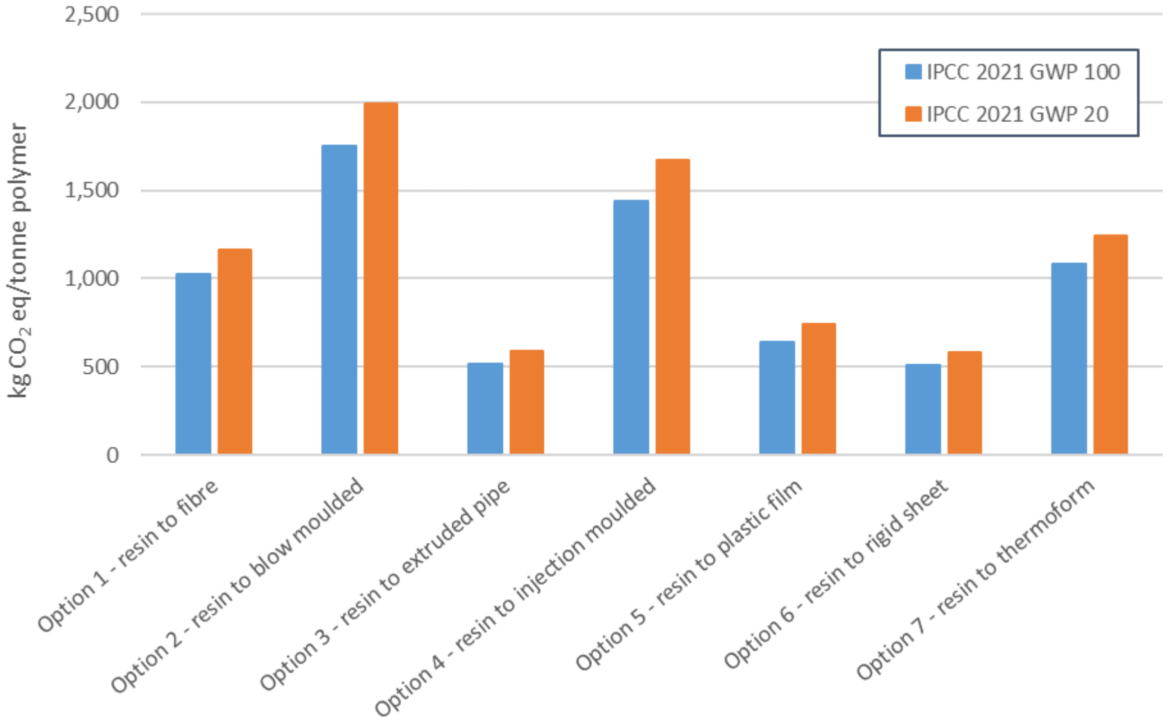
Table 11 Transport inputs – Polymer production – CO_2 based

Parameter description	Value	Unit	Data sources / comments
Transport – articulated truck (PET only)	200	km	Road transport allowance for terephthalic acid and ethylene glycol transport (Blue Environment, 2023).

3.3.4 Product manufacture

Plastic polymers go into many products with diverse manufacturing pathways and non-plastics components. For context, provided in Figure 2 are the carbon emissions associated with the major types of plastic to product conversion processes, excluding the upstream plastic production related inputs.

Figure 2 Conversion of plastic to product carbon emissions, by conversion process



The plastic to product conversion processes adopted in this study vary by plastic type. The adopted conversions are summarised in Table 12.

Table 12 Plastic to products conversion modelling assumptions

Plastic	Assumed conversion requirement
PET	Assumed 1:1 ratio between fibre (option 1) and blow moulded (option 2).
HDPE	Assumed 1:1:1 ratio between blow moulded (option 2), injection moulded (option 4) and film (option 5).
PVC	Assumed 1:1 ratio between extruded pipe (option 3) and film (option 5).
PP	Assumed 1:1:1:1 ratio between blow moulded (option 2), injection moulded (option 4), film (option 5) and thermoform (option 7).
PLA	Assumed 100% to film (option 5) as this is the dominant form used Australia.

The plastic to product conversion processes data sources and other details are summarised in Table 13.

Table 13 Plastic to products conversion processes data sources and other details

Conversion process	Comments / Data sources
Fibre	Source is ecoinvent LCI database (v3.8) process 'polyester fibre production, finished | fibre, polyester | APOS, S'. Modified version to exclude the default PET resin inputs. Data is not published elsewhere. The dataset covers (PET) granulate as input for the melt spinning process. Polyester melt spinning processes are based on global data. Data is 'rest-of-world' data (adopted as global). Data for the melt spinning process date from 2001 and 2013. Data reported as current to 2022.

Conversion process	Comments / Data sources
Blow moulding	Source is ecoinvent LCI database (v3.8) process 'blow moulding | blow moulding | APOS, S'. Data is not published elsewhere. The dataset covers 1 kg of input plastic to produce 0.997 kg of blow moulded plastics (e.g. bottles). Processes are based on global data. Data reported as current to 2021.
Extruded pipe	Source is ecoinvent LCI database (v3.8) process 'market for extrusion, plastic pipes | extrusion, plastic pipes | APOS, S'. Data is not published elsewhere. The dataset describes the continuous manufacture of a semifinished plastic product (film, sheet, pipe, profile), with 0.976 kg of extruded plastic corresponding to 1 kg of this process. Processes are based on global data. Data reported as current to 2021.
Injection moulding	Source is ecoinvent LCI database (v3.8) process 'market for injection moulding | injection moulding | APOS, S'. Data is not published elsewhere. Injection moulding is a discontinuous process in which plastic pellets, granules or powder is melted and injected under pressure into the cavity of a mould, where it is solidified by cooling or thermally cross-linked. In the service of injection moulding, 1 kg of this process corresponds to 0.994 kg of injection moulded plastics. Processes are based on global data. Data reported as current to 2021.
Film	Source is ecoinvent LCI database (v3.8) process 'market for extrusion, plastic film | extrusion, plastic film | APOS, S'. Data is not published elsewhere. Extrusion (of film) is the term used to describe the continuous manufacture of a semifinished plastic product (film, sheet, pipe, profile). In the service of extrusion, 0.976 kg of extruded plastic film corresponds to 1 kg of this process. Processes are based on global data. Data reported as current to 2021.
Rigid sheets	Source is ecoinvent LCI database (v3.8) process extrusion, co-extrusion of plastic sheets | extrusion, co-extrusion | APOS, S'. Data is not published elsewhere. This service activity consists in transforming plastic pellets into plastic sheets of 200 microns to 2 mm thickness for the food industry. The inventory refers to an input of 1 kg of plastic pellets with 0.969 kg of sheet output. Processes are based on global data. Data reported as current to 2021.
Thermoforming	Source is ecoinvent LCI database (v3.8) process 'extrusion of plastic sheets and thermoforming, inline | extrusion of plastic sheets and thermoforming, inline | APOS, U'. Data is not published elsewhere. This service activity represents the inline extrusion and thermoforming of plastic pellets for the food industry. An input of 1 kg of plastic yields 0.94 kg of thermoformed plastic sheets. Thermoforming is a stretching technique of manufacture of three-dimensional mouldings from flat plastic preforms such as films or sheets, under the influence of heat and pressure or vacuum. Processes are based on French companies extrapolated to global data. Data reported as current to 2021.

With respect to energy inputs into polymer conversion (product manufacturing) it is important to highlight that the modelled conversion processes include overseas (approximately global average) inputs of electricity.

However, while 61% of plastics consumed in Australia in 2019–20 were imported in converted forms, 39% of plastics consumed in Australia were converted locally, using Australian grid electricity inputs. It is worth noting that the proportion of locally converted plastics has been steady decreasing for decades.

Ideally this issue would be corrected by constructing conversion processes that included proportions of both the overseas and Australian electricity supplies. However, this would add significant complexity to the modelling requirement and has not been undertaken.

For context, the global average carbon emissions for the supply of 1 kWh of electricity is 0.73 kg CO_2-e (ecoinvent LCI database v3.8 published data for global low voltage supply, current to 2021, GWP-100 basis), compared with the equivalent Australian average of 0.81 kg CO_2-e/kWh in 2021 (DISER, 2021, p. 79), and so the electricity related emissions associated with Australian plastics conversion are approximately 10% higher than the global average.

This means that the emissions associated with product manufacture are typically understated by something in the order of 3–4%, and that across the full modelled lifecycle flows from polymer production to product EoL emissions, particularly for conventional fossil carbon based plastics use to landfill disposal, would generally be around the 1% cut-off.

Product manufacturing losses

While likely not quite below the 1% cut-off, product manufacturing losses of plastic polymers have been excluded from the scope to simplify the modelling requirement.

For context on the significance of this scope exclusion, packaging only related data from APCO (APCO, 2021) indicates that a total of 683,000 tonnes of polymer was locally converted into packaging in Australia in 2019–20. Of this 21,000 tonnes (3%) was generated as pre-consumer waste by packaging manufacturers. Of the 21,000 tonnes, 18,000 (84%) was subsequently sent to mechanical recycling and 3,000 (16%) was sent to landfill. A very small quantity of the 21,000 tonnes may have been sent to energy recovery in either NSW or SA, however this quantity is unknown and is ignored.

The packaging related data above is likely to also be reasonably indicative of non-packaging product manufacturing losses. However, there is no specific data available on manufacturing losses by non-packaging plastic product manufacturers either here in Australia or overseas.

As most of the pre-consumer scrap is mechanically recycled and returned back as an input into plastic product (or packaging) manufacturing, the inputs into product manufacturing will be understated by (mostly) the mechanical recycling inputs required to convert the 18,000 tonnes of pre-consumer scrap into a manufacturing ready input.

Product manufacturing transport

The other type of inputs into the product manufacturing processes are transport inputs. The key related transport parameters are summarised in the following table. These transport inputs are from the polymer producers gate to the product manufacturers gate.

Table 14 Transport inputs – Product manufacture

Parameter description	Value	Unit	Data sources / comments
Proportion of imported polymer with country A to country B transfer	0.25	Proportion	Proportion of all overseas sourced polymer that requires an international transfer of unconverted plastics from producing regions, to the region of conversion into products, followed by transport to Australia. Data is for 2018-19. Blue Environment estimate based on DFAT (2020).
Proportion of Australian consumption that is imported polymer	Polymer dependent	Proportion	Proportion of polymer that was imported for Australian use in 2019–20 both in unconverted and converted forms (Envisage Works, 2021).
Proportion of Australian consumption that is imported polymer resin	Polymer dependent	Proportion	Proportion of polymer that was imported for Australian use in 2019–20 in unconverted forms (Envisage Works, 2021).
Transport – sea – global weighted average transport distance – all countries	8,600	km	Approximation of the distance from global production sources to (overseas) global intermediate destinations, Data is for calendar year 2019 (S&P Global, 2020).
Transport – sea – global weighted average transport distance – to Australia	13,100	km	Distance from global production sources to Australia, in kilometres, mass weighted with respect to the global plastics production market share of all major producing countries or regions (Sea-Distances.org, 2023; Statista, 2022; Blue Environment, 2023).
Transport – articulated truck – from polymer production (country A) to product manufacture (country B)	400	km	Road freight transport allowance (2 legs) from polymer production (country A) to product manufacture (country B) (Blue Environment, 2023).
Transport – articulated truck – from polymer production (overseas) to product manufacture (Australia)	400	km	Road freight transport allowance (2 legs) from polymer production (overseas) to product manufacture (Australia) (Blue Environment, 2023).
Transport – articulated truck – from polymer production (Australia) to product manufacture (Australia)	200	km	Road freight transport allowance from polymer production (Australia) to product manufacture (Australia). Applied to Australian production of unconverted resins, both virgin and recycled (Blue Environment, 2023).

3.3.5 Product use stage

The product use stage only includes transport allowances from the location of product manufacture to the point of sale in Australia.

Table 15 Transport inputs – Product use

Parameter description	Value	Unit	Data sources / comments
Proportion of Australian consumption that is imported products	Polymer dependent	Proportion	Proportion of polymer that was imported for Australian use in 2019–20 in converted forms (Envisage Works, 2021).
Transport – sea – global weighted average transport distance – to Australia	13,100	km	Distance from global production sources to Australia, in kilometres, mass weighted with respect to the global plastics production market share of all major producing countries or regions (Sea-Distances.org, 2023; Statista, 2022; Blue Environment, 2023).
Transport – articulated truck – from product manufacture (overseas) to product use (Australia)	400	km	Road freight transport allowance (2 legs) from product manufacture (overseas) to product use (Australia) (Blue Environment, 2023).
Transport – articulated truck – from product manufacture (Australia) to product use (Australia)	200	km	Road freight transport allowance from product manufacture (Australia) to product use (Australia) (Blue Environment, 2023).

Refer to Section 3.6.1 for a detailed discussion on the implications of the restricted scope of inputs into the product use stage.

3.3.6 Product end-of-life

Modelling context

Following disposal, plastic products in Australia have historically largely been sent to landfill. Relatively much lower quantities (typically around 12–15% of end-of-life generation) have been sent to mechanical recycling, most significantly a range of forms of rigid plastic packaging. Much smaller quantities have been sent to energy recovery (at cement kilns) in NSW and SA. The growth in mechanical recycling capacity has been static or slowly growing for decades.

This picture is now changing in the following regards:

- New mechanical recycling capacity, of the order of 300 kt/yr, is anticipated to come into operation across the period of 2022–2025.
- New chemical recycling capacity, of the order of 200–300 kt/yr, is anticipated to come into operation by 2025.
- New waste-to-energy (WtE) facilities are planned or under construction nationally, with the plastics fraction of the waste considered an important contributor to the energy content of the incoming feedstock fuel. The plastics treatment capacity of these facilities is not known.

  The combustion of fossil carbon in plastics will contribute to the carbon emissions of plastics, which is currently offset to a degree by the avoided use of fossil fuels to generate electricity.

  As electricity grids continue decarbonising nationally, electricity generated through the combustion of waste plastics will become more and more carbon intensive relative to the competing (increasingly renewable) electricity generators. In an electricity grid where all other electricity generators are renewable, fossil carbon based plastics WtE generated electricity will no longer receive an avoided carbon emission credit for exported electricity.

The plastics end-of-life (EoL) fates that have been modelled are:

- mechanical recycling
- chemical recycling
- composting (PLA only)
- waste-to-energy
- incineration
- landfill

Reuse of plastics, or rather the products containing the plastics, is not considered an EoL fate, so reuse is excluded from the project scope.

The modelling of the EoL management of plastics is primarily based on the guidance provided in ISO (2018). For mechanical and chemical recycling a modified form of the 'closed loop allocation procedure' (or 0/100 method) has been adopted (ISO, 2018, pp. 38-39; WRI & WBCSC, 2011a, p. 71). See Section 3.7.2 for more detailed discussion on the closed loop allocation procedure.

Mechanical recycling

High value-adding mechanical recycling processes have been modelled. These include the collection, sorting, shredding, washing, drying of flaked plastics, ready for sale and assumed virgin equivalent, or repelletised, ready for sale and assumed virgin equivalent.

Table 16 Mechanical recycling process data

Parameter description	Value	Unit	Data sources / comments
Transport – articulated truck – to recycling	100	km	Road freight transport allowance from the location of product EoL generation to mechanical recycling, including an allowance for transport to and from an intervening sorting location (Blue Environment, 2023).
Electricity – MRF sorting	17	kWh/tonne	Aggregated Material Recycling Facility (MRF) sorting process electricity inputs as drawn from the AusLCI database v1.40 (Grant, 2010). It is assumed that all EoL products sent to mechanical recycling will require an initial sorting activity that has an equivalent electricity input to MRF sorting. See Section 3.11.1 for more discussion on this assumption.
Electricity – mechanical recycling – flake	1,480	kWh/tonne	Plastics reprocessing facility energy input for the reprocessing of sorted plastics into virgin equivalent flakes (Blue Environment, 2023).
Electricity – mechanical recycling – pellets	2,230	kWh/tonne	Plastics reprocessing facility energy input for the reprocessing of sorted plastics into virgin equivalent pellets (Blue Environment, 2023).
Proportion of mechanically recycled plastics to pellets	0.50	Proportion	Proportion of locally mechanically reprocessed plastics that are reprocessed in pellet form (versus flake form). The proportion, as of end-2022, is closer to 0.3 to pellets (Envisage Works, 2021). However, as there is significant new pelletising capacity coming online in Australia over the period of 2022–2025, an average ratio in the order of 1:1 is considered to be a more appropriate longer-term average between flake and pellets production (post-2025) (Blue Environment, 2023).

Chemical recycling

The modelled chemical recycling process includes front-end pre-sorting, shredding and decontamination to prepare the incoming plastics into a suitable reactor feed, and the processing of the plastics into a virgin equivalent product, to the outgoing gate of the facility that produces the recycled plastic.

In Australia the physical fate of the recovered carbon in chemically recycled plastics will mostly be to liquid fuels for the foreseeable future. However, a proportion may be recovered back into new polymer production, which may be significant if a mass balance carbon accounting method is adopted, e.g. the ISCC PLUS system certification (ISCC, 2021, p. 16).

However, for the purposes of this study, the scope requires the closed loop chemical recycling of plastics into new (virgin equivalent) plastic, ready for manufacture into new products, or plastics to plastics as it is commonly described. That is, what are the carbon emissions associated with the chemical recycling of 1 tonne of polymer (with consideration of any inherent and unavoidable material losses due to the specifics of the recycling process) back into new (virgin equivalent) plastic.

The chemical recycling of all 5 plastics has been modelled. The modelled processes are summarised in Table 17, and the major parameters incorporated into each chemical recycling process are detailed in Table 18 to Table 21. For context, also provided in Table 17 are the carbon emission estimates (GWP 100 year basis) associated with the chemical recycling processes only, and excluding any associated MRF sorting, preprocessing or transport inputs.

Table 17 Summary of modelled chemical recycling processes

Polymer	Description / comments	Carbon emissions (output polymer basis)
PET	The modelled process for PET is protein-based catalyst (enzyme) mediated chemical recycling with hydrolysis of pre-processed (mechanically) PET to terephthalic acid and ethylene glycol, followed by (re)polymerisation to PET. Examples are *Samsara Eco* and *Carbios*. Another promising technology internationally is metal-based (usually) catalyst mediated chemical recycling with methanolysis of PET to dimethyl terephthalate (DMT) and ethylene glycol, hydrolysis of the DMT to terephthalic acid, followed by (re)polymerisation to PET. An example is *Loop Industries*. See Payne & Jones (2021, p. 4061) for a summary of the potential closed loop chemistry pathways for the chemical recycling of PET.	600 kg CO_2 eq/tonne
HDPE	The modelled process for HDPE is a modified form of hydrothermal liquefaction based chemical recycling, with the liquid co-product (chemical recycling crude or CR crude) to refining and then to polymerisation of HDPE. An example is *Licella* (in partnership with Viva Energy and Viva Polymers).	3,060 kg CO_2 eq/tonne
PVC	The modelled process for PVC is solvent based chemical recycling involving the dissolution of pre-processed (mechanically) PVC in a mixture of methyl ethyl ketone (MEK), hexane and water (Sherwood, 2020, p. 9), followed by precipitation and drying of the precipitated PVC. An example is *VinyLoop*. There was no PVC chemical recycling technology development identified locally, and little internationally. The VinyLoop Ferrara facility (in Italy) identified above ceased operating in 2018.	1,050 kg CO_2 eq/tonne
PP	The modelled process for PP is a modified form of hydrothermal liquefaction based chemical recycling, with the liquid co-product (chemical recycling crude or CR crude) to refining and then to polymerisation of PP. An example is *Licella* (in partnership with Viva Energy and Viva Polymers).	3,130 kg CO_2 eq/tonne

Polymer	Description / comments	Carbon emissions (output polymer basis)
PLA	The modelled process for PLA is solvent based chemical recycling with hydrolysis to lactic acid, conversion to lactide, followed by (re)polymerisation to PLA. An example is NatureWorks, which is the largest PLA chemical recycler globally. See Payne & Jones (2021, p. 4047) for a summary of the potential closed loop chemistry pathways for the chemical recycling of PLA.	2,230 kg CO_2 eq/tonne

Table 18 Chemical recycling process data – PET

Parameter description	Value	Unit	Data sources / comments
Transport – articulated truck	100	km	Road freight transport allowance from the location of product EoL generation to chemical recycling, including an allowance for transport to and from an intervening sorting location (Blue Environment, 2023).
Electricity – MRF sorting	17	kWh/tonne	Aggregated Material Recycling Facility (MRF) sorting process electricity inputs as drawn from the AusLCI database v1.40 (Grant, 2010). It is assumed that all EoL products sent to chemical recycling will require an initial offsite sorting activity that has an equivalent electricity input to MRF sorting. See Section 3.11.1 for more discussion on this assumption.
Electricity – front-end pre-processing	80	kWh/tonne	Electricity inputs to operate the front-end pre-processing of the incoming scrap plastics (confidential source). This energy input is potentially less dependent on the future mix of chemical recycling reactor technologies that are adopted. Contaminant losses, which would likely go to landfill, are ignored.
Electricity – reactor	40	kWh/tonne	Electricity inputs to operate the chemical recycling reactor. Co-products from the reactor are terephthalic acid and ethylene glycol. No published data available, so electricity requirement estimated from first principles and is highly uncertain (Blue Environment, 2023). Estimate includes allowances for direct heat inputs, which are assumed 100% supplied through electrical (resistive) heating, and operation of ancillary equipment. Reactor operating temperature is approximately 60–70 ^{0}C, so process heat requirement is low.
Chemical recycling recovery rate	90%	% of incoming plastic	It is assumed that 90% of the incoming PET is recovered back into new PET resin (Tournier, et al., 2020, p. 1). The 10% loss is assumed sent to landfill.
Terephthalic acid and ethylene glycol conversion to PET (numerous input and output parameters)	Various	Various	The terephthalic acid and ethylene glycol conversion inputs are based on pre-existing background process published in the ecoinvent LCI database v3.8 (Hischier, 2007a), modified for terephthalic acid and ethylene glycol sourced from chemical recycling. Adopted 1:1 split between amorphous and crystalline PET production due to the absence of specific data. Most PET products are a mixture of amorphous and crystalline PET. For context, fossil-based amorphous PET has 9% higher carbon emissions than crystalline PET (GWP-100 basis) (Hischier, 2007a).

Table 19 Chemical recycling process data – HDPE and PP

Parameter description	Value	Unit	Data sources / comments
Transport – articulated truck	100	km	Road freight transport allowance from the location of product EoL generation to chemical recycling, including an allowance for transport to and from an intervening sorting location (Blue Environment, 2023).
Electricity – MRF sorting	17	kWh/tonne	Aggregated Material Recycling Facility (MRF) sorting process electricity inputs as drawn from the AusLCI database v1.40 (Grant, 2010).

Parameter description	Value	Unit	Data sources / comments
			It is assumed that all EoL products sent to chemical recycling will require an initial offsite sorting activity that has an equivalent electricity input to MRF sorting. See Section 3.11.1 for more discussion on this assumption.
Electricity – front-end pre-processing	80	kWh/tonne	Electricity inputs to operate the front-end pre-processing of the incoming scrap plastics (confidential source). This energy input is potentially less dependent on the future mix of chemical recycling reactor technologies that are adopted. Contaminant losses, which would likely go to landfill, are ignored.
Electricity – reactor	210	kWh/tonne	Electricity inputs to operate the chemical recycling reactor (confidential source). This excludes the required direct heat inputs, which are assumed 100% supplied through the onsite use of the mixed hydrocarbon gas co-product that is generated by the reactor. This energy input is potentially more dependent on the future mix of chemical recycling reactor technologies that are adopted. However, due to both a lack of knowledge of the future proportional capacities by reactor type, and information on the reactor electricity requirements by reactor type, this value is for a single reactor type for which well-quantified data was available, and is likely to see major uptake in Australia.
Water	[excluded]	kL/tonne	Chemical recycling reactor processes can be water or other solvent mediated (e.g. hydrothermal liquefaction), but many are not. The carbon emissions associated with water supply and treatment are excluded as assumed below the 1% cut-off for the contribution of the proportion of plastics that are chemically recycled via this kind of process.
Incoming plastic to liquid co-product (CR crude)	85%	% of incoming plastic	To approximate a mix of future proportional capacities by reactor type (due to a lack of real-world data) a simplified chemical recycling modelling approach has been adopted, that assumes 85% of the incoming carbon is recovered into a liquid co-product (and sent for downstream processing into fuels or plastics), and 15% is recovered into a gas co-product and combusted for facility energy generation or flared (Blue Environment estimates). The gas co-product is assumed 100% converted to CO_2. The liquid co-product is referred to in this report as 'chemical recycling crude' or CR crude. The practical and economic feasibility of purifying and exporting excess gas from chemical recycling facilities is unknown, so this activity is not considered, and excess gas is assumed flared. If this activity did occur to some degree, then this would incur onsite gas processing inputs, but avoid the inputs required to produce the current competing gas supply from fossil hydrocarbon sources. Chemical recycling facility operators probably have a strong economic incentive to maximise liquids production, and so minimise gas production to a level that matches the onsite heating requirement, and so improvements in feedstock quality and technology performance over the next few decades may continually decrease excess gas production.
Incoming plastic to gas co-product	15%	% of incoming plastic	
Fuel energy – CR crude to ethene conversion	35.6	GJ/tonne ethene	This is the adopted fuel energy input required to convert the CR crude into ethene or propene. This is based on approximations from the literature for the total energy requirement for the theoretical energy requirement for the steam cracking and purification of the CR crude to ethene. For the purposes of this project, the requirement is to determine the carbon emissions of plastics to plastics (closed-loop) chemical recycling of plastics, and provide comparability with the other modelled EoL fates, so therefore the energy requirement for achieving this outcome is the subject of interest. This approach avoids allocation of energy requirements within refinery processes, between the numerous and variable co-products from

Parameter description	Value	Unit	Data sources / comments
			refineries, by artificially dividing the combined refinery unit processes into theoretical CR crude to ethene sub-processes. CR crude is assumed to be equivalent to a Class D distillate (gas oil), as this was the closest infeed compositional match that was identified in the published literature for the conversion of the various potential hydrocarbon refinery infeeds to ethene. The average composition of CR crude is not known and likely to be variable in any case. In general terms CR crude is a complex mixture of naphtha (C5–C12 alkanes), kerosene (typically C9–C16 alkanes), diesel (typically C9–C25 alkanes), fuel oils (typically C20–C70 alkanes), waxes (typically C20–C40 alkanes) and a non-carbon based residue. Class D distillate is possibly more likely to have a lower energy requirement for conversion to ethene than CR crude. The adopted CR crude to ethene production primary energy requirement is 37.1 GJ/tonne (Worrell, et al., 2000, p. 15). This data is assumed to include allowances for the operation of auxiliary equipment, however, that is unclear in the source. This energy requirement is split between heat of reaction demand (33%), compression (11%), and heating and separation (55%). This energy is mostly supplied through the combustion of fuels, but will also include an imported electricity contribution, along with electricity generated onsite through the combustion of fuels. No specific data was identified on the proportion split of CR crude (or Class D distillate) to ethene production primary energy supply. However, refineries in the US are reported to source an average of 4% of offsite energy supply from electricity imports (Energetics, 2012, p. 73). This value was adopted as the best available estimate of the required fuel (onsite combustion) to electricity imports for ethene synthesis. This allows for the estimate of the onsite fuel energy demand of 35.6 GJ/tonne ethene and an offsite electricity demand of 412 kWh/tonne ethene. The onsite fuel energy demand is assumed supplied by 'Refinery gas and liquids' with emissions of 54.8 kg CO_2-e/GJ (DISER, 2021, p. 14), with assumed 100% conversion to CO_2. Insufficient literature data was identified to directly specify the CR crude to propene conversion related energy inputs. It can be derived from international processes data published in the ecoinvent LCI database v3.8 (Hischier, 2007b) that the conventional average production of propene has carbon emissions that are 2.8% higher than ethene (GWP-100 basis), but this includes the upstream (from refineries) carbon emissions of the upstream oil and gas production, which are the same (or probably very similar) for both propene and ethene, so therefore the refinery level carbon emissions are possibly more than 2.8% for propene relative to ethene. However, due to a lack of specific data, the refinery level energy inputs for propene synthesis are assumed to be the same as for ethene. This assumption may understate the actual energy requirement to convert CR crude to propene to a small degree.
Electricity – CR crude to ethene conversion	412	kWh/tonne ethene	This is the adopted electricity input required to convert the CR crude into ethene or propene. See main comment immediately above.
Ethene to HDPE conversion (numerous input and output parameters)	Various	Various	The ethene to HDPE conversion inputs are based on pre-existing background processes, modified for ethene sourced from chemical recycling (Grant, 2014b; Blue Environment, 2023).
Propene to PP conversion (numerous input and output parameters)	Various	Various	The propene to PP conversion inputs are based on pre-existing background processes, modified for propene sourced from chemical recycling (Grant, 2014b; Blue Environment, 2023).

Table 20 Chemical recycling process data – PVC

Parameter description	Value	Unit	Data sources / comments
Transport – articulated truck	100	km	Road freight transport allowance from the location of product EoL generation to chemical recycling, including an allowance for transport to and from an intervening sorting location (Blue Environment, 2023).
Electricity – MRF sorting	17	kWh/tonne	Aggregated Material Recycling Facility (MRF) sorting process electricity inputs as drawn from the AusLCI database v1.40 (Grant, 2010). It is assumed that all EoL products sent to chemical recycling will require an initial offsite sorting activity that has an equivalent electricity input to MRF sorting. See Section 3.11.1 for more discussion on this assumption.
Electricity – front-end pre-processing	80	kWh/tonne	Electricity inputs to operate the front-end pre-processing of the incoming scrap plastics (confidential source). This energy input is potentially less dependent on the future mix of chemical recycling reactor technologies that are adopted. Contaminant losses, which would likely go to landfill, are ignored.
Electricity – chemical recycling	30	kWh/tonne	Electricity inputs to operate the chemical recycling reactor. Products from the reactor is dissolved PVC. No published data available, so electricity requirement estimated from first principles and is highly uncertain (Blue Environment, 2023). Estimate includes the operation of ancillary equipment and drying, but excludes direct heat inputs, which are assumed 100% supplied through steam. Reactor operating temperature is approximately 100 ^{0}C, so process heat requirement is low.
Fuel energy – process steam	7,900	MJ steam /tonne PVC	Steam requirement for the distillation column is 3.6 kg/kg PVC (Sherwood, 2020, p. 9). No data identified on process steam pressure, so assumed to be 2 bar (absolute), as the heating requirement is low, and so a relatively low pressure (to minimise energy use) is assumed. Energy content of 2 bar steam is 2,202 kJ/kg (Engineering Toolbox, 2003). This gives a steam energy requirement of 7,900 MJ/tonne PVC (incoming).
Solvents	0	kg/kg PVC	The MEK and hexane are closed-loop recycled and are not destroyed in the process, so solvent inputs are assumed below the 1% cut-off and are excluded from the modelling.
Chemical recycling recovery rate	95%	% of incoming plastic	No data on PVC losses identified, however appears likely to be low. Assumed allowance for the loss of some PVC, with 95% of the incoming PVC is recovered back into new PVC resin. The 5% loss is assumed sent to landfill.

Table 21 Chemical recycling process data – PLA

Parameter description	Value	Unit	Data sources / comments
Transport – articulated truck	100	km	Road freight transport allowance from the location of product EoL generation to chemical recycling, including an allowance for transport to and from an intervening sorting location (Blue Environment, 2023).
Electricity – MRF sorting	17	kWh/tonne	Aggregated Material Recycling Facility (MRF) sorting process electricity inputs as drawn from the AusLCI database v1.40 (Grant, 2010). It is assumed that all EoL products sent to chemical recycling will require an initial offsite sorting activity that has an equivalent electricity input to MRF sorting. See Section 3.11.1 for more discussion on this assumption.
Electricity – front-end pre-processing	80	kWh/tonne	Electricity inputs to operate the front-end pre-processing of the incoming scrap plastics (confidential source). This energy input is potentially less dependent on the future mix of chemical recycling reactor technologies that are adopted. Contaminant losses, which would likely go to landfill, are ignored.

Parameter description	Value	Unit	Data sources / comments
Chemical recycling recovery rate	90%	% of incoming plastic	It is assumed that 90% of the incoming PLA is recovered back into new PLA resin (Payne & Jones, 2021, p. 4047). The 10% loss is assumed sent to landfill.
PLA processing to rPLA (numerous input and output parameters)	Various	Various	The PLA to rPLA conversion inputs are based on a pre-existing background process published in the ecoinvent LCI database v3.8 (Althaus, et al., 2007), modified from maize grain sourced starch as the major feedstock to lactic acid sourced from chemical recycling. This process is specifically based on NatureWorks production in the US. Due to a lack of information in the pre-existing process on the energy demand that is attributable to the conversion of maize starch to lactic acid the modified PLA production processes might overstate the carbon emissions. However, the literature review did not reveal any better data, and so the modified pre-existing process data has been adopted as the best available proxy data. It is considered indicative only.

Composting

The modelled composting process is for PLA composting in an aerobic industrial composting facility (open windrow). PET, HDPE, PVC and PP are not compostable and so have not been modelled to EoL processing by composting.

Table 22 Composting process data – PLA

Parameter description	Value	Unit	Data sources / comments
Transport – articulated truck	100	km	Road freight transport allowance from the location of product EoL generation to composting (Blue Environment, 2023).
PLA processing to compost (numerous input and output parameters)	Various	Various	The PLA to compost inputs are based on a pre-existing background process published in a modified version of ecoinvent 2.2 (most recent available), with upstream processes linked to Australian data from the AusLCI database v1.40.
Avoided fertiliser	Not applicable	Not applicable	Composted PLA is assumed to have no avoided fertiliser benefit as it consists of carbon, hydrogen and oxygen only.
Carbon sequestration	Not applicable	Not applicable	Composted PLA is assumed to have no carbon sequestration benefit as any PLA related carbon, hydrogen and oxygen retained in the compost is assumed to fully degrade into CO_2 and water within a few years. There will likely be some carbon retained in compost after 20, or even 100 years. However, this is assumed to not be related to a relatively available (for decomposition) simple polymer such as PLA.

Waste-to-energy

Waste-to-energy processes were developed for each of the 5 plastic types. There was no applicable Australian specific data identified through the literature review, and so pre-existing lifecycle inventory data, prior work by Blue Environment, and international data was drawn on to construct indicative waste-to-energy processes for the Australian context.

Table 23 Waste-to-energy process data

Parameter description	Value	Unit	Data sources / comments
Transport – articulated truck	100	km	Road freight transport allowance from the location of product EoL generation to a waste-to-energy facility (Blue Environment, 2023).
Heating value – PET	23.2	GJ/tonne	The amount of heat (lower heating value) released during the combustion of 1 tonne of PET (Walters, et al., 2000, p. 250).
Heating value – HDPE	44.6	GJ/tonne	The amount of heat (lower heating value) released during the combustion of 1 tonne of HDPE (Walters, et al., 2000, p. 250).
Heating value – PVC	19.2	GJ/tonne	The amount of heat (lower heating value) released during the combustion of 1 tonne of PVC (Ioelovich, 2018, p. 16)
Heating value – PP	42.7	GJ/tonne	The amount of heat (lower heating value) released during the combustion of 1 tonne of PP (Walters, et al., 2000, p. 250).
Heating value – PLA	15.7	GJ/tonne	The amount of heat (lower heating value) released during the combustion of 1 tonne of PLA (Walters, et al., 2000, p. 249; Yi-Chi, et al., 2010, p. 850). Calculated from the higher heating value (HHV).
Gross heat energy (LHV) conversion to electricity	20%	%	Rate of available heat energy conversion (lower heating value) to electricity, for both onsite use and export (confidential source).
Onsite electricity use	260	kWh/tonne of incoming plastic	Waste-to-energy electricity onsite requirement per tonne of incoming plastic or other material (Blue Environment, 2023). Includes an allowance for a minor degree of pre-sorting (e.g. to remove metals).
Energy export – electricity – PET	1,000	kWh/tonne of incoming plastic	Waste-to-energy electricity export per tonne of incoming plastic (Blue Environment, 2023). Assumed high voltage export at Australian weighted average mix. The marginal (avoided) source of electricity is not considered, noting that this is likely to be a combination of coal and/or fossil gas at the current time.
Energy export – electricity – HDPE	2,200	kWh/tonne of incoming plastic	
Energy export – electricity – PVC	800	kWh/tonne of incoming plastic	
Energy export – electricity – PP	2,200	kWh/tonne of incoming plastic	
Energy export – electricity – PLA	600	kWh/tonne of incoming plastic	
Fuel energy	0	MJ/tonne incoming plastic	Assumed no external fuel input requirement during normal operation. There will be some fuel required (e.g. fossil gas) during start-up, and for control of the combustion chamber temperature during operations, to avoid temperatures that are below the operational range. However, this energy input is largely required to respond to variability in the water content or the energy content of other (non-plastic) materials entering the combustion chamber, and is assumed negligibility contributed to by high energy content materials such as plastics.
Energy export – heat	0	MJ/tonne incoming plastic	It is assumed in Australia that waste-to-energy facilities will generally not be collocated with industrial facilities with a compatible and significant demand for heat, or that it will not be otherwise technically or economically feasible to export a significant fraction of waste heat from waste-to-energy facilities, and so avoid an offsite heating demand from other energy sources. For these reasons it is assumed that there is no heat export credit for waste-to-energy treatment of waste plastics.

Parameter description	Value	Unit	Data sources / comments
Waste treatment	0	kg/tonne incoming plastic	The carbon emissions associated with the solid waste management of PET, HDPE, PP and PLA are assumed below the 1% cut-off. These emissions likely to be low relative to the overall life cycle emissions of these plastics when sent to waste-to-energy. These polymer types are likely to be fully oxidised (or close to) when combusted in a waste-to-energy facility. The chlorine in PVC will have a notably more significant solid waste generation associated with combustion, due the requirement to scrub the chlorine from the combustion gases and stabilise it in a solid form (e.g. as filtercake). However, due to a lack of sufficient data on the related inputs (e.g. NaOH if wet scrubbing is undertaken), and as the scrubbing of the chlorine is considered unlikely to have a significant impact on the overall life cycle carbon emissions for PVC from production to waste-to-energy treatment, the inputs associated with scrubbing the chlorine have been ignored.

Incineration

Incineration processes (combustion with no energy recovery) were developed for each of the 5 plastic types. There was no applicable Australian specific data identified through the literature review, and so pre-existing lifecycle inventory data, prior work by Blue Environment, and international data was drawn on to construct indicative incineration processes for the Australian context.

Table 24 Incineration process data

Parameter description	Value	Unit	Data sources / comments
Transport – articulated truck	100	km	Road freight transport allowance from the location of product EoL generation to an incineration facility (Blue Environment, 2023).
Incineration – PET (numerous input and output parameters)	Various	Various	The PET to incineration process inputs and outputs are based on a pre-existing background process published in the ecoinvent LCI database v3.8 (Doka, 2013a), modified to assume that the plastic undergoes 100% combustion, as this is the same approach adopted in the energy recovery EoL processes, and improves comparability.
Incineration – HDPE (numerous input and output parameters)	Various	Various	The HDPE to incineration process inputs and outputs are based on a pre-existing background process published in the ecoinvent LCI database v3.8 (Doka, 2013b), modified to assume that the plastic undergoes 100% combustion, as this is the same approach adopted in the energy recovery EoL processes, and improves comparability.
Incineration – PVC (numerous input and output parameters)	Various	Various	The PVC to incineration process inputs and outputs are based on a pre-existing background process published in the ecoinvent LCI database v3.8 (Doka, 2013c), modified to assume that the plastic undergoes (carbon) 100% combustion, as this is the same approach adopted in the energy recovery EoL processes, and improves comparability.
Incineration – PP (numerous input and output parameters)	Various	Various	The PVC to incineration process inputs and outputs are based on a pre-existing background process published in the ecoinvent LCI database v3.8 (Doka, 2013d), modified to assume that the plastic undergoes (carbon) 100% combustion, as this is the same approach adopted in the energy recovery EoL processes, and improves comparability.

Parameter description	Value	Unit	Data sources / comments
Incineration – PLA (numerous input and output parameters)	Various	Various	The PLA to incineration process inputs and outputs are based on a modified version of the PET incineration process as the best available proxy, as there was no pre-existing background process available for the incineration of PLA. The process was modified to assume that PLA undergoes 100% combustion.

Landfill

Landfill processes were developed for each of the 5 plastic types, with disposal to Australian landfill with Australian average landfill gas collection and combustion.

A landfill can be considered 'an ecological system, where the inputs are solid waste and water, and the outputs are leachate and gas produced by the joint action of biological, chemical, and physical processes' (Wojnowska-Baryła, et al., 2022, p. 3).

Within landfills complex biochemical reactions and physical changes occur, and plastics in landfill can be subjected to severe environmental conditions, such as low and high pHs, high salinity, fluctuating temperature, physical stress, and microbial degradation. For these reasons an extensive literature review was undertaken to determine the landfill conditions and decomposition modelling assumptions for each plastic type, the findings of which are summarised in the following table.

Table 25 Landfill conditions and decomposition assumptions

Polymer	Adopted conditions	Comments
PET	Polymer form: Bottle or fibre Landfill conditions: Anaerobic, reasonably acidic, and with moisture available.	Assumed negligible (below cut-off) anaerobic decomposition over either 20 or 100 years (Chamas, et al., 2020, p. 3502). **Assumed no decomposition in modelling.**
HDPE	Polymer form: Packaging film or bottle Landfill conditions: Anaerobic, reasonably acidic, and with moisture available.	Decomposition probably not negligible over either 20 years or 100 years (Chamas, et al., 2020, p. 3502; Zhou, et al., 2014, pp. 84-85), in particular for films. Possibly carbon loss in the order of 0–10% over 20 years, and 10–30% over 100 years, via hydrolysis (assuming H_2O is available) and then methanogenesis. However, highly uncertain. Insufficient literature evidence to support modelling decomposition in landfill. **Assumed no decomposition in modelling.**
PVC	Polymer form: Pipe Landfill conditions: Anaerobic, reasonably acidic, and with moisture available.	Assumed negligible (below cut-off) anaerobic decomposition over either 20 or 100 years (Chamas, et al., 2020, p. 3502). **Assumed no decomposition in modelling.**
PP	Polymer form: Packaging film or container Landfill conditions: Anaerobic, reasonably acidic, and with moisture available.	Decomposition probably not negligible over either 20 years or 100 years (Chamas, et al., 2020, p. 3502; Zhou, et al., 2014, pp. 84-85), in particular for films. Similar, if somewhat slower rate than HDPE. However, highly uncertain. Insufficient literature evidence to support modelling decomposition in landfill. **Assumed no decomposition in modelling.**

Polymer	Adopted conditions	Comments
PLA	Polymer form: Packaging film made from either amorphous or semi-crystalline PLA Landfill conditions: Anaerobic, reasonably acidic, and with moisture available.	Reasonable level of evidence that PLA films, in particular those that have a higher level of amorphous PLA in the formulation, will undergo a significant level of decomposition in landfills over either 20 years or 100 years (Chamas, et al., 2020, p. 3502; Kolstad, et al., 2012, p. 1139; Xochitl, et al., 2021, pp. 8-9). However, no usable literature data was identified for the specific decomposition rates over either 20 or 100 years. To avoid the modelling assumption that PLA does not decompose in landfill, from first principles it is known that PLA polymer is potentially 100% degradable via hydrolysis followed by methanogenesis, given sufficient time. PLA is 50% carbon, so the degradable organic carbon (DOC) fraction is 0.50. The fraction of degradable organic carbon (DOCf) is unknown. The DOCf of the two groupings of textiles, and rubber and leather are both 0.50 (DISER, 2021, p. 82). These values appear the best available proxies for the DOCf for PLA. This DOCf is over 100 years. For the lack of better data, the DOCf of PLA over 20 years is assumed to be 0.10. That is, the decomposition rate of PLA film in landfill is linear. **Assumed 50% decomposition of carbon over 100 years and 10% decomposition over 20 years in modelling.**

Table 26 Landfill process data

Parameter description	Value	Unit	Data sources / comments
Transport – articulated truck	50	km	Road freight transport allowance from the location of product EoL generation to landfill (Blue Environment, 2023).
Landfill – Non-degradable plastics (numerous input and output parameters)	Various	Various	The non-degradable plastics (PET, HDPE, PVC and PP) to landfill process inputs and outputs are based on a pre-existing background process published in the AusLCI database v1.40 (Grant, 2012).
Emissions – methane – PLA (20 years)	16	kg CH_4/tonne PLA	The PLA to landfill methane emissions (biogenic) from landfill due to the landfilling of 1 tonne of PLA for 20 years (Blue Environment, 2023). Methane capture rate of 47% adopted (DISER, 2022, p. 338).
Emissions – methane – PLA (100 years)	79	kg CH_4/tonne PLA	The PLA to landfill methane emissions (biogenic) from landfill due to the landfilling of 1 tonne of PLA for 100 years (Blue Environment, 2023). Methane capture rate of 47% adopted (DISER, 2022, p. 338).
Carbon sequestration – biobased – PLA (20 years)	1,650	kg CO_2/tonne PLA	The carbon dioxide (biobased) sequestration credit assigned to PLA for the retention of carbon in landfill by 1 tonne of PLA after 20 years (Blue Environment, 2023).
Carbon sequestration – biobased – PLA (100 years)	920	kg CO_2/tonne PLA	The carbon dioxide (biobased) sequestration credit assigned to PLA for the retention of carbon in landfill by 1 tonne of PLA after 100 years (Blue Environment, 2023).

3.3.7 Other scope aspects of note

Plastics additives

Plastic additives are excluded from the scope of the study. Examples of these include stabilisers, plasticisers, fillers, colourants and lubricants. For context, additives contribute approximately 6% by weight to global plastic products consumption (Geyer, et al., 2017b, p. 11).

3.4 System boundaries

3.4.1 Geographical boundaries

The geographic boundary for the study are plastics that are consumed and management at end-of-life within Australia that have been imported as finished products, produced from imported resin, made from locally synthesised resins, and made locally from recycled plastics.

All plastics recycling (to virgin equivalent polymer) is assumed to be undertaken in Australia (in line with the scrap plastic export restrictions from July 2022), and recycled plastics are assumed sold locally and to export on a 1:1 ratio, which was the approximate ratio in 2019–20 (Envisage Works, 2021).

No state/territory level modelling has been undertaken, and aggregated national data or weighted average national (e.g. for electricity supply) has been used.

3.4.2 Time boundaries

The target baseline year for modelling is the 2019–20 financial year, as detailed plastics flows data is available for 2019–20.

The modelled points of time under the system change scenarios (as outlined in Section 4) are 2019–20, 2029–30 and 2049–50.

In this report, unless otherwise stated, where years are referred to in the form of 2030 or 2050 (for example), this should be assumed to be the short-form of the Australian financial year (e.g. 2029–30 or 2049–50), which covers the 12 month period of 1 July–30 June.

In most part, published life cycle inventory data has been drawn upon in the completion of the modelling requirement for this project. The time boundaries for this data are highly variable, with the most recent available data selected in all cases.

3.4.3 Boundaries to nature

As required by ISO 14040:2006 the boundaries towards nature are the flow of material and energy resources from nature into the system and emissions from the systems to air and water and waste out of the systems.

3.4.4 Boundaries to other product life cycles

The boundaries towards other product (technical) systems describe the inflow of material and components from other systems and the outflow of material to other systems.

There are no inflows that have been identified as of note.

Potential outflows include:

- **Liquid fuel recovered from chemical recycling** – However, for the purposes of this project it has been assumed that all liquid hydrocarbon recovered from chemical recycling are returned into plastics (closed-loop recycled).
- **Composted PLA sold as marketable fertiliser** – The outflow of composted PLA has been excluded from the modelled (as an avoided product) as it considered trivial, and likely to be below the 1% cut-off.

3.5 Data and data quality

3.5.1 Primary data requirements

There was no primary data collected.

3.5.2 Secondary data requirements

Except where otherwise stated in this report, the major sources of secondary data utilised in this study were:

- ecoinvent LCI database v3.8 (European and global average data)
- AusLCI database v1.40 (Australian centric data).

3.5.3 Data quality assessment

A key objective of the study was to utilise the highest possible quality international and Australian data that was representative of the modelled plastics systems, as was available within scope and budgetary limitations. Across Sections 3.3.3–3.3.6 all major data sources have been identified, including the year they were published.

Data quality summary comments are:

- Time-related coverage – The preferred age of data is ideally within the last five years, however in many cases the data is of a greater age than this.
- Geographical coverage – geographical area for data is ideally Australia, in most cases data is Australia specific, or is European data which has been modified for Australian conditions.
- Technology coverage – technology mix (e.g. weighted average of the actual process mix, best available technology or worst operating unit) is ideally specific to the actual life cycles modelled. Generally the technology mix is composed of industry averages.

However, given the extensive nature of the modelling undertaken for this study, it is not possible to provide a more detailed assessment of (secondary) data quality in this report.

3.6 Significant scope exclusions

Significant scope exclusions are outlined here.

3.6.1 Use of plastic products

With the exception of transport allowances from the location of product manufacture to the point of sale, the study scope excludes the product use stage impacts of products containing plastics. That is, the carbon emissions associated with the use of a product (e.g. the electricity required to run a computer containing plastics) are excluded from the scope.

In the framing a number of the system change scenarios presented in this report, reductions in plastics consumption are assumed. This has significant potential implications for the findings of this report if these reductions in consumption result in consequences that are not modelled, in particular:

- substitution with other materials
- shifts from single-use packaging systems (with relatively low use stage impacts) to reusable packaging systems (with higher use stage impacts).

There are many approaches to reducing plastics consumption that do not rely on substitution to other materials. The highly regarded report *Breaking the Plastic Wave* (Pew & SystemIQ, 2020, p. 25) found that plastics consumption could be reduced by 30% by 2040 before any requirement for material substitution arises.

Energy efficiency is often described as the 'first fuel' (IEA, 2019), or more occasionally the 'forgotten fuel'. Likewise, materials efficiency is the 'first material', and can be achieved without substitution to other materials through multiple and often complementary approaches. These include:

- Avoided unnecessary plastics use.
- Redesign of products and packaging to reduce plastics use (i.e. lightweighting).
- Redesign of products for durability, and for repairability and upgradability.
- Development of new delivery models, such as shifting from single-use to reusable packaging systems.
- Extended Producer Responsibility (EPR) programs that hold manufacturers accountable for the lifecycle of their products, which provides an incentive to use materials more efficiently.
- Consumer behaviour change programs to underpin the approaches listed above, and further drive reductions in the use of plastics and materials consumption more generally. For example, encourage consumers in the uptake of smaller homes, smaller vehicles, and less electronic devices (that also have longer lifespans).

The system change scenario in this study that assumes a 60% reduction in plastics use by 2050 is clearer higher than the Pew & SystemIQ (2020, p. 25) estimate of 30% by 2040. However, this scenario is provided in this report to illustrate the comparative performance of this stretch target outcome, and could be achievable with sufficient societal support and effort.

A contributing approach to achieving reductions in plastics consumption to 2050 is a shift from single-use packaging systems (with relatively low use stage impacts) to reusable packaging systems (with higher use stage impacts).

For context, approximately 30% of plastics consumption in 2019–20 was into single-use packaging (Envisage Works, 2021). The proportion of this that could be potentially shifted to reusable packaging, or would need to be to achieve any given reduction in future plastics consumption, has not been quantitatively determined.

Assuming that half of this 30% of plastics consumption could be avoided by shifting to reusable plastic packaging systems, then the system change scenarios assuming significant reductions in plastics consumption may understate the contribution of this 15% to the product use process in the related scenarios to a degree, particularly with respect to the 'current energy' modelling.

However, any understatement in the product use process carbon emissions will be significantly reduced in the 'renewable energy' modelling, as the additional Australian product use processes required to support reusable packaging systems (e.g. additional transport inputs and reusable packaging cleaning) will be much closer to carbon neutral.

3.6.2 Capital goods inputs

The impacts of capital equipment are generally low compared to the direct use elements of the life cycles and are thus excluded.

However, where capital goods inputs are already incorporated into background life cycle inventory data that is used, they were retained to simplify the modelling requirement.

The impact of retaining the pre-existing capital goods inputs in the background LCI data was reviewed for fossil polymer production, where it was likely to be of the most significance, and was found to contribute less than 1 g CO_2 eq per tonne of polymer produced, so is negligible.

3.6.3 Labour related inputs

It is not common practice when undertaking LCAs to include an assessment of human labour burdens (impacts), due to difficulties in allocation, drawing boundaries, obtaining data and differentiating between labour and capital equipment.

Labour related inputs have been excluded from the study.

3.7 Allocation procedures

3.7.1 Allocation procedure – Production

In practice, industrial processes often do not linearly yield a single product, complicating the allocation of inputs and outputs to the life cycles of products.

A key allocation related consideration for this project is the production of fossil hydrocarbons that goes into both energy and materials. The pre-existing allocation procedures in ecoinvent v3.8 and AusLCI V1.40 have been retained in this study.

3.7.2 Allocation procedures – End-of-life

A modified form of the ‘closed loop allocation procedure’ (or 0/100 method) has been applied to mechanical and chemical recycling (ISO, 2018, pp. 38-39; WRI & WBCSC, 2011a, p. 71). The closed loop allocation procedure has been modified to exclude the end-of-life recycling credit, which has instead been allocated (effectively) to the 'production' process of plastics sourced from recycling. This approach is considered most appropriate with reference to the primary declared unit that has been adopted for the study (i.e. it supports the build-up of the system change scenarios).

In more detail, ISO 14067 (2018, p. 39) states:

> *In the case of the closed-loop allocation procedure, the product system under study includes, as end-of-life operations, all processes from the end-of-life product to the recycled material, up to the point where it fulfills the same quality requirements as the primary material that it substitutes.*

This means that the inputs for recycled polymer production are relatively minor under the adopted modelling framework, and are for transport from the outgoing gate of the recycling facility (either mechanical or chemical), which is the outgoing boundary of the product EoL process, to a local or overseas warehouse. The mechanical and chemical recycling product EoL processes include the activities (and associated emissions) from the product use process outgoing boundary (EoL generation), to the point at which the recycled polymer is equivalent in quality to virgin polymer.

3.8 Inventory analysis outline

The inventory analysis synthesises all inputs and outputs associated with flow pathways. This analysis includes energy inputs, raw material inputs, and discharge of greenhouse gases (GHG) emissions to the atmosphere.

The result of the analysis is an inventory of inputs and outputs for each processing step and aggregated across the full life cycle. The completion of the development of the inventory then leads into the life cycle impact assessment phase.

The inventory analysis phase does not have an LCA goal and scope descriptive requirement, so this section is provided here for general information only.

3.9 Impact assessment outline

3.9.1 Overview

The impact assessment phase quantifies the potential climate change impact of each GHG emitted and removed by the modelled systems. The objective of the impact assessment phase is to provide comparative analysis around the impacts resulting from the inventory results for each of the modelled plastics systems.

The impact categories, category indicators and characterisation models adopted in this study are:

Table 27 Impact categories, category indicators and characterisation models

Indicator	Impact category	Indicator (unit)	Characterisation model	Comments
Climate change	**Global warming potential (GWP) – 20 year timeframe**	kg $CO_{2\text{-}e}$	IPCC 2021 GWP 20	These indicators (both 20 year and 100 year timeframes) are based upon the IPCC 2021 method developed by the International Panel on Climate Change (IPCC Sixth Assessment Report – The Physical Science Basis). Climate change factors of IPCC. Indicator of increased concentrations of greenhouse gases in the atmosphere, i.e., gases that trap heat and lead to higher global temperatures. The major greenhouse gases are CO_2, CH_4 and N_2O.
Climate change	**Global warming potential (GWP) – 100 year timeframe**	kg $CO_{2\text{-}e}$	IPCC 2021 GWP 100	

There are the following requirements specified in ISO (2018, p. 29):

1. The most recent GWP values issued by the Intergovernmental Panel on Climate Change (IPCC) should be used in the study. These are available from the IPCC's 6th Assessment Report (AR6) (IPCC, 2021, p. 1017), and are copied to Figure 3 below.

   In the modelling undertaken for this study, atmospheric CO_2 uptake (either for biobased or CO_2 based plastics) is included in the polymer production stage, so GWP values for CH_4 emissions from fossil and biogenic sources are the same.

2. That the GHGs emitted and removed by the product system shall be calculated using the 100-year GWPs (GWP-100) given by the IPCC.

However, ISO (2018, p. 29) also notes that there is no scientific basis for choosing a 100-year time horizon compared to other time horizons, and that any time horizon is a value judgement. Furthermore, it states that other time horizons (e.g. 20-year GWPs or GWP-20) may be used in addition to GWP-100, as long as the results are reported separately. Both GWP-100 and GWP-20 values are reported for this study.

Figure 3 GWP values published in the AR6 (IPCC, 2021, p. 1017)

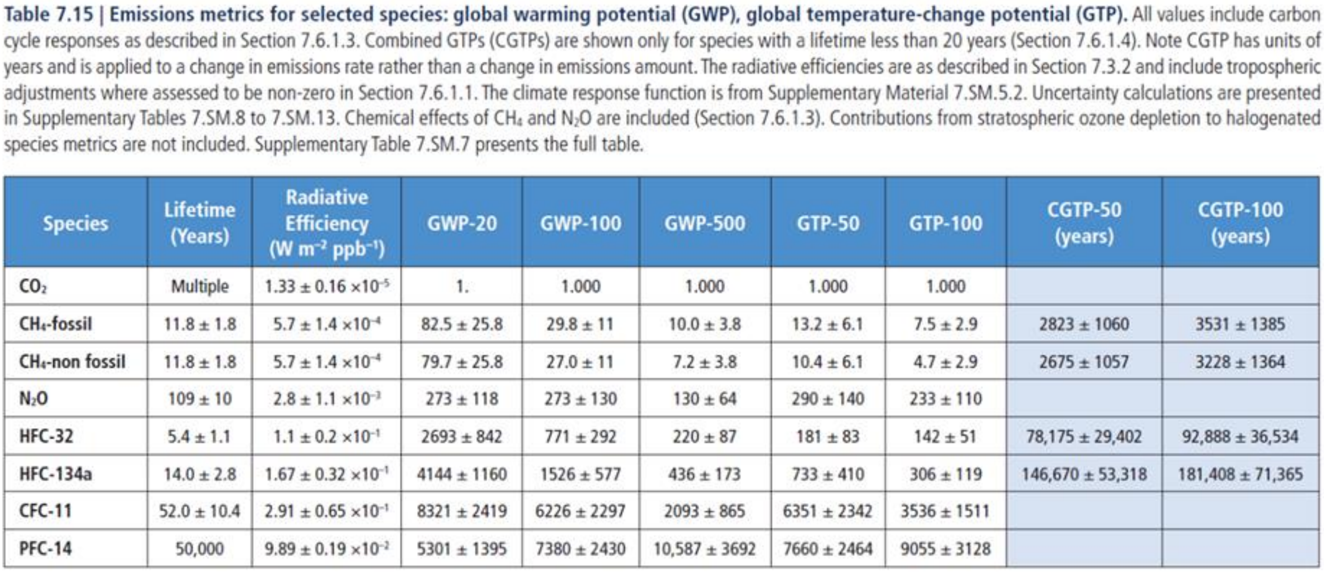


Table 7.15 | Emissions metrics for selected species: global warming potential (GWP), global temperature-change potential (GTP). All values include carbon cycle responses as described in Section 7.6.1.3. Combined GTPs (CGTPs) are shown only for species with a lifetime less than 20 years (Section 7.6.1.4). Note CGTP has units of years and is applied to a change in emissions rate rather than a change in emissions amount. The radiative efficiencies are as described in Section 7.3.2 and include tropospheric adjustments where assessed to be non-zero in Section 7.6.1.1. The climate response function is from Supplementary Material 7.SM.5.2. Uncertainty calculations are presented in Supplementary Tables 7.SM.8 to 7.SM.13. Chemical effects of CH_4 and N_2O are included (Section 7.6.1.3). Contributions from stratospheric ozone depletion to halogenated species metrics are not included. Supplementary Table 7.SM.7 presents the full table.

Species	Lifetime (Years)	Radiative Efficiency ($W\ m^{-2}\ ppb^{-1}$)	GWP-20	GWP-100	GWP-500	GTP-50	GTP-100	CGTP-50 (years)	CGTP-100 (years)
CO_2	Multiple	$1.33 \pm 0.16 \times 10^{-5}$	1.	1.000	1.000	1.000	1.000		
CH_4-fossil	11.8 ± 1.8	$5.7 \pm 1.4 \times 10^{-4}$	82.5 ± 25.8	29.8 ± 11	10.0 ± 3.8	13.2 ± 6.1	7.5 ± 2.9	2823 ± 1060	3531 ± 1385
CH_4-non fossil	11.8 ± 1.8	$5.7 \pm 1.4 \times 10^{-4}$	79.7 ± 25.8	27.0 ± 11	7.2 ± 3.8	10.4 ± 6.1	4.7 ± 2.9	2675 ± 1057	3228 ± 1364
N_2O	109 ± 10	$2.8 \pm 1.1 \times 10^{-3}$	273 ± 118	273 ± 130	130 ± 64	290 ± 140	233 ± 110		
HFC-32	5.4 ± 1.1	$1.1 \pm 0.2 \times 10^{-1}$	2693 ± 842	771 ± 292	220 ± 87	181 ± 83	142 ± 51	78,175 ± 29,402	92,888 ± 36,534
HFC-134a	14.0 ± 2.8	$1.67 \pm 0.32 \times 10^{-1}$	4144 ± 1160	1526 ± 577	436 ± 173	733 ± 410	306 ± 119	146,670 ± 53,318	181,408 ± 71,365
CFC-11	52.0 ± 10.4	$2.91 \pm 0.65 \times 10^{-1}$	8321 ± 2419	6226 ± 2297	2093 ± 865	6351 ± 2342	3536 ± 1511		
PFC-14	50,000	$9.89 \pm 0.19 \times 10^{-2}$	5301 ± 1395	7380 ± 2430	10,587 ± 3692	7660 ± 2464	9055 ± 3128		

3.9.2 Modelling software

The LCA modelling software openLCA has been used for this study, along with MS Excel to support the required time-series system change scenario modelling. A key output of this study is the development of an MS Excel data tool that can be used for further scenario analysis, beyond that published in this report.

3.9.3 Sensitivity analyses

Refer to Section 6.3.3 for further details.

3.10 Interpretation outline

The interpretation phase of the study is intended to analyse results, reach conclusions, explain limitations and provide recommendations based on the findings of the preceding phases of the study, and to report the results of the interpretation in a transparent manner (AS/NZS ISO 14044:2006).

The interpretation phase does not have an LCA goal and scope descriptive requirement, so this section is provided here for general information only. See Section 6 for more details.

3.11 Key assumptions and limitations

Outlined in this section are key assumptions, value choices, optional elements and limitations.

3.11.1 Assumptions

EoL product sorting electricity inputs proxied by MRF sorting of packaging

The modelling adopts the available data on kerbside packaging MRF sorting electricity inputs, for EoL products to mechanical recycling and chemical recycling. Plastics to composting, waste-to-energy, incineration and landfill are assumed to not go via a MRF equivalent sorting process.

The actual required sorting energy inputs are highly variable, from very low (e.g. for EoL products that are generated as a single polymer source segregated stream, such as consumer drop-off PET bottles collected via a container deposit scheme), to potentially much higher (for sorting mixed C&D waste to recover PVC from the built environment).

In general many EoL products from the built environment, electrical and electronic applications, transport, packaging and numerous other applications have a significant sorting requirement prior to being sent to a material recovery related downstream process. However, due to the unavailability of readily available and specific sorting energy inputs by polymer type and application area source, it is assumed that the sorting energy inputs for mechanical and chemical recycling are reasonably proxied by the available data on the energy inputs (electricity) for MRF sorting.

Scenario analysis polymer consumption projections

The polymer consumption and EoL generation projections across the period of 2019–20 to 2049–50 are drawn from the report *Australian Plastics Flows and Fates Study 2019–20* (Envisage Works, 2021). This data is used as the basis for the business-as-usual (BAU) system change scenario, and thus in all the scenarios.

In the analysis for this study the future market shares of each polymer type are assumed to be steady. That is, each polymer type has the same proportion of the total plastics market to 2049–50.

3.11.2 Cut-off

A cut-off criterion of 1% of mass or energy flows was allowed for with the aim that not more than 5% of flows were excluded from the study. For small flows, estimates were used in preference to exclusion, where possible.

3.11.3 Limitations of the study

The main limitations to this study are:

- GWP is the only impact category that is assessed.
- As a number of polymers have been modelled using proxy emission factors the modelled emissions for these polymers may not reflect the actual emissions as quantified in the system change scenario modelling undertaken by this study.
- Data validation of the findings of this report against the published literature has not been undertaken, due to resource constraints. Ideally any future updates of this study would also include a literature review to validate and contextualise the findings of the study.

4 Inventory analysis

The inventory analysis phase of the study involves the compilation and quantification of the inputs and outputs of the processes making up each of the modelled plastic polymer systems.

The inventory analysis phase of the project consists of the following steps:

- Data collection and validation.
- Relating data to unit processes and the declared unit (refer to Section 3.3).
- Refining the system boundary (refer to Section 3.4).
- Allocation (refer to Section 3.7).
- Carbon emissions and removals.

4.1 Data collection and validation

This section of the report typically summarises the data estimates and sources for the significant unit processes incorporated into the modelling. However, for this study all the major data estimates and sources have been described in Section 3.

There has been no primary data collection undertaken for the study, and all data is drawn from (existing) secondary published sources.

4.2 GHG emissions and removals

4.2.1 Timing considerations

In line with ISO (2018) carbon emissions and removals have been calculated as if released or removed at the beginning of the assessment period without taking into account an effect of delayed emissions and removals.

There is a minor exception in the approach taken to quantifying the emission of CH_4 and CO_2 from the decomposition of PLA in landfill over either 20 or 100 years, which have been modelled in line with the approach outlined in Section 3.3.6.

4.2.2 Fossil and biogenic carbon considerations

The carbon emission modelling undertaken for this study does separately quantify fossil and non-fossil (both biogenic and CO_2 sourced) carbon dioxide and methane. However, due to the significant complexity it would add to the presentation of the results, fossil and biogenic carbon are not reported separately, and net emission totals only are provided.

In the modelling carbon removals from the atmosphere are allocated to the polymer production life cycle stage. These are quantified using the data provided in Table 28.

Table 28 Embodied carbon and carbon dioxide atmospheric removals associated with the production of biogenic and CO_2 based polymers

Polymer	**Carbon** (kg C/t polymer)	**CO_2** (kg CO_2/t polymer)
Polyethylene terephthalate (PET)	630	2,300
High density polyethylene (HDPE)	860	3,200
Polyvinyl chloride (PVC)	380	1,400
Polypropylene (PP)	860	3,200
Poly(lactic acid) (PLA)	500	1,800

Note: Values in table rounded to 2 significant figures.

5 Impact assessment

5.1 Impact assessment indicators and characterisation model

In the impact assessment phase of this study, the potential climate change impact of each greenhouse gas emitted and removed by the product system is calculated by multiplying the mass released or removed by the 100 year and 20 year GWPs given by the IPCC in units of kg CO_2 eq per kg emission (with carbon feedbacks, according to IPCC).

In this report a positive value denotes an emission to the atmosphere, while a negative value can be interpreted as a removal from the atmosphere.

The impact assessment indicators and characterisation model have been described in Section 3.9.

5.2 Results

5.2.1 Carbon emissions by process and plastic type

Figure 4 and Figure 5 (and associated data tables) present the estimated carbon emissions for the 5 modelled plastic types by process, with a 'current' energy supply, and on a GWP 100 and GWP 20 year basis respectively.

The current energy supply is based on the available pre-existing data in the ecoinvent LCI database (v3.8) for international inputs, and AusLCI (v1.40) data for Australian electricity inputs.

Figure 4 Modelled carbon emissions by process and plastic type – Current energy supply (GWP 100 year basis)

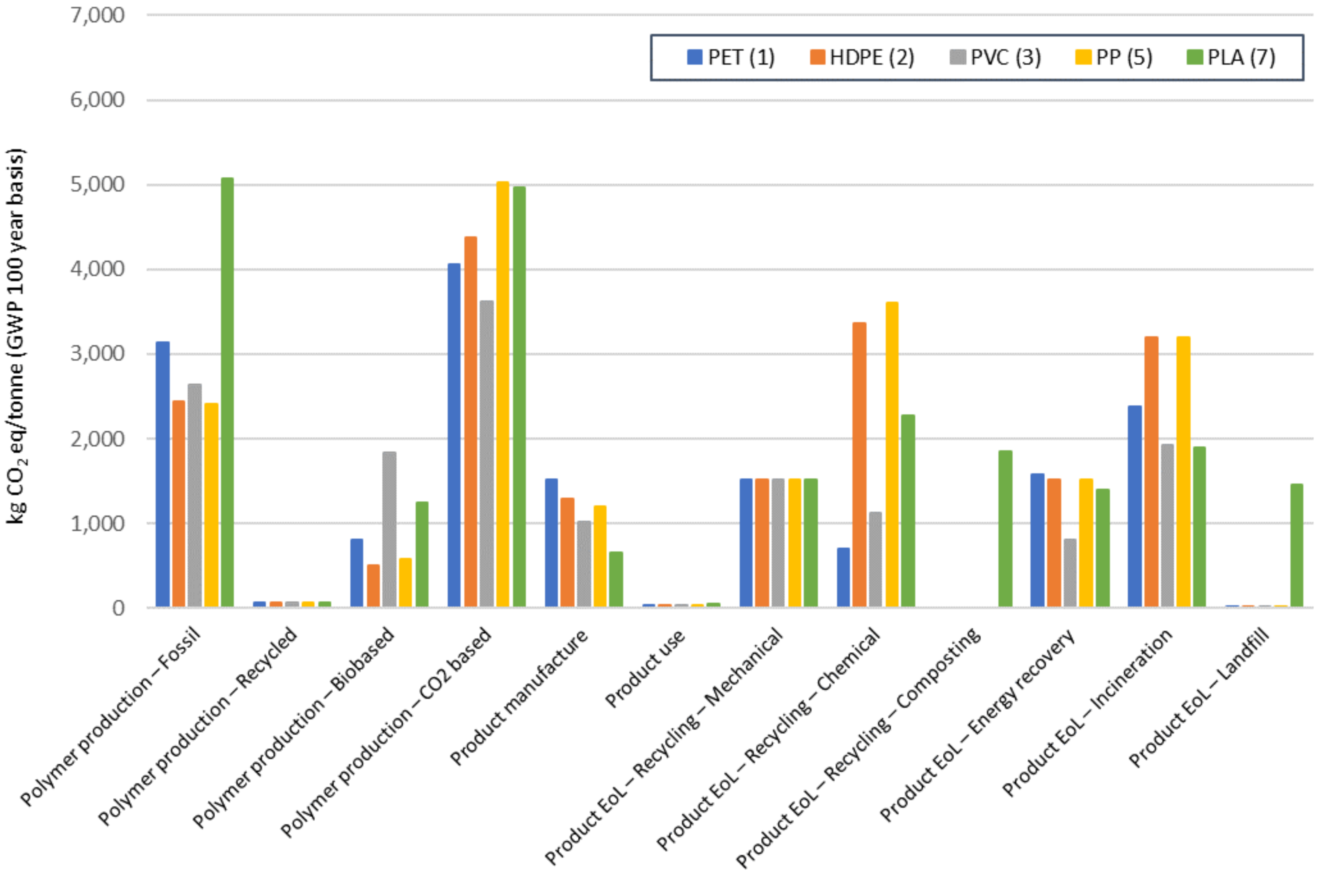


Table 29 Modelled carbon emissions by process and plastic type – Current energy supply – GWP 100 year basis (kg CO_2 eq/tonne)

Process	PET (1)	HDPE (2)	PVC (3)	PP (5)	PLA (7)
Polymer production – Fossil	3,130	2,440	2,640	2,410	5,070
Polymer production – Recycled	60	60	60	60	60
Polymer production – Biobased	810	500	1,840	580	1,240
Polymer production – CO_2 based	4,060	4,380	3,620	5,020	4,960
Product manufacture	1,510	1,290	1,010	1,200	650
Product use	40	30	30	30	50
Product EoL – Recycling – Mechanical	1,510	1,510	1,510	1,510	1,510
Product EoL – Recycling – Chemical	700	3,360	1,130	3,610	2,280
Product EoL – Recycling – Composting	0	0	0	0	1,850
Product EoL – Energy recovery	1,570	1,510	810	1,510	1,400
Product EoL – Incineration	2,380	3,200	1,920	3,200	1,900
Product EoL – Landfill	10	10	10	10	1,460

Figure 5 Modelled carbon emissions by process and plastic type – Current energy supply (GWP 20 year basis)

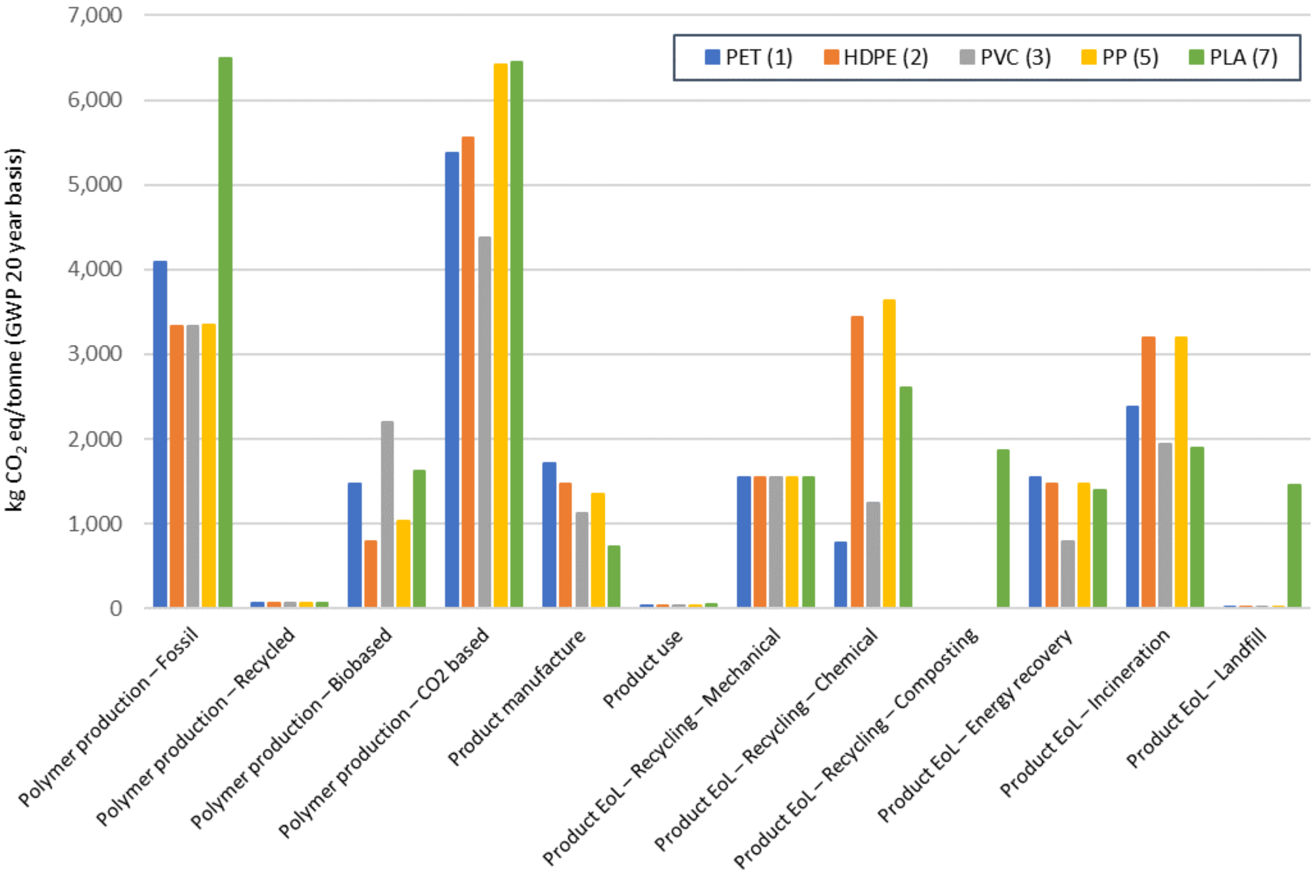


Table 30 Modelled carbon emissions by process and plastic type – Current energy supply – GWP 20 year basis (kg CO_2 eq/tonne)

Process	PET (1)	HDPE (2)	PVC (3)	PP (5)	PLA (7)
Polymer production – Fossil	4,090	3,330	3,330	3,350	6,490
Polymer production – Recycled	60	60	60	60	60
Polymer production – Biobased	1,470	790	2,200	1,030	1,620
Polymer production – CO_2 based	5,370	5,550	4,380	6,410	6,440
Product manufacture	1,710	1,470	1,130	1,350	730
Product use	40	30	30	30	50
Product EoL – Recycling – Mechanical	1,550	1,550	1,550	1,550	1,550
Product EoL – Recycling – Chemical	780	3,440	1,250	3,640	2,600
Product EoL – Recycling – Composting	0	0	0	0	1,860
Product EoL – Energy recovery	1,550	1,470	790	1,470	1,390
Product EoL – Incineration	2,380	3,200	1,940	3,200	1,900
Product EoL – Landfill	10	10	10	10	1,460

Figure 6 and Figure 7 (and associated data tables) present the estimated carbon emissions for the 5 modelled plastic types by process, with a 'renewable' energy supply, and on a GWP 100 and GWP 20 year basis respectively.

The renewable energy supply assumes that all processes including plastic production and downstream are electrified, and that electricity supply is 100% renewable, and that all transport is emissions free.

Figure 6 Modelled carbon emissions by process and plastic type – Renewable energy supply (GWP 100 year basis)

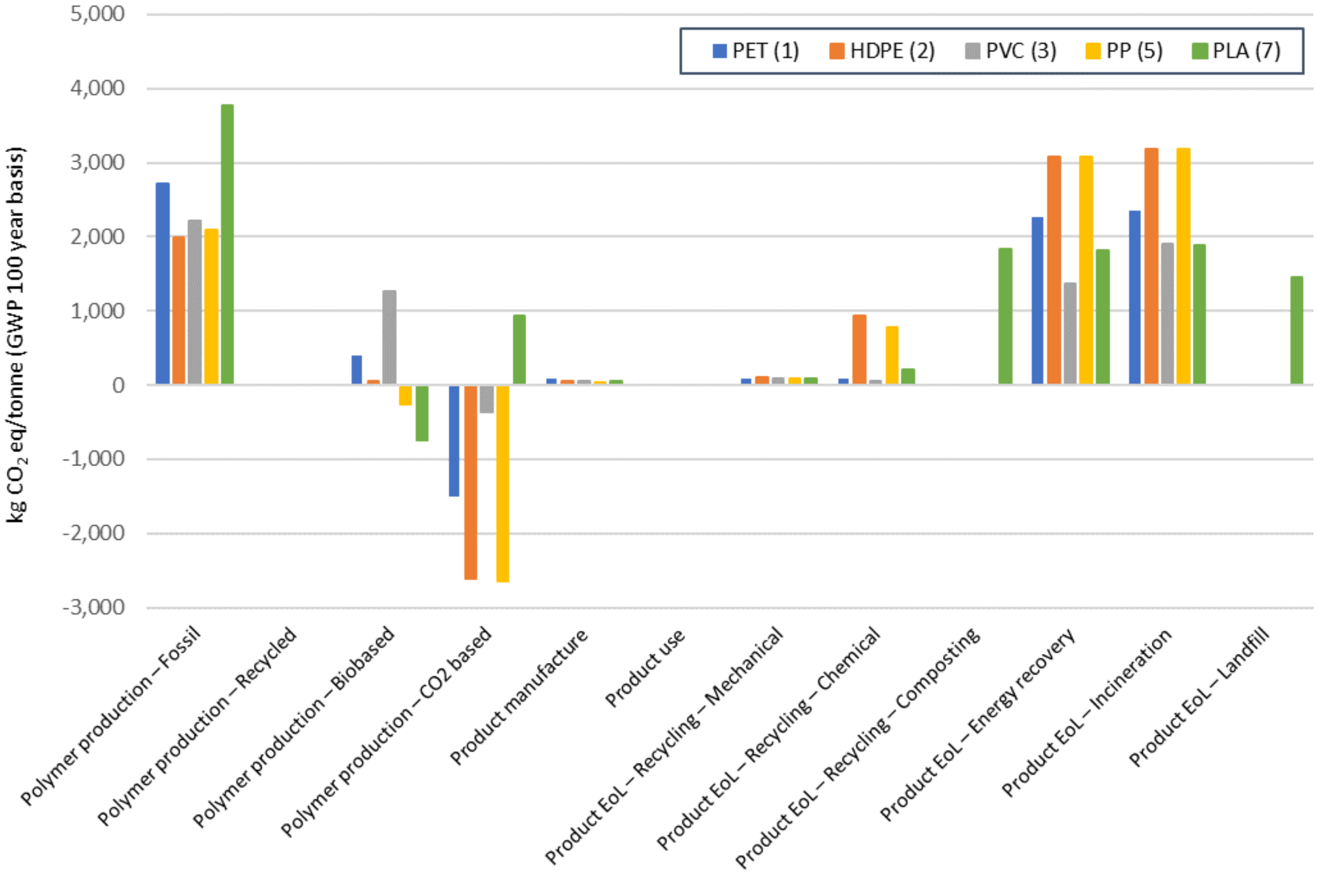


Table 31 Modelled carbon emissions by process and plastic type – Renewable energy supply – GWP 100 year basis (kg CO_2 eq/tonne)

Process	PET (1)	HDPE (2)	PVC (3)	PP (5)	PLA (7)
Polymer production – Fossil	2,720	1,990	2,210	2,090	3,770
Polymer production – Recycled	0	0	0	0	0
Polymer production – Biobased	400	50	1,260	-260	-750
Polymer production – CO_2 based	-1,500	-2,610	-370	-2,650	940
Product manufacture	80	60	60	30	50
Product use	0	0	0	0	0
Product EoL – Recycling – Mechanical	80	110	80	80	80
Product EoL – Recycling – Chemical	80	930	60	780	200
Product EoL – Recycling – Composting	0	0	0	0	1,840
Product EoL – Energy recovery	2,270	3,070	1,360	3,070	1,810
Product EoL – Incineration	2,360	3,180	1,900	3,180	1,880
Product EoL – Landfill	0	0	0	0	1,450

Figure 7 Modelled carbon emissions by process and plastic type – Renewable energy supply (GWP 20 year basis)

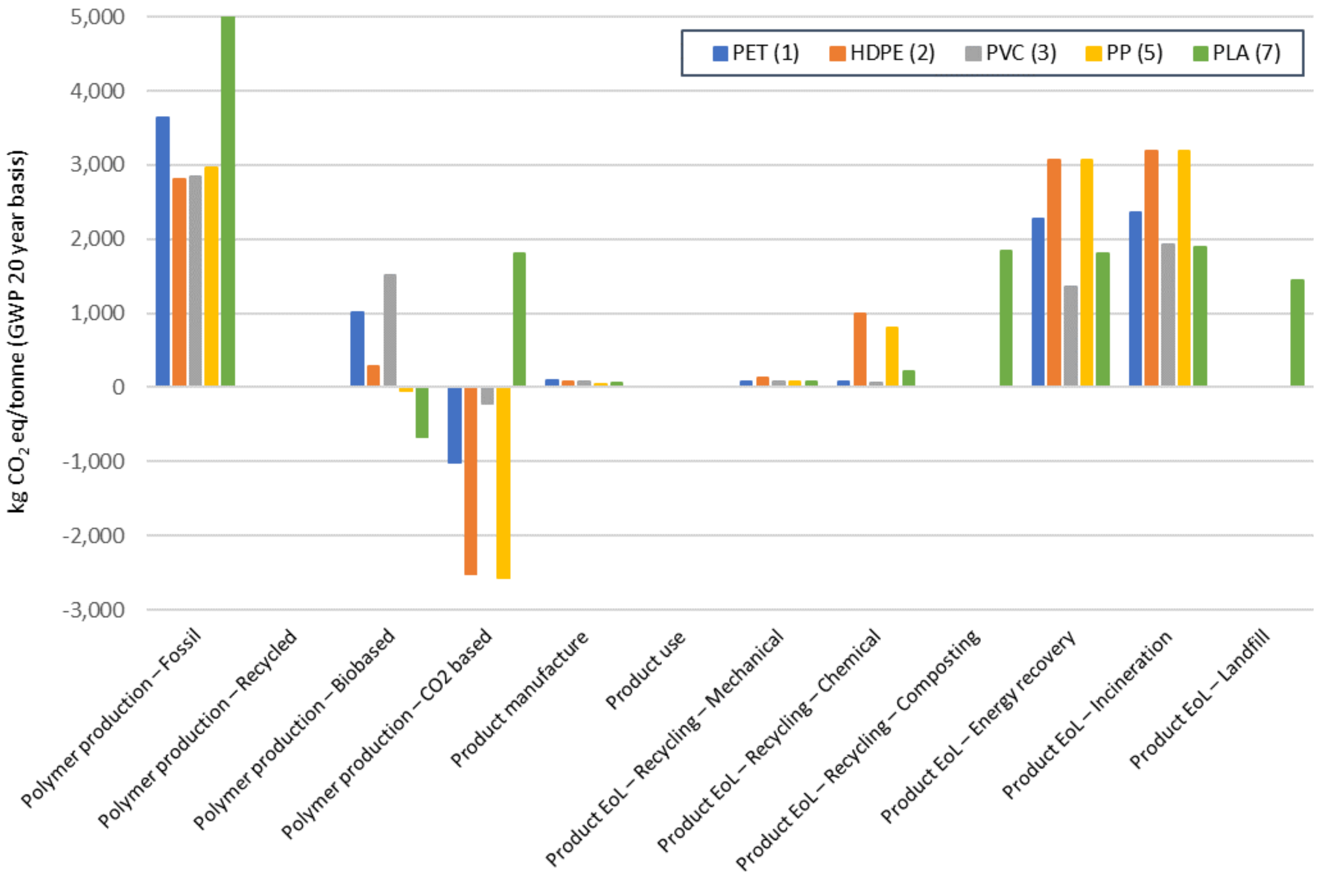


Table 32 Modelled carbon emissions by process and plastic type – Renewable energy supply – GWP 20 year basis (kg CO_2 eq/tonne)

Process	PET (1)	HDPE (2)	PVC (3)	PP (5)	PLA (7)
Polymer production – Fossil	3,630	2,810	2,850	2,970	5,010
Polymer production – Recycled	0	0	0	0	0
Polymer production – Biobased	1,010	280	1,510	-50	-660
Polymer production – CO_2 based	-1,010	-2,520	-220	-2,560	1,810
Product manufacture	90	70	70	40	60
Product use	0	0	0	0	0
Product EoL – Recycling – Mechanical	80	130	80	80	80
Product EoL – Recycling – Chemical	80	1,000	60	800	220
Product EoL – Recycling – Composting	0	0	0	0	1,840
Product EoL – Energy recovery	2,270	3,070	1,360	3,070	1,810
Product EoL – Incineration	2,360	3,190	1,930	3,180	1,890
Product EoL – Landfill	0	0	0	0	1,450

Figure 4 to Figure 7 on the previous pages provide the process level emissions data presented in the structure required to support the system change scenario modelling in Section 5.2.2.

To provide context on the polymer production related carbon emissions specifically, presented in Figure 8 and Table 33 are the carbon emissions associated with each polymer production option, including the recycling related emissions required to produce recycled polymer, and based on the current energy mix. Key observations are:

- Biobased polymer production has the lowest carbon emissions on average, due in large part to the emissions credit for the related drawdown of atmospheric CO_2.
- Mechanically recycled polymer production has the second lowest carbon emissions on average.
- CO_2 based polymer production has the highest carbon emissions, if based on the current energy mix. This highlights that CO_2 based polymer production can only be of benefit from a carbon emissions perspective if it is undertaken in combination with a shift to renewable energy.

Figure 8 Carbon emissions by polymer type and polymer production option – Current energy supply – GWP 20 basis

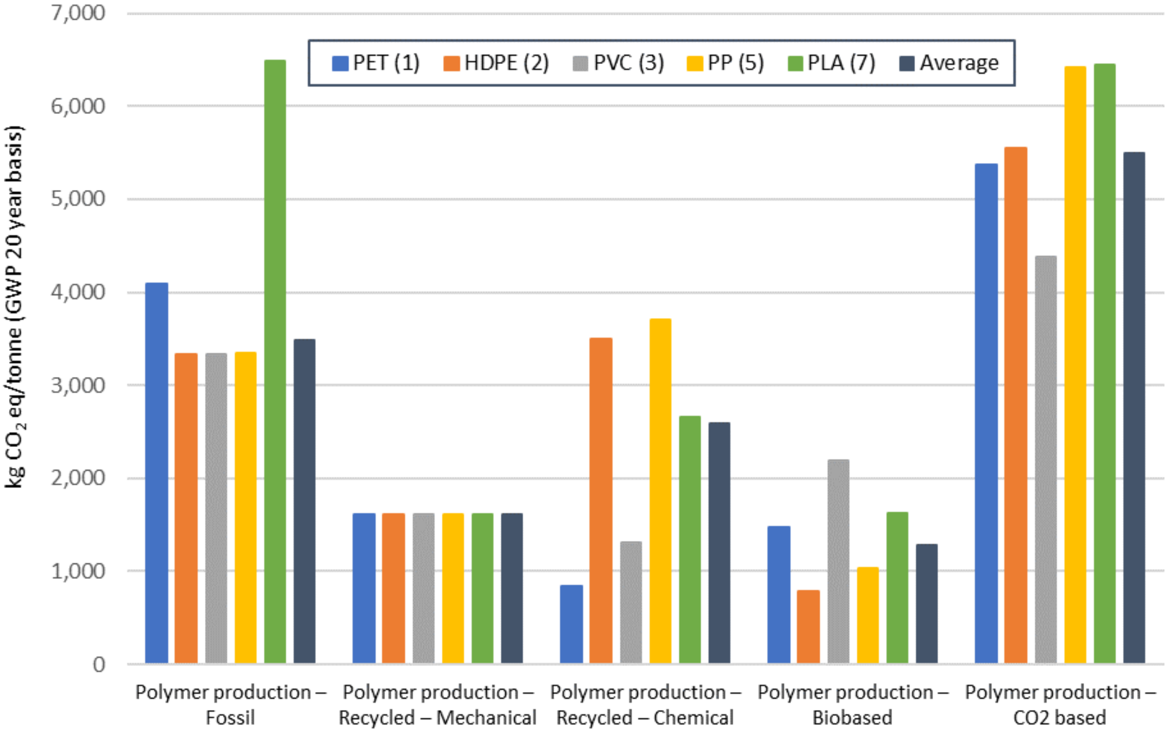


Table 33 Carbon emissions by polymer type and polymer production option – Current energy supply – GWP 20 basis (kg CO_2 eq/tonne)

Process	PET (1)	HDPE (2)	PVC (3)	PP (5)	PLA (7)	Average[1]
Polymer production – Fossil	4,090	3,330	3,330	3,350	6,490	3,490
Polymer production – Recycled – Mechanical	1,610	1,610	1,610	1,610	1,610	1,610
Polymer production – Recycled – Chemical	840	3,500	1,310	3,700	2,660	2,590
Polymer production – Biobased	1,470	790	2,200	1,030	1,620	1,280
Polymer production – CO_2 based	5,370	5,550	4,380	6,410	6,440	5,500

1. Weighted average emissions based on 2019–20 EoL generation for each of the 5 polymer types

To provide a clearer standalone representation of the carbon emissions associated with each EoL management option, Figure 9 and Table 34 present the carbon emissions data by polymer type and EoL management option, using the closed loop allocation method, and based on the current energy mix.

It is important to note that the data in Figure 4 to Figure 7 for the 'Polymer production – Recycled' process are not the emissions of producing closed-loop recycled polymer directly out of the 'Product use' process. Also see Section 3.7.2 for more detail on this modelling aspect.

Instead, the 'Product EoL – Recycling – Mechanical' and 'Product EoL – Recycling – Chemical' processes include the activities from the product use process outgoing boundary (EoL generation), to the point at which the recycled polymer is equivalent in quality to virgin polymer, which is the outgoing boundary of the product EoL processes for recycling. These recycling related EoL management carbon emissions are included in Figure 9 and Table 34.

Key observations on the EoL management options carbon emissions are:

- Mechanical recycling has the lowest carbon emissions on average, due to the relatively low carbon intensity of mechanical recycling and the avoided virgin polymer production credit.
- Chemical recycling has the second lowest carbon emissions on average. However, this is highly chemical recycling process (polymer) dependent, due to the significantly differing losses of carbon to the atmosphere, variation in the avoided virgin polymer production credit, and the required energy inputs at the refining (where relevant) and repolymerisation stages.
- Incineration has the highest carbon emissions, due to the conversion of the polymer to CO_2 and no avoided virgin polymer production credit.

Figure 9 Carbon emissions by polymer type and EoL management option – Closed loop allocation – Current energy – GWP 20 basis

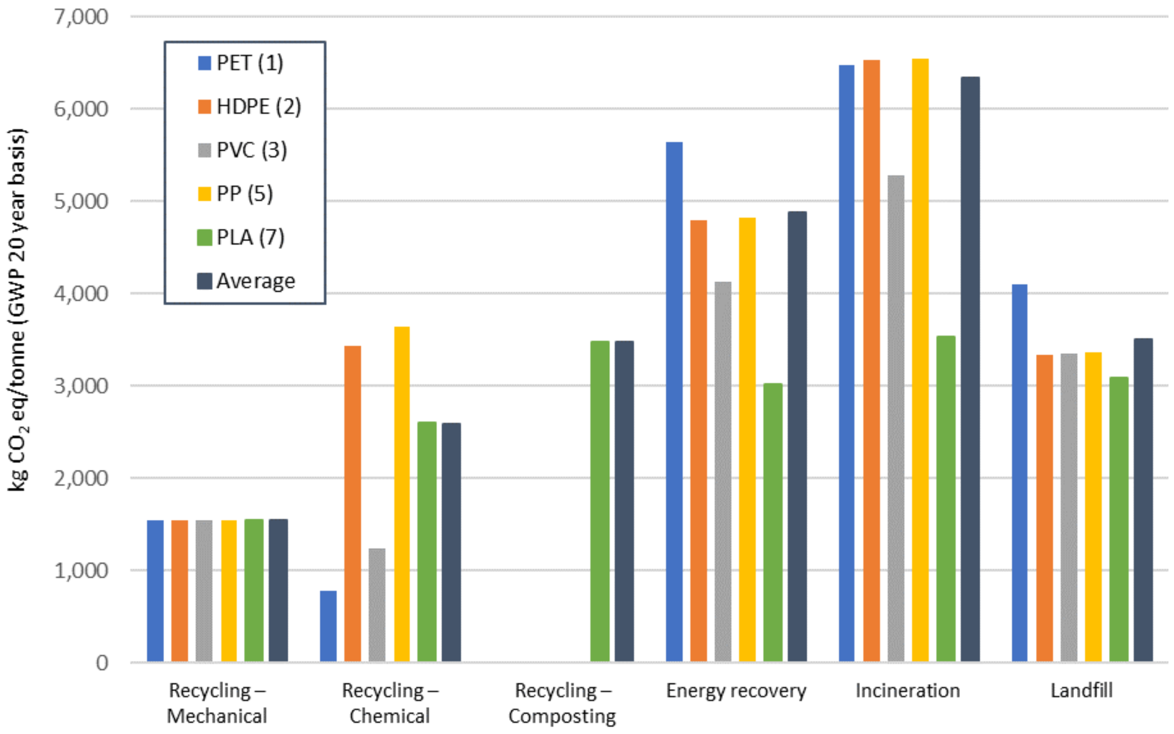


Table 34 Carbon emissions by polymer type and EoL management option – Closed loop allocation – Current energy – GWP 20 basis (kg CO_2 eq/tonne)

Process	PET (1)	HDPE (2)	PVC (3)	PP (5)	PLA (7)	Average[1]
Recycling – Mechanical	1,550	1,550	1,550	1,550	1,550	1,550
Recycling – Chemical	780	3,440	1,250	3,640	2,600	2,590
Recycling – Composting	N/A	N/A	N/A	N/A	3,480	3,480
Energy recovery	5,640	4,800	4,120	4,820	3,010	4,880
Incineration	6,470	6,530	5,280	6,540	3,530	6,330
Landfill	4,100	3,340	3,340	3,360	3,090	3,510

1. Weighted average emissions based on 2019–20 EoL generation for each of the 5 polymer types

5.2.2 System change scenario results for all plastics

The system change scenarios assessed in this study are outlined in Table 35, and the summary BAU 2019–20 and 2049–50 plastics flows data are provided in Table 36 (Envisage Works, 2021).

The system change scenarios have been selected to explore the emissions landscape in relation to changes in consumption quantities and material sources, recovery and energy sources. The scenarios are not forecasts or predictions. The consumption reduction related scenarios assume that substitution with other materials or services is not required.

Table 35 System change scenarios assessed in this study

Scenario	Description	Comments
Scenario 1 – Business-as-usual	Current consumption and EoL generation projections to 2050.	> Current projections are drawn from Envisage Works (2021).
Scenario 2a – Flat consumption to 2050	Flat consumption and recovery relative to 2019–20.	> Flat consumption and recovery from 2019–20 to 2049–50.
Scenario 2b – 10% consumption fall by 2050	10% reduction in consumption relative to 2019–20.	> Reduction in consumption of 10% for each polymer from 2019–20 to 2049–50, with no per capita adjustment. > Reductions in consumption are assumed to be a time-lagged proxy for the same reduction in EoL generation. > Recycled quantity assumed flat relative to 2019–20.
Scenario 2c – 40% consumption fall by 2050	40% reduction in consumption relative to 2019–20.	> Reduction in consumption of 40% for each polymer from 2019–20 to 2049–50, with no per capita adjustment. > Reductions in consumption are assumed to be a time-lagged proxy for the same reduction in EoL generation. > Recycled quantity assumed flat relative to 2019–20.
Scenario 2d – 60% consumption fall by 2050	60% reduction in consumption relative to 2019–20.	> Reduction in consumption of 60% for each polymer from 2019–20 to 2049–50, with no per capita adjustment. > Reductions in consumption are assumed to be a time-lagged proxy for the same reduction in EoL generation. > Recycled quantity assumed flat relative to 2019–20.
Scenario 3a – 50% recovery by 2050	50% recycling rate by 2050.	> 50% recycling rate by 2049–50 (linear increase). > Assumed average 3:1 ratio mechanical to chemical recycling to 2049–50.
Scenario 3b – 100% recovery by 2050	100% recycling rate by 2050.	> 100% recycling rate by 2049–50 (linear increase). > Assumed average 3:1 ratio mechanical to chemical recycling to 2049–50. Note: For different plastics this scenario may need additional technology development to maintain polymer quality and this level of closed-loop recycling, particularly as the 100% recycling rate is approached by 2049–50.
Scenario 4 – 100% renewable energy	100% renewable energy globally by 2050.	> Assumed 100% renewable energy supply for transport and stationary energy by 2049–50 (linear increase). Except for fossil hydrocarbon supply where the combustion of fossil hydrocarbons is embedded into the current supply chain, for which fossil hydrocarbon combustion is assumed ongoing.
Scenario 5a – Combined scenario 1	10% reduction in consumption relative to 2019–20 / 100% recovery rate by 2050 / 100% renewable energy by 2050.	> Reduction in consumption of 10% for each polymer from 2019–20 to 2049–50, with no per capita adjustment. > Reductions in consumption are assumed to be a time-lagged proxy for the same reduction in EoL generation. > 100% recycling rate by 2049–50 (linear increase). > Assumed average 3:1 ratio mechanical to chemical recycling to 2049–50.
Scenario 5b – Combined scenario 2	100% recovery rate by 2050 / 100% renewable energy by 2050 / 100% biobased or CO_2 based by 2050.	> 100% recycling rate by 2049–50 (linear increase). > Assumed average 3:1 ratio mechanical to chemical recycling to 2049–50. > Assumed 100% renewable energy supply for transport and stationary energy. Except for fossil hydrocarbon supply where the combustion of fossil hydrocarbons is embedded into the current supply chain, for which fossil hydrocarbon combustion is assumed ongoing.

Scenario	Description	Comments
		> Assumed 100% carbon supply from biobased or CO_2 (+ H_2) based sources by 2049–50.
Scenario 5c – Combined scenario 3	10% reduction in consumption relative to 2019–20 / 100% recovery rate by 2050 / 100% renewable energy by 2050 / 100% biobased or CO_2 based by 2050.	> Reduction in consumption of 10% for each polymer from 2019–20 to 2049–50, with no per capita adjustment. > Reductions in consumption are assumed to be a time-lagged proxy for the same reduction in EoL generation. > 100% recycling rate by 2049–50 (linear increase). > Assumed average 3:1 ratio mechanical to chemical recycling to 2049–50. > Assumed 100% renewable energy supply for transport and stationary energy. Except for fossil hydrocarbon supply where the combustion of fossil hydrocarbons is embedded into the current supply chain, for which fossil hydrocarbon combustion is assumed ongoing. > Assumed 100% carbon supply from biobased or CO_2 (+ H_2) based sources by 2049–50.

1. A standalone scenario for the 100% carbon supply from biobased or CO_2 (+ H_2) based sources has not been modelled, as this action must be undertaken in combination with a shift to renewable energy to be of benefit relative to the BAU scenario, and if modelled as a standalone 'current energy' scenario would perform worse than the BAU scenario. For this reason, combined scenarios 5b and 5c, which include this shift to biobased or CO2 (+ H2) based sources, also include the shift to 100% renewable energy by 2049–50.

Table 36 Summary BAU data for all plastics (for both modelled and proxied polymer types)

Life cycle stage	Process	2019–20 data		2049–50 data
		(tonnes)	(% of stage)	(tonnes)
Polymer production	Polymer production – Fossil	3,148,000	91.7%	8,025,000
	Polymer production – Recycled	274,000	8.0%	663,000
	Polymer production – Biobased	10,000	0.3%	66,000
	Polymer production – CO_2 based	0	0.0%	0
	Total	**3,431,000**	**100.0%**	**8,754,000**
Product manufacture	Product manufacture	3,431,000	100.0%	8,754,000
Product use	Product use	3,431,000	100.0%	8,754,000
Product EoL	Product EoL – Recycling – Mechanical	274,000	11.0%	663,000
	Product EoL – Recycling – Chemical	0	0.0%	0
	Product EoL – Recycling – Composting	0	0.0%	1,000
	Product EoL – Energy recovery	4,000	0.2%	8,000
	Product EoL – Incineration	0	0.0%	0
	Product EoL – Landfill	2,219,000	88.9%	5,206,000
	Total	**2,497,000**	**100.0%**	**5,878,000**

Provided in Figure 10 and Figure 11 are the scenario results for all plastics, across the period of 2019–20 to 2049–50, on GWP 100 year and GWP 20 year bases respectively.

Figure 10 System change scenario results for all plastics – 2020 to 2050 – GWP 100 year basis

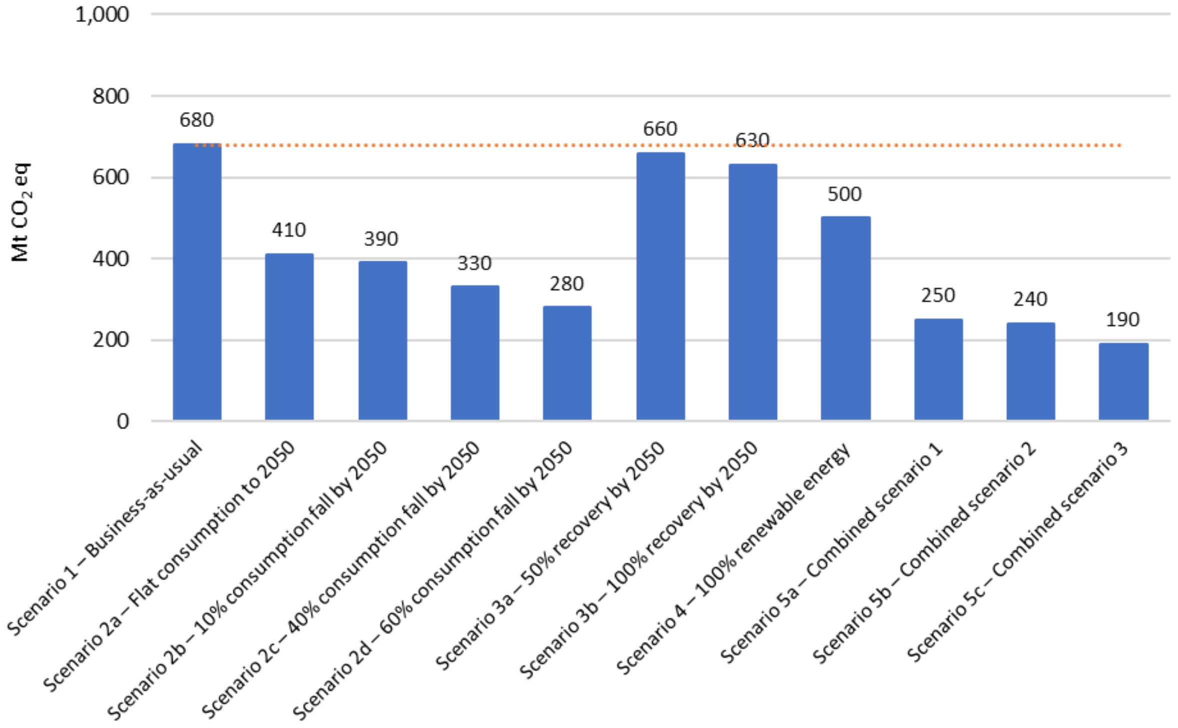


Table 37 System change scenario results for all plastics – 2020 to 2050 – GWP 100 year basis

Scenario	Aggregated time period emissions			Annual emissions	
	2020 to 2030 (Mt CO_2 eq)	2020 to 2050 (Mt CO_2 eq)	(% BAU in 2050) (Mt CO_2 eq)	2020 (Mt CO_2 eq)	2050 (Mt CO_2 eq)
Scenario 1 – Business-as-usual	170	680	0.0%	13.2	33.9
Scenario 2a – Flat consumption to 2050	150	410	-39.3%	13.2	13.2
Scenario 2b – 10% consumption fall by 2050	140	390	-42.4%	13.2	11.9
Scenario 2c – 40% consumption fall by 2050	140	330	-51.7%	13.2	7.8
Scenario 2d – 60% consumption fall by 2050	130	280	-57.9%	13.2	5.1
Scenario 3a – 50% recovery by 2050	170	660	-2.4%	13.2	32.5
Scenario 3b – 100% recovery by 2050	170	630	-6.4%	13.2	30.1
Scenario 4 – 100% renewable energy	160	500	-26.6%	13.2	18.5
Scenario 5a – Combined scenario 1	130	250	-63.7%	13.2	2.6
Scenario 5b – Combined scenario 2	140	240	-63.8%	13.2	-3.2
Scenario 5c – Combined scenario 3	120	190	-71.6%	13.2	-0.8

Figure 11 System change scenario results for all plastics – 2020 to 2050 – GWP 20 year basis

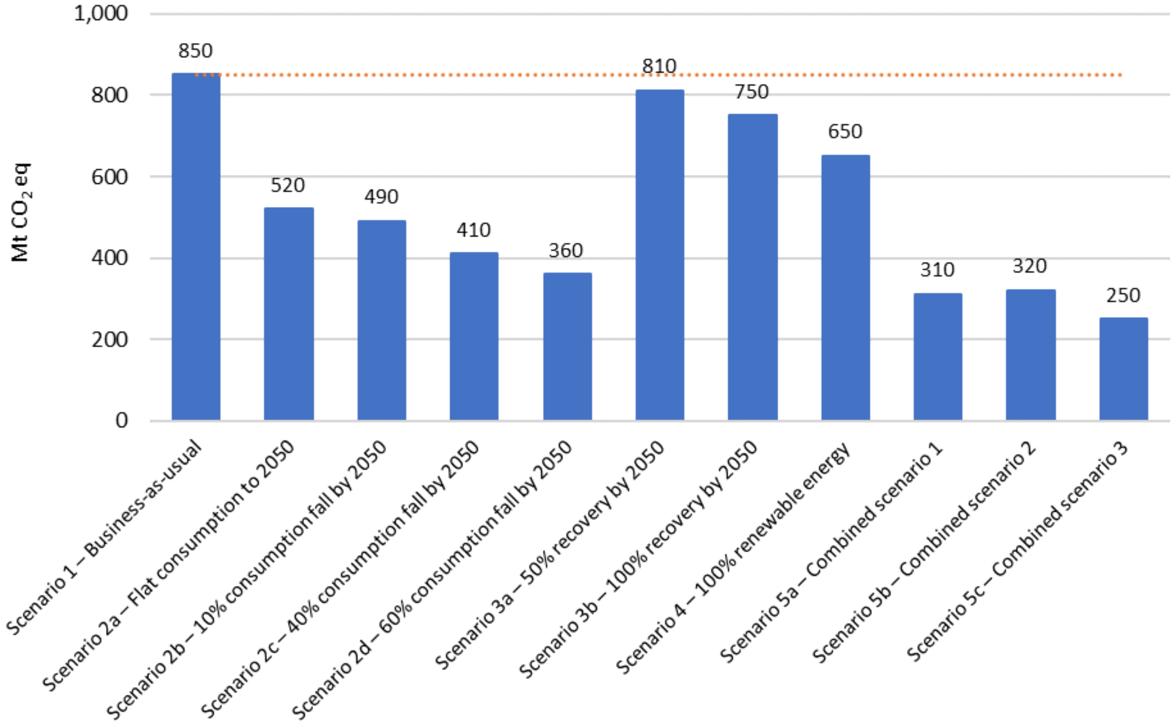
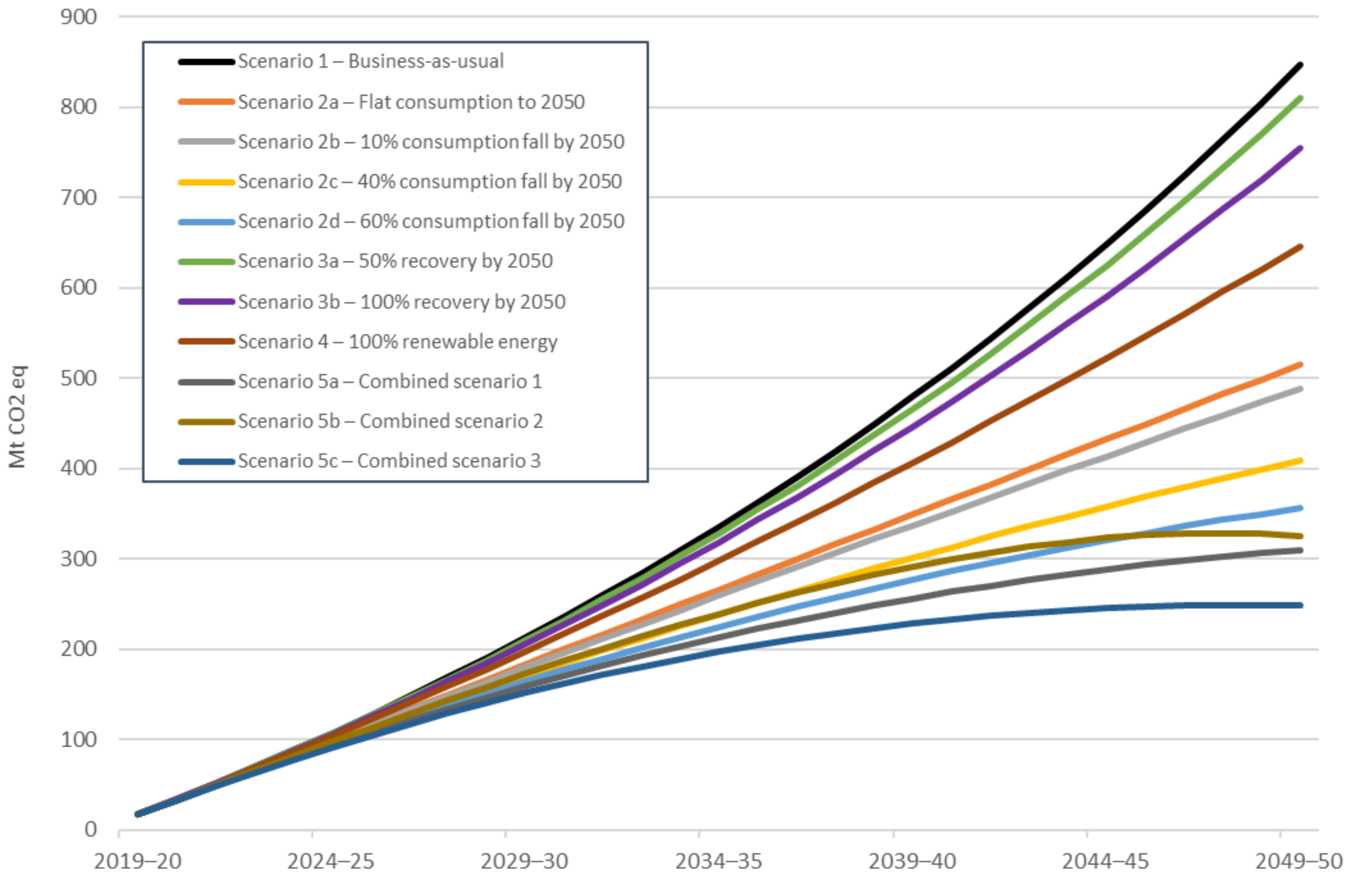


Table 38 System change scenario results for all plastics – 2020 to 2050 – GWP 20 year basis

Scenario	Aggregated time period emissions			Annual emissions	
	2020 to 2030 (Mt CO_2 eq)	2020 to 2050 (Mt CO_2 eq)	(% BAU in 2050) (Mt CO_2 eq)	2020 (Mt CO_2 eq)	2050 (Mt CO_2 eq)
Scenario 1 – Business-as-usual	210	850	0.0%	16.6	42.5
Scenario 2a – Flat consumption to 2050	180	520	-39.2%	16.6	16.6
Scenario 2b – 10% consumption fall by 2050	180	490	-42.3%	16.6	14.9
Scenario 2c – 40% consumption fall by 2050	170	410	-51.7%	16.6	9.8
Scenario 2d – 60% consumption fall by 2050	160	360	-58.0%	16.6	6.3
Scenario 3a – 50% recovery by 2050	210	810	-4.5%	16.6	39.2
Scenario 3b – 100% recovery by 2050	210	750	-11.0%	16.6	34.4
Scenario 4 – 100% renewable energy	200	650	-23.8%	16.6	25.2
Scenario 5a – Combined scenario 1	160	310	-63.5%	16.6	3.3
Scenario 5b – Combined scenario 2	170	330	-61.6%	16.6	-2.4
Scenario 5c – Combined scenario 3	150	250	-70.7%	16.6	-0.6

Provided in Figure 12 are the estimated annual accumulated carbon emissions by scenario on a GWP 20 year basis, from 2019–20 to 2049–50.

Figure 12 Annual accumulated carbon emissions by scenario, from 2019–20 to 2049–50 – GWP 20 year basis



On both a GWP 100 year and GWP 20 year basis, the scenario that provides for the greatest reduction in carbon emissions is Scenario 5c. This is followed by either Scenario 5b (GWP 100 basis) or Scenario 5a (GWP 20 basis). In summary:

- GWP 100 year basis – Scenarios 5c and 5b provide reductions from the BAU carbon emissions (Scenario 1) of 72% and 64% respectively.
- GWP 20 year basis – Scenarios 5c and 5a provide reductions from the BAU carbon emissions (Scenario 1) of 71% and 64% respectively.

6 Interpretation

6.1 Overview

In the life cycle interpretation stage of this carbon emissions study the findings of the inventory analysis and the impact assessment are evaluated in relation to the defined goal and scope in order to reach conclusions, explain limitations and provide recommendations.

The primary goal of the project is to estimate the aggregated carbon emissions of plastics use in Australia, across the period of 2020 to 2050, with comparison of various scenarios across hydrocarbon sources into new plastic products, and pathways for the end-of-life management of used plastic products.

The interpretation stage includes the following components:

- Identification of significant issues based on the results of the carbon emission quantifications in accordance on the life cycle inventory analysis and impact assessment phases of the study.
- An evaluation that considers completeness, consistency and sensitivity analysis.
- Conclusions, limitations and recommendations.

6.2 Significant issues

There were no significant issues identified in the life cycle inventory analysis and impact assessment phases of the study.

However, a scope related potential issue is the exclusion from the scope of any additional inputs (mainly in the product use stage) required due to a shift from single-use to reusable packaging systems. This shift could be undertaken as an action to contribute to the scenarios that include reductions in plastics consumption to 2050. For context approximately 30% of plastics consumption in 2019–20 was into single-use packaging (Envisage Works, 2021). The proportion of this that could be potentially shifted to reusable packaging, or would need to be to achieve any given reduction in future plastics consumption, has not been determined.

As normalisation, ranking or weighting have not been undertaken, there are no value choices requiring justification, other than the selection of the single impact category (climate change), which is specified by the goal of the study.

6.3 Completeness, consistency and sensitivity analysis

6.3.1 Completeness checks

Completeness checks are undertaken to establish confidence in the results for the carbon emission assessment are sufficient for reaching conclusions in accordance with the goal and scope definition.

Section 3 outlines in detail the data sources used in this study and provides commentary on data quality. The data sources used in the study are almost entirely secondary in nature (i.e. pre-existing published information), and are drawn from pre-existing LCI databased (ecoinvent v3.8 and AusLCI v1.40), the academic literature, or Blue Environment prior work and estimates.

The major exception to this, with relevance to the scenario modelling, but minimally to the carbon emission quantifications by process, is that the plastics mass flow data across the period of 2019–20 to 2049–50 is drawn from primary research undertaken to determine this data for Australia (Envisage Works, 2021).

Overall, the data and information needed for the study is considered relevant and complete. However, it is important to highlight there were significant gaps in the existing background LCI databases for processes for which there is minimal data in the public domain or that do not currently exist in Australia or overseas. These processes were:

- Polymer production processes for biobased plastics (except for PLA), and CO_2 based plastics – These gaps were resolved through the literature review, which supported the development of theoretical production processes, as detailed in Section 3.3.3.
- Product EoL processes for chemical recycling – These gaps were resolved through the literature review and prior Blue Environment work, which supported the development of theoretical EoL processes, as detailed in the 'Chemical recycling' subsection in Section 3.3.6.

6.3.2 Consistency checks

Consistency checks are undertaken to verify that the assumptions, methods and data are consistently applied throughout the study and are in accordance with the goal and scope definition performed before conclusions are reached.

The assumptions, methods and data applied during this study are materially consistent with the goal and scope. The chosen declared unit is considered to provide a fair basis for comparison between the scenarios that have been modelled.

Any differences in data quality between the modelled scenarios are not believed to be significant, from a decision making perspective, at the level of the aggregated national total carbon emissions and time frame (2019–20 to 2049–50) scenario modelling that has been undertaken.

In relation to allocation rules established for the study and related considerations:

- Any allocation that occurs within pre-existing databases has not been modified from the published data. For example, a key allocation consideration is the production of fossil hydrocarbons that go into both energy and materials. The pre-existing allocation procedures in ecoinvent v3.8 and AusLCI V1.40 have been retained in this study.
- A modified form of the ‘closed loop allocation procedure’ (or 0/100 method) has been applied to mechanical and chemical recycling (ISO, 2018, pp. 38-39; WRI & WBCSC, 2011a, p. 71). The closed loop allocation procedure has been modified to exclude the end-of-life recycling credit, which has instead been allocated (effectively) to the 'production' process of plastics sourced from recycling.

6.3.3 Sensitivity analysis

Sensitivity analysis is undertaken as an important checking and verification tool. Sensitivity analysis is used to estimate the effects of the choices made regarding methods and data on the outcome of a study, and involves choosing different values from the range of those possible for particular parameters. The parameters selected are those expected to strongly affect the results when different values are selected.

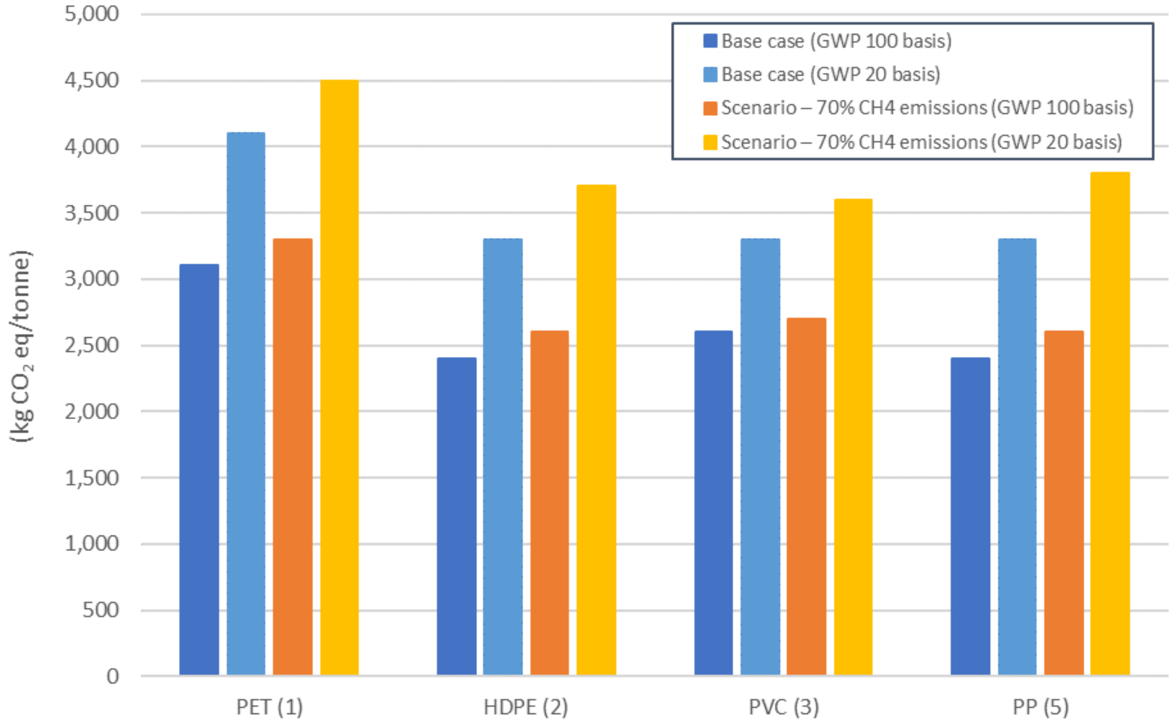
Sensitivity analysis of one key parameter has been undertaken, which is particularly subject to high uncertainty in its value.

Production related methane emissions

As outlined in Section 3.3.3 the International Energy Agency 2022 update of its *Global Methane Tracker* (IEA, 2023) found that global methane emissions '*are about 70% greater than the sum of estimates submitted by national governments*'. This includes methane emissions across gas, oil and coal. It is possible that the additional methane emission allowance adopted in this study of 32.5% significantly understates the true upstream methane emissions associated with gas and oil production, and for this reason the impact of the IEA (2023) reported 70% value is tested in the sensitivity analysis undertaken here.

The impact of increasing the upstream methane emissions to 70% are presented in Figure 13 below. PLA is excluded from the figure as it is rarely based on fossil carbon sources.

Figure 13 Carbon emissions of polymer production from fossil sources



On a GWP 100 year basis:

- The largest increases are for PP (6.1%) and HDPE (5.8%). These polymers contributed 38.5% of Australian plastics consumption in 2019–20.
- PET has a 4.9% increase, with PET contributing 12.0% of Australian plastics consumption in 2019–20.
- PVC has a 4.1% increase, with PVC contributing 13.4% of Australian plastics consumption in 2019–20.

As can be seen from the data above, large changes in upstream methane emission estimates can have a moderately significant impact on the carbon emissions of polymer production from fossil carbon sources. It is also worth noting that there is a developing pattern over the last few years of production related methane emissions being continually revised upwards in the academic literature as data collection technologies improve.

6.4 Conclusions, limitations and recommendations

6.4.1 Conclusions

On both a GWP 100 year and GWP 20 year basis, the scenario that provides for the greatest reduction in carbon emissions is Scenario 5c. This is followed by either Scenario 5b (GWP 100 basis) or Scenario 5a (GWP 20 basis). In summary:

- **GWP 100 year basis** – Scenarios 5c and 5b provide reductions from the BAU carbon emissions (Scenario 1) of 72% and 64% respectively.
- **GWP 20 year basis** – Scenarios 5c and 5a provide reductions from the BAU carbon emissions (Scenario 1) of 71% and 64% respectively.

Scenarios that solely rely on reductions in consumption also perform well. The achievement of flat growth in consumption (scenario 2a) as an outcome between 2019–20 and 2049–50 results in nearly a 40% fall in carbon emissions relative to BAU.

Scenario 4 (100% renewable energy by 2049–50) performs moderately well as a single system change, and is a key contributor to the combined scenarios that achieve high reductions in carbon emissions relative to BAU.

Scenarios that solely rely on dramatic increases in recycling rates perform only marginally better than BAU by 2049–50.

Overall, the study findings strongly indicate that multiple complementary system level changes are required to significantly reduce the carbon emissions relating to plastics use. These changes include absolute reductions in plastics use, decoupling polymer production from fossil hydrocarbons, decarbonising energy systems globally, and significantly increasing recycling rates.

6.4.2 Limitations

The major limitations and related considerations for this study include:

- Limitations of the system boundaries for the modelled processes, which do not necessarily include all inputs and outputs of every process, since there are cut-offs and data gaps. This is particularly relevant to the theoretical processes that have been developed for this study, which by necessity focused on the major identified carbon emission related inputs/outputs only.
- As a number of polymers have been modelled using proxy emission factors the modelled emissions for these polymers may not reflect the actual emissions as quantified in the system change scenario modelling undertaken by this study.
- Limitations of the inventory analysis phase of the study, related particularly to the data quality of the available LCI database and literature data. The significant limitations relate to the requirement for the determination of the carbon emissions related to processes that do not currently exist in Australia or overseas. However, data quality is generally considered to be of acceptable quality for the goal and purposes of this study, and the best available given the large gaps in the published LCI databases and academic literature.
- Carbon emissions can be an important environmental aspect of the life cycle of a product affecting the area of concern 'climate change'. A product's life cycle can have impacts related to other areas of concern (e.g. resource depletion, air, water, soil and ecosystems health). A more comprehensive life cycle assessment (LCA) can also cover further areas of concern in addition to climate change, which are also relevant for the product life cycle.

  An objective of LCA is to allow an informed decision regarding environmental impacts. Climate change attributable to carbon emissions is only one of a variety of environmental impacts that can arise from a product life cycle. and the relative importance of different impacts can vary with different products and materials.

In some cases, action to minimise a single environmental impact can result in greater impacts arising from other environmental aspects (e.g. activities to reduce water pollution can result in increased greenhouse gas emissions from the life cycle of a product, while the use of biomass to reduce emissions can negatively affect biodiversity).

Decisions about product impacts that are only based on a single environmental issue can be in conflict with goals and objectives related to other environmental issues. Carbon emissions should not be the sole component of a decision-making process.

- The life cycle inventory databases drawn on for this study do include allowances for upstream fossil gas emissions. However, there is increasing evidence generated by relatively recent aircraft and satellite based atmospheric methane monitoring that methane emissions from natural gas extraction and processing are notably larger than those included in the LCI databases used in this study. For this reason, correction factors have been applied for the required additional upstream natural gas extraction and production methane emissions in the life cycle inventory data incorporated into this study. The correction factors have a high level of uncertainty, and on balance are likely to be on the low side, and so understate the true carbon emissions associated with the production of fossil carbon based plastics.

6.4.3 Recommendations

This study has found that the implementation of multiple complementary system level changes are needed in order to significantly reduce the carbon emissions relating to plastics use. These changes include absolute reductions in plastics use, decoupling polymer production from fossil hydrocarbons, decarbonising energy systems globally, and significantly increasing recycling rates.

The recommendations arising from the findings of this study are:

1. Reduce growth in plastics consumption dramatically within the next 10 years, through a combination of approaches such as avoiding unnecessary plastics use, redesigning products and packaging, shifting from single-use to reusable packaging systems, and consumer behaviour change.
2. Decouple plastics production entirely from fossil carbon dependency as the carbon source in the plastic. The preferred additional carbon source, within the scope coverage of this study, is generally CO_2.
3. Shift to a 100% renewable energy system for both stationary energy and transport, and electrify plastics production, product manufacture, product use and product EoL management.
4. Maximise product EoL recycling, with a strong preference for mechanical recycling where feasible.
5. Avoid the EoL management of plastics via energy recovery or incineration, which in a future state with an otherwise fully renewable energy system, have effectively the same carbon emissions averaged across all plastics.

7 References

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8 Glossary and abbreviations

Term	Definition
Biobased	Material that is composed in whole, or in significant part, of biological products or renewable agricultural and forestry resources such as plant starch from sugarcane or corn, cellulose, or plant/animal proteins.
Biodegradable	A generic term that indicates a polymer is biologically available for microbial decomposition, with typically no detail on breakdown products, time or extent of degradation or end environments. A certified compostable plastic (product or package) is biodegradable, however, a biodegradable polymer is not necessarily certified compostable.
Bioplastics	Plastics that are biobased, biodegradable or both. Bioplastics fall into three broad groupings, which are: biobased (but not biodegradable); biodegradable (but not biobased); or biobased and biodegradable. Conventional polymers (e.g. PET and HDPE) can also be fully or partially 'biobased'.
Biopolymer	Variable usages. Can be used with the same meaning as either bioplastic or biobased plastic.
Bio-PE	Biobased polyethylene.
Bio-PP	Biobased polypropylene.
Bio-PET	Biobased polyethylene terephthalate.
Capacity (reprocessing)	The industrial capacity available to reprocess waste materials per year, overall or by polymer type. 'Current capacity' is the maximum quantity possible to be reprocessed at a facility per year. 'Spare capacity' is the unused or potential quantity of reprocessing ability at a facility per year, in excess of actual reprocessed quantity. 'Planned capacity' is the quantity per year, beyond the current capacity, that the reprocessor has committed (funded) plans to install or develop.
Certified compostable	Means that claims of compliance with Australian Standard 4736-2006, compostable and biodegradable plastics – "Biodegradable plastics suitable for composting and other microbial treatment" and Australian Standard AS 5810-2010 Home Composting – "Biodegradable plastics suitable for home composting" have been verified.
Chemical recycling	The use of chemical processes such as hydrothermal liquefaction (HTL), gasification, pyrolysis and solvolysis to convert scrap plastics into a hydrocarbon gas or liquid that is usable as a fuel or as an input for manufacturing chemicals, including plastics. Also called advanced recycling or feedstock recycling.
Circular economy	A systems-level approach to economic development designed to benefit businesses, society, and the environment. A circular economy aims to decouple economic growth from the consumption of finite resources and build economic, natural, and social capital. The CE concept is built on and applies three key principles: • design out waste and pollution • keep products and material in use • regenerate natural systems.
Closed-loop recycling	Material from a product system is recycled in the same product system and is of the same quality and functionality as the original material. In terms of end-of-life fates, closed-loop recycling will typically provide greatest environmental benefits, with the key attribute being the displacement (competition with) virgin resource extraction. Closed-loop recycling of plastics is always considered to be virgin resin competing. Also see 'Open-loop recycling' and 'Downcycling'.
Compostable	In this report compostable is used as a specific term that describes a biodegradable bioplastic based article (usually packaging) that degrades and meets the requirements of the Australian Standards for commercial composting (AS 4736–2006) and/or home composting (AS 5810–2010), or meets similar overseas standards such as the European

Term	Definition
	standard is EN 13432. To be called compostable, packaging must biologically decompose and disintegrate in a composting system (under either commercial or home composting conditions) to set levels within a defined period of time. The compost must also meet specific quality criteria relating to eco-toxicity and other characteristics.
Composting	Predominantly an aerobic biological process that turns organic material into compost, which can be a useful soil additive. This process diverts organic material from landfill and so prevents the production of methane (a powerful greenhouse gas).
Consumption	Total use of product by Australian industry and consumers. Includes locally made and used product, imported product and locally utilised recyclate. Does not include locally made product that is exported for sale.
Converter	Company which converts resin, either virgin resin or recycled content resin, into plastic products.
Degradable	A broad term applied to polymers or plastics that disintegrate by a number of processes, including physical disintegration, chemical degradation, and biodegradation by biological mechanisms. As a result of this definition, a polymer may be degradable but not biodegradable.
Disposal	The deposit of solid waste in a landfill or incinerator, excluding solid waste that is sent to energy recovery.
Diversion rate	Recovery (at a defined point) as a percentage of end-of-life disposal. Also see 'Recovery rate' and 'Recycling rate'.
Downcycling	Recycled material is of lower quality and functionality than the original material(s). Materials are recycled into different applications with less stringent performance specifications, and where the recycled materials are typically substituting for (competing with) materials other than the original high quality virgin materials. Examples of this include the recycling of mixed polymer rigid plastics, e.g. a mixture of HDPE, low-density polyethylene (LDPE) and polypropylene (PP) into timber substitute products (e.g. outdoor furniture, pallets, and fencing), where the recovered plastics are competing primarily with timber as the alternative material. Down-cycled materials are potentially more difficult to recycle at end-of-life (although they often have long functional lifespans) and are more likely to be disposed to landfill at end-of-life. Also see 'Closed-loop recycling' and 'Open-loop recycling'.
End-of-life (EoL) generation or arisings	The term for when a product or material reaches the end of its intended purpose (life cycle) and is disposed to waste streams. EoL generation has the same meaning as ‘waste generation’ and ‘EoL arisings’
Energy recovery	Combustion of waste plastics as either a fuel substitute (e.g. in cement kilns), or in specialised waste combustion facilities to create heat, which is then generally used for steam production. The steam is then used directly in industrial processes and/or used to generate electricity. Excludes incineration where a substantial portion of energy value in the waste plastic is not recovered.
Export for reprocessing	Material sent for reprocessing overseas.
Feedstock recycling	Same meaning as ‘Chemical recycling’
Final sink	A final sink is a physical environment (environmental compartment) where materials have very long residence times (>1,000 years).
Flexible plastics	Soft (flexible) plastics are generally defined as plastics that can be scrunched into a ball, unlike ‘rigid’ plastics such as bottles and tubs, which are moulded and hold their shape. Also refer to the 'Rigid packaging' entry.
Local/Locally	In Australia.
Local reprocessing	Scrap plastics reprocessed in Australia. As an example, locally reprocessed scrap plastics recovered from WA are generally reprocessed in WA but may also be reprocessed at interstate facilities. Both WA and interstate reprocessing facilities are defined as local facilities.

Term	Definition
Local use	Recyclate used within Australia by an Australian company in the manufacture of a new product.
Material flow analysis	Material flow analysis (MFA) is a mass balanced based analytical method to quantify flows and stocks of materials or substances for a well-defined system and time period. MFA is also referred to as substance flow analysis (SFA).
Mechanical recycling	The use of physical processes such as sorting, chipping, grinding, washing and extruding to convert scrap plastics to a usable input for the manufacture of new products.
MRF	Material Recovery Facility – a facility for the sorting of recyclables (typically packaging) into various product streams.
Non-packaging / durable	Long-term use item; not designed to be single use or disposable within a 12-month period.
Open-loop recycling	Material from a product system is recycled into a different product system and may be of lower quality and functionality than the original material. Importantly, the recycled materials substitute for, and avoid the use of virgin materials in the new applications. Examples of this include the recycling of PET bottles into fibre for use in clothing and other textiles, and high-density polyethylene (HDPE) milk bottles into mobile garbage bins and milk crates. Open-loop recycling can be as environmentally beneficial as closed-loop recycling, particularly if the use competes with virgin resin. However, open-loop recycling can also be less environmentally beneficial than closed-loop recycling, particularly where used in applications that are not virgin resin competing. Also see 'Closed-loop recycling' and 'Downcycling'.
Out-the-gate	Material leaving a facility following reprocessing and excludes most contamination. Also see ‘In-the-gate’.
Packaging	Material used for the containment, protection, marketing, or handling of product. Includes primary, secondary and tertiary/freight packaging in both consumer and industrial packaging applications.
PA (polyamides or nylons)	Polyamides (PIC 7). Typically referred to as ‘nylon’.
PE-HD or HDPE	High density polyethylene (PIC 2). Typically referred to as HDPE.
PE-LD/LLD or LDPE/LLDPE	Both low density polyethylene and linear low density polyethylene (PIC 4). Typically referred to as LDPE/LLDPE.
PE-LD or LDPE	Low density polyethylene (PIC 4). Typically referred to as LDPE.
PE-LLD or LLDPE	Linear low density polyethylene (PIC 4). Typically referred to as LLDPE.
PET	Polyethylene terephthalate (PIC 1).
PLA polyester	Poly-lactic acid (PLA)
Plastic	A plastic material is any of a wide range of synthetic or semi-synthetic organic solids that are mouldable. Plastics are typically organic polymers of high molecular mass, but they often contain other substances. They are usually synthetic, most commonly derived from petrochemicals, but many are either partially natural or fully natural (i.e. biobased).
Plastics identification code (PIC)	A voluntary coding system for plastic polymers using the numbers 1–7. The PIC is used to identify the polymer composition of plastic products, potentially facilitating the post-consumer waste management of plastic goods. Also known overseas as the Resin Identification Code (RIC).
Polyolefin	A polyolefin is a type of polymer produced from an alkene monomer (general formula C_nH_{2n}). Polyethylenes (HDPE and LDPE) and polypropylene are polyolefins.
PU or PUR	Polyurethane (PIC 7).
PP	Polypropylene (PIC 5).
Process engineered fuel (PEF)	PEF is a name for solid fuel of a specified size profile and energy content manufactured from high-energy content end-of-life materials, such as timber from building demolition,

Term	Definition
	and scrap plastics from pre-consumer and post-consumer sources. PEF is burnt to generate heat for energy generation and is typically used in cement kilns to reduce coal and gas use.
PS	Polystyrene (PIC 6).
PS-E or EPS	Expanded polystyrene (PIC 6). Typically referred to as EPS.
PVC	Polyvinyl chloride (PIC 3).
Recover / recovery / resource recovery	The process of recovering resources from waste for reuse or reprocessing. This includes the collection, sorting and aggregation of materials, and the conversion of waste into a material suitable for manufacturing new products. The term recovery, as applied in this report, includes the reprocessing of recovered plastics in (material) recycling processes, composting of biodegradable plastics, and the combustion of recovered plastics in energy recovery.
Recovery rate	Recovery (at a defined point) as a percentage of end-of-life disposal. Similar meaning to 'Recycling rate' but can include material into composting and energy recovery. Excludes reused products, and contaminants and residual wastes sent to landfill. Also see 'Diversion rate' and 'Recycling rate'.
Recyclate	Recyclate is any recovered scrap material from both pre-consumer and post-consumer sources, either before or after reprocessing. It includes scrap plastics (before reprocessing), pellets, fines, and flakes (after reprocessing), but excludes material sent to energy recovery. Also see ‘Scrap plastics’.
Recycling	Activities in which solid wastes are collected, sorted, processed (including through composting), and converted into raw materials to be used in the production of new products (the amount of solid waste recycled is net of any residuals disposed). Excludes energy recovery and stockpiles.
Recycling rate	Recycling (at a defined point) as a percentage of end-of-life disposal. Similar meaning to 'Recovery rate' but excludes material into energy recovery, and reused products. Also see 'Diversion rate' and 'Recovery rate'.
Reprocess / reprocessing	Processing of recovered materials to make raw materials for use in making new products or direct use.
Reprocessor / reprocessing facility / reprocessing infrastructure	Facility that uses an industrial process to change the physical structure and properties of a waste material so it can be used again. This can include facilities that dismantle products, such as tyres, e-waste and mattresses, and energy from waste facilities that use materials to generate energy.
Resin	Raw polymer material.
Rigid packaging	Rigid plastic packaging such as bottles and tubs, which are (generally) moulded and hold their shape. Also refer to the 'Flexible packaging' entry.
Scrap plastics	Used plastic material (including used tyres), either pre-consumer or post-consumer, that has been recovered for reprocessing, but has not yet been reprocessed.
Secondary processing	A process undertaken after sorting in which a recovered material is put through an industrial process to change it so that it can be used as an input for the manufacture of new products. Also see ‘Reprocessor’.
Single-use plastic packaging	Single-use plastic packaging is likely to be designed to be discarded after single use and is routinely disposed of after its contents have been unpacked or exhausted.
Solid recovered fuel (SRF)	A fuel derived from solid waste produced to meet a specification. Term established by the EU via CEN/TC343 standard. In Australia, the commonly used term of ‘processed engineered fuel’ (PEF) has the same meaning.
Sorting / primary sorting	A process typically between collection and reprocessing in which collected end-of-life materials are sorted (or disassembled) into more usable and economically valuable

Term	Definition
	material fractions. Secondary sorting can also be undertaken on some material flows. Material recovery facilities (MRFs) are (primary) sorting facilities.
Unknown polymers	Unknown polymers are plastics flows for which the polymer type cannot be identified. For example, plastic imports for which the quantity and application are identified, however, the polymer type cannot be determined either directly or through supporting investigations.
Virgin material	Material that has been sourced through primary resource extraction. Virgin materials are often referred to as primary materials. Virgin materials are not sourced from recycled materials (sometimes called secondary materials).
Waste	Any discarded, rejected, unwanted, surplus or abandoned matter, including where intended for recycling, reprocessing, recovery, purification or sale. Anything that is no longer valued by its owner for use or sale and which is, or will be, discarded.

Appendix A Critical review statement

Critical Review Statement for Carbon emissions assessment of Australian plastics consumption – Project report commissioned by the Australian Marine Conservation Society and World Wide Fund for Nature Australia

30th June 2023

This study was commissioned by the Australian Marine Conservation Society (AMCS) and World Wide Fund for Nature Australia (WWF) to assess the carbon emissions associated with Australia's consumption and waste management of plastics. Additionally, the study aimed to evaluate the potential carbon emissions resulting from various system change scenarios.

Three rounds of review were undertaken by the review panel in addition to an earlier goal and scope review by the review chairperson. The final report review was dated 28th June and was Version 3 of the report.

The study was initially reviewed as a life cycle assessment in accordance with ISO 14044 however as the aims of the study were less product focused and more sector focused it was suggested that the ISO 14044 was not as relevant and that the study would be review for quality and independence with reference to the ISO climate related standards ISO 14067 and reporting procedure in ISO 14064.

The study provides valuable insights into the overall carbon footprint of plastic material flows connected to demand for plastic products. The reviewers recognise the difficulty in the scope of the project and the limits to available data both currently and in projections.

The reviewers note that the results were not validated against other reported inventories, results or literature. This lack of validation limited our ability to confirm the accuracy or correctness of the models. However, the reviewers are satisfied that the models of carbon impact of polymers both per tonne and per year are of similar magnitude to other reported data and therefore represent an accurate measure of these.

The reviewers hold reservations on the limits to policy scenario's which do not include modelling of the impacts of plastics reduction either through direct substitution of with other materials (e.g. reduction in plastic consumption resulting in a switch to alternative materials), alternative consumption models (such as reuse), or indirect effects from changes functionality of systems where plastic has been removed (such as product protection/shelf life), and choice of proxy data.

We also have reservations on the suitability on the assumptions for a number of the policy scenarios, which are 100% recovery and recycling, 100% plastics from biobased or CO_2 based carbon sources, and 100% renewable electricity generation. Our reservations on these assumptions relate to the current state of readiness of these systems and technologies. We are comfortable with the limitations that the authors have placed on these assumptions. We therefore suggest care be taken when communicating the results from the scenarios to indicate that they are not viable points but are more theoretical or idealistic maximum points.

Mr Tim Grant, Director, Lifecycles

Assoc. Prof. Enda Crossin, , University of Canterbury

Mr Josh Key, Principal Consultant , Joshua Key Perspektiv