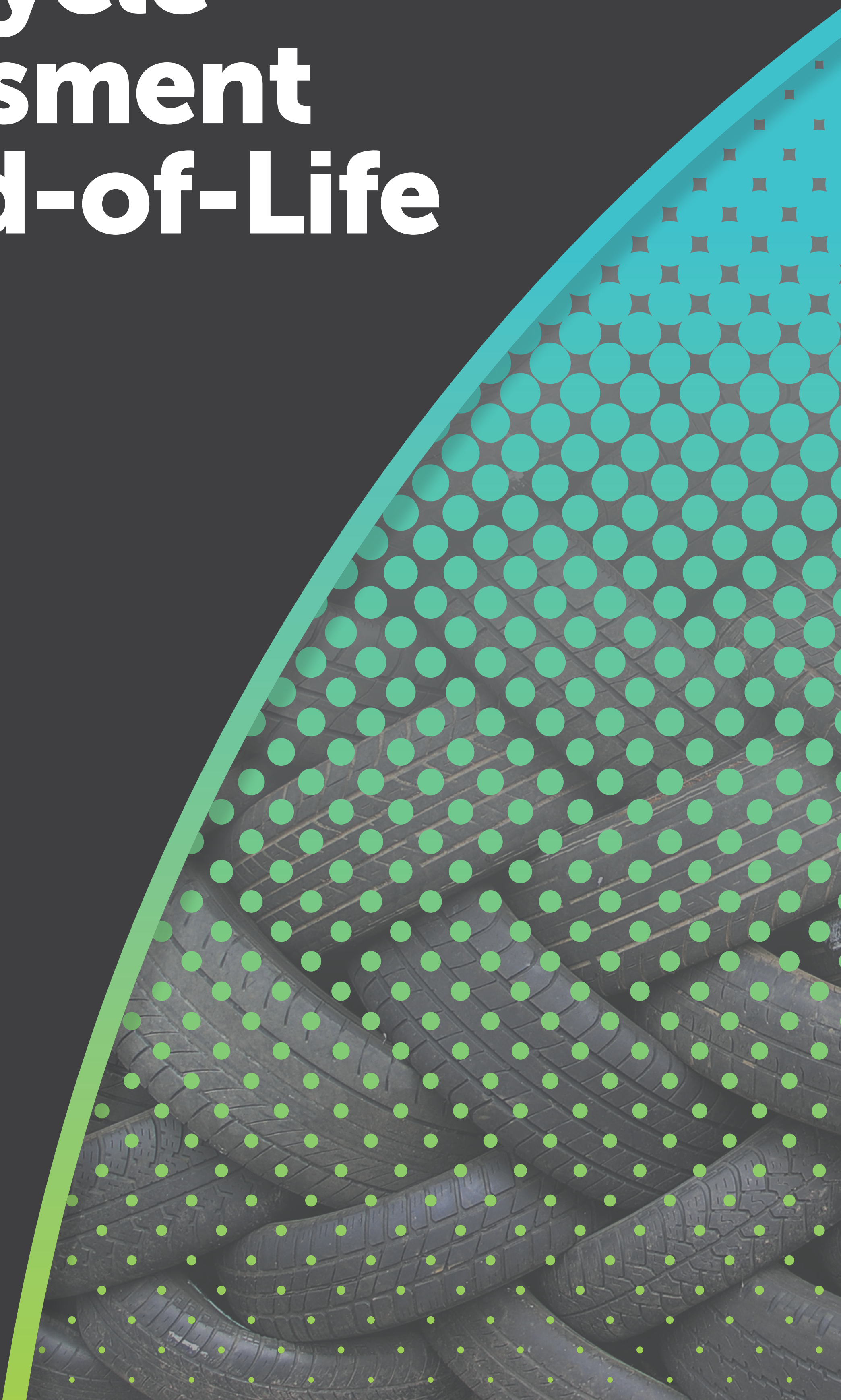
TSA Driving sustainable outcomes for end-of-life tyres

TyreStewardship AUSTRALIA

Life Cycle Assessment of End-of-Life Tyres



Australian Government Accredited Product Stewardship Scheme

Life Cycle Assessment of End-of-Life Tyres

Version 6.1

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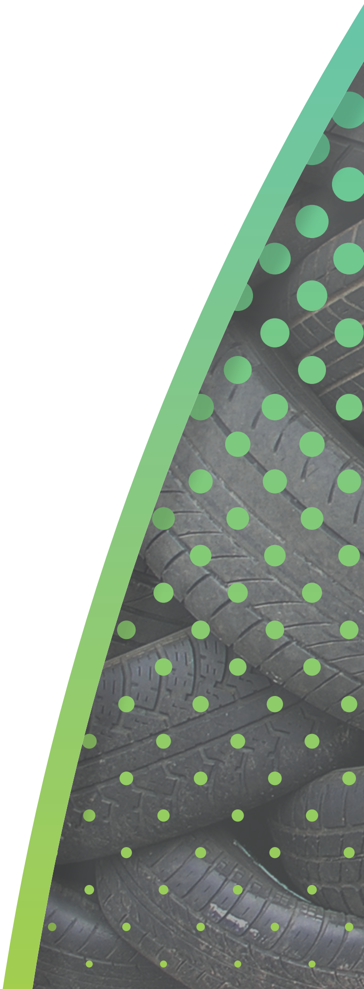

Executive Summary

Edge Environment was commissioned by Tyre Stewardship Australia (TSA) to understand the greenhouse gas (GHG) emissions of waste tyre recovery, including the GHG emissions of end-of-life tyres (EOLT) and a range of tyre derived products (TDP). The objective of this study is to understand the GHG implications of these products and the potential contribution these products could make to a range of different end markets. The aim is to encourage the use of EOLT in current and potential markets, diverting EOLTs from landfill.

This report discusses EOLT recovery technologies and focuses more on EOLTs handling and the end market products they can replace that normally occur in Australia. Figure 1 shows the system boundary included in this study, which starts with the collection and transport of the EOLT and ends with TDP replacing conventional products in end markets, such as asphalt aggregate or binder in road construction.

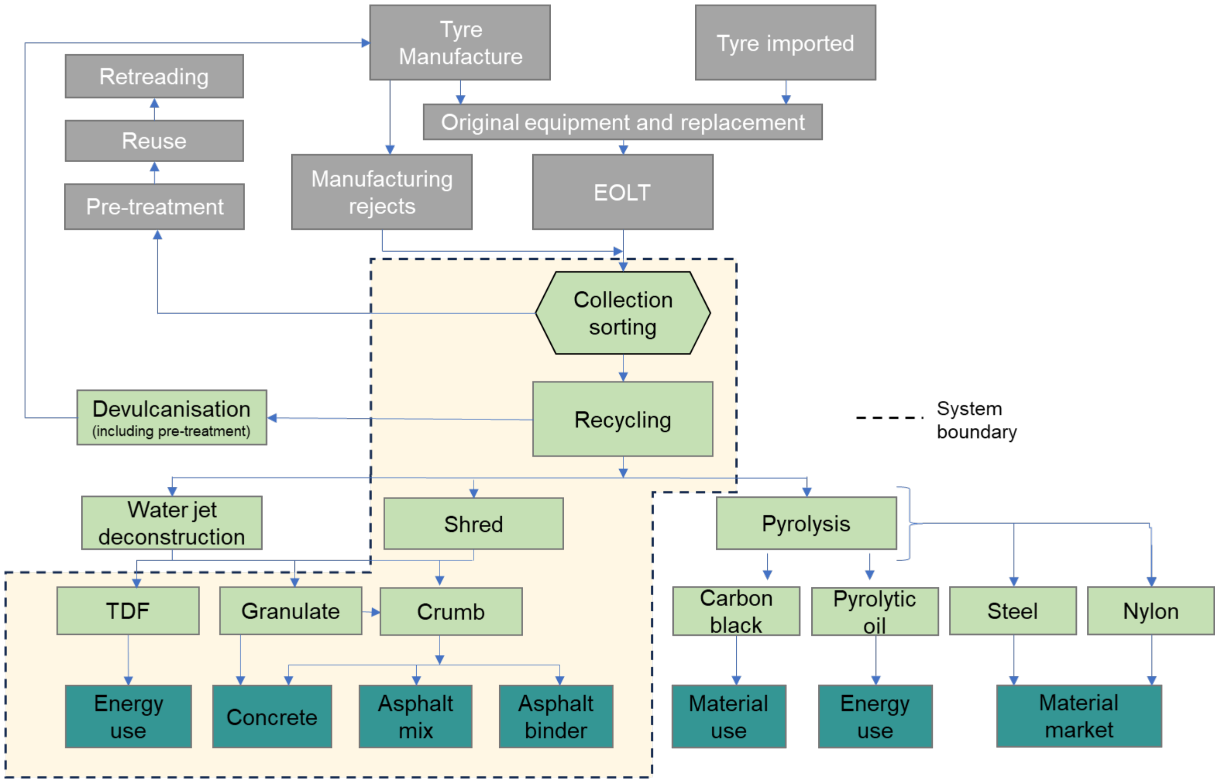

Figure 1 | Process flow and system diagram for EOLT recycling, showing system boundary for current assessment.

This report presents the research, methodology, data, results and interpretation of these EOLT and TDP processes. The report is set out in three parts based on the three stages of the project.

Stage 1: Desktop review and preliminary assessment

- Summary of the relevant calculation methods for EOLT and TDP markets.
- Quantify the GHG emissions and other environmental impacts of EOLT and the processing of EOLT into products for the TDP end market, including rubber shreds, granules, and crumb rubber.
- Preliminary comparison of the processed EOLT products compared to the conventional products they will replace.

Stage 2: Detailed assessment

- Extend the results of Stage 1 by modelling the detailed TDP end markets, including consideration of any additional processing required and any performance benefits of replacing conventional products with EOLT.

Stage 3: Evaluation and recommendations

- Contextualise the results of Stage 2 in terms of existing reporting and management systems. This includes summaries of existing quantification and certification schemes, voluntary reporting programs, existing standards and frameworks, carbon trading mechanisms and any funding mechanisms that might be relevant.
- Identify potential ways forward for TSA and their stakeholders to encourage further uptake of EOLT and TDPs.

Methodology

The LCA method has been used in the assessment of environmental impact for this project, developed to comply with ISO 14040:2006 and ISO14044:2006+A1:2018 which describe the principles, framework, requirements, and provides guidelines for life cycle assessment (LCA) (ISO, 2006; ISO, 2018).

The life cycle model was created in a leading LCA software tool, SimaPro. SimaPro is a platform that links LCA background databases with environmental impact assessment methods, making it possible to calculate impacts from an inventory model. In line with EPD and ARENA methodologies, we have considered recycled materials in the next life cycle as free of embodied emissions from the previous life cycle. This means that only the collection and processing of EOLTs are inputs into its next product life cycle. While this encourages the use of recycled materials as an input material, it should be noted that there may be requirements to use other reporting methods for certain use cases. The figures reported in this report should be interpreted in this light. Table 1 summarises the EOLT materials modelled, and the assumptions used, and Table 2 provides the detailed TDP scenarios that were modelled based on the results from Table 1. Note this report only considers passenger and truck tyres, with off-the-road (OTR) tyres excluded due to differences in recovery pathways. The report outlines GHG emission impacts, as this is a key metric for both producers and consumers in the TDP end market. However, other environmental impacts have also been quantified and commentary provided where relevant.

Table 1 | Modelling assumptions for the collection and processing of EOLT into a material for TDP

	Crumb rubber	Rubber granules	Shredded rubber
Raw material	EOLT (zero burden)	EOLT (zero burden)	EOLT (zero burden)
Collection distance (Pick up to Processing)	Distance: 50% collected in 50 km (urban), 50% collected in 200 km (regional)	Distance: 50% collected in 50 km (urban), 50% collected in 200 km (regional)	Distance: 50% collected in 50 km (urban), 50% collected in 200 km (regional)
Collection truck type	40 t truck	40 t truck	40 t truck
Processing data source	AEPD, 2019	Rouwette, 2020	Corti et al, 2004

Table 2 | TDP end market scenarios modelled.

	Use case	TDP	Conventional Product	Functional Unit	System Boundary
Scenario 1	Default	N/A	Landfill of EOLT	1 t of EOLT	N/A
Scenario 2	Road construction	Crumb rubber binder in asphalt for road construction, using a wet process to incorporate	Polymer modified binder (PMB) in asphalt for road construction	1 km of road	Cradle to gate
Scenario 3	Road construction	Crumb rubber binder in asphalt for road construction, using a dry process to incorporate	Polymer modified binder (PMB) in asphalt for road construction	1 km of road	Cradle to gate
Scenario 4	Sprayed seal	Crumb rubber binder in sprayed seal mix	PMB in sprayed seal mix	1 t sprayed seal	Cradle to gate
Scenario 5	Concrete	Crumb rubber in concrete mix	Conventional concrete mix	1 m^3 of concrete	Cradle to gate
Scenario 6	Concrete	Rubber granules in concrete mix	Conventional concrete mix	1 m^3 of concrete	Cradle to gate
Scenario 7	Permeable pavement	Rubber granules to replace gravel as an aggregate in permeable pavement	Conventional permeable pavement	1 m^2 of paved surface	Cradle only
Scenario 8	Combustion	Shredded rubber used in coal co-combustion at a cement kiln	Coal-derived fuel for combustion at a cement kiln	1 MJ of energy	Cradle to gate

*Cradle to gate includes raw material extraction, transport of materials and manufacture of product. Cradle refers only to raw material extraction.

While the modelling process may require adjustments for each specific scenario, the general modelling process for each scenario is summarised below.

1. Define the TDP and conventional product.
2. Consider appropriate system boundary:
   - Cradle – raw material supply only;
   - Cradle to gate – product stage only – raw material supply, transport of materials and the manufacturing of the product;
   - Cradle to gate plus construction stage – as above, plus transport to site and construction/installation process;
   - Cradle to grave – as above, plus use stage (such as usage, maintenance, repair, replacement, refurbishment and operational utilities), end-of-life stage (such as demolition/deconstruction, transport to waste processing site, landfill/recycling processing) and any benefits or loads beyond the system boundary (such as the recycling potential).

   The decision should factor in whether data is available for each stage and whether modelling the additional stages will provide additional insights into the benefit or detriment of the compared systems.
3. Consider performance benefits of the TDP compared to conventional product and incorporate in the functional unit.
4. Confirm any additional manufacturing inputs required for the TDP compared to the conventional product (if modelling construction/installation impacts).
5. Collect inventory data on the additional materials and other inputs required, utilising the EOLT processing results as the raw material input for the TDP component.
6. Model in Simapro, following LCA principles and using the impact assessment methodology consistent with the EPD method used for midpoint impact categories.
7. Review and report on results.

Key Findings from Existing Quantification Standards

Key findings from the desktop review were:

- The environmental impact of waste materials in subsequent life cycles is determined by the rules outlined in impact assessment schemes.
  - Current LCA-based methods used in Australia, namely the ARENA LCA guidelines for energy-related products and the EPD product category rules *EN 15804:2012+A2:2019* for construction products assume zero burden for waste materials being used in subsequent life cycles. The implication is that impacts are only quantified from waste collection and processing onwards and does not include the embodied impacts of the material.
  - The National Greenhouse Emission Reporting (NGER) Scheme relies on a different methodology and systems boundary and will therefore yield different results compared to LCA-based methods.

Key Results on Processing EOLTs

- Transport emissions factors from the collection of EOLT varied according to truck type and distance travelled. From a GHG emissions perspective, the worst case is a smaller truck, due to the proportionally higher energy consumption required per tonne of goods transported. Transport emissions can be a significant component of overall impact of end market products, particularly where recycled EOLT content is a high proportion of total materials and collection distances are long.
  - Larger trucks have a lower GHG emission factor than smaller trucks per tonne of EOLT transported over one km (1.59 kg CO_2-e/tkm for a 10 t truck, 0.57 kg CO_2-e/tkm for a 20 t truck and 0.32 kg CO_2-e/tkm for a 40 t truck).
  - For the scenarios assessed, the worst case was 500 km interstate travel in a 10t truck (794 kg CO_2-e/t tyres) and the best case was 50 km urban travel in a 40 t truck (16 kg CO_2-e/t tyres).
- Processing EOLTs into finer products using the physical decomposition method requires considerably more energy. Producing rubber granules produces almost 3 times the GHG emissions compared to shredded rubber, while the more refined fine rubber granules and crumb rubber produces 7-8 times the emissions of shredded rubber. These trends are similar across all impact categories. However, the additional processing does widen the potential end markets for the TDP and the environmental and other benefits in the end market may offset these initial emissions.

Key Results on End Market Products

A detailed assessment of several end market scenarios including processing and transport were modelled. GHG emission reductions were found for 6 of the total 8 scenarios, compared to the conventional product. The TDPs had mixed impacts across the other environmental impacts indicators. Key findings were:

- The environmental impact of landfill is potentially quite significant, with GHG emissions of 350 and 528 kg CO_2 eq per t EOLT, for passenger and truck tyres respectively (Scenario 1, section 8.3.1).
- Crumb rubber used as 15-20% of an asphalt binder in the wet process has a **7% improvement** in GHG emissions on average compared to an average polymer modified binder (PMB) if the service life is assumed to be the same, from 14,431 kg CO_2 eq to 15,549 kg CO_2 eq per km of road respectively (Scenario 2, section 8.3.2). Improvements were found across all environmental impact categories except water scarcity.
- Crumb rubber used as 27% of an asphalt binder in the dry process has a **6% improvement** in GHG emissions compared to a comparable PMB mix, from 15,248 kg CO_2 eq to 16,414 kg CO_2 eq per km of road respectively (Scenario 3, section 8.3.3). Improvements were found across all environmental impact categories except water scarcity.
- Crumb rubber used as 15% of a bitumen mix sprayed seal has a **9% improvement** in GHG emissions compared to PMB sprayed seal, from 695 kg CO_2 eq to 761 kg CO_2 eq per tonne of sprayed seal respectively (Scenario 4, section 8.3.4). Significant improvements were found across all environmental impact categories except water scarcity.

- Crumb rubber used to replace 5% of the sand in a concrete mix showed a **5% increase** in GHG emissions compared to conventional concrete, increasing from 315 kg CO_2 eq to 372 kg CO_2 eq per m^3 of concrete (Scenario 5, section 8.3.5). The TDP had worse impacts across all indicators. Note however, there may be other benefits of TDP compared to conventional sand, including the potential shortage of natural sand supplies in Australia.
- Rubber granules used to replace 30% of the gravel in a concrete mix showed an **18% increase** in GHG emissions compared to conventional concrete, increasing from 315 kg CO_2 eq to 332 kg CO_2 eq per m^3 of concrete (Scenario 6, section 8.3.6). The TDP had worse impacts across all indicators. Note however, there may be other benefits of TDP compared to conventional gravel.
- Rubber granules used at 15% of an aggregate mix for permeable pavements showed a **5% improvement** in GHG emissions compared to conventional aggregate for permeable pavements, from 16.3 kg CO_2 eq to 17.1 kg CO_2 eq per m^2 of paved surface respectively (Scenario 7, section 8.3.7). The TDP also had significant reductions in eutrophication and ecotoxicity impacts.
- 5% shredded rubber blended with coal used in the cement clinker process showed a **4% improvement** in GHG emissions compared to pure bituminous coal, from 0.068 kg CO_2 eq/MJ to 0.072 kg CO_2 eq/MJ respectively (Scenario 8, section 8.3.8). However, the TDF had mixed impacts across the other environmental impact indicators.

The results showed reductions in environmental impact when the processed EOLT material replaces conventional materials with high environmental burden, such as bitumen or coal. However, in scenarios where the recycled rubber is replacing a low-impact material such as sand or aggregates, environmental impacts are worse compared to the conventional case. This highlights the importance of identifying the appropriate end market for TDPs, such as the replacement of high-impact fossil-based materials. While GHG emissions are the dominant concern for key stakeholders, it is important to consider whether the use of a TDP causes detriment in other environmental impact categories.

Review of Existing Reporting Frameworks

It is important to understand the relevant reporting, certification and compliance schemes that apply to producers and purchasers of EOLTs and TDPs. Understanding how to leverage the GHG emissions outcomes of Stage 1 and Stage 2 in the context of these schemes can encourage the uptake of TDPs and divert EOLTs from landfill. To help producers and purchasers understand the relevant of each scheme, a rating system was applied. This system has four criteria:

- **Robustness:** Does the scheme require third-party verification or is compliance to certification requirements self-declared?
- **Uptake:** Does the scheme demonstrate breadth and depth of uptake by producers/purchasers at a national scale? E.g., multiple large-scale organizations, or uptake across multiple industries.
- **Impact:** Is the reporting based on transparency in reporting, or does it promote impact reduction initiatives?
- **Eligibility:** Are producers/purchasers eligible to become accredited against the scheme, and is it accessible to acquire (e.g., applicable fees are reasonable).

For each criterion, a value of 1 or 0 is applied depending on whether the scheme demonstrates the best-value outcome or not. Table 3 evaluates existing schemes against these criteria and provides a recommendation of its relevance to TSA in particular.

Table 3 | Summary of schemes and regulations relevant to EOLT/TDP producers and purchasers

Type	Category	Key schemes	Rating	Recommendation for TSA action
Reporting and certification schemes	Environmental Labels	GECA ecolabel	★★★★	TSA should consider developing sector wide EPD. This encourages the use of TDP as a product category, but also supports members to develop their own EPDs. EPDs are recognised by a range of schemes including GECA, Climate Active and the IS Rating Scheme. TSA can also develop an industry wide tool to allow comparison of existing products with TDP alternatives. The tool allows producers to understand how to market their products and gives purchasers confidence in the products they buy. The voluntary reporting standards are more relevant at the organisation and product level and provides opportunity to educate TSA members on how to position their TDP products.
		EPD	★★☆★	
		ANZ EPD Climate Declaration	★★★★	
		Climate Active	★★★★	
	Other tools and schemes	AfPA LCA Calculator for Asphalt	★☆☆★	
		IS Rating Scheme	★★★☆	
	Voluntary reporting	Science Based Targets	★★★★	
		Carbon Disclosure Project	☆★★★	
		MECLA	☆★★★	
		GHG Protocol	★★☆☆	
		Declare Product Labelling	☆★☆★	
		GRI Standards	☆★☆★	
		SASB	☆★☆☆	
Compliance considerations	Compulsory standards and regulations	State-based and national standards	N/A – mandatory	TSA should explore the need and potential to lead the development of state/territory-based or Australia-wide standards for pyrolysis fuels to ensure quality of this new stream and generate confidence in the new market entrant to foster strong uptake by industry.
		European Parliament PEF	★★★★	
		ISO 14064-1 GHG specification	★★☆★	
		NGER scheme	N/A – mandatory	
		IPCC Guidelines for National GHG Inventories	N/A – mandatory	
Fiscal opportunities	Carbon trading mechanisms	VCUs	★★★★	While TSA should not be providing financial advice, TSA can provide some general information on schemes relevant to producers.
		VERs	★★★☆	
	Funding mechanisms	State-based grants	N/A – consider eligibity and availability at time of application	TSA can proactively seek funding grants that producers may be eligible for and use their knowledge and resources to support their applications.

Recommendations

TSA has the opportunity to accelerate the transition towards a circular economy in sectors that can benefit from EOLT and TDP. Armed with quantitative data demonstrating the benefits of EOLT and TDP outputs in GHG emissions reduction, TSA is well-positioned to leverage this information as momentum to influence sector-wide change. Key recommendations for next steps by TSA to accelerate and support the uptake of EOLT and TDP by industry and end-users are:

1. Develop a tool to assist companies, which can include Marginal Cost Curves, similar to the tool developed for a local council (for roads and buildings). This will allow the comparison of existing products in the markets with TDP alternatives, to provide an indication of the GHG saving. If other impact categories are included, these can also be included in the tool.
2. Develop a sector wide EPD on selected TDPs using input data from member companies. A verified sector wide EPD would help encourage the use of the TPD compared to alternatives in the same category. It can also be provided to TSA members who provided the input data to allow development of their own specific EPDs. Edge is currently developing a sector wide EPD with Cement, Concrete and Aggregates Australia to encourage the use of clinker, cement and concrete products compared to alternatives in those categories.
3. Undertake a feasibility study to assess the current market capacity to collect & process EOLT, and manufacture and produce TDP across Australia. This will identify gaps in capacity, and/or areas of inefficiency to be addressed. Market review could include review of existing infrastructure in alternative uses that could potentially be leveraged for EOLT/TDP applications.
4. Commission a comparative LCA of TDPs in typically cementitious applications, against new carbon neutral/ low carbon concrete products, such as ECOPact – Low carbon concrete by Holcim, to understand the GHG emissions and cost comparison of these two alternatives to traditional materials. This will proactively address queries from producers/purchasers who may be considering emissions-reducing initiatives, but who are unsure which alternatives are most appropriate for their business activities.
5. Prioritizing the EOLT/TDP applications with the largest potential demand (e.g., crumb rubber), undertake a cost-benefit analysis of the EOLT/TDP life cycle, to calculate the cost savings (and potentially, a different cost distribution profile) of recycled content over virgin materials. This will allow producers/purchasers to present a business case for transitioning to EOLT/TDP and inform discussions with key business stakeholders. There is opportunity to develop a tool for calculating costs for select EOLT & TDP uses or sectors to allow producers/purchasers to apply business specific cost data.
6. Translate GHG emissions data into public-facing marketing and communications collateral to allow industry and community to rapidly digest the benefits of EOLT/TDP applications. This will accelerate the transition to EOLT/TDP by mitigating effort required by producers/purchasers to create buy-in from end-users.
7. Establish further partnerships with national and international research institutions and circular economy associations such as CSIRO, and the Victorian Circular Activator, to understand future direction of pyrolysis technology and potential application to new TDP products in the energy and thermal use sectors. Partnerships may provide the opportunity for TSA or industry stakeholders to participate in trials or pilot programs for innovative applications of EOLT.
8. Explore potential to apply blockchain technology to create digital ledgers of EOLT/TDP outputs to establish transparency of supply chain, product/ content and quality, and contribute to improving the collection and management of data in the circular economy in Australia.
9. Develop or commission training material for the internal TSA team to educate them on the content of this project and its outcomes, to improve their understanding and empower them to communicate the outcomes to stakeholders.

Contents

Executive Summary ... 3
Glossary ... 13
1 Introduction ... 14
1.1 Objectives of this project ... 14
2 Overview of Existing Standards ... 15
2.1 Life Cycle Assessment ... 15
2.1.1 Environmental Product Declarations (EPD) – construction products ... 15
2.1.2 ARENA Life Cycle Assessment – energy products ... 16
2.2 National Greenhouse Emission Reporting Scheme ... 18
3 EOLT Characteristics ... 20
3.1 Tyre Composition ... 20
3.2 Tyre Weights ... 20
4 EOLT Collection ... 22
4.1 Collection rates ... 22
4.2 EOLT collection process ... 23
5 Processing EOLT ... 24
5.1 Annual EOLT Processing Rates ... 24
5.2 Retreading ... 25
5.3 Physical Deconstruction ... 25
5.3.1 Process Description ... 25
5.3.2 System diagram ... 25
5.4 Pyrolysis ... 26
5.4.1 Process Description ... 26
5.4.2 System diagram ... 27
5.5 Water Jet Deconstruction ... 28
5.5.1 Process Description ... 28
5.5.2 System Diagram ... 28
5.6 Devulcanisation ... 28
5.6.1 Process Description ... 28
6 LCA Introduction and Method ... 30
6.1 Goal and Scope ... 30
6.1.1 Goal ... 30
6.1.2 Scope ... 30
6.1.3 Functional unit ... 31
6.1.4 System diagram and boundary ... 31
6.1.5 Geographic and Temporal Coverage ... 32
6.1.6 Limitations of the study ... 32

6.2 **Project assessment methodology** ... **32**
6.2.1 General modelling process ... 32
6.2.2 Environmental impact quantification ... 33
6.2.3 Allocation considerations ... 35
6.3 **Data quality and validation** ... **36**
6.3.1 Cut-off rules and Exclusion of Small Amounts ... 38
6.4 **Third party verification** ... **38**
7 **Life Cycle Inventory** ... **39**
7.1 **Collection and Processing Data** ... **39**
7.1.1 Collection ... 39
7.1.2 Crumb Rubber and Fine Rubber Granules ... 40
7.1.3 Shreds and Granules ... 40
7.2 **End Market Data** ... **41**
7.2.1 Scenario 1: Landfill of EOLTs ... 41
7.2.2 Scenario 2: Asphalt Binders (Wet Process) ... 42
7.2.3 Scenario 3: Asphalt Binders (Dry Process) ... 44
7.2.4 Scenario 4: Sprayed seal ... 45
7.2.5 Scenario 5: Concrete (sand replacement) ... 46
7.2.6 Scenario 6: Concrete (coarse aggregate replacement) ... 46
7.2.7 Scenario 7: Permeable Pavements ... 46
7.2.8 Scenario 8: Combustion in cement kilns ... 46
8 **Results** ... **48**
8.1 **Collection Impacts** ... **48**
8.2 **Processing Impacts** ... **48**
8.2.1 Physical decomposition of EOLTs ... 48
8.3 **End Market Impacts** ... **49**
8.3.1 Scenario 1: Landfilling of EOLT ... 49
8.3.2 Scenario 2: Asphalt binders (wet process) ... 50
8.3.3 Scenario 3: Asphalt binders (dry process) ... 52
8.3.4 Scenario 4: Sprayed seal ... 54
8.3.5 Scenario 5: Concrete (sand replacement) ... 55
8.3.6 Scenario 6: Concrete (coarse aggregate replacement) ... 56
8.3.7 Scenario 7: Permeable pavements ... 57
8.3.8 Scenario 8: Combustion in cement kilns ... 58
8.4 **Sensitivity Analysis** ... **59**
8.4.1 Impact of EOLT Collection ... 59
8.4.2 Impact of Different Processing Technologies ... 60
8.4.3 Impact of Performance Improvement for Road Construction ... 61
8.5 **Overall Benefits of Processing EOLTs and TDP End Markets** ... **62**

9 Reporting, Certification & Compliance Considerations & Fiscal Opportunities 63
9.1 Evaluation Criteria and Approach 63
9.2 Reporting & Certification Schemes 64
9.2.1 Quantification Schemes 64
9.2.2 Voluntary Reporting 71
9.3 Compliance Considerations 77
9.4 Fiscal Opportunities 83
9.4.1 Carbon Trading Mechanisms 83
9.4.2 Funding Mechanisms 86
9.5 Summary of schemes and regulations 89
10 Recommendations for Delivering Benefits of EOLT & TDP 91
References 92
Appendix A – Background data 95
Appendix B – Biogenic Carbon 97

Glossary

Abbreviation	Description
ACCUs	Australian Carbon Credit Units
AEPD	Australian EPD programme
AfPA	Australian Flexible Pavement Association
ARENA	Australian Renewable Energy Agency
CDP	Carbon Disclosure Project
CERs	Certified Emissions Reduction
EOLT	End of life tyres
EPA	Environmental Protection Agency
EPD	Environmental product declaration
GBCA	Green Building Council of Australia
GECA	Good Environmental Choice Australia
GHG	Greenhouse gas emissions
GRI	Global Reporting Initiative
GWP	Global warming potential
IPCC	Intergovernmental Panel on Climate Change
ISCA	Infrastructure Council of Australia
ISO	International Standards Organisation
LCA	Life cycle assessment
MECLA	Materials and Embodied Carbon Leaders' Alliance
MRF	Material recovery facilities
NGER	National Greenhouse Emission Reporting scheme
OTR	Off the road tyres
PCR	Product category rules (for producing an EPD)
PDS	Product disclosure statement
PEF	European Parliament Product Environmental Footprint
PMB	Polymer modified binder
RMF	Recycling Modernisation Fund
SASB	Sustainability Accounting Standards Board
SBTi	Science Based Targets initiative
TCFD	Task Force on Climate Related Financial Disclosures
TDF	Tyre derived fuel
TDP	Tyre derived products
TSA	Tyre Stewardship Australia
VCS	Verified Carbon Standard
VCUs	Verified Carbon Units
VERs	Voluntary Emissions Reduction
WRI	World Resources Institute

1 Introduction

1.1 Objectives of this project

The overall objectives of this project are to:

- Analyse and quantify the greenhouse gas (GHG) and other environmental implications of waste tyre recovery and associated activities.
- Understand the potential contribution that end-of-life tyres (EOLT) and tyre derived products (TDP) can have to a range of current and potential markets.
- Facilitate the expansion and creation of new markets for EOLT to avoid landfill and dumping.
- Develop a process to assess the impacts of new and emerging TDP products.
- Understand the risks and benefits of the Australian tyre recovery sector of GHG and carbon related factors.

Tyre Stewardship Australia (TSA), who has commissioned this work, intends to use the results to:

- Identify risks and benefits of carbon and climate factors on the tyre resource recovery sector.
- Develop rigorous and sound metrics on behalf of the sector to provide standardised factors and protocols to assess carbon and climate change factors via a consistent, sector wide approach.
- Identify initiatives that TSA and industry can undertake to support enhanced recovery of tyres through realising GHG and carbon benefits and mitigating associated risks across the supply chain.

The project has been split into three stages. The specific objectives for each stage are:

Stage 1: Desktop review and preliminary assessment

- Summarise the relevant calculation methods in Australia for EOLT and TDP markets.
- Quantify the GHG emissions and other environmental impacts of EOLT and the processing of EOLT into products for the TDP end market, including rubber shreds, granules, crumb rubber and pyrolysis derived products.
- Preliminary comparison of the processed EOLT products compared to the conventional products they will replace.

Stage 2: Detailed assessment

- Extend the results of Stage 1 by modelling the detailed TDP end markets, including consideration of any additional processing required and any performance benefits of replacing conventional products with EOLT.

Stage 3: Evaluation and recommendations

- Contextualise the results of Stage 2 in terms of existing reporting and management systems. This includes summaries of existing quantification and certification schemes, voluntary reporting programs, existing standards and frameworks, carbon trading mechanisms and any funding mechanisms that might be relevant.
- Identify potential ways forward for TSA and their stakeholders to encourage further uptake of EOLT and TDPs.

This report consolidates the findings from each of these stages.

2 Overview of Existing Standards

This section details the certifications and/or standards currently used in Australia for the calculation of the environmental impacts related to the use of TDP. This section aims to summarise some of the key considerations related to impact quantification through a discussion of standards considered most relevant to the scenarios quantified in this study. Note that this is not an exhaustive discussion of all certifications and standards that may relate to TDP. Section 10 provides a more comprehensive summary of the certification schemes and regulations in Australia, and its potential relevance to TDPs. Note this section provides a general summary of some key methodologies used in Australia, rather than the specific methodology within this report. The specific methodology used for this report has been summarised in Section 6.

2.1 Life Cycle Assessment

Life Cycle Assessment (LCA) is an internationally standardised framework for quantifying the environmental impact of resource use from cradle to grave of a system. LCA models the life cycle of physical processes by linking input and output material and energy flows to background environmental impact models to determine the environmental impact across various impact categories including potential GHG emissions. The methodology is underpinned by ISO14040 and ISO14044 standards, which includes the following steps:

1. Identify the goal and scope of study, and the life cycle to be reviewed.
2. Identify the energy, water and materials used, pollution emitted, and waste generated through the life cycle.
3. Assess the potential environmental impacts across the life cycle, acknowledging the uncertainties and assumptions used.
4. Highlight any significant results and implications.

LCA provides the foundational methodology for the application of a range of certification schemes, including Environmental Product Declarations (EPD) and the Australian Renewable Energy Agency (ARENA) LCA scheme. These applications are based on LCA methodology but will have specific rules for particular product groups to ensure suitability for benchmarking products in the same groups.

In terms of TDP used as construction materials, the Environmental Product Declaration (EPD) system and corresponding Product Category Rules (PCR) for construction products are most relevant and is summarised in Section 2.1.1. For TDP used in energy markets, the Australian Renewable Energy Agency (ARENA) Life Cycle Assessment (LCA) guidelines are most relevant and is summarised in Section 2.1.2. Notably, both methods allow for the use of waste products with zero burden as an input into a new product life cycle. That is, the environmental impacts of the waste product are allocated to the previous product life cycle, with zero impacts carried over into the new system.

2.1.1 Environmental Product Declarations (EPD) – construction products

An EPD is a report developed voluntarily to provide quality-assured and comparable environmental performance information about a product. The standards for developing EPDs follows the ISO 14040 methodology. The relevant PCR for EOLT and TDP end markets for construction products is *EN 15804:2012+A2:2019 (Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products)*.

EPDs can be used in several ways to benefit a product's design and marketability. With consumer's increasing attention on environmental and sustainability aspects of products, an EPD can indicate a company's focus on environmentally minded thinking, by highlighting the hot spots in the life cycle of the product and assisting the company to reduce impacts. An EPD can act as a benchmark against which to measure ongoing improvements and innovations in the environmental sphere.

Table 4 | Summary of relevant EPD guidelines EN 15804:2012+A2:2019 for construction products

	EPD for construction products

System boundary	Cradle to grave EPDs are grouped into the following life cycle modules:
	• A1-A3 Product stage (compulsory)
	    o A1 – raw material supply
	    o A2 – transport
	    o A3 - manufacturing
	• A4-A5 Construction process stage (optional)
	    o A4 – transport
	    o A5 – construction/ installation
	• B1–B7 Use stage (optional) [not included in this study]
	• C1-C4 End of Life Stage (compulsory)
	    o C1 – deconstruction and demolition
	    o C2 – transport
	    o C3 – re-use and recycling
	    o C4 – final disposal
	• D Benefits and loads beyond system boundary (compulsory)
	Cradle to gate EPDs can be done for certain exempt products (modules A1-A3).

Functional unit	As per ISO 14044, a Declared unit is used if a functional unit cannot be defined e.g., mass of cement which is incorporated into various products at different amounts with different functions.
Allocation rules for waste products and waste recycling	**Input waste products**: for input of secondary materials or energy recovered from secondary fuels, the impacts up until end-of-waste state should be allocated to the previous system. **Output waste products**: for waste flows leaving the system at the end of waste boundary of the product stage (Module A1-A3), the loads and benefits should be allocated as co-products. For waste at end-of-life stage (Module C1-C4), the system boundary should reach end-of-waste state if the recovered material has market demand. These secondary materials and fuels are then calculated as a benefit or load (Module D) to indicate the benefits of avoided use of primary materials. Note: End-of-waste state includes the processing of waste such as recovery or recycling processes.
Treatment of carbon flows	Biogenic carbon content needs to be separately declared for the product and packaging unless it is less than 5% of the product/packaging mass.
Reporting and review	A condensed EPD document with the LCA results and a product description are published on the EPD platform. The EPD needs to undergo third-party verification and is valid for 5 years after issue. A comprehensive LCA background report is required for verification but not published publicly.
Mandated impact categories will depend on the relevant PCR for the end product.	

2.1.2 ARENA Life Cycle Assessment – energy products

The ARENA was established to make renewable energy solutions more commercially competitive and increase renewable energy supply in the Australian market. It is a funding mechanism for renewable energy projects. This includes energy-from-waste initiatives, though it should be verified whether a particular application of TDPs would be included in this scope.

ARENA requires proponents to produce a LCA report for all funded bioenergy and biofuel projects, using their *Method and guidance for undertaking life cycle assessment (LCA) of Bioenergy Products and Projects (2016)* (hereafter referred to as the ARENA LCA Guideline). This Guideline is based on ISO 14040, 14044, ISO/TS 14067 and ISO 13065, with specific details included for Australian conditions, and was developed using an extensive stakeholder engagement process. The ARENA LCA Guideline is being used by some state environmental protection and planning agencies for new bioenergy and waste recovery projects and will be relevant if waste tyres are to be promoted as an alternative renewable fuel source.

The ARENA LCA Guideline requires a high-level *Proof of Concept LCA* to be produced for the first funding milestone, with a more comprehensive *Commercialisation LCA* to be produced as a final milestone deliverable.

Table 5 | Extract from ARENA LCA guidelines

	Proof of Concept LCA	Commercialisation LCA
System boundary	Cradle to gate	Cradle to grave
Functional unit	If product is readily substitutable with the reference fuel and combustion data is not available, a declared unit can be used e.g., 1MJ of fuel produced excluding conversion to energy.	Production of fuel and conversion to delivered energy.
Zero burden assumption for wastes	Materials that are wastes or co-products not fully utilised can be used without carrying any burden from the production system which produces them.	
Allocation rules for waste products and waste recycling	As per ISO 14044 LCA standard. Specifically: • Input waste products: Benefits and impacts of diverting utilised waste products from the current waste treatment system should be added in the system boundary (e.g., avoided landfill impacts), • Input co-products: if a co-product is a determining product in the bioenergy system, substitutes for each non-determining co-product should be subtracted from the impacts of the co-producing system. If the co-product is a non-determining coproduct, then a substitute for the material should be used as the impact for supplying the co-product, • Output co-products: products displaced by the co-product should be an environmental credit to the bioenergy system.	
Treatment of carbon flows	All flows of carbon between different carbon pools (atmosphere, fossil, biosphere) shall be included and documented separately in the inventory. These include emission from: • GHG emissions and removals arising from fossil and biogenic carbon sources and sinks, • GHG emissions and removals occurring as a result of direct land use changes, • GHG emissions and removals from soil carbon change, if not already calculated as part of land use change. A carbon balance is required after any allocation is applied to inventory data.	
Reporting and review	Summary report submitted to ARENA	Summary report and ISO 14044 compliant background report submitted to ARENA ISO 14044 compliant critical review
Impact categories		
Climate change	Mandatory	Mandatory
Fossil fuels resource depletion	Mandatory	Mandatory
Fossil fuel energy use (net calorific value)	Mandatory	Mandatory
Particulate matter formation	Optional	Mandatory
Eutrophication	Optional	Mandatory
Consumptive water use	Optional	Mandatory
Land use	Optional	Mandatory

The ARENA LCA guidelines provide additional guidance on the functional unit for different bioenergy and biofuel scenarios and a list of common reference systems that are comparable with these scenarios, which are easily extracted from the AusLCI database. Table 6 is an excerpt of the fuel sources that are equivalent to those from TDP.

Table 6 | Reference fuels and functional units for different bioenergy systems (ARENA LCA guidelines)

Bioenergy fuel source	Output	Application	Reference fuel	Functional unit
Biomass	Pellets	Cement kiln/ Industrial boiler	Coal combustion cement kiln/ Coal use in boiler	Combustion of 1 GJ of solid fuel in cement kiln/ industrial boiler
Bio-oil, syngas or biomethane	Advanced/renewable/"drop-in" biofuels including diesel, aviation kerosene and heavy fuel oil	Functionally equivalent to fossil-oil derived fuel product (chemically identical, fully miscible)	Petroleum product mix from fossil crudes	Production of petroleum products produced from 1 tonne of biocrude input

2.2 National Greenhouse Emission Reporting Scheme

It is important to distinguish between the methodologies of LCA and the National Greenhouse Emission Reporting (NGER) scheme. NGER was established as a national framework for the reporting of GHG emissions, energy production and energy consumption. NGER is relevant to TDP used as energy by Australian companies. It is mandatory for Australian corporations that meet a certain threshold to report their emissions and energy information annually under this scheme. NGERs only reports on GHG emissions, unlike the multi-impact indicator requirements of ARENA and EPDs.

In comparison to a full LCA, the system boundaries for NGER are often smaller. Emissions factors derived from NGER methods are likely to be lower than the equivalent figures taken from an LCA study or database. The default method for the calculation of emissions under the NGER is using specified emissions factors. These are published by the Australian government and are regularly updated to reflect improvements in emission estimation methods and in response to industry feedback. The published factors for EOLT combustion have been calculated by converting its total carbon content to a carbon dioxide emissions equivalent and correcting for biomass content and calorific value.

Table 7 | Extract from NGER scheme guidelines (NGER, 2008)

Issue	Details
System boundary	**Included**: Scope 1 emissions – emissions released to the atmosphere as a direct result of activities at a facility level. Scope 2 emissions – emissions released to the atmosphere from the indirect consumption of an energy commodity. Energy consumption and production – the extraction or capture of energy from natural sources for final consumption by the facility, and the use or disposal of energy from the operation of the facility. **Excluded**: Scope 3 emissions – emissions released to the atmosphere from indirect activities of the wider economy that are a consequence of activities of a facility but are from sources not owned or controlled by the facility's business.
Impact Categories	Greenhouse gas emissions measured in kilotonnes of carbon dioxide equivalence. This includes carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_20), sulphur hexafluoride (SF_6) and specified kinds of hydro fluorocarbons and perfluorocarbons.

The emissions factors provided by NGER are detailed in Table 8 and includes separate factors for both passenger tyres and truck tyres. These factors are lower than others within the solid fuel category due to the high biogenic carbon content of natural rubber (McGrath, 2021, TSA, 2020a). These factors show that the substitution of EOLT for coal as an energy source will reduce GHG emissions by approximately 30%. This presents an attractive case for EOLT as a potential energy source.

Table 8 | Energy content and adopted GHG emissions factors of fuels (NGER, 2023)

Fuel combusted	**Density**	**Energy content factor**	**Emission factor**			**Total GHG per unit of fuel**
			CO_2	CH_4	N_2O	
Solid fuel combustion		GJ/t	$kgCO_2e/GJ$			**kg CO_2e/GJ**
Bituminous coal	N/A	27.0	90.0	0.04	0.2	90.24
Brown coal	N/A	10.2	93.5	0.02	0.3	93.82
Coking coal	N/A	30.0	91.8	0.03	0.2	92.03
Coal coke	N/A	27.0	107.0	0.03	0.2	107.23
Industrial materials and tyres that are derived from fossil fuels, if recycled and combusted to product heat or electricity	N/A	26.3	81.6	0.03	0.2	81.83
Passenger car tyres, if recycled and combusted to produce heat or electricity	N/A	32.0	62.8	0.03	0.2	63.03
Truck and off-road tyres, if recycled and combusted to produce heat or electricity	N/A	27.1	55.9	0.03	0.2	56.13
Liquid fuels	kL/t	GJ/kL	$kgCO_2e/GJ$			kg CO_2e/GJ
Heating oil	1.238	37.3	69.5	0.03	0.2	69.73
Diesel oil	1.182	38.6	69.9	0.1	0.2	70.20
Fuel oil	1.110	39.7	73.6	0.04	0.2	73.84
Gaseous fuels	kg/m^3	GJ/m^3	$kgCO_2e/GJ$			kg CO_2e/GJ
Biogas (methane only)	0.717	0.0377	0.0	4.8	0.03	6.43
Landfill biogas (methane only)	0.717	0.0377	0.0	6.4	0.03	6.43
Natural gas	0.8	0.0399	51.4	0.1	0.03	51.53

3 EOLT Characteristics

3.1 Tyre Composition

Tyre composition will vary across tyre types and brands, so an average composition was derived for each tyre type from various international data sources (UN, 2002, ETRMA, 2013, L. S. Rodriguez et al., 2017, A Gursel et al., 2018, US Tire Manufacturers Association (USTMA), 2020, Continental, 2021, Shuman, 2021). This is summarised in Table 9.

Natural rubber is the main source of biogenic carbon in tyres. Most tyres also include small quantities of stearic acids (Rodriguez et al, 2017), but are considered to have minimal contribution to the overall environmental impact and have been excluded from Table 9.

Table 9 | Material composition by tyre (UN, 2002, ETRMA, 2013, L. S. Rodriguez et al., 2017, A Gursel et al., 2018, USTMA, 2020, Continental, 2021, Shuman, 2021)

	Passenger Tyre %	Truck Tyre %	Civil Engineering (incl construction) Tyre %
Natural rubber	18.4%	33.2%	39.7%
Synthetic rubber	26.5%	13.6%	16.2%
Carbon black / silica (fillers)	24.9%	23.0%	27.5%
Oils / antidegradants / resins	7.8%	3.3%	3.94%
Metal reinforcement	13.1%	22.4%	9.91%
Fabric (nylon / rayon)	5.3%	1.0%	0.36%
Zinc oxide	2.1%	2.1%	1.23%
Curing agents (sulphur etc.)	1.9%	1.5%	1.15%
Total	100%	100%	100%

The current assessment methods in Australia (ARENA and EPD) specify a zero-burden allocation of recycled waste materials, where all the burden is allocated to the first life cycle. In these instances, the emissions impacts of the new tyre materials do not have to be accounted for in the calculation of TDP impacts. As a result, the GHG emissions impact of the new tyre has not been quantified for the purposes of this study. Note this compositional data will be used to model the potential emissions impacts of landfilling EOLTs in section 7.2.1. This data also provides an indication of the potential yields from processing different tyre types.

Currently, passenger tyres are commonly destined for tyre derived fuels (TDF) due to their high fabric content. Not all processing facilities are able to remove the fibre reinforcements. As shown in Table 9, truck tyres have high steel content but negligible fibre reinforcement, which can be processed more easily and by more facilities as magnetic separation can be used. Passenger tyres also have a higher calorific value, and therefore are often preferred as TDF in kilns. Based on industry experience, truck tyres have been preferred as crumb rubber input into asphalt binders. The high natural rubber content has been attributed to improved modification of the binder and therefore improved overall performance (Austroads, 2022). However, preliminary findings from recent research has found that synthetic rubber offers greater resistance to degradation and have recommended a blend of both passenger and truck tyres, as long as metal and fibre content is reduced to a minimum (Austroads, 2022). This presents an opportunity to increase the recycling of passenger tyres into materials such as crumb rubber and granules.

3.2 Tyre Weights

Table 10 provides an indication of the range of tyre weights for the tyre types modelled. A uniform loss rate of 16% has been provided by TSA and applied for all tyre types. The material loss is assumed to apply for all tyre components except the metal reinforcement and fibre, as these components are not part of the tread. These figures also assume that the tread composition is representative of the whole tyre composition. The dimensions and weight of the EOLT will have an impact on the total tyres collected with each truck load.

Table 10 | Indicative tyre weights (TSA, 2022)

Tyre type	New tyre kg/unit	EOLT kg/unit	EPU Equivalent passenger unit
Passenger	9.50	8.00	1.00
Light commercial / SUV	14.25	12.00	1.50
Light truck	19.00	16.0	2.0
Truck	47.50	40.0	5.0
Forklift large (0.45–0.60 m)	57.0	48.0	6.0

4 EOLT Collection

4.1 Collection rates

For the purpose of this report, collection volumes include end-of-life tyres used for any application except onsite disposal, dumping or stockpiling. Tyres shredded and sent to landfill are included in collection volumes. Table 11 provides an indication of EOLT collection rates in Australia by tyre type for the 2018-19 financial year and more updated data will be available soon. A further breakdown of the fates of EOLT collection data is shown below in table 14. These figures illustrate that there are well established recovery streams for passenger and truck tyres, with over 90% of these tyres collected annually. This translates to a steady supply for utilisation in TDP. On the other hand, the majority of OTR tyres are not recovered, with 81% disposed onsite during the 2018-2019 financial year (TSA, 2020c). This is the largest pathway for EOLT tyres not currently recovered (TSA, 2020c) and an increased market for TDP could encourage these recovery rates to increase.

Table 11 | EOLT collection rate in Australia in 2018-19 (TSA, 2020c)

Annual average	Passenger Tyres (t)	Truck Tyres (t)	OTR (t)	Total (t)
Generated EOLT	190,100	157,700	117,600	465,400
Collected EOLT to recovery	169,500	139,900	13,200	322,600
Collected EOLT to landfill	18,500	12,200	4,200	34,900
Total collected by tyre type	98.9%	96.4%	14.8%	76.8%
% total collected EOLT	52.6%	42.5%	4.9%	100%

As Table 12 shows, about 96% of all recovered passenger tyres were exported, primarily as shred, in shipping containers to be used as tyre-derived fuel (TDF). A higher portion of truck tyres remain in the domestic market as its high natural rubber content is more suitable as rubber granules and crumb rubber. Since that report was written, the price of shipping containers has increased significantly for COVID-related reasons, thus increasing the price of exporting shredded tyres and reducing the financial viability of this TDP market (personnel communication, March 2022, TSA personnel). This will have impacts on the fate of EOLT, and is motivation to explore and encourage more non-truck tyre processing for domestic TDP markets. Passenger tyres have a high proportion of fibres which is more complicated to recycle into higher order products such as crumb rubber and granules due to requirements for specialist fibre-separating equipment.

Table 12 | EOLT end market by tyre type (TSA, 2020c)

End market	Passenger Tyres (%)	Truck Tyres (%)	OTR (%)
Domestic	4	34	1
Exported	85	55	10
Not recovered	11	11	89

4.2 EOLT collection process

The EOLT collection process is a well-established system of regular collections from tyre retailers. The tyres are manually packed onto trucks and transported either to a collection site or directly to the processing site. No packaging and little or no washing is required for the process market (personnel communication, March 2022, TSA personnel).

EOLT tyres are dropped off at processing facilities which conduct the primary shredding process in Melbourne, Sydney, Perth, Brisbane, Adelaide and Hobart. Processing shredded EOLT into smaller rubber granules and crumbs in a more specialised process and is only occurs at processing facilities in Sydney, Melbourne and Brisbane.

Through conversations with an Australian EOLT tyre collection company and TSA, it was determined that the collection routes and truck types used can vary significantly. EOLT tyres can be collected using a range of trucks based on availability, from a 4-tonne truck to a large towing trailer and each collection run can have multiple stops. Due to the high variation in collection distances and truck types, a range of truck types and distances have been modelled in Section 8.4 to illustrate the potential range of transportation impacts. Due to the bulky nature of tyres, the capacity of each truck is restricted by the volume of tyres. Routes are generally optimised to fill the truck close to the initial pick-up location. Moreover, the truck does not run empty on the journey to the collection point. The approximate capacity of different truck types is based on tyre volumes and summarised below based on information provided by the tyre collection company.

Table 13 | Approximate capacity of EOLT by truck type.

Truck Type	Approx. capacity*
<10t Truck	300 EPU
10-20t Truck	350 – 800 EPU
>20t Truck	1200 – 1500 EPU

*Note – each EPU is 8 - 9 kg, so 300 EPU is 2.4 – 2.7 tonnes.

5 Processing EOLT

5.1 Annual EOLT Processing Rates

The main processing technology to produce TDP from EOLT is physical deconstruction, with the initial output as shredded tyres, which are then further processed into crumbs and granules. An emerging technology is pyrolysis, with a market share in Australia of under 1%. Unfortunately, 23% of all EOLT are still not collected in 2018-19, mostly OTRs. Table 14 provides a breakdown of tyre types, EOL processing and fate for 2018-19.

Table 14 | EOLT tyres processing types and fate in 2018-19 (TSA, 2020c)

Process	Output	Application	Passen-ger (t)	Truck (t)	OTR (t)	Total (t)	% of total
Physical deconstruction	Shreds/whole	Exported, primarily as TDF for thermal energy use	160,900	86,500	11,500	258,900	56%
		For kilns / boilers / furnaces	0	0	0	0	0%
Physical deconstruction	Crumb and granules	Highly processed rubber products with a wide range of uses incl road construction, tile adhesive	5,800	27,000	100	32,900	7%
Physical deconstruction	Shred, crumb	Civil engineering applications e.g. construction of retaining walls or permeable pavements	900	1,100	1,100	3,100	1%
Retread	Casings & seconds	Re-treaded for reuse	1,500	24,900	0	26,400	6%
Pyrolysis	Pyrolysis	Carbon black, oil, syngas, steel	400	400	500	1,300	<1%
Landfill	Landfill	Legal landfilling sites, mostly in QLD where there was no landfill levy. QLD has since introduced a landfill levy and this figure should fall	18,500	12,200	4,200	34,900	7%
None	EOLT	Onsite disposal, dumping and stockpiles	2,100	5,600	100,200	107,900	23%
	Total		190,100	157,700	117,600	465,400	100%

5.2 Retreading

Retreading is an established market, has been well-researched previously and is out of scope for this report as it is not considered an EOLT.

According to TSA (2019), tyre retreading is where the existing tread of a worn tyre is buffed off and a new, pre-cured tread is bonded to the casing. This process allows tyres to be returned to service without compromising safety or quality. This is a common process used worldwide, particularly for aviation and commercial truck tyres. Unfortunately, the retreading of passenger tyres is generally not cost effective in Australia.

The retreading process can be repeated up to three times, to extend the lifespan of the original casing by up to an additional 500,000 km. Each retreading process only uses 1/3 of the oil required to manufacture a new truck tyre, using 26.5 litres compared to 83 litres for the average new truck tyre.

Unfortunately, the rate of truck tyre retreading in Australia has been declining over the last decade, due to competition from low quality, cheap truck tyres. However, it is important to consider the benefits to the local economy and the beneficial environmental outcomes that retreading provides. Expansion of the system boundary of the current study to include recovery pathways such as retreading and reuse has been identified for future work.

5.3 Physical Deconstruction

5.3.1 Process Description

Physical deconstruction is the most common fate of EOLT, with 63% of all EOLT processed into shreds (50-80 mm), granules (2-15 mm), fine rubber granules (<2 mm) and crumbs (<0.595 mm). The processing of EOLT initially involves size reduction, usually through physical shredding. This separates the rubber component from the non-rubber components such as steel and nylon, so they can be reprocessed or disposed of separately. Note that not all of the steel components are separated in the initial shredding step. Magnets are used in subsequent processing to remove the remaining steel. Most of the steel is removed in the initial process so for simplicity, modelling will assume only the initial steel removal stage.

The shredded rubber can then be used directly as TDF or processed into smaller sizes, each of which have different uses. Figure 2 provides an explanation of the processes and products that are produced. The use of rubber granules includes the creation of soft-fall surfaces for playgrounds and underlay and incorporation into infill materials for sporting facilities. Crumb rubber, at 30 mesh particle size (or <0.595 mm), is often used as a component in asphalt or as a substitute for polymer modified binders in road construction. Finer processing into crumbs and granules is more suited to truck tyres whereas passenger tyres are generally only used as TDF shreds due to the higher percentage of nylon fibres. However, the usage of passenger tyres is expanding due to improvements in processing technology and the finite supply of truck tyres.

5.3.2 System diagram

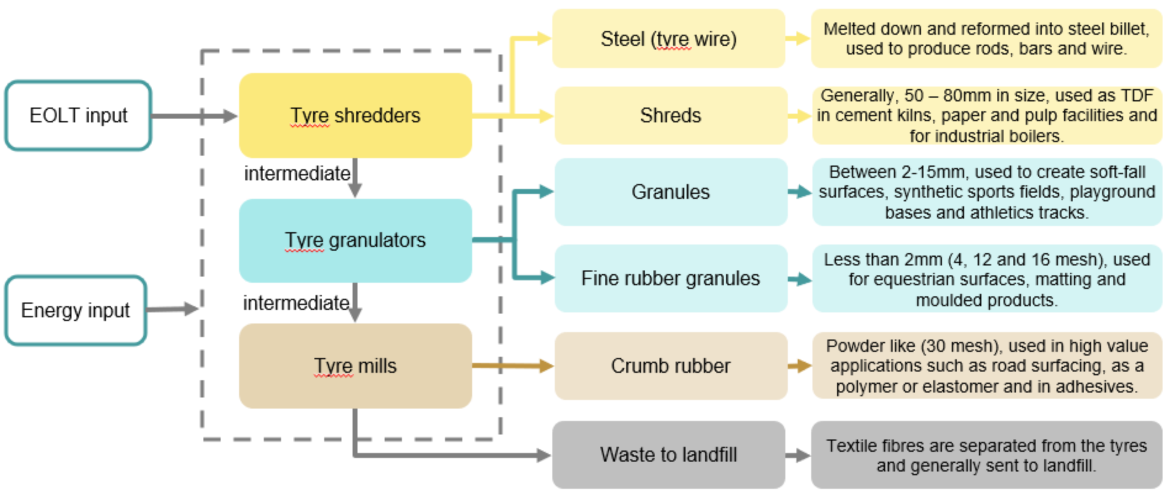

Figure 2 | Process diagram for the physical decomposition of truck tyres (adapted from Rouwette, 2020 and Matt et al., 2017)

Figure 2 is a generalised process diagram for physical deconstruction. Collected EOLT are put through tyre shredders to remove steel wire and create rubber shreds. The shreds can be used as TDF, and the steel scrap is sent to recyclers. The shredded tyres can undergo further processing through tyre granulators, creating various grades of granules. Further processing creates a powder called crumb rubber. Each of these processing stages requires additional energy per kg of product. There is therefore a trade-off between the added environmental impacts and processing costs and the opportunity for higher value applications.

5.4 Pyrolysis

Pyrolysis is an innovative technology with a great potential to be promoted, and is now in demonstration phase within Australia (TSA, 2018). Various pyrolysis technologies such as slow pyrolysis, fast pyrolysis, and flash pyrolysis differ significantly regarding residence time, temperature, flow rate, reactor geometry, and catalyst required, and many of them are currently at a pilot-scale (Al-Rumaihi et al., 2022). For example, several types of reactors including fixed, moving, fluidized and rotating beds are available in the market, while the fixed bed reactor is mainly used for processing waste tyres (Arya et al., 2020). The presence of catalyst results in lower liquid yields. Accordingly, the diversity in pyrolysis technologies and their operation principles including energy demand, and the variation of production distribution lead to a great uncertainty in GHG burdens (Roy and Dias, 2017).

A little investigation via LCA of pyrolysis process has landed in Australia. In this context, a preliminary analysis for the environmental impact of pyrolysis, relying on secondary data, was conducted based on different research, technologies, and markets. This exercise was conducted to give an insight into its potential utilisation, but the outcomes are yet to be confirmed aligning to Australian cases. As the pyrolysis technology for the commercial scale and specific end-markets are yet to be established in Australia (TSA, 2023), the scenarios for pyrolysis will be revised and reflected once the commercial maturity of pyrolysis technologies is confirmed.

5.4.1 Process Description

Pyrolysis refers to the heating in the absence of reactive gases such as air or oxygen. Tyres are a good candidate for pyrolysis as they break down at relatively low temperatures and produce usable outputs (Schandl, 2021).

Four end products are created through pyrolysis if the pyrolysis plant is using shredded tyres before material recovery – carbon black (also known as char), fuel oil, syngas and scrap steel. The process is highly energy intensive and releases pollutants (Buadit, 2020) and Table 15 shows the average output from a pyrolysis process using EOLT as the feed material.

Pyrolysis is an emerging processing method for EOLT recovery in Australia (Schandl, 2021, TSA, 2018), as there are a limited number of pyrolysis plants in operation, and they are mostly at the pilot or demonstration stage. Entyre, in Queensland, is the only plant processing significant quantities of EOLT in Australia (16,000 tonnes per year). Chip Tyre is another company in Queensland that is planning to commence commercial operations this year. Key hurdles include:

- High cost of plant,
- Distributed input material,
- Lack of consolidated markets to support economies of scale,
- Limited successful plants to base the process on, distance from supply and end-markets, and
- A lack of extended producer responsibility.

Plants are operating commercially in Europe where extended producer responsibility has underpinned the business case for the construction of plants. These markets also have stable EOLT supplies and end-markets for the outputs.

Table 15 | Average output from pyrolysis of EOLT and the market for these products (TSA, 2018)

TDP	Proportion of Output	End Market Use
Carbon black	30%	Rubber strengthening, new tyre production, fuel cells, plastic applications, coke in steel production etc.
Steel	15%	Scrap steel market
Oil	45%	Liquid fuel in industrial furnaces, power plants, boilers. Unrefined oil can be used as bunker oil.
Syngas	10%	Fuel for on-site electricity generation, however, generally will require further refinement as a natural gas substitute. Can instead be used to fuel the pyrolysis plant.

5.4.2 System diagram

There are three broad stages of pyrolysis.

1. Pre-treatment: Steel and fibre are separated from the rubber through shredding the EOLT into small pieces. If the pyrolysis plant uses TDF from shredding plants as the feed material, then it will already have had the steel removed and will be in small pieces.
2. Feed-in system: Small pieces of pre-treated tyres are loaded into a hopper, conveyor or cartridge system where they are fed into a reactor.
3. Heating in the reactor: Tyres are heated in the absence of oxygen. At lower temperatures, more liquid products are produced and at higher temperatures, more gaseous products are produced. Temperatures range from 400 – 1,200ºC.

Note that processes can vary significantly between processing plants and this will affect the overall environmental footprint of the pyrolysis derived products. For example, some plants are able to batch feed, and therefore take larger tyres.

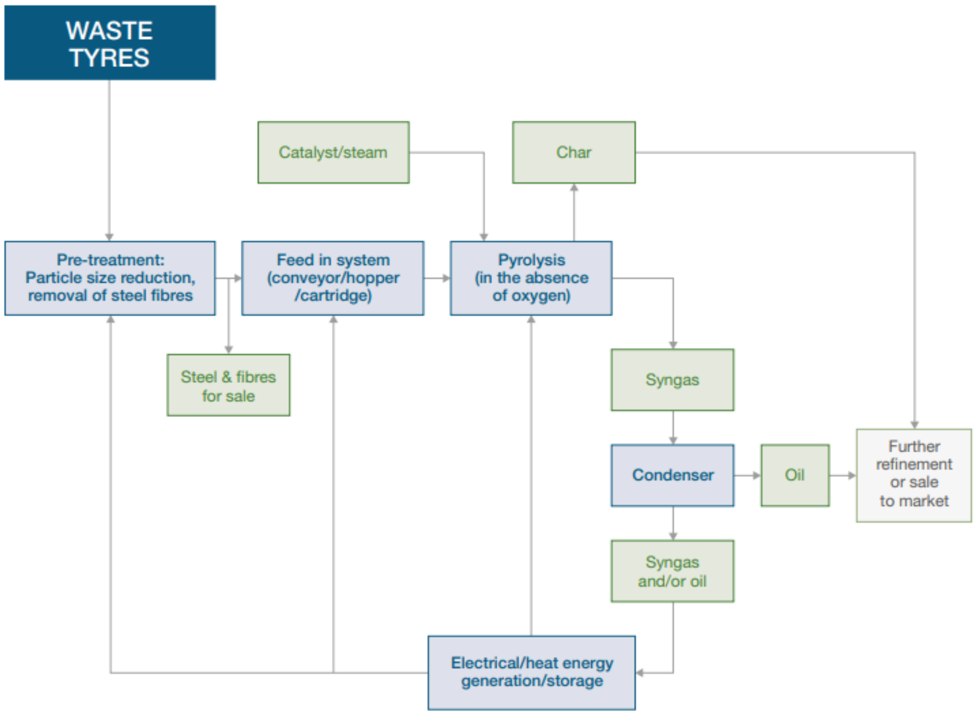

Figure 3 | Process diagram for pyrolysis (TSA, 2018)

5.5 Water Jet Deconstruction

Water jet deconstruction is an emerging technology with only one known processor in Australia working towards commercialisation of their operations. Thus far, there have not been any published LCAs on this process. As no data is currently available on the process, it has not been modelled in this report. A general overview of the current technology has been provided in this section.

5.5.1 Process Description

This is an emerging technique that takes advantage of ultra-high pressure water jet technology to pulverise the EOLT. The technique produces either rubber powder or granules and there are several companies globally that recycle tyres using this technique. Water jet deconstruction requires a high energy input to push water through a nozzle, generating ultra-high pressure water jets (Zefeng et al. 2018). The jets spray directly onto the surface of the tyres to pulverise the material and the resulting particles are filtered to remove any textile fibres and steel wires. Finally, the rubber powder or granules are dried and are then ready for reuse. The water is a closed loop system and is reused for the pulverisation process.

5.5.2 System Diagram

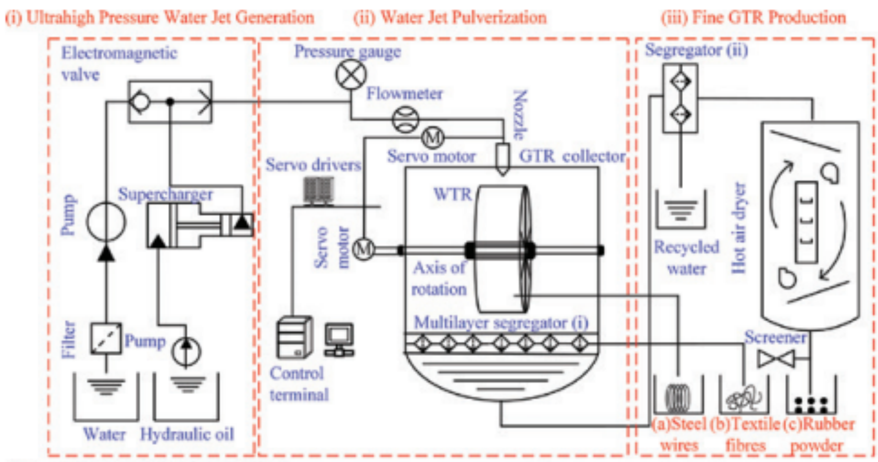

Figure 4 | System diagram for the water jet deconstruction process (Zefeng et al., 2018)

5.6 Devulcanisation

As with water jet deconstruction, devulcanisation is an emerging technology with only one known processor in Australia working towards commercialisation of their operations. As such, no data is currently available on the process and it has not been modelled in this report. A general overview of the current technology has been provided in this section.

5.6.1 Process Description

Devulcanisation converts EOLT back to a material that is similar to virgin rubber (Bockstat et al., 2019) and the process is not yet an economically viable. Vulcanisation involves the chemical formation of sulphur bonds with rubber, using agents such as sulphur groups, zinc oxide and stearic acid. The reverse step is therefore devulcanization, which again involves a chemical change. This breaks up the sulphur cross links to restore the properties of the initial rubber material.

There are several devulcanisation processes that have been researched and trialled, in two main categories – physical and chemical. Note that in both types, a chemical change still occurs in the rubber. The properties of the reclaimed rubber from each process will vary and, in some instances, will require blending with virgin rubber when used.

The key physical processes are:

- **Thermo-mechanical process** – uses mechanical shearing and temperatures of around 200°C.
- **Mechano-chemical process** – uses a combination of mechanical shearing, high temperatures and chemical reactions using chemical agents such as zinc chloride or pentachlorothiophenol.
- **Grinding** – pre-treatment through cryo-mechanical process is required to ensure particle homogeneity. This is where small pieces of crumb rubber are immersed in liquid nitrogen and then transferred to mill to be ground into finer particles. The tyre pieces then undergo mechanical grinding in either dry or wet conditions.

- **Microwave method** – carbon-carbon bonds are broken down using a specific frequency and energy level of microwave radiation.
- **Ultrasonic method** – mechanical waves at high frequencies are used to stress the tyre and create cavitation bubbles that produce enough energy to break the carbon-sulphur and sulfur-sulfur bonds in the material.

The key chemical processes are:

- **Organic disulphides and mercaptans** – involves several reaction steps and addition of heat to separate the rubber.
- **Catalysts, inorganic and sulphur free organic compounds** – the sulphide bonds are split using molten sodium at high temperatures in anaerobic conditions.
- **Solvents** – EOLT are mixed with a blend of solvent liquids and heated at moderately high to high temperatures to convert the EOLT into an oil or gas.

6 LCA Introduction and Method

6.1 Goal and Scope

6.1.1 Goal

The goal of this LCA study is to quantify the GHG emissions of EOLT and the processing of EOLT into products for the TDP end market, including rubber shreds, granules, and crumb rubber. The study also aims to identify the potential benefits associated with these products when compared to conventional applications. The outcomes of this study are intended to assist with initial decision making for tyre recyclers and TDP procurers.

6.1.2 Scope

The end market scenarios included in this study represent some of the common TDP end markets in Australia, while emerging technologies and corresponding TDPs are out of scope. Note this is not an exhaustive list and the use of EOLTs in TDP markets will continue to evolve as the innovative technology and use cases arise. Table 16 outlines the scenarios selected as key TDP markets to include in the detailed assessment of GHG emissions and the functional unit used to compare the conventional product with the TDP alternative. The conventional products were chosen in consultation with TSA and was based on industry experience and validated with EOLT processors and TDP manufacturers where relevant.

The following factors in particular have been considered beyond the material processing impacts:

- The impact of additional processing required at the installation life cycle stage of TDP compared to conventional products, such as additional energy requirements or GHG emissions released.
- The impact of enhanced performance of TDP products during the use life cycle stage.
- Any potential GHG benefits of displacing conventional materials.

This study only refers to the impacts of the two most commonly processed tyre types, namely passenger/car and truck tyres. Off-the-road (OTR) have been excluded from this study as there is high variation in recovery pathways due to the size and location of the tyres. Quantification of the embodied emissions of OTR recovery has been identified for future work. However, OTR tyres used for construction/civil engineering have a similar recovery pathway and composition to truck tyres and are expected to have similar impacts. Subsequent references to EOLT in this report therefore refer only to passenger and truck tyres.

Table 16 | TDP end market scenarios modelled and functional units.

	Use case	TDP	Conventional Product	Functional Unit	System Boundary
Scenario 1	Default	N/A	Landfill of EOLT	1 t of EOLT	N/A
Scenario 2	Road construction	Crumb rubber binder in asphalt for road construction, using a wet process to incorporate	Polymer modified binder (PMB) in asphalt for road construction	1 km of road	Cradle to gate
Scenario 3	Road construction	Crumb rubber binder in asphalt for road construction, using a dry process to incorporate	Polymer modified binder (PMB) in asphalt for road construction	1 km of road	Cradle to gate
Scenario 4	Sprayed seal	Crumb rubber binder in sprayed seal mix	PMB in sprayed seal mix	1 t sprayed seal	Cradle to gate
Scenario 5	Concrete	Crumb rubber in concrete mix	Conventional concrete mix	1 m^3 of concrete	Cradle to gate
Scenario 6	Concrete	Rubber granules in concrete mix	Conventional concrete mix	1 m^3 of concrete	Cradle to gate

	Use case	TDP	Conventional Product	Functional Unit	System Boundary
Scenario 7	Permeable pavement	Rubber granules in permeable pavement	Conventional permeable pavement	1 m^2 of paved surface	Cradle only
Scenario 8	Combustion	Shredded rubber used in coal co-combustion at a cement kiln	Coal-derived fuel for combustion at a cement kiln	1 MJ of energy	Cradle to gate
*Cradle to gate includes raw material extraction, transport of materials and manufacture of product. Cradle refers only to raw material extraction. Scenarios cannot be compared different functional units and systems boundaries are used.					

6.1.3 Functional unit

The functional unit is a measure of the function of the studied product system, providing the baseline reference to which the inputs and outputs of each system can be compared.

In the analysis of end market products, it is relevant to use a reference unit which relates to the function of the product in that market, particularly for energy products. Table 16 summarises the functional units chosen for each of these scenarios. This provides a product perspective of the benefits of each application. From a waste benefit perspective, values can be converted to 1 tonne recovered EOLT using the density or calorific value of the TDP, for example 32 GJ/t for passenger tyres and 27.1 GJ/t for truck tyres (McGrath, 2021).

6.1.4 System diagram and boundary

Figure 5 provides a summary of the general life cycle of a tyre from cradle to grave, with a particular focus on the processes involved in handling EOLTs and the end markets they can replace. The figure shows the system boundary included in this study, which starts with the collection and transport of the EOLT and ends with TDP end uses such as road construction as an asphalt aggregate or binder. As mentioned in section 1.2.1, the system boundary of this study only includes passenger and truck tyres. For the purposes of this report, truck tyres include construction tyres such as forklift and industrial tyres. These tyres have the same recovery pathway as truck tyres, with no specialist equipment required for processing. While these tyres have a higher component of natural rubber, the life cycle inventory data presented presents the average processing yield which would take this into consideration.

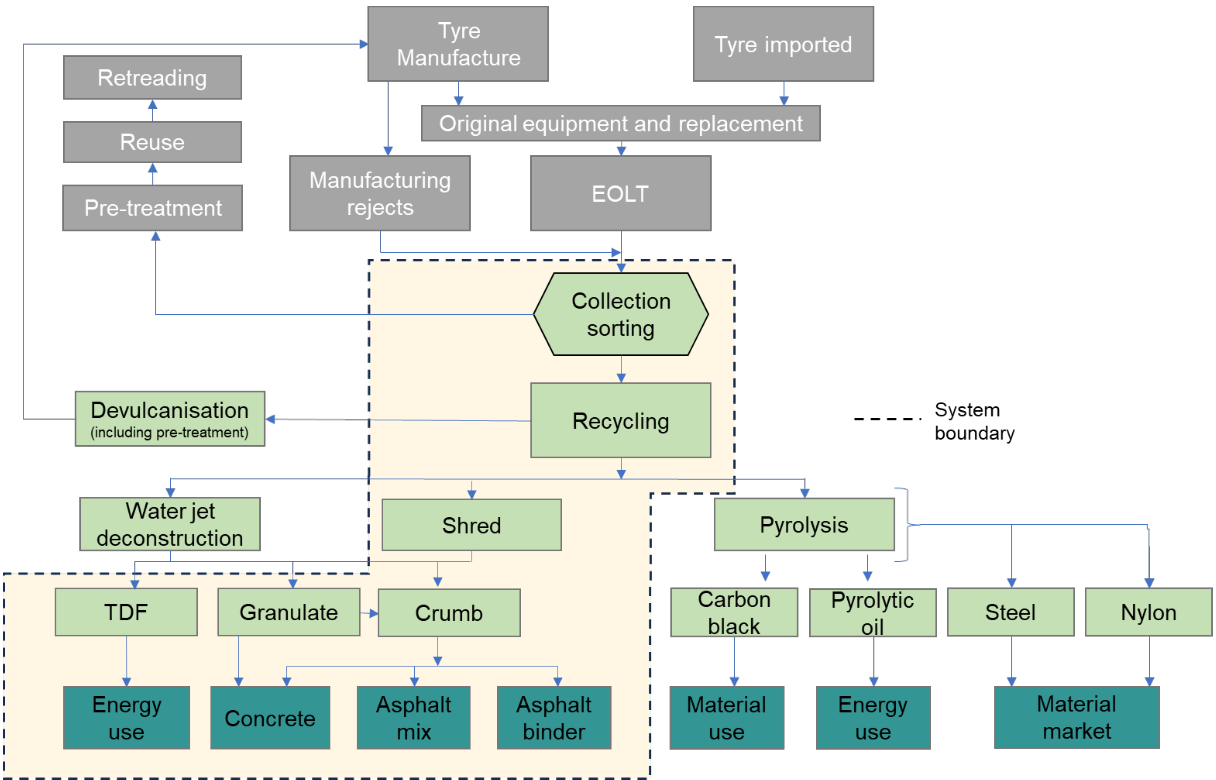

Figure 5 | Process flow and system diagram for EOLT recycling, showing system boundary for current assessment.

6.1.5 Geographic and Temporal Coverage

The intended geographical scope is Australia. The time reference is year 2022, with the data sourced to reflects current technology and energy mixes.

6.1.6 Limitations of the study

Note that the scenarios modelled represent specific applications of TDPs. TDPs can potential be used in a broad range of applications that are not limited to these scenarios. Furthermore, the environmental impacts modelled by these scenarios only represents a potential impact, the actual impact will vary based on specific processing plants and other factors. The EOLT recycling industry is continuing to innovate, and with that, there will be constant changes in processing and end market technologies.

Data was based on a combination of data sourced from current industry practices and from publicly available third-party sources. The publicly available data is limited and therefore the results need to be considered with the assessed data quality in mind. The data quality assessment is found in Table 19.

The intention of this study was to provide an indication of the potential range environmental impacts of TDP applications and as such only major material components and a reasonable use case was modelled. For example, for scenario 2 and 3, generic asphalt mixes were used based on AustRoads specifications. For specific asphalt mixes available on the market, specific EPDs and LCA studies should be referenced.

6.2 Project assessment methodology

6.2.1 General modelling process

The following steps provide a broad overview of the modelling process used.

1. Define the TDP and conventional product.
2. Consider appropriate system boundary:
    - Cradle - raw material supply only.
    - Cradle to gate – product stage only – raw material supply, transport of materials and the manufacturing of the product.
    - Cradle to gate plus construction stage – as above, plus transport to site and construction/installation process.
    - Cradle to grave – as above, plus use stage (such as usage, maintenance, repair, replacement, refurbishment, and operational utilities), end-of-life stage (such as demolition/deconstruction, transport to waste processing site, landfill/recycling processing) and any benefits or loads beyond the system boundary (such as the recycling potential).

   The decision should factor in whether data is available for each stage and whether modelling the additional stages will provide additional insights into the benefit or detriment of the compared systems.
3. Consider performance benefits of the TDP compared to conventional product and incorporate in the functional unit.
4. Confirm any additional manufacturing inputs required for the TDP compared to the conventional product (if modelling construction/installation impacts).
5. Collect inventory data on the additional materials and other inputs required, utilising the EOLT processing results as the raw material input for the TDP component.
6. Model in Simapro, following LCA principles, using the impact assessment methodology consistent with the EPD method used for midpoint impact categories. Adjust the impact assessment methodology as required if the assessment is for the purpose of other regulatory schemes.
7. Review and report on results.

6.2.2 Environmental impact quantification

The LCA method used in the assessment of environmental impact for this project was developed to comply with ISO 14040:2006 and ISO14044:2006+A1:2018, which describe the principles, framework, requirements, and provides guidelines for life cycle assessment (LCA) (ISO, 2006; ISO, 2018).

The life cycle model was created in a leading LCA software tool, SimaPro. SimaPro is a platform that links LCA background databases with environmental impact assessment methods, making it possible to calculate impacts from an inventory model. In line with EPD and ARENA methodologies, we have considered recycled materials in the next life cycle as free of embodied emissions from the previous life cycle. This means that only the collection and processing of EOLTs are inputs into its next product life cycle. While this encourages the use of recycled materials as an input material, it should be noted that there may be requirements to use other reporting methods for certain use cases. The figures reported in this report should be interpreted in this light.

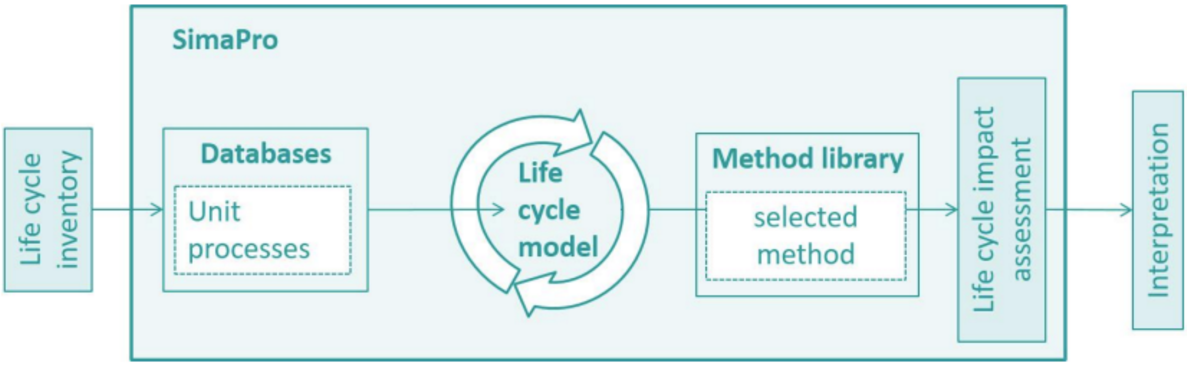

Figure 6 | Use of SimaPro in LCA.

Several other impact categories, including water scarcity, have been included in this study. These are summarised in Table 17. These categories have been identified to likely have some impact within the EOLT recovery pathway and have therefore been included. It is acknowledged that TDP products may have broader environmental benefits or detriment beyond these impact categories. However, these impacts have not been considered within the scope of this study.

Table 17 | Life cycle impact categories, measurement units and methods used in this study.

Impact Category	Description	Measurement Unit	Assessment Method and Implementation
Global warming potential (fossil) (GWP fossil)	Estimates global warming potential (GWP) of GHG emissions resulting from the oxidation or reduction of fossil fuels or fossil carbon substances.	kg CO_2 eq.	Baseline model of 100 years of the Intergovernmental Panel on Climate Change (IPCC) based on IPCC 2013
Global warming potential (biogenic) (GWP biogenic)	Estimates the GWP of GHG emissions resulting from biomass.	kg CO_2 eq.	Baseline model of 100 years of the IPCC based on IPCC 2013
Global warming potential - Land use and Land use change (GWP land use)	Estimates GHG warming effect for land use and land use change.	kg CO_2 eq.	Baseline model of 100 years of the IPCC based on IPCC 2013
Global warming potential – Total (GWP total)	Estimates the total GHG warming effect. This is a sum of the GWP fossil, GWP biogenic and GWP land use categories.	kg CO_2 eq.	Baseline model of 100 years of the IPCC based on IPCC 2013
Eutrophication, terrestrial	Estimates the potential increment of nutrients in land.	mol N equivalent	Accumulated Exceedance, Seppälä et al. 2006, Posch et al.
Ecotoxicity, freshwater	Estimates the potential impact on fresh water ecosystems, as a result of emissions of toxic substances to air, water and soil.	CTUe	USEtox
Water scarcity	Estimates the potential of water deprivation, to either humans or ecosystems, and serves in calculating the impact score of water consumption at midpoint in LCA or to calculate a water scarcity footprint as per ISO 14046.	m^3 equivalent deprived	Available WAter REmaining (AWARE) Boulay et al., 2016
Resource use - fossil	Estimates the impact on fossil fuels reserves.	MJ	CML (v4.1)

A key metric for both producers and consumers in TDP markets is GHG emissions. The GHG emissions quoted in this report refers to ‘Global warming potential – Total’ in Table 17 below. The calculated GHG emissions has been split into three sub-categories, fossil, biogenic and land use. Biogenic GWP impacts refer to the embodied carbon in biomass that continues to be stored in a product over time. Typically, the biogenic carbon for new tyres are negative due to the use of natural rubber. Natural rubber absorbs GHG when the rubber tree grows and is captured within the product when extracted from the tree and used. This biogenic carbon (in the form of CO_2) is released when the product decomposes or is combusted. This is a neutral process that represents the natural carbon cycle. Therefore, both the biogenic carbon uptake and the biogenic carbon release has been excluded. This impacts scenario 1 (landfill) and scenario 11 (combustion in cement kilns). Note that there may still be biogenic GWP impacts, from the release of other GHGs such as methane. Appendix B provides details of the calculation.

6.2.3 Allocation considerations

Allocation is an important consideration in LCA, to partition the input and output flows of a process to the appropriate product system. This occurs in situations where there are multi-input and/or output process that are shared with other product systems. Allocation is also important in situations where materials are shared between primary and secondary life cycles, such as with recycled materials. In the case of EOLTs, these situations arise in the following scenarios:

- Co-product allocation – in physical deconstruction processes, the EOLT is processed to produce rubber (shreds, granulates and crumb rubber), textile fibres and steel/iron scraps.
- Recycled materials - the EOLT tyre is recycled to produce TDP for subsequent product markets.

Co-product allocation within a life cycle

The ISO 14040 and 14044 standards for LCA provide some guidance on how allocation occurs. The standards provide that where possible, allocation should be avoided. This can be achieved by disaggregating processes and allocating input and output data to these sub-processes; or by expanding the product system to include the functions of the co-products. In the case of physical decomposition for shredded and granulated rubber, it was possible to separate the processing inputs between tyre shredders and tyre granulators to avoid allocation considerations. In comparison of end markets, allocation was avoided by expanding the system boundary to tyre-derived products, compared to the equivalent conventional end product.

Where allocation cannot be avoided, allocation is either determined through physical relationship or economic value. For this study, allocation to each output was based on economic value. Economic allocation uses the market rate of each product to apportion the material impacts. This was applied for the allocation of processes to crumb rubber. The detailed economic allocation factors used are detailed in the inventory section, in section 7.1.2.

Allocation of recycled materials between life cycles

Where a material is to be recycled into a new product or is recycled material from a product, the impacts of production, disposal and recycling of the materials need to be allocated. There are a number of commonly used methods – cut-off approach, end-of-life recycling approach and the Product Environmental Footprint (PEF) framework (Hermansson, 2022). In the cut-off approach, the impacts of raw material extraction, processing and manufacturing are allocated to the product where the primary material is used, with the impacts of recycling including collection and processing assigned to the product where the recycled material is used (Hermansson, 2022). This is aligned with the rules designated by EPDs and ARENA LCAs. This is the approach that has been followed in this study, given its alignment with common LCA applications in Australia. As such, the processes related to the extraction of raw materials, the manufacturing of new tyres and the use of new tyres has been excluded.

It is worth noting the other methods commonly used for allocation. The allocation of impacts can potentially change as the uptake of recycled materials changes. The end-of-life recycling approach provides that the impacts of recycling are assigned to the product generating the material for recycling – i.e. the new tyre life cycle (Hermansson, 2022). A recycling credit is assigned to account for the avoided primary material production. In the PEF framework, a proportion of the impacts arising from the new tyre can potentially be apportioned between the two life cycles. The impacts of recycling and a credit for the avoided materials are apportioned between the two product life cycles. The allocation reflects the quality losses during the recycling process, and the supply and demand for the recycled material. The allocation factor is selected based on the market price of the recycled material compared to the primary material, with the allocation set at a 50% split where the market situation is balanced or unknown (European Commission, 2019).

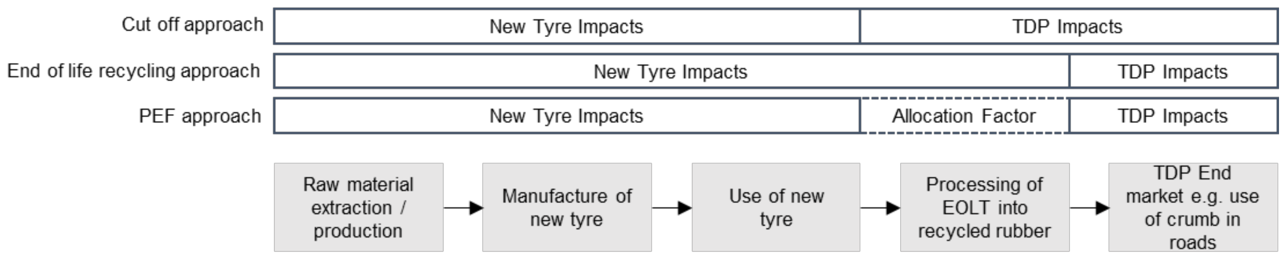

Figure 7 | Illustration of process allocation between life cycles for commonly used LCA methodologies.

6.3 Data quality and validation

Data used for the purposes of modelling was selected based on the following criteria:

- **Time coverage:** the data collected represents recent practice for the construction of the project.
- **Geographical coverage**: the data collected are representative of the sourcing of materials, whether from Australia or overseas, and are in line with the goal of the study.
- **Technical coverage**: the data collected represents the specific technology or technology mix used in the production of the product inputs and outputs.

The following principles were also considered in selecting data sources:

- **Relevance:** select sources, data, and methods appropriate to assessing the chosen product's LCI.
- **Completeness:** include all LCI items that provide a material's contribution to a product's life cycle emissions.
- **Consistency:** enable meaningful comparisons in life cycle impact assessment (LCIA) information.
- **Accuracy:** reduce bias and uncertainty as far as is practical.
- **Transparency:** when communicating, disclose enough information to allow third parties to make decisions.

Table 18 summarises the data quality assessment matrix applied in the selection and evaluation of data sources. For any background data, the quality was considered very good when processes chosen were geographically, temporal, and technologically relevant as shown in Table 18. For data that was based on assumptions, quality was considered fair, unless based on official reports.

Table 18 | Data quality assessment scheme[1]

Quality	Geographical representativeness	Technical representativeness	Temporal representativeness
Very good	Data from area under study	Data from processes and products under study. Same technology applied as defined in goal and scope (i.e., identical technology)	Less than 3 years difference between the reference years according to the documentation and the time period for which data are representative.
Good	Average data from larger area in which the area under study is included	Data from processes and products under study with similar technology. Evidence of variations in state of technology, e.g. different by-product.	Less than 6 years difference between the reference year according to the documentation and the time period for which data are representative.
Fair	Data from area with similar production conditions	Data from processes and products under study but from different technology. This score is applied when no technology is specified.	Less than 10 years difference between the reference year according to the documentation and the time period for which data are representative.
Poor	Data from area with slightly similar production conditions	Data on related processes or products.	Less than 15 years difference between the reference year according to the documentation and the time period for which data are representative.

Very poor	Data from unknown or distinctly different area (North America instead of Middle East, OECD-Europe instead of Russia)	Data on related processes or products but with a different scale or from different technology.	Age of data unknown or more than 15 years difference between the reference year according to the documentation and the time period for which data are representative.

Foreground data was based on third party sources from Australian EOLT processors and TDP manufacturers and from industry and academic literature. For any background data, the Australian Life Cycle Inventory (AusLCI) database was used, which includes representative practices of Australian industries and energy mixes. Where unavailable, ecoinvent v3.8 was used. ecoinvent is a world leading database and contains several thousand Life Cycle Inventory (LCI) datasets. The data sources and their assessed quality are detailed in Table 19. Overall, the quality of the data is said to be 'Good'.

Table 19 | Data source and quality

		Data quality assessment		
Stage	**Data source**	**Geographic**	**Technical**	**Temporal**
Collection	Assumption based on industry practices	Very good	Good	Very good
Processing - crumb rubber	Literature, adjusted for Australia	Good	Good	Good
Processing - granules/shred	Data averaged from three Australian tyre recyclers	Very good	Very good	Very good
Scenario 1 - landfill	Background databases	Good	Good	Good
Scenario 2 and 3 – road	National specifications for inputs and published data for construction	Very good	Good	Very Good
Scenario 4 – sprayed seal	National specifications for inputs, background database for construction	Very good	Good	Very Good
Scenario 5, 6 - concrete	Background database for conventional product and manufacturing	Good	Good	Good
Scenario 7 - pavements	Inputs provided by Australian producer, background database for conventional product and production	Very good	Good	Good
Scenario 8 – cement kiln	Literature, adjusted for Australia	Fair	Fair	Poor

6.3.1 Cut-off rules and Exclusion of Small Amounts

It is common practice in LCA/LCI protocols to propose exclusion limits for inputs and outputs that fall below a threshold percentage of the total, but with the exception that where the input/output has a "significant" impact it should be included. Exclusion of small amounts in background data used in this study follows the standard approach of *ecoinvent* modelling.

For foreground data, exclusions were based on the following system boundary settings:

- Environmental impact from capital equipment and buildings that are not directly consumed in the production process are not accounted for in the LCI. Capital equipment and buildings typically account for less than a few percent of nearly all LCIs. For this project, it is assumed that capital equipment makes a negligible contribution to the impacts as demonstrated by previous studies (Frischknecht, 2007).
- Personnel-related impacts, such as transportation to and from work, are also not accounted for in the LCI. The impacts of employees are excluded on the basis that if they were not employed for this production or service function, they would be employed for another. It is also difficult to accurately determine the proportion of the overall employee's impacts to allocate to their employment.

6.4 Third party verification

This study intends to support comparative assertions intended to be disclosed to the public. Life cycle assessments (LCA), as with all scientific work, requires significant judgement from the LCA practitioner to justify the assumptions and therefore the outcomes of the work. It is therefore difficult to have objective criteria for the quality of the LCA and the judgement of peers becomes the ultimate quality assurance for the work conducted. This ensures credibility when communicating the results of a LCA study. As such, ISO 14040 requires that a mandatory critical review is conducted "for any LCA studies used to make a comparative assertion that is disclosed to the public" and is optional in other circumstances. This report has been submitted for verification in compliance with these standards. The report has been verified by certified LCA practitioner Paul-Antoine Bontinck (certification number 2021-671).

7 Life Cycle Inventory

Life cycle inventory (LCI) data quantifies each input and output required for a defined process. This section describes the data, data sources and assumptions used for each modelled scenario. Background unit processes for all inputs and outputs are provided in Appendix A.

7.1 Collection and Processing Data

Table 20 provides the detailed assumptions for the collection and processing of EOLTs in each TDP scenario. The assumptions have been derived in consultation with TSA, based on industry knowledge and confirmed from conversations with Australian EOLT processors. Recall that EOLT shredding occurs in all states but crumb rubber, and rubber granules occur in limited locations. For modelling purposes, it has been assumed that the costs of interstate collection are too prohibitive and therefore the supply of EOLT is limited to urban and regional collection within the state. The material itself is considered zero burden, as per EPD and ARENA guidelines. This means that only the collection and processing inputs and outputs are included in the calculation of footprint of each scenario.

Note there were two data sources reflecting the physical processing of EOLTs into crumb, granules and shred – a study commissioned by TSA entitled *Life Cycle Inventory (LCI) of secondary rubber products* (Rouwette, 2020) ("TSA study") and an LCI published by the Australasian EPD programme for asphalt mixes (AEPD, 2019) ("Asphalt PCR"). Both studies provide LCI data for the processing of EOLTs into crumb rubber. The LCI data from the Asphalt PCR (Table 21) was used in scenarios where crumb rubber is required as it has been peer reviewed and verified. The following scenarios use the LCI provided in the TSA study (Rouwette, 2020):

- Scenarios 6 and 7, where granulated rubber is used as a substitute for gravel. The TSA study models a coarser grade rubber granule and is therefore a more appropriate alternative compared to the finer grade rubber granules modelled by the Asphalt PCR.
- Scenario 8, where shredded rubber is used as a fuel. The Asphalt PCR does not split the processing into a shredded product which is suitable as a fuel.

Table 20 | Modelling assumptions for the collection and processing of EOLT into a material for TDP

	Shredded rubber	Rubber granules	Crumb rubber
Applicable scenarios	Scenario 8	Scenarios 6 and 7	Scenarios 2, 3, 4 and 5
Raw material	EOLT (zero burden)	EOLT (zero burden)	EOLT (zero burden)
Collection distance (Pick up to Processing)	Distance: 50% collected in 50 km (urban), 50% collected in 200 km (regional)	Distance: 50% collected in 50 km (urban), 50% collected in 200 km (regional)	Distance: 50% collected in 50 km (urban), 50% collected in 200 km (regional)
Collection truck type	40 t truck	40 t truck	40 t truck
Processing data source	TSA study (Rouwette, 2020)	TSA study (Rouwette, 2020)	Asphalt PCR (AEPD, 2019)

7.1.1 Collection

As discussed in section 4.2, the collection of EOLTs is limited by volume due to the bulky nature of tyres. For simplicity, we have assumed a 40 t truck for collection with a carrying load of 1500 EPU. This translates to a weight of 12-13.5 tonnes, translating to an average 30% of total weight capacity. As it is most cost effective to maximise load at the closest point of collection, a full load has been assumed. The journey from depot to the collection point has been excluded on the basis that it does not run empty and is often used for other purposes.

7.1.2 Crumb Rubber and Fine Rubber Granules

The following LCI data was produced by the Australian Flexible Pavement Association (AfPA) and start2see and published by the Australasian EPD Programme (AEPD). It was published in the PCR for the EPD of asphalt mixtures ('Asphalt PCR') to ensure consistent LCA outputs between product manufacturers. It was based on a US study by Corti and Lombardi in 2004 and adjusted for the Australian context. Note that in this process, EOLT is processed directly into ground rubber and crumb rubber, without a separate shredding process. Economic value and allocation factors were included in the publication and used for this study.

Table 21 | LCI for 1 tonne crumb rubber in asphalt mixtures (AEPD, 2019)

Category	Process	Unit	Amount
Inputs			
Raw Material	EOLT, at tyre recycling plant	tonne	1.0
Material	Tap water	kg	149.97
Material	Steel	kg	0.44
Energy	Electricity from grid	kWh	1095.4
Energy	Lubricating oil	kg	0.019
Outputs			
Product	Crumb rubber (<0.7mm), at tyre recycling plant Co-product allocation: 66% (approx. $650/t)	tonne	0.46
Product	Fine rubber granules (<2 mm), at tyre recycling plant Co-product allocation: 28% (approx. $550/t)	tonne	0.23
Product	Iron scrap, at tyre recycling plant Co-product allocation: 6% (approx. $100/t)	tonne	0.28
Product	Nylon fibres from waste tyres Co-product allocation: 0% (approx. $0/t)	tonne	0.043
Emissions to air	Particulates, <2.5 um	kg	0.19
Wastewater	Sewage, to treatment plant	kg	149.97

7.1.3 Shreds and Granules

The following 3 tables represents the tyre shredding, granulating and milling processes respectively. This has been sourced from three Australian tyre recyclers and completed by Rob Rouwette, as commissioned by TSA (Rouwette, 2020). It provides a representative sample of Australia's EOLT recycling industry ('TSA study'). EOLTs are shredded in tyre shredders, the output is then forklifted to tyre granulators to be processed into granules and the granules are then forklifted to tyre mills to be processed into crumb rubber. In this instance, the author has applied a 100% allocation of the impacts to the shredded rubber process and 0% to the steel scrap output. The reasoning behind this is that TDF can sometimes have a negative value, where recyclers pay to dispose of the product, such as to landfill. The steel scrap is sold to steel recyclers for economic value. In the case where the TDF value is negative, the EOLT recycling processes should be assigned to the product system that has generated the waste. If the shredded rubber undergoes further processing into granules (as in Table 23), this has a positive value, and the impacts of processing should be assigned to the end market products.

Table 22 | Life cycle inventory for conversion of 1 tonne EOLT into shredded rubber in a tyre shredder (Rouwette, 2020)

Category	Process	Unit	Amount
Inputs			
Raw Material	EOLT, at tyre recycling plant	tonne	1
Energy	Electricity from grid	kWh	21
Energy	Diesel	L	2.1
Energy	LPG	kg	0.62
Outputs			
Product	Shredded rubber, at tyre recycling plant Co-product allocation: 100%	tonne	0.74
Co-Product	Steel scrap, at tyre recycling plant Co-product allocation: 0%	tonne	0.26

Table 23 | Life cycle inventory for conversion of 0.737 tonne shredded rubber from 1 tonne EOLT input into rubber granules in tyre granulator (Rouwette, 2020)

Category	Process	Unit	Amount
Inputs			
Raw Material	Shredded rubber, at tyre recycling plant	tonne	0.74
Energy	Electricity from grid	kWh	92.85
Energy	Diesel	L	2.18
Energy	LPG	kg	0.62
Outputs			
Product	Rubber granules (<15mm), at tyre recycling plant	tonne	0.70
Waste	Nylon fibres from waste tyres	kg	0.037

7.2 End Market Data

7.2.1 Scenario 1: Landfill of EOLTs

Scenario 1 investigates the environmental impact of the default scenario where EOLT are disposed of in a landfill. Landfill is problematic as degradation occurs in an anaerobic environment, leading to the production of methane.

This scenario includes the transport to landfill and landfill operations. Landfill impacts are based on the composition of the tyres provided in Table 9, with the biomass within the tyres likely to decompose. It is assumed that natural rubber will decompose, but the remaining materials are inert in landfill. A 16% loss factor has been applied, which excludes the metal reinforcement and fibres. The material quantities are summarised in Table 24. Note the emissions factors used to estimate these emissions are based on National Inventory Report factors, derived from IPCC recommendations. It assumes managed sanitary landfill conditions, and includes electricity and diesel for waste handling, a portion of facility construction and any emissions to air and water where relevant for the material type. As discussed in section 6.2.2, biogenic CO_2 attributed to the degradation of natural rubber has been excluded from the results.

Table 24 | Material decomposition in landfill for each tyre type, for 1 tonne of EOLTs.

Material	Landfill process	Passenger tyres (t)	Truck tyres (t)
Natural rubber	Rubber	0.176	0.312
Synthetic rubber	Inert waste	0.254	0.128
Carbon black / silica (fillers)	Inert waste	0.238	0.216
Oils / anti-degradants / resins	Inert waste	0.075	0.031
Metal reinforcement	Steel	0.156	0.267
Fabric (nylon / rayon)	Inert waste	0.063	0.012
Zinc oxide	Inert waste	0.02	0.02
Curing agents (sulphur etc.)	Inert waste	0.018	0.014

EOLT are assumed to be sent directly to the local municipal landfill facilities. As EOLT processors are located in urban centres, the distance to landfill facilities is likely to be similar distances in urban areas but shorter in regional areas. Therefore, a shorter distance of 50 km was assumed. EOLT were transported to the landfill by a 40 tonne-truck.

Some states do not permit the landfilling of whole EOLT. These states are New South Wales, Victoria, South Australia and Tasmania, where the shredding of passenger and truck tyres is mandated (NSW EPA, 2016; *Environmental Protection Regulations 2021* (Vic); *Environmental Protection (Waste to Resources) Policy 2010* (SA); EPA Tasmania, 2021). Whole tyres cannot be compacted and may move towards the surface of the landfill over time, creating stability risks (NSW EPA, 2016). In these instances, the collection of tyres at a distance of 125 km and shredding of EOLT was also included, applying the same assumptions as in section 7.1.1 and section 7.1.3. Based on the consumption of tyres in FY2018/2019 in Table 25, it was assumed that 66% of passenger tyres and 60% of truck tyres were shredded.

Table 25 | Passenger and truck tyre consumption in FY 2018/2019 (TSA, 2020a).

Jurisdiction	Treatment	Passenger tyres	Truck tyres
ACT	Whole	4,000	2,000
NSW	Shredded	66,000	54,000
NT	Whole	2,000	3,000
QLD	Whole	45,000	49,000
SA	Shredded	17,000	13,000
TAS	Shredded	5,000	6,000
VIC	Shredded	59,000	44,000
WA	Whole	25,000	24,000
Total shredded		147,000	117,000

7.2.2 Scenario 2: Asphalt Binders (Wet Process)

This scenario compares the use of asphalt in road construction, replacing a proportion of conventional bitumen in asphalt binder with alternative materials using the wet process. In the wet process, the crumb rubber is added to the bitumen binder mixture and blended prior to the addition of the aggregates. On the other hand, the dry process involves mixing the crumb rubber with the aggregates at high temperatures prior to the addition of the bitumen binder. The wet process yields greater improved performance properties, but the dry process is considered simpler to produce.

The materials required for 1 km of road was based on a one laned road with a width of 3.5m, a lane length of 1 km and an asphalt surface layer of 40mm. Crumb rubber binders could potentially extend the lifespan of asphalt compared to conventional bitumen binders from 6 years to 9 years. The impacts are not well understood, and AustRoads is currently undertaking further studies to understand whether these performance benefits are seen, particularly when compared to other commonly used bitumen replacements such as PMB. As such, the modelling has not considered any potential performance gains. This scenario includes product materials, transport, and manufacturing stages. The scenario excludes the transport of the asphalt mixture to a construction site and the installation of the road, as it is considered to have the same impacts for all cases.

The composition of asphalt binder in road construction is based on AustRoads specifications and is outlined in Table 26. As the collective body representing all Australian and New Zealand government transport agencies, AustRoads's activities includes providing technical guidelines on best-practice road design and operation.

Three types of crumb rubber asphalt mixes have been modelled – gap graded asphalt (GGA), open graded asphalt (OGA) and dense graded asphalt (DGA). Each type is produced with the same processing methods, but the composition of each varies based on performance requirements. GGA mixes have a higher binder content and is designed to improve durability, and therefore useful as a surface layer for high volume roads. OGA mixes are designed to be water permeable, with a lower percentage of sand. They can only be used for the surface layer and are generally used for highways and freeways. They reduce tyre spray in wet weather and reduce noise pollution but more susceptible to tyre wear. For both GGA and OGA, 18% is the typical crumb rubber content trialled in Australia but 22% has been successfully applied in the US, so an average 20% has been applied in these scenarios. DGA mixes are for general use and suitable for all road types. GGA is the most applied by volume, followed by OGA and DGA.

Two conventional PMB mixes have been modelled, the first mix is used for GGA and the second mix for OGA and DGA. For these mixes, combining oil is often added. However, the formulation is proprietary information that is company dependent and so has not been included in the mix design.

Table 26 | Composition of asphalt mix (wet process)

Material	TDP: Crumb rubber binder (%)			Conventional: PMB (%)	
	Gap Graded Asphalt (GGA)	Open Graded Asphalt (OGA)	Dense Graded Asphalt (DGA)	Default 1: GGA	Default 2: OGA/DGA
Binder – bitumen and alternatives	7.5% binder, with 20% crumb rubber in binder[2] i.e. 6.00% bitumen, 1.50% crumb rubber	6.0% binder, with 20% crumb rubber in binder[3] i.e. 4.80% bitumen, 1.20% crumb rubber	5.5% binder, with 15% crumb rubber in binder[4] i.e. 4.68% bitumen, 0.82% crumb rubber	6.5% binder, with 5% PMB (Styrene-butadiene-styrene SBS) in binder[5] i.e. 6.18% bitumen, 0.33% SBS	5% binder, with 5% PMB (Styrene-butadiene-styrene SBS) in binder[6] i.e. 4.75% bitumen, 0.25% SBS
Aggregate – gravel	74.0%	79.5%	61.4%	59.1%	60.0%
Aggregate – sand	18.5%	14.5%	33.1%	34.4%	35.0%

Additional heating may be required for crumb rubber binders manufactured using the wet process compared to conventional bitumen, however, no evidence of energy differences were found when comparing crumb rubber binders and PMB. The modelling therefore assumes the same energy requirements are needed at the manufacturing stage. The assumptions are summarised in Table 27.

Table 27 | Scenario 2 assumptions per tonne of asphalt mix (Reconophalt EPD, 2020)

Stage	Material	Quantity
Material transport (excl crumb rubber)	Transport of bitumen, SBS, aggregates	100 km with a 40 t truck
Asphalt manufacturing	Electricity	2.7 kWh
	Gas	250 MJ

The assumed densities of each material and the calculated weights in each mix design have been provided in Table 42.

[2] Based on the AfPA Pilot Specification, with a goal of 18-22% crumb rubber.

[3] Based on the AfPA Pilot Specification, with a goal of 18-22% crumb rubber.

[4] Based on AustRoads S45R specification. The industry goal is to achieve an 18% crumb rubber mix, however, there is currently no specification for this.

[5] Based on AustRoads ATS3110 specification.

Table 28 | Material weight in tonnes per 1 km of road

Material		TDP: Crumb rubber binder (tonnes)			Conventional: PMB (tonnes)	
Material	Density (t/m³)	Gap Graded Asphalt (GGA)	Open Graded Asphalt (OGA)	Dense Graded Asphalt (DGA)	Default 1: GGA	Default 2: OGA/DGA
Gravel	1.52	157.68	169.35	130.88	125.83	127.85
Sand	1.50	38.85	30.50	69.46	72.34	73.50
Bitumen	1.36	11.44	9.15	8.91	11.77	9.06
Crumb rubber	1.15	2.42	1.93	1.33	0	0
SBS	0.96	0	0	0	0.44	0.34
Total		210.39	210.93	210.58	210.38	210.74

7.2.3 Scenario 3: Asphalt Binders (Dry Process)

This scenario compares the use of asphalt in road construction, replacing a proportion of conventional bitumen in asphalt binder with crumb rubber using the dry process. This is where the crumb rubber is mixed with the aggregates at high temperatures prior to the addition of the bitumen binder. The functional unit used for this case was 1 km road. The same conventional PMB mixes used for scenario 2 were used for this scenario. Crumb rubber incorporated using the dry process may also have similar performance benefits on lifespan as the wet process. However, specific research on service life improvements for the dry process is yet to be conducted. As such, the modelling has not considered potential performance improvements. This scenario includes product materials, transport and manufacturing stages. The scenario excludes the transport of the asphalt mixture to a construction site and the installation of the road, as it is considered to have the same impacts for all cases. The composition of the asphalt mix in road construction is based on AustRoads specifications and is outlined in Table 31. No additional heating requirements are assumed ot be required for the addition of crumb rubber by the dry process. The same energy requirements have been assumed at the manufacturing stages for both binder types. The assumptions are the same as for scenario 2 and are summarised in Table 29. Table 32 provides the material quantities for the TDP scenario.

Table 29 | Composition of asphalt mix (dry process)

Material	TDP: Crumb rubber binder (%) Gap Graded Asphalt (GGA)	Conventional: PMB (%) Default 1: GGA
Binder – bitumen and alternatives	7.5% binder, with 27% crumb rubber in binder[7], i.e. 5.5% bitumen, 2.0% crumb rubber	6.5% binder, with 5% PMB (Styrene-butadiene-styrene SBS) in binder i.e. 6.18% bitumen, 0.33% SBS
Aggregate – gravel	74.0%	59.1%
Aggregate – sand	18.5%	34.4%

[7] Based on AustRoads A27RF specification. The specification allows for 25-30% crumb rubber in the binder mix, to be added dry.

Table 30 | Material weight in tonnes per 1 km of road

		TDP: Crumb rubber binder (%)	Conventional: PMB (%)
Material	Density (t/m^3)	Gap Graded Asphalt (GGA)	Gap Graded Asphalt (GGA)
Sand	1.50	38.85	72.34
Gravel	1.52	157.68	125.83
Bitumen	1.36	10.49	11.77
Crumb rubber	1.15	3.22	0
SBS	0.96	0	0.44
Total		210.24	210.38

7.2.4 Scenario 4: Sprayed seal

Sprayed seal is an asphalt binder that is sprayed on top of cracked asphalt surfaces to prolong the lifespan of an existing road. No information was available on the volume of binder required for a given road surface as volume of sprayed seal may vary based on the severity of road damage. The functional unit of 1 tonne of sprayed seal was therefore considered appropriate. For this reason, the system boundary for this scenario is only the product material and manufacturing stage, with construction stage impacts excluded from the modelling.

The sprayed seal components outlined in Table 31 has been guided by AustRoads specifications. No additional benefits from using crumb rubber as a sprayed seal additive have been included in this scenario.

Table 31 | Composition of sprayed seal mix for 1 tonne of sprayed seal

Material	TDP: Crumb rubber binder (%)[8]	Conventional: Bitumen (%)[9]
Bitumen	85%	89%
Crumb rubber	15%	0%
PMB (SBS)	0%	5%
Combining oil (assumed same as diesel)	0%	6%

The input assumptions for the production of 1 tonne of sprayed seal are outlined in Table 32. Similar to scenarios 2 and 3, no additional heating or other production requirements were assumed for the TDP compared to the conventional product. The conventional product was modelled on *Bitumen, at consumer/AU U*, from the Australasian Unit Process LCI database.

Table 32 | Input assumptions for the production of 1 tonne sprayed seal mix, based on ecoinvent database process *Bitumen adhesive compound, hot {RER}| production | Cut-off, U*

Stage	Material	Quantity
Raw material	Sprayed seal mix	1 tonne
Raw material transport (excl. crumb rubber)	Transport by rail	200 km
	Transport by 16t truck	100 km
Sprayed seal manufacturing	Natural gas	1260 MJ
Sprayed seal manufacturing	Bitumen waste	0.01 tonne

[8] Based on S45R binder used in AustRoads ATS3110 Sprayed seal Specification. The specification allows for 5-20%, varying based on contractor preference, however 15% is recommended.

[9] Based on S20E PMB binder used in AustRoads ATS3110 Specification.

7.2.5 Scenario 5: Concrete (sand replacement)

This scenario compares a conventional concrete mix to a modified concrete mix where 5% of the sand component is replaced with crumb rubber. The functional unit is 1 m^3 of concrete mix at a strength of 20 MPa. The modelling includes the product stage of the system, that is, the raw material supply and transport, and the manufacturing of the product. It is assumed that there is no performance lifespan difference, and sand is replaced at a 1 to 1 mass ratio, with no additional inputs required to manufacture the concrete mix. Data was based on the production process *Concrete, 20 MPa, at batching plant/AU U* in the AusLCI database. For the TDP scenario, 5% of the sand was replaced with crumb rubber of the same weight.

7.2.6 Scenario 6: Concrete (coarse aggregate replacement)

This scenario compares a conventional concrete mix with a modified concrete mix where 30% of gravel is replaced by rubber granules. The functional unit is 1 m^3 of concrete mix at a strength of 20 MPa. The modelling accounts for the product stage of the system, that is, the raw material supply and transport, and the manufacturing of the product. It is assumed that there is no performance or lifespan difference, and gravel is replaced at a 1 to 1 mass ratio, with no additional inputs required to manufacture the concrete mix. Data was based on the production process *Concrete, 20 MPa, at batching plant/AU U* in the AusLCI database. For the TDP scenario, 30% of the gravel content was replaced with rubber granules of the same weight.

7.2.7 Scenario 7: Permeable Pavements

This scenario compares the environmental impacts when constructing 1 m^2 of permeable pavement using conventional aggregate compared to an aggregate mix with rubber granules incorporated. This scenario focuses on the extraction and transport of raw materials. The construction stage is excluded due to similar energy and processes required for mixing, producing and installing the mixture.

The TDP data has been provided by Porous Lane, an Australian company pioneering the use of EOLT in permeable pavements in Australia. Utilisation of rubber granules in the mixture helps to reduce the quantity of conventional aggregate and binder required. The overall weight of material is reduced due to the density of the crumb rubber compared to aggregates. The binder contains 4% polyurethane, which helps bond the rubber and provide the required mechanical properties. This was modelled based on *Bitumen adhesive compound, hot {RER}| production* | *Cut-off,U* from the ecoinvent database and the bitumen component adjusted to contain 4% polyurethane. The conventional scenario data was also provided by Porous Lane and includes 90% of aggregate and 10% of conventional unmodified binder. Table 33 summarises the materials required for 1 m^2 of permeable pavement.

Table 33 | Materials required for 1 m^2 of permeable pavement (provided by Porous Lane)

Material	Unit	Conventional aggregate	TDP: Aggregate mix with rubber granules
Crushed rock	kg	80	*
Conventional bitumen binder	kg	9	*
Polyurethane binder	kg	0	*
Rubber granules	kg	0	*

*Data removed for confidentiality reasons.

7.2.8 Scenario 8: Combustion in cement kilns

This scenario explores the environmental impacts when using TDF as a fuel in the production of cement clinker. TDF used as a waste fuel will typically only supplement a proportion of coal. For this scenario, it is assumed that TDF would form 5% of the fuel mix, with 95% coal. Tyres cannot completely replace other fuels due to their high zinc content, which would adversely affect the quality of the clinker (Giere et al, 2004). It is assumed that the processing of EOLT is co-located or is processed near the clinker facility, as is common practice in the cement industry (Corti et. al, 2004). It has been assumed that the EOLT were collected and transported a distance of 125 km and then processed at the site. The coal was assumed to be transported 200km by rail and 100km by truck to the clinker site. In this case, it is assumed that the EOLT have been shredded. It is worth noting that TDF is commonly in shredded form, however, the fabric and steel components do not have to be fully removed prior to combusted, with the steel content reducing raw material need (Giere et al, 2004). The emissions to air from the combustion have been included for both scenarios. The emissions to air was modelled based on the study by Giere et al (2006), where conventional coal and a blended coal plus TDF was combusted in a commercial power plant. The energy content of the TDF was 35.1 MJ/kg, with the blended TDF assumed to be 26.4 MJ/kg. Coal was assumed to have a calorific value of 25.9 MJ/kg. As discussed in section 6.2.2, biogenic CO_2 attributed to the release of CO_2 from the combustion of natural rubber has been excluded from the results.

Table 34 | Materials required for 1 MJ of energy

Stage	Material	Unit	Coal with 5% rubber	Coal
Raw material	Shredded rubber	Kg	0.0019	0
	Thermal coal	Kg	0.0361	0.038
Raw material transport (excl. rubber)	Transport by rail	Km	200	200
	Transport by 16t truck	Km	100	100
Combustion	Diesel	Kg	1.19E-05	0
	Electricity	MJ	1.18E-05	0
Emissions	Carbon monoxide	g	0.0117	0.0195
	Nitrogen oxides	g	0.265	0.246
	Sulfur dioxide	g	1.42	1.52
	Hydrogen chloride	g	0.00429	0.00269
	Hydrogen fluoride	g	0.000896	0.000779
	Hydrocarbons, unspecified	mg	9.35E-05	0.00046
	Dioxins (unspec.)	ng	6.62E-05	0.000074
	Particulates	g	6.62E-05	0.053
	Beryllium	g	2.73E-06	7.79E-07
	Aluminium	g	0.00285	0.000238
	Calcium	g	0.00016	0.000039
	Vanadium	g	2.34E-05	3.51E-06
	Chromium	g	1.52E-05	3.55E-06
	Manganese	g	0.000171	0.000187
	Cobalt	g	1.56E-05	4.29E-06
	Nickel	g	1.56E-05	1.75E-05
	Copper	g	5.06E-05	1.29E-05
	Zinc	g	0.00933	5.84E-05
	Arsenic	g	0.000101	2.34E-05
	Selenium	g	4.29E-05	4.68E-05
	Molybdenum	g	7.01E-06	5.45E-06
	Cadmium	g	9.35E-07	1.95E-07
	Tin	g	5.45E-06	5.45E-06
	Antimony	g	5.84E-06	1.75E-06
	Tellurium	g	7.01E-06	3.51E-06
	Barium	g	2.73E-06	7.79E-07
	Tungsten	g	5.45E-06	5.45E-06
	Mercury	g	1.75E-06	1.75E-06
	Thallium	g	6.62E-06	1.75E-06
	Lead	g	7.79E-05	3.12E-05
	Uranium	g	5.45E-05	5.45E-05
	Carbon dioxide	g	0.2	0.202
	Oxygen	g	0.11	0.105

8 Results

8.1 Collection Impacts

Table 35 summarises the environmental impacts of collecting 1 tonne of EOLTs and transporting them 125 km to a processing facility. The emissions impacts of collection are 30% lower than the less emissions intensive processing type, shredding. However, reliance on fossil resource use and impacts on terrestrial eutrophication are 81% and 18% higher respectively. This is attributed to the use of fossil-based fuels in the operation of the truck. Further analysis on the sensitivity of transportation is detailed in section 8.4.

Table 35 | Potential impacts for the collection of 1 tonne of EOLT.

Impact category	Unit	125 km
GWP fossil	kg CO_2 eq	40.27
GWP biogenic	kg CO_2 eq	0.0015
GWP land use	kg CO_2 eq	0.00032
GWP total	kg CO_2 eq	40.27
Eutrophication, terrestrial	mol N eq	0.67
Ecotoxicity, freshwater	CTUe	313.71
Water scarcity	m^3 equivalent deprived	357.80
Resource use - fossil	MJ	554.56

8.2 Processing Impacts

8.2.1 Physical decomposition of EOLTs

Table 36 rovides details on the potential environmental impacts for processing 1 tonne of recycled rubber from EOLT. This excludes any collection transportation impacts. The results show that the processing of EOLT into finer graded products result in considerable increase to environmental impact due to the additional energy requirements. Producing rubber granules produces almost 3 times the GHG emissions compared to shredded rubber, while the more refined fine rubber granules and crumb rubber produces 7-8 times the emissions of shredded rubber. Unsurprisingly, the trends are similar across all impact categories. There is high water scarcity impact in the processing of crumb rubber and fine rubber granules, at 8-9 times higher compared to shredded rubber. Interestingly, the use of water as an input into the process has little impact on this metric. The high water scarcity impact is due to electricity requirements. It is assumed this electricity is sourced from Australia's energy grid, which includes a proportion of hydropower. The grid mix will vary between states and over time, and so the contribution to water scarcity will change depending on the location of the facility and the time of production. The exception is freshwater ecotoxicity, where all three finer graded products are about 1-2 times higher than the shredded rubber product. However, the additional processing does widen the potential end markets for the TDP and the environmental and other benefits in the end market may offset these initial emissions.

Over 99% of impacts across all categories are attributed to electricity requirements, except for freshwater ecotoxicity, where 90% of impacts are due to electricity usage. There is therefore opportunity for environmental impact of the processing of EOLTs to be significantly minimised as Australia's electricity grid transitions to renewable energy. These results also reflect a particular technology available for processing EOLT. As the industry innovates, and a range of technologies become commercially available for processing EOLTs, energy consumption is an important consideration when selecting the most appropriate technology.

Table 36 | Potential impacts from physical decomposition for 1 tonne of recycled rubber output.

Impact category	Unit	Crumb rubber	Fine rubber granules (< 2mm)	Rubber granules (<15mm)	Shredded rubber
GWP fossil	kg CO_2 eq	453.46	390.96	149.69	54.93
GWP biogenic	kg CO_2 eq	0.75	0.64	0.59	0.087
GWP land use	kg CO_2 eq	0.00045	0.00039	1.68E-05	4.49E-06
GWP total	kg CO_2 eq	454.21	391.61	150.28	55.02
Eutrophication, terrestrial	mol N eq	4.73	4.07	1.66	0.56
Ecotoxicity, freshwater	CTUe	1563.29	1347.82	1192.05	703.52
Water scarcity	m^3 equivalent deprived	12482.5	10762.04	1439.446	1348.97
Resource use - fossil	MJ	2356.99	2032.12	792.24	306.11

8.3 End Market Impacts

8.3.1 Scenario 1: Landfilling of EOLT

As illustrated in Figure 8, the landfill of 1 tonne of EOLT may produce potential GHG impact of 271 to 561 kg CO_2 eq. This is significant considering over 34,000 tonnes of EOLTs are still being landfilled annually, or about 7% of total EOLT generated (Table 14). The different impacts across the tyre types are due to the difference proportions of natural rubber in each tyre. Passenger tyres have a relatively low percentage of natural rubber compared to truck and OTR tyres, at about 18% compared to 30-40%.

Table 37 summarises the environment impacts. The majority of impacts are associated with the decomposition of the natural rubber component of the tyre. The average tyre produces similar GHG emissions to the processing of crumb rubber, however, has low environmental impacts across all other categories. Note that a TSA study is currently underway to understand the potential impacts of leaching in landfills which may impact these results.

Table 37 | Potential impacts from the landfill of one tonne EOLTs.

Impact category	Unit	Truck Tyres	Passenger Tyres	Average Tyre
GWP fossil	kg CO_2 eq	54.35	82.84	68.59
GWP biogenic	kg CO_2 eq	474.05	267.43	370.74
GWP land use	kg CO_2 eq	0.00058	0.00063	0.00060
GWP total	kg CO_2 eq	528.40	350.27	439.33
Eutrophication, terrestrial	mol N eq	4.01	3.07	3.54
Ecotoxicity, freshwater	CTUe	936.42	1131.09	1033.75
Water scarcity	m^3 equivalent deprived	1195.05	1323.69	1259.37
Resource use - fossil	MJ	1044.15	1211.57	1127.86

Figure 8 illustrates that the majority of the GHG emissions are attributed to the landfill processes, with the collection of tyres representing under 6% of total emissions. The total GHG emissions are largely biogenic GHG. For example, the total GHG emissions for passenger tyres is split into 267 kg CO_2 eq of biogenic GHG and 83 kg CO_2 eq of fossil based GHG. For a truck tyre, it was 474 and 54 kg CO_2 eq, respectively. The high level of biogenic GHG is a result of the EOLT materials, particularly natural rubber, decomposing in landfill conditions, thereby releasing GHG emissions such as methane. Note that the biogenic CO_2 has been removed as that is considered a natural carbon cycle process.

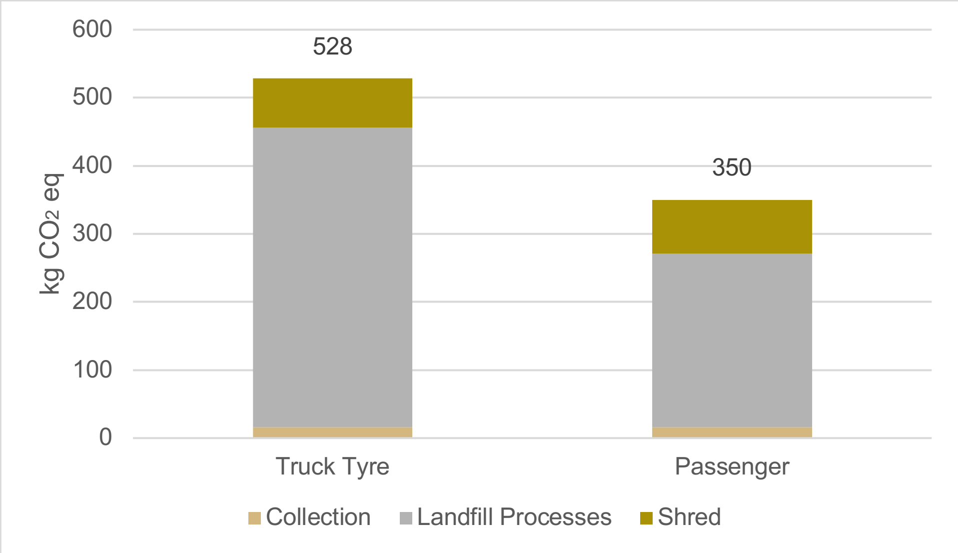

Figure 8 | Total potential GHG emissions from landfilling 1 t of EOLT for different tyre types.

8.3.2 Scenario 2: Asphalt binders (wet process)

Table 38 summarises the potential impacts of the producing asphalt mixture required to construct 1 km of road. As discussed, the construction of the road has been excluded as the process is assumed to be the same irrespective of asphalt mix type. Across all environmental indicators, impacts increase with an increased binder proportion, due to the higher quantity of bitumen. An average of the three crumb rubber mixes shows a 7% reduction in GHG emissions compared to the average of the two conventional PMB mixes, due to the lower burden of the crumb rubber materials compared to the fossil derived PMB. The average crumb rubber mix increases water scarcity burdens by 26%, due to the water impacts during the EOLT processing stage. It is important to note that these water burdens are due to an assumption that electricity is sourced from Australia's energy grid, with 6% generated from hydropower. The grid mix will vary between states and contribution to water scarcity may be overstated depending on the location of the facility.

On the other hand, there is an 18% decrease in reliance on fossil resources, due to the substitute of PMB with crumb rubber. Emissions are primarily from fossil-based GWP, with negligible attribution to biogenic and land use GWP. This will be consistent across scenarios 2 – 10, as the TDP is not combusted or subject to degradation. Assuming the crumb rubber binder demonstrates similar performance outcomes to the PMB binder, the TDP offers opportunity for reduction in environmental impact. When comparing each TDP mix to the comparable conventional PMB mix, GHG emissions reductions of up to 12% and eutrophication and ecotoxicity reductions of up to 6% are demonstrated.

Table 38 | Potential impacts from a wet process asphalt mix compared to a PMB asphalt mix required in 1 km of road.

Impact category	Unit	TDP: Crumb rubber binder			Conventional: PMB binder	
		Gap Graded Asphalt (GGA)	**Open Graded Asphalt (OGA)**	**Dense Graded Asphalt (DGA)**	**Default 1 (GGA)**	**Default 2 (OGA/DGA)**
		7.5% binder	**6.0% binder**	**5.5% binder**	**6.5% binder**	**5.0% binder**
GWP fossil	kg CO_2 eq	15,499.37	14,044.73	13,450.09	16,414.43	14,445.10
GWP biogenic	kg CO_2 eq	22.34	22.84	18.49	29.07	26.20
GWP land use	kg CO_2 eq	1.87	2.01	1.56	1.56	1.57
GWP total	kg CO_2 eq	15,523.58	14,069.58	13,470.13	16,445.06	14,472.88
Eutrophication, terrestrial	mol N eq	153.57	139.41	130.70	149.78	132.35
Ecotoxicity, freshwater	CTUe	1,024,947.69	830,382.40	803,910.55	1,061,349.00	826,027.25
Water scarcity	m^3 equivalent deprived	106,676.32	94,415.98	90,160.40	80,765.43	74,537.41
Resource use - fossil	MJ	131,269.75	128,032.15	121,866.10	160,912.81	148,362.40

Figure 9 shows the total GWP of the three crumb rubber asphalt mixes, compared to the two conventional PMB asphalt mixes. It is important to consider the percentage of bitumen binder in the overall mix design when comparing the TDP and conventional alternatives. For example, the DGA mix has 5.5% bitumen binder, and results in a 7% reduction in emissions compared to the equivalent conventional mix with 5% bitumen binder. The GGA mix reduces emissions by 6% when compared to a default mix with 6.5% bitumen binder. Figure 9 shows the largest contributor to GHG emissions is from the asphalt binder, with approximately 45-50% of each mix attributed to the binder. The crumb rubber processing contributes 4-7% of total emissions. The collection of EOLTs has a negligible contribution to the overall emissions. Asphalt production has the second highest impact, contributing 25-30% of total emissions.

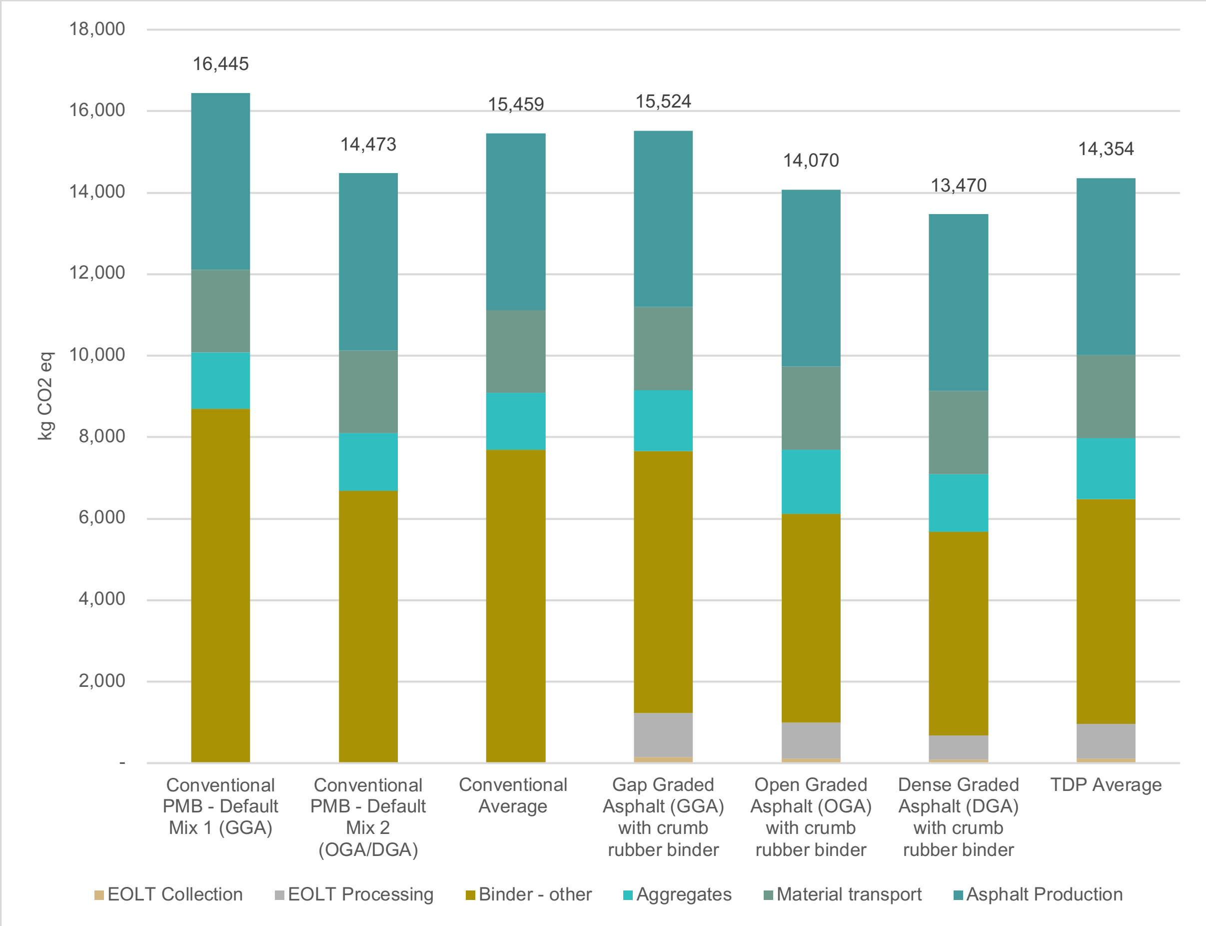

Figure 9 | Total GWP of wet-process asphalt mix compared to a PMB asphalt mix in 1 km of road.

It is worth noting that for EPD reporting purposes, the use of recycled materials as an input material is encouraged as they have lower burdens. EPDs of asphalt mixtures and other construction-based products are often used to identify low carbon products to include in infrastructure projects. The inclusion of crumb rubber in this scenario will therefore produce a more favourable result compared to PMB and other conventional asphalt mixes.

8.3.3 Scenario 3: Asphalt binders (dry process)

The results for a gap graded asphalt with a crumb rubber binder derived from the dry process is summarised in Table 39. The results are very similar to the equivalent gap graded asphalt mix in scenario 2. The emissions impact of the TDP is in between the two conventional mixes, despite a higher bitumen binder content. It shows a 6% reduction in impacts compared to a conventional PMB mix with 6.5% binder. The substitution of PMB with crumb rubber also results in an 11% reduction in ecotoxicity impacts and 19% decrease in reliance on fossil resources. However, water scarcity impacts increase by 41%. Again, this is attributed to the assumed electricity grid mix in Australia, and may vary between crumb rubber processing locations. Changes to Australia's electricity generation sources and opportunities for processing plants to independently generate electricity would further reduce the impacts of the crumb rubber binder.

Table 39 | Potential impacts from dry process asphalt mix compared to a PMB asphalt mix required in 1 km of road.

Impact category	Unit	TDP: Crumb rubber binder (%) **Gap Graded Asphalt (GGA)** **7.5% binder**	Conventional: PMB (%) **Conventional PMB (GGA)** **6.5% binder**
GWP fossil	kg CO_2 eq	15,372.29	16,414.43
GWP biogenic	kg CO_2 eq	22.80	29.07
GWP land use	kg CO_2 eq	1.87	1.56
GWP total	kg CO_2 eq	15,396.96	16,445.06
Eutrophication, terrestrial	mol N eq	152.75	149.78
Ecotoxicity, freshwater	CTUe	945,231.83	1,061,349.00
Water scarcity	m^3 equivalent deprived	114,928.48	80,765.43
Resource use - fossil	MJ	132,430.22	160,912.81

Figure 10 compares the total GWP for crumb rubber incorporated using a dry process, compared to a conventional PMB binder. Total GWP impacts are comparable when performance benefits are not factored in due to the small proportion of crumb rubber in the overall asphalt mixture. In this scenario, the crumb rubber reduces the overall emissions impacts by 6% when compared to the conventional GGA mix, which has a 6.5% bitumen binder mix, compared to 7.5% for the TDP mix. The environmental impact of the GGA mix is very similar when incorporated using either the wet or dry process and has relatively high impacts relative to the average TDP or PMB asphalt mix.

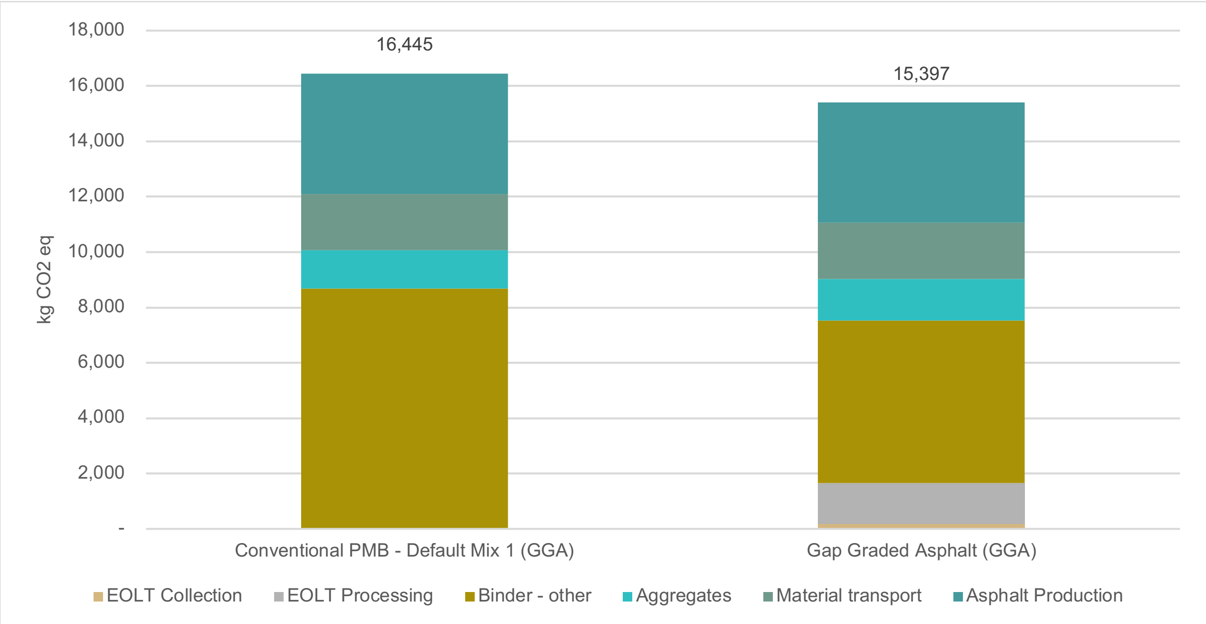

Figure 10 | Total GWP of a dry-process crumb rubber asphalt mix compared to a PMB asphalt mix in 1 km of road.

8.3.4 Scenario 4: Sprayed seal

Table 40 summarises the impacts of 1 tonne of sprayed seal, including raw materials, transport and production of the sprayed seal mix. The environmental impacts for sprayed seal follow similar trends to scenario 2 and 3 due to the similar material compositions. The crumb rubber sprayed seal shows a 9% reduction in GHG emissions compared to the conventional PMB sprayed seal. Terrestrial eutrophication impacts are significantly reduced, with a 37% decrease compared to the PMB sprayed seal. This is due to the high impacts attributed to the SBS additive and bitumen, which in total constitutes 94% of the total mix, compared to 85% for the TDP alternative. Ecotoxicity impacts are also reduced, by 8%. Ecotoxicity impacts are attributed to the lower bitumen content in the crumb rubber sprayed seal. Fossil-based resource is 59% lower in the crumb rubber sprayed seal. Each component of the PMB sprayed seal, namely the bitumen, SBS additive and the combining oil, are all fossil derived materials; while crumb rubber has relatively small impacts.

Table 40 | Potential impacts from 1 tonne crumb rubber sprayed seal compared to a PMB sprayed seal.

Impact category	Unit	TDP: Crumb rubber sprayed seal	Conventional: PMB sprayed seal
GWP fossil	kg CO_2 eq	694.64	764.01
GWP biogenic	kg CO_2 eq	0.32	0.43
GWP land use	kg CO_2 eq	0.00	0.01
GWP total	kg CO_2 eq	694.96	764.45
Eutrophication, terrestrial	mol N eq	6.69	9.91
Ecotoxicity, freshwater	CTUe	73,921.29	80,478.56
Water scarcity	m^3 equivalent deprived	4,000.85	2,174.63
Resource use - fossil	MJ	3,286.93	8,060.09

Figure 11 shows the total GWP impacts of crumb rubber sprayed seal compared to a PMB sprayed seal. This reduces emissions by 9%, due to the high quantity of crumb rubber incorporated into the mix. However, it is important to note that while the reductions at face value may be higher than in scenario 2 and 3, the overall quantity of sprayed seal mix may be quite small compared to the quantity of asphalt mix required for new road construction.

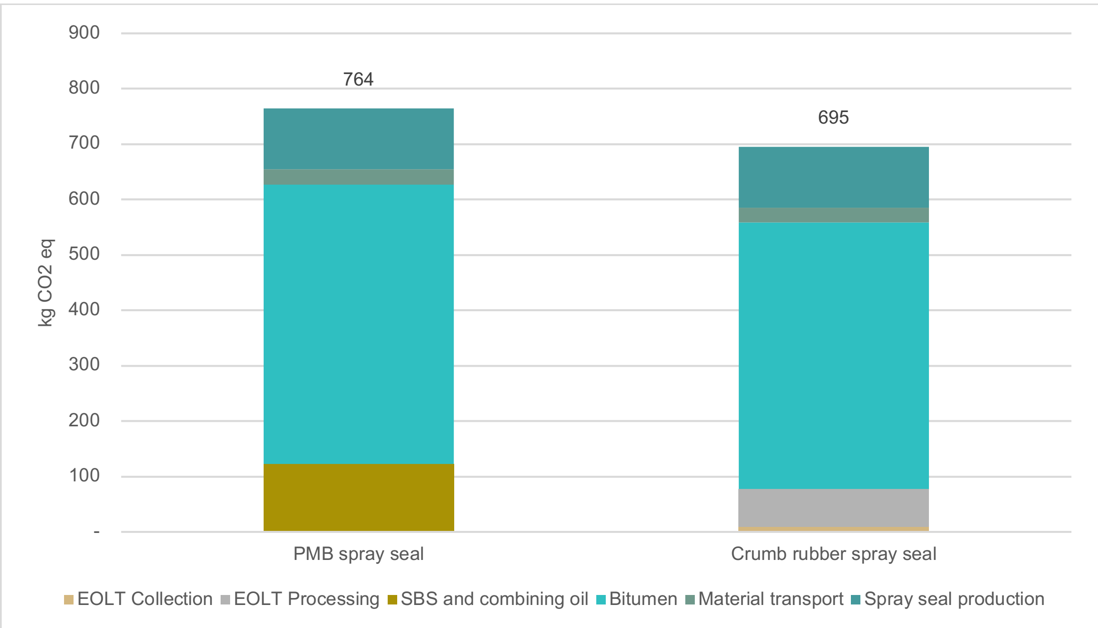

Figure 11 | Total GWP of a crumb rubber sprayed seal compared to a conventional PMB sprayed seal, per tonne of sprayed seal.

8.3.5 Scenario 5: Concrete (sand replacement)

Table 41 summarises the potential environmental impacts of concrete with crumb rubber as a replacement for sand, compared to conventional concrete. The results show that the TDP performs worse than the conventional product across all considered environmental indicators. Overall GHG emissions increases by 5%, with eutrophication and eutrophication impacts both increasing by 4%. Water scarcity impacts increases by 61% and fossil-based resource use by 10%. These impacts are attributed to the higher intensity of processing EOLTs into crumb rubber. This is because sand is a very low burden material that requires minimal energy for extraction. However, innovations in low density concrete could reduce the materials required in the TDP, and therefore reduce environmental impacts, given the relatively low density of crumb rubber.

Table 41 | Potential impacts from 1m^3 conventional concrete compared to a modified concrete with 5% of the sand replaced by crumb rubber.

Impact category	Unit	TDP: Concrete 20 MPa with crumb rubber	Conventional: Concrete 20 MPa
GWP fossil	kg CO_2 eq	332.18	314.98
GWP biogenic	kg CO_2 eq	0.21	0.19
GWP land use	kg CO_2 eq	0.00	0.00
GWP total	kg CO_2 eq	332.39	315.16
Eutrophication, terrestrial	mol N eq	4.52	4.33
Ecotoxicity, freshwater	CTUe	1,659.20	1,591.71
Water scarcity	m^3 equivalent deprived	1,158.49	719.84
Resource use - fossil	MJ	1,155.11	1,049.25

As Figure 12 shows, there is a 5% increase in emissions when 5% of sand is replaced with crumb rubber. Crumb rubber produces 100 times the emissions compared to the equivalent quantity of sand. It is important to acknowledge that while there are limited benefits from the perspective of GHG emissions, there may be potential other application benefits such as performance enhancement, which are not included in the current analysis. There are also potential supply constraints for natural sand in Australia.

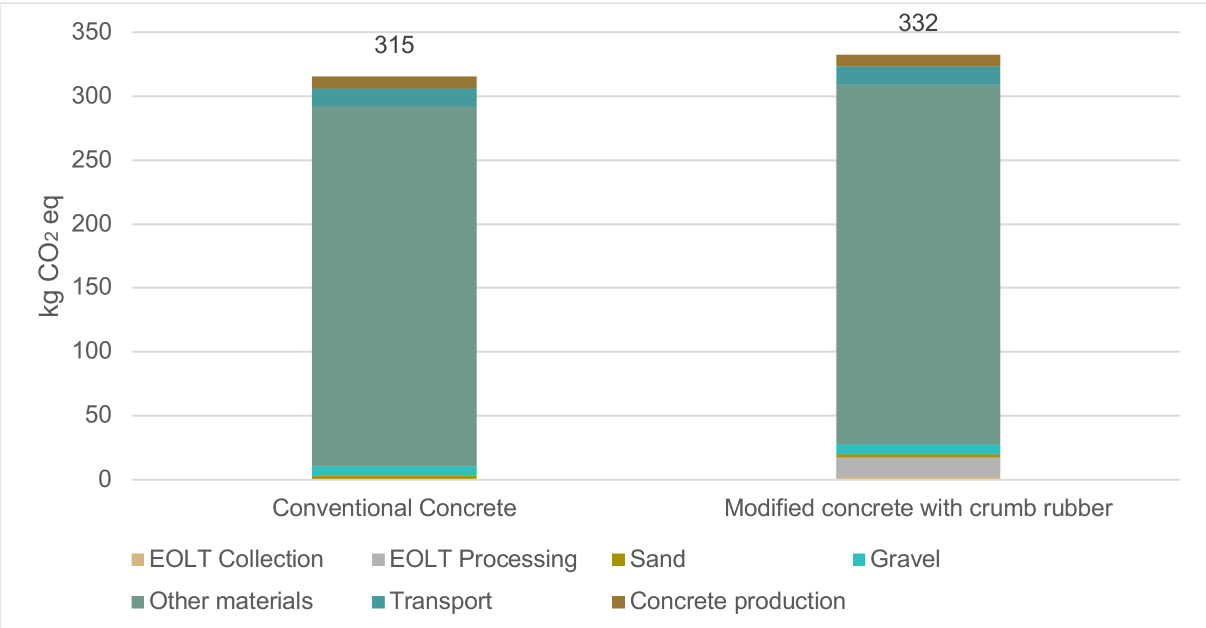

Figure 12 | Total potential GWP emissions of conventional concrete compared to a modified concrete with 5% of the sand replaced by crumb rubber.

8.3.6 Scenario 6: Concrete (coarse aggregate replacement)

Table 42 summarises the potential environmental impacts of concrete with rubber granules as a replacement for gravel, compared to conventional concrete. The results show that the TDP performs worse than the conventional product across all considered environmental indicators. The TDP performs worse in this scenario compared to scenario 8 due to the higher percentage of rubber in the product, despite rubber granules having a lower impact than crumb rubber.

Overall GHG emissions increases by 18%, with eutrophication and eutrophication impacts increasing by 8% and 12% respectively. Water scarcity impacts increases by 58% and fossil-based resource use by 15%. These impacts are attributed to the higher intensity of processing EOLTs into crumb rubber. This is because gravel is a very low burden material that requires minimal energy for extraction. However, innovations in low density concrete could reduce the materials required in the TDP, and therefore reduce environmental impacts, given the relatively low density of rubber granules.

Table 42 | Potential impacts from 1m^3 conventional concrete compared to a modified concrete with 30% of the gravel replaced by rubber granules.

Impact category	Unit	TDP: Concrete 20 MPa with rubber granules	Conventional: Concrete 20 MPa
GWP fossil	kg CO_2 eq	371.63	314.98
GWP biogenic	kg CO_2 eq	0.31	0.19
GWP land use	kg CO_2 eq	0.00	0.00
GWP total	kg CO_2 eq	371.94	315.16
Eutrophication, terrestrial	mol N eq	5.10	4.33
Ecotoxicity, freshwater	CTUe	2,043.43	1,591.71
Water scarcity	m^3 equivalent deprived	1,243.69	719.84
Resource use - fossil	MJ	1,559.27	1,049.25

Figure 13 shows that the substitution of rubber granules will increase GHG emissions by 18%. Rubber granules produces 15 times the emissions compared to the equivalent quantity of gravel. In comparison to scenario 8, the emissions from the collection of EOLTs is no longer negligible, contributing 7% of total emissions. It is important to acknowledge that while there are limited benefits from the perspective of GHG emissions, there may be other potential benefits such as from a performance perspective.

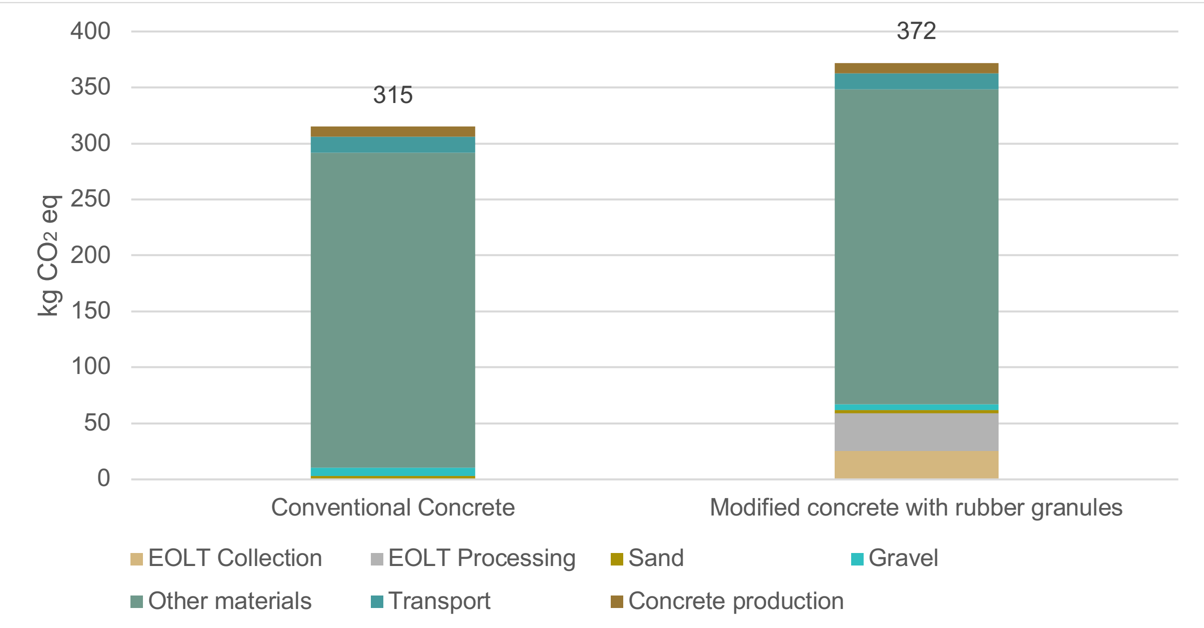

Figure 13 | Total potential GWP emissions of conventional concrete compared to a modified concrete with 30% of the gravel replaced by rubber granules.

8.3.7 Scenario 7: Permeable pavements

Table 49 compares the emissions impact of the product stage for 1m^2 of permeable pavement for the two types of mixtures. The inclusion of tyre derived rubber granules helps to reduce emissions by 5% when used in permeable pavements as a substitute for conventional aggregates. The TDP also has lower potential impacts across both eutrophication and ecotoxicity impacts, reducing impacts by 26% and 57% respectively. However, both water scarcity impacts and reliance on fossil based resources increases, by 51% and 71% respectively. As discussed in previous scenarios, the high water scarcity impacts are due to the reliance on Australian grid electricity for the processing of EOLT into rubber granules. The increase in fossil-use is due to the use of a polyurethane binder, compared to a conventional bitumen binder.

Table 43 | Potential impacts from 1m^2 of permeable pavement using conventional aggregate compared to an aggregate mixed with rubber granules.

Impact category	Unit	TDP: Permeable pavement with rubber granules	Conventional: Permeable pavement
GWP fossil	kg CO_2 eq	16.24	16.97
GWP biogenic	kg CO_2 eq	0.03	0.05
GWP land use	kg CO_2 eq	0.00	0.04
GWP total	kg CO_2 eq	16.28	17.06
Eutrophication, terrestrial	mol N eq	0.15	0.20
Ecotoxicity, freshwater	CTUe	217.31	503.22
Water scarcity	m^3 equivalent deprived	58.30	38.62
Resource use - fossil	MJ	736.18	431.05

The use of rubber granules reduces the required rock and binder required. This is due to the density of the rubber granules, as the product is relatively light compared to its volume. This is significant as the bitumen-based binders are key GHG emissions producers, contributing 93% and 81% to total emissions of the conventional and TDP products respectively. This also reduces the per tonne transportation for the raw materials at the production and installation stages, which have not been included in this analysis. Reduction in both raw materials and transportation lead to lower emissions of using rubber granules method.

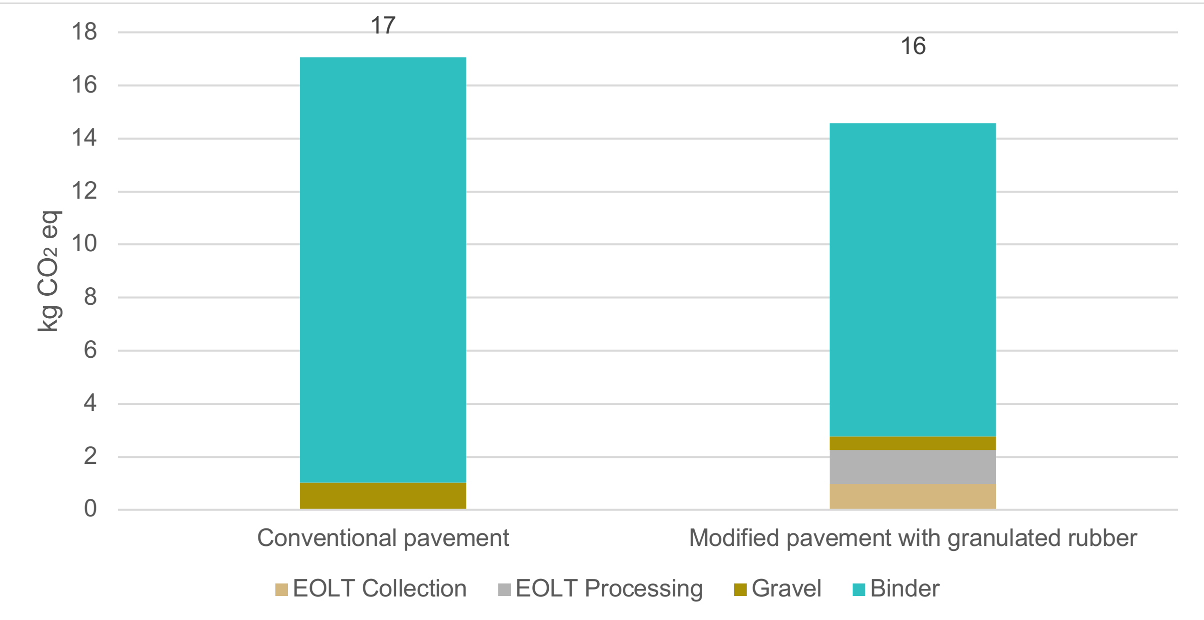

Figure 14 | Potential GHG emissions of 1 m^2 of permeable pavement using conventional aggregate compared to an aggregate mixed with rubber granules.

8.3.8 Scenario 8: Combustion in cement kilns

Table 44 summarises the environmental impacts of combustion in a cement kiln using 100% bituminous coal compared to coal blended with 5% shredded rubber. The blended TDF has mixed impacts across the environmental impact indicators, for example, increasing water scarcity impacts by 252% and ecotoxicity by 1011%. The increase in water scarcity is due to electricity usage and the increase in ecotoxicity is due to the combustion of rubber materials. The blended TDF does reduce GHG emissions by 4% and reliance on fossil-based materials by 5%. Given the mixed environmental outcomes, it is important to consider whether these outcomes are desirable, despite the improvements in GHG emissions, in considering whether opportunities to use TDF more widely as a fuel in Australia are worthwhile. In particular, these results reflect a 5% shredded rubber blend, and while GHG emissions reductions would increase with higher blends, impacts across other categories may worsen. It is also important to note that combustion processes will vary by facility, and this will influence the environmental impacts of the combustion process.

Table 44 | Potential impacts from 1 MJ of energy is generated from combustion in cement kilns using 100% bituminous coal compared to coal with 5% shredded rubber.

Impact category	Unit	TDP: Coal with 5% EOLT	Conventional: 100% coal
GWP fossil	kg CO_2 eq	0.069	0.072
GWP biogenic	kg CO_2 eq	-0.0008	0.0000
GWP land use	kg CO_2 eq	0.0000	0.0000
GWP total	kg CO_2 eq	0.068	0.072
Eutrophication, terrestrial	mol N eq	0.0035	0.0033
Ecotoxicity, freshwater	CTUe	1.71	0.15
Water scarcity	m^3 equivalent deprived	0.0035	0.0010
Resource use - fossil	MJ	1.01	1.06

One MJ of energy generated by the blended TDF combustion process has lower potential GHG emissions. There is a reduction in GHG emissions of 4% compared to conventional bituminous coal. This is largely due to the avoided transportation impacts due to the co-location of EOLT processing plant, and high supply of tyres in urban locations. Studies have shown that the atmospheric emissions from combustion of a blended coal and TDF fuel does not provide significant benefits, with higher emissions across gases such as carbon monoxide and polycyclic aromatic hydrocarbons. However, biogenic CO_2 emissions have been excluded from the system boundary of these results, which reduces the impacts of the combustion process. A benefit of using EOLTs is that the release of biogenic CO_2 is a neutral process that is part of the natural carbon cycle, and therefore is not releasing additional CO_2.

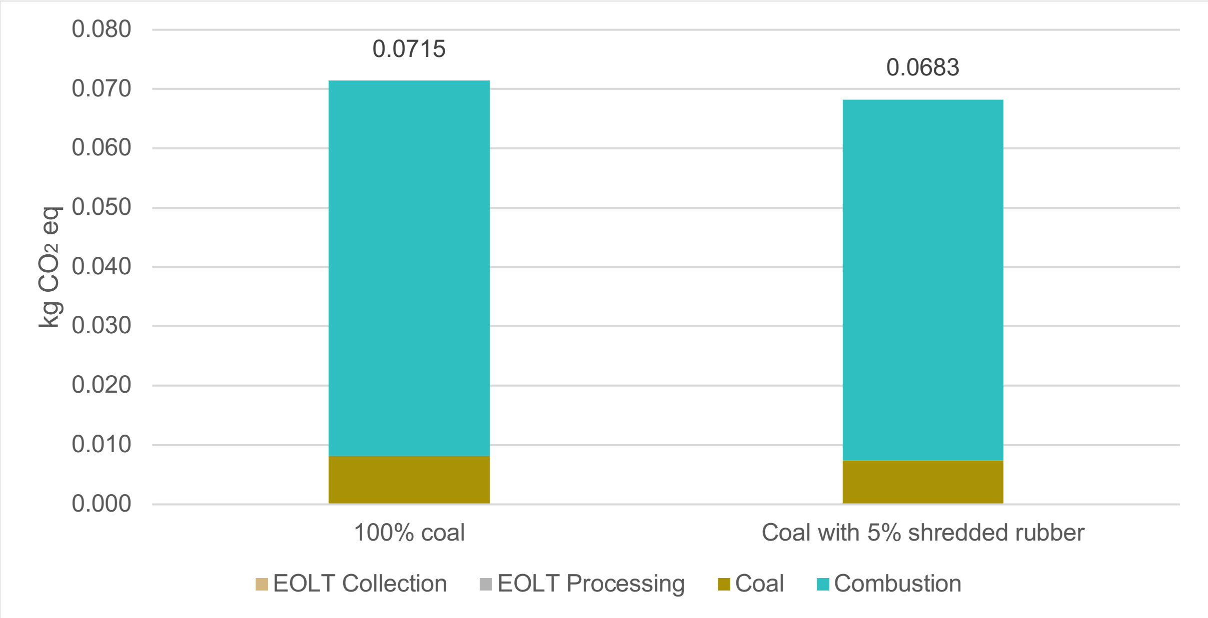

Figure 15 | Potential GHG emissions when 1 MJ of energy is generated from combustion in cement kilns using 100% bituminous coal compared to coal with 5% shredded rubber.

8.4 Sensitivity Analysis

Sensitivity analysis is used to test and explore key assumptions, data uncertainties and to provide a depth of information to meet the goals stated. As the study focuses on the potential impacts of EOLT processing and TDPs compared to their conventional counterparts, the key uncertainties considered are as follows:

- Collection and transportation of waste tyres to tyre processers. There is considerable variation in distances and truck types used, and so reasonable assumptions were made based on anecdotal evidence provided by Australian tyre recyclers.
- Varying technologies between processors for the processing of EOLTs into crumb rubber, granules and shreds. There were two sources of LCI data which represented different processes for the production of crumb rubber.
- Changes to performance of end market products through the inclusion of recycled rubber material. Research is currently being conducted into the potential improvement in the performance of roads with the inclusion of crumb rubber binders.
- The proportion of recycled rubber material in end market products.

8.4.1 Impact of EOLT Collection

The potential environmental impacts of illustrative EOLT collection distances are shown in Table 45 per tkm, a unit of measure for freight transport that multiples the distance travelled by the weight of goods transported. One tkm represents the transport of one tonne of goods over a distance of one kilometre. The results show that smaller vehicles typically generate higher impacts per tonne of load compared to larger trucks, because the energy consumption for a smaller truck is proportionally higher than a larger truck per tonne of goods.

Table 45 | Potential impacts of EOLT collection per tkm.

Impact category	Unit	10t truck	20t truck	40t truck
GWP fossil	kg CO_2 eq	1.59	0.57	0.32
GWP biogenic	kg CO_2 eq	0.00	0.00	0.00
GWP land use	kg CO_2 eq	0.00	0.00	0.00
GWP total	kg CO_2 eq	1.59	0.57	0.32
Eutrophication, terrestrial	mol N eq	0.04	0.01	0.01
Ecotoxicity, freshwater	CTUe	11.96	4.33	2.51
Water scarcity	m^3 equivalent deprived	0.53	0.17	2.86
Resource use - fossil	MJ	20.09	7.63	4.44

The potential GHG emissions impact of illustrative EOLT collection distances are shown in Table 46. For the scenarios assessed, the worst case was 500 km interstate travel in a 10 t truck (794 kg CO2-e/ t tyres) and the best case 50 km urban travel in a 40 t truck (16 kg CO2-e/ t tyres). The results for a 40t truck at all distances are relatively insignificant compared to the GHG emissions from the landfill of the tyres. Encouragement of widespread recycling of EOLTs would allow for higher capacity trucks to be used, and ensure adequate quantities are able to be collected with each collection run. Proximity of the processing facility to the location of EOLTs is also important, particularly as the bulky nature of EOLTs means that transport of EOLTs is less efficient than the recycled rubber output.

Table 46 | Potential GHG impacts of EOLT collection per tkm with illustrative distances.

Truck Type	Approx. full capacity*	kg CO_2-e emissions per tkm	kg CO_2-e emission per t EOLT, for fixed distances		
			50km (urban)	200km (regional)	500km (interstate)
10t Truck	300 EPU	1.59	79.44	317.76	794.40
20t Truck	800 EPU	0.57	28.27	113.10	282.74
40t Truck	1500 EPU	0.32	16.11	64.44	161.10

*Note – each EPU is 8 - 9 kg, so 300 EPU is 2.4 – 2.7 tonnes.

Figure 16 shows the impact of adjusting the waste tyre collection assumption from 125 km to 250 km and 500 km on GHG emissions for each end market scenario, compared to the conventional product. Distances can be highly variable depending on the location of the waste tyres, particularly in regional locations. The increase from 125 km to 250 km and 500 km had little effect on overall impacts for end market use cases where recycled rubber content is relatively low. However, these results show that collection can be a significant component of overall environmental impact, particularly in cases when rubber content is high or where only cradle impacts (product materials only) are considered, for example, in scenario 9 and 10. In these cases, it is particularly important to consider how the collection of EOLTs can be optimised to reduce transportation distances and therefore environmental impacts.

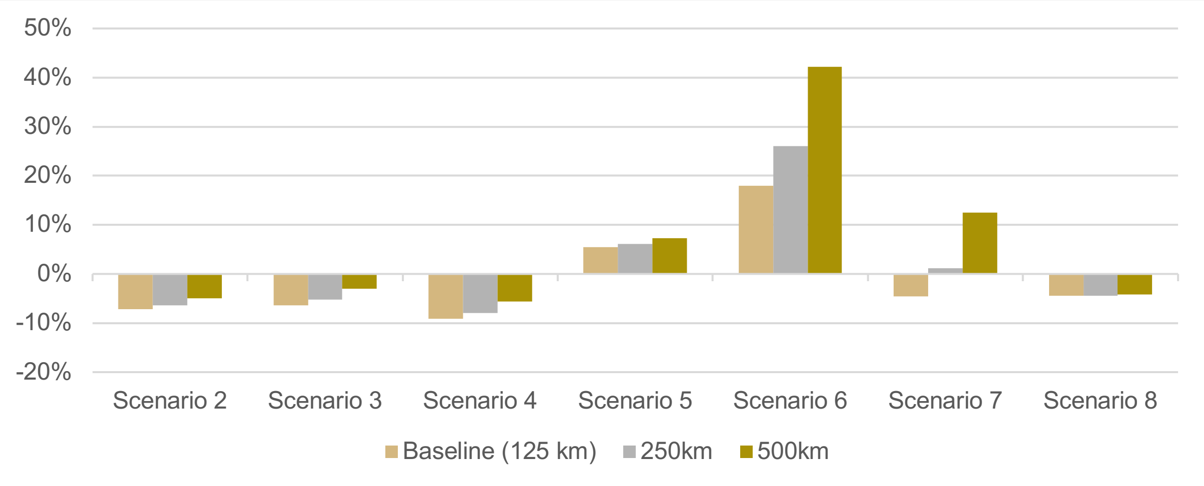

Figure 16 | Effect of increasing EOLT collection distances on the overall emissions impact as a percentage difference compared to the conventional product. For example, in Scenario 2, the baseline scenario reduces overall emissions impacts by 7% compared to the conventional scenario. This becomes a 5% reduction in emissions impact in the 500 km scenario.

Impact of Different Processing Technologies

Table 47 compares the processing of crumb rubber using two alternative data sources. The processing data used for this report from AEPD has lower environmental impacts in all environmental impact categories except water scarcity. GHG emissions and reliance on fossil-based resources are both 7% lower. Eutrophication and ecotoxicity impacts are both 15% lower. However, water scarcity impacts are 8 times higher.

Table 47 | Potential impacts of different crumb rubber processing technologies.

Impact category	Unit	Asphalt PCR (AEPD, 2019) - currently used	TSA study (Rouwette, 2020)
GWP fossil	kg CO_2 eq	453.46	484.10
GWP biogenic	kg CO_2 eq	0.75	2.54
GWP land use	kg CO_2 eq	0.00	0.00
GWP total	kg CO_2 eq	454.21	486.64
Eutrophication, terrestrial	mol N eq	4.73	5.53
Ecotoxicity, freshwater	CTUe	1563.29	1821.06
Water scarcity	m^3 equivalent deprived	12482.50	1485.18
Resource use - fossil	MJ	2356.99	2545.58

The differences can be explained by difference in the processes being quantified:

- The Asphalt PCR produces fine rubber granules and crumb rubber in one single process, whereas the primary sources in the TSA study separates the three processes, with the output of each process used as feedstock into the next.
- The Asphalt PCR process uses electricity as the primary energy source to produce crumb rubber, whereas the TSA study uses LPG in addition to electricity. These fuel sources each have a different environmental impact profile.
- The TSA study includes the diesel required to forklift the pre-shredded EOLT between the tyre shredders and the tyre granulators within the recycling plant, which is not required in the Asphalt PCR.

These results illustrate the sensitivity of the overall environmental benefits of TDPs to the processing technology and therefore the importance of continued innovation in EOLT processing technology and commitment to clean energy sources.

8.4.2 Impact of Performance Improvement for Road Construction

To illustrate the potential impact of potential performance improvement from the use of recycled rubber, the impact of changes to the lifespan of roads constructed with a crumb rubber binder has been calculated. Initial research suggests a crumb rubber binder increases the road lifespan from 6 years to 9 years compared to a conventional bitumen binder. Note this scenario compares a crumb rubber binder to a PMB binder, research is still being conducted on the potential improvements compared to a PMB binder. GHG emissions attributed to the asphalt mixes with crumb rubber binders are reduced by 38-41% compared to an asphalt mix with a comparable PMB binder content. This is compared to 6-12% reduction when the lifespan is not adjusted.

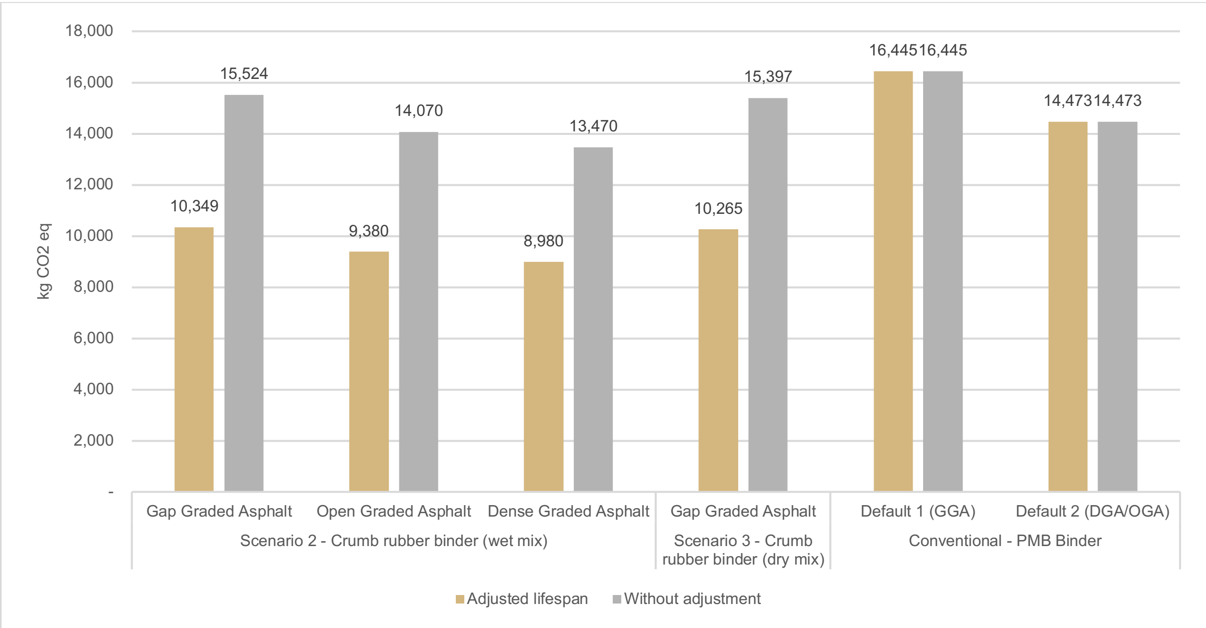

Figure 17 | Comparison of total GWP impacts for a crumb rubber binder compared to a conventional binder in asphalt mixes used the construction of 1 km of road over a 6-year lifespan. The adjusted lifespan assumes the crumb rubber binder extends the lifespan of the road from 6 years to 9 years.

When adjusted for lifespan, there is significant improvement across all environmental impact indicators for asphalt mixes produced using both the wet and dry process. This is despite the high binder content, particularly in the GGA mix considered in the dry process. Eutrophication and ecotoxicity impacts are reduced by approximately 35% and 30% respectively for the wet and dry processes. Water scarcity impacts are also reduced, by 16% and 2% respectively. These results demonstrate that it is important to consider potential performance and other benefits in encouraging the uptake of TDPs. The potential lifespan extension of roads through use of crumb rubber should be further researched and assessed to identify the exact benefits of the TDPs.

Table 48 | Potential impacts of crumb rubber binder compared to a conventional binder in an average asphalt mix used the construction of 1 km of road over a 6-year lifespan. The adjusted lifespan assumes the crumb rubber binder extends the lifespan of the road from 6 years to 9 years.

Impact category	Unit	TDP: Crumb Rubber Binder (Wet Process) – GGA, adjusted	TDP: Crumb Rubber Binder (Wet Process) – OGA, adjusted	TDP: Crumb Rubber Binder (Wet Process) – DGA, adjusted	TDP: Crumb Rubber Binder (Dry Process) – GGA, adjusted	Conventional: PMB Binder – Default 1 (GGA)	Conventional: PMB Binder – Default 2 (DGA / OGA)
GWP fossil	kg CO_2 eq	10,332.92	9,363.15	8,966.73	10,248.19	16,414.43	14,445.10
GWP biogenic	kg CO_2 eq	14.89	15.23	12.32	15.20	29.07	26.20
GWP land use	kg CO_2 eq	1.25	1.34	1.04	1.25	1.56	1.57
GWP total	kg CO_2 eq	10,349.06	9,379.72	8,980.09	10,264.64	16,445.06	14,472.88
Eutrophication, terrestrial	mol N eq	102.38	92.94	87.13	101.83	149.78	132.35
Ecotoxicity, freshwater	CTUe	683,298.46	553,588.27	535,940.37	630,154.56	1,061,349.00	826,027.25
Water scarcity	m^3 equivalent deprived	71,117.55	62,943.98	60,106.93	76,618.98	80,765.43	74,537.41
Resource use - fossil	MJ	87,513.16	85,354.77	81,244.07	88,286.81	160,912.81	148,362.40

8.5 Overall Benefits of Processing EOLTs and TDP End Markets

While the uptake of TDPs should be encouraged more broadly to avoid the detrimental impact of landfill, the outcomes of this study suggest there are end markets where TDPs are more effectively reducing impact compared to the conventional product. Strategies to increase uptake should therefore be targeted to TDP scenarios where environmental impact reduction is maximised.

The overall burden of EOLT-derived materials such as crumb rubber and shreds are attributed to both the collection of EOLTs and to the energy required to process the EOLTs. In most end market use cases, these impacts are relatively small compared to the overall impacts. However, the results in this report assume collection distances of 125km. As the market for TDP expands and recovery of OTR tyres improves, the collection of EOLTs is likely to involve collection of tyres in more regional and remote areas where distances can be quite significant. Long distances and inefficient loading would degrade the potential environmental benefits of TDPs, and potentially even increase impacts. Exploration of how logistics can be optimised and scaled will play an important role in ensuring that the TDPs still offer environmental impact reductions. The location of processing facilities is also important, as there are currently limited facilities which are concentrated in urban areas within Australia. As markets expand, it is worthwhile considering how processing and/or consolidation locations can be optimised to reduce transport distances.

Energy requirements are the dominant contributor to processing EOLTs, for example, contributing over 90% to the GHG emissions of physical decomposition. This is particularly relevant for finer grade rubber outputs such as crumb rubber. There is potential for a green crumb rubber processed with renewable energy. Facilitating this transition to cleaner energy sources can help existing tyre recyclers further reduce the impacts of EOLT processing. This would result in even more compelling environmental impact reductions, particularly in water scarcity impacts.

The results showed reductions in environmental impact when the processed EOLT material replaces conventional materials with high environmental burden, such as bitumen or coal. However, in scenarios where the recycled rubber is replacing a low-impact material such as sand or aggregates, environmental impacts are worse compared to the conventional case. This highlights the importance of identifying the appropriate end market for TDPs, such as the replacement of high-impact fossil-based materials. While GHG emissions are the dominant concern for key stakeholders, it is important to consider whether the use of a TDP causes detriment in other environmental impact categories.

9 Reporting, Certification & Compliance Considerations & Fiscal Opportunities

In conjunction with understanding the GHG emissions of various EOLT and TDP pathways, it is important to understand the relevant reporting, certification and compliance schemes that apply to producers and purchasers of EOLTs and TDPs. These may be either mandatory or voluntary, and span emissions quantification and certification schemes, reporting programs and initiatives, and standards and regulatory frameworks. Alongside these, there is opportunity to leverage carbon trading and funding mechanisms (e.g., government grants) to realise benefits in producing or purchasing EOLT and TDP products and pursue further development of these products.

The following sections provide an overview of the available schemes, alongside an indicative rating scheme of the relevance and impact of each scheme for producers and purchasers respectively.

The work completed in Stage 1 and Stage 2 of this report provides a foundation to identify the TDP use cases that are likely to be most beneficial. This information can be read in conjunction with those use cases in mind to identify the most relevant schemes to target for that particular industry. The modelling completed in this report has been based on EPD standards, which is recognised by a range of existing certification schemes. In terms of next steps, once a relevant reporting or certification scheme has been identified, the work in this report can be updated and extended for the particular scenario before following the required verification or scheme-specific processes.

9.1 Evaluation Criteria and Approach

To help producers and purchasers understand the relevance of each scheme or initiative, and select the best option(s) for their business, a rating has been applied, assessing each scheme against four criteria:

Robustness: Does the scheme require third-party verification or is compliance to certification requirements self-declared?

Uptake: Does the scheme demonstrate breadth and depth of uptake by producers/purchasers at a national scale? E.g., multiple large-scale organisations, or uptake across multiple industries.

Impact: Is the reporting based on transparency in reporting, or does it promote impact reduction initiatives?

Eligibility: Are producers/purchasers eligible to become accredited against the scheme, and is it accessible to acquire (e.g., applicable fees are reasonable).

For each criterion, a value of 1 or 0 is applied depending on whether the scheme demonstrates the best-value outcome or not. Table 56 below demonstrates how this rating is applied to each scheme.

Table 49 | Rating System applied to Evaluation Criteria

Criterion	Greater Outcome (1)	Lesser Outcome (0)
Robustness	Third-party verified	Self-declared
Uptake	Widespread uptake of scheme	Minimal demonstrated uptake of scheme across industry
Impact	Impact reduction	Transparent reporting only
Eligibility	Eligible & accessible	Not eligible and/or accessible

For example, a scheme that is third-party verified, demonstrates uptake across the national industry, is based on transparent reporting and is applicable to EOLT/TDP producers and purchasers, would attract a score of 3 out of 4.

9.2 Reporting & Certification Schemes

9.2.1 Quantification Schemes

Quantification schemes use scientifically rigorous processes to communicate the environmental credentials of a product, service or organisation. It also provides the opportunity to assess the full product value chain from a scientifically rigorous perspective, often leading to the identification of new opportunities for efficiencies, engagement both within and outside an organisation and new opportunities for communication and market positioning.

Under ISO 14020, there are three types of environmental labelling:

Type I environmental labelling - these are eco-labelling schemes with clearly defined criteria for products. These are governed by ISO 14024 and includes eco-labels such as the GECA ecolabel, Global Green Tag Certification and Green Tick Sustainable Certified. These schemes will often rate a product or service based on its environmental performance, using transparent and well-defined criteria for the evaluation.

Type II self-declared environmental claims – these are labels developed by the producer themselves and are neither criteria nor labelling schemes. These are governed by ISO 14021.

Type III environmental declarations – these are schemes that specify a format for reporting quantifiable life cycle data. These are governed by ISO 14025 and includes Environmental Product Declarations (EPDs) and Climate Active. These schemes will not rate environmental performance, but instead provides an objective, scientifically rigorous process to understand the full product or service value chain.

Table 50 to Table 53 summarises the key environmental labels used in Australia - GECA, EPDs and Climate Active. In addition to environmental labelling, there are other tools and standards available that facilitate the calculation and understanding of environmental emissions. The objective of these tools may be to simply aid calculation, such as the AfPA LCA calculator for asphalt in

Table 54, or form part of their own certification schemes, such as the Infrastructure Sustainability Council of Australia's rating tool in Table 55.

Table 50 | GECA Ecolabel

<table>
<tr><th></th><th colspan="5">Scheme Details</th></tr>
<tr><td>Summary</td><td colspan="5">The Good Environmental Choice Australia (GECA) ecolabel is a verified Type I ecolabelling program. GECA considers a range of environmental impacts across the entire life cycle of a product and service. It also looks at social impacts such as safe and ethical working conditions within the supply chain. It has issued ecolabels across a broad range of products and services in green building, hospitality, education, healthcare, government, and consumer sectors. It is designed as a tool to empower consumers and producers to choose products that are made in the most planet friendly way. It helps communicate to consumers that the product or service is taking environmental responsibility seriously and helps government and other product purchasers make informed procurement decisions.</td></tr>
<tr><td>Applicability to Producers and Purchasers</td><td colspan="5">For EOLT/TDP producers, GECA certification is a marketing tool to promote the environmental benefits of their products and increase their customer base.

For purchasers, the GECA label is a clear indication of the environmental benefits. The credentials also make it easy to comply with key green infrastructure schemes.</td></tr>
<tr><td>Governing Body</td><td colspan="5">Good Environmental Choice Australia</td></tr>
<tr><td>Applicable Region</td><td colspan="5">Australia</td></tr>
<tr><td>Recognition with other schemes</td><td colspan="5">GECA complies with ISO 14024 standards. GECA certified products are recognised by key infrastructure schemes such as Green Building Council of Australia’s (GBCA) Green Star and the Infrastructure Council of Australia (ISCA) rating scheme. GECA and EPD Australasia have also announced an agreement to provide discounts to support the obtaining of both ecolabels and EPDs.</td></tr>
<tr><td>Assessment Process</td><td colspan="5">The application process involves the submission of an application form, after which GECA will review the product and appoint an independent third-party provider to assess the product. If successful, the business is awarded a GECA license, and the ecolabel can be used on their products.</td></tr>
<tr><td>Assessment Criteria</td><td colspan="5">Comprehensive standards for each product category, for example, recycled products.</td></tr>
<tr><td>Accreditation Model</td><td colspan="5">Ongoing audit requirements</td></tr>
<tr><td>Applicable fees</td><td colspan="5">Initial certification and registration fee and then an annual license fees estimated based on first year turnover. The initial fees have not been disclosed.</td></tr>
<tr><td>Further information</td><td colspan="5">https://geca.eco/</td></tr>
<tr><td rowspan="2">Rating</td><td>Robustness</td><td>Uptake</td><td>Impact</td><td>Eligibility</td><td>Total</td></tr>
<tr><td>1</td><td>1</td><td>1</td><td>1</td><td>4/4</td></tr>
</table>

Table 51 | Environmental Product Declaration (EPD) scheme

	Scheme Details
Summary	An EPD is an independently verified and registered document that communicates transparent and comparable data on environmental impacts about the life cycle of a product. It is a scientifically rigorous process that quantifies impacts but does not provide an environmental performance rating for the product. As such, it is a Type III environmental declaration under ISO 14025. EPDs are useful for explaining the impacts at each aspect of the product life cycle. It ensures consistency within product categories, ensuring data is comparable so that business customers and consumers are able to make informed decisions. EPDs are increasingly essential to enable participation in sustainable supply chains and major infrastructure projects, with many projects mandating EPDs for the products they procure. Note that while EPDs are generally done for specific products and processes, a sector wide EPD can also be developed to encourage the use of the product category more generally and also support industry members to develop their own EPDs. Edge is currently developing a sector-wide EPD for Cement, Concrete and Aggregates Australia for clinker, cement and concrete products, with the objective to provide the necessary information to encourage further use of these products.
Applicability to Producers and Purchasers	**Producers** can choose to develop an EPD for their product to provide transparency and accountability of product emissions and impacts. EPDs are also recognised by key eco-labelling schemes, creating additional marketing opportunities. **Purchasers** can rely on published EPD data to understand the environmental impact of the EOLT/TDP product and make an informed decision. EPDs are also recognised under key rating schemes, therefore streamlining sustainable procurement processes.
Governing Body	EPD Australasia
Applicable Region	Australia and New Zealand
Recognition with other schemes	EPDs are eligible for Climate Active certification. They are also recognised for under green rating and eco-labelling schemes, such as Green Star, ISCA and GECA.
Assessment Process	Producers would seek technical expertise to assist in the development of an EPD, including undertaking a life cycle assessment, reporting on environmental and technical information, relevant product comparisons, and impacts. Once prepared, the EPD must be subjected to a third-party verification process to verify the data and claims made, and compliance with the relevant PCR. The verified EPD is then registered and published by EPD – Australasia. An LCA study must be undertaken and a background LCA report and EPD report produced for third-party verification. Once certified, the EPD is registered and published on the EPD website.
Assessment Criteria	The methodology is based on the relevant PCR for the product studied. For example, construction products follow the guidelines set in *EN 15804+A2:2019 Sustainability of construction works – environmental product declarations – core rules for the product category of construction products*. For buildings and civil engineering works, the standards to follow are *ISO 21930:2017 Sustainability in buildings and civil engineering works – core rules for environmental product declarations of construction products and services*.
Accreditation Model	EPDs are typically valid for a period of five years unless the product content or processes materially change.

	Scheme Details
Applicable fees	To develop an EPD, producers will be subject to fees for technical experts to undertake the EPD LCA and reporting, and third-party verification, along with a one-off registration fee. The EPD registration fee is $1,785 for an organisations' first EPD, however heavily discounted for subsequent EPDs. Most of the cost incurred will be in the development of the EPD. This will vary depending on the technical expert and third-party verifier engaged.
Further information	https://epd-australasia.com/

Rating	Robustness	Uptake	Impact	Eligibility	Total
	1	1	0	1	**3/4**

Table 52 | ANZ EPD Climate Declarations

	Scheme Details
Summary	A statement declaring carbon emissions for an organisation, as a supplementary communication to full EPDs (Environmental Product Declarations).
Applicability to Producers and Purchasers	Relevant to all EOLT/TDP applications. Should a **Producer** choose to pursue an EPD for a product, producers can register to declare the applicable emissions for this product to establish reputability from end users and purchasers by demonstrating transparency. N/A for **Purchasers**, however purchasers can benefit from producers pursuing this declaration to help inform purchasing decisions.
Governing Body	EPD Australasia
Applicable Region	Australasia
Assessment Process	Completion of a registration form as an extra step to the EPD process.
Assessment Criteria	**N/A – criteria is addressed within EPD process (** Table 51).
Accreditation Model	N/A
Applicable fees	Not applicable; all fees relate to the EPD process itself.
Further information	epd-australasia.com/climate-declarations/

Rating	Robustness	Uptake	Impact	Eligibility	Total
	1	1	1	1	**4/4**

Table 53 | Climate Active Carbon Neutral Certification

	Scheme Details				
Summary	Carbon neutral product, service and/or organisation certification; a public reporting scheme that allows organisations to demonstrate actions are being taken to offset emissions produced by their organisation or for a specific product or service.				
Applicability to Producers and Purchasers	Relevant to all EOLT/TDP applications. **Producers/Purchasers** can demonstrate their EOLT processing operations or TDP product, and/or organisation is carbon neutral by presenting an inventory of the GHG emissions of their product/operations, and subsequent actions to offset these emissions.				
Governing Body	Climate Active, on behalf of the Australian Government				
Applicable Region	Australia-wide				
Assessment Process	Applicants prepare a Product Disclosure Statement (PDS) and Inventory of carbon emissions sources (in partnership with a registered Climate Active consultant) to demonstrate total emissions production to be neutralized by carbon offset activities. If applicants have already developed and Environmental Product Declaration (EPD) for their product, the process and fees can be streamlined given most data and verification is already completed as part of the EPD process.				
Assessment Criteria	Carbon inventory and demonstrated plan to offset calculated emissions to be presented for third-party verification.				
Accreditation Model	Active if an active License Agreement with Climate Active is in place (annual agreement).				
Applicable fees	Fees include cost of engaging a Registered Climate Active consultant to prepare the certification documentation (PDS and inventory), fee for a third party to undertake the verification, costs for offsets and certification through Climate Active (varies for each application).				
Further information	Climateactive.org.au				
Rating	**Robustness**	**Uptake**	**Impact**	**Eligibility**	**Total**
	1	1	1	1	**4/4**

Table 54 | AfPA LCA calculator for asphalt

	Scheme Details				
Summary	An LCA calculator developed in 2021 as a quick and easy way for asphalt producers to calculate the cradle-to-grave environmental footprint of their products, using specific data from their asphalt plants. The tool has flexibility to cover a broad range of mix designs.				
Applicability to Producers and Purchasers	This tool is an easy way for TDP **producers** and EOLT **purchasers** to assess the environmental footprint of TDP for asphalt applications. While the figures cannot be used for certification, the tool can be used to inform product design considerations and possible avenues for further research.				
Governing Body	Developed by start2see for the Australian Flexible Pavement Association (AfPA)				
Applicable Region	Australia				
Recognition with other schemes	Endorsed by AfPA but not currently recognised by any certification schemes. The methodology aligns with EPD EN 15804+A1.				
Assessment Process	Simply input plant and product specific mixes and the tool will output the environmental impacts of the mix.				
Assessment Criteria	N/A				
Accreditation Model	N/A				
Applicable fees	Free				
Further information	https://form.123formbuilder.com/6005084/form				
Rating	**Robustness**	**Uptake**	**Impact**	**Eligibility**	**Total**
	1	0	0	1	**2/4**

Table 55 | IS Rating Scheme, Infrastructure Council of Australia (ISCA)

<table>
<tr><th></th><th colspan="5">Scheme Details</th></tr>
<tr><td>Summary</td><td colspan="5">The IS rating scheme is a method used by the Infrastructure Sustainability Council of Australia (ISCA) to evaluate the overall economic, social and environmental performance of infrastructure assets, across the planning, design, construction and operational phases of infrastructure assets. It is a voluntary, third party assured assessment. The tool is less prescriptive than rating systems such as Green Star and LCA, allowing for more flexibility in proving compliance.

The rating scheme is split by process stage - an IS Planning rating, an IS Design and As-Built rating and an IS Operations rating. The program also has rating schemes for projects between $5-100m (IS Essentials) and for global assets (IS International).

The ratings are an opportunity to encourage dialogue with stakeholders including the leadership team and suppliers. The rating system also helps identify sustainability initiatives, for example, developing an EPD for a product so that the project team can understand the GHG emissions involved and therefore make greater sustainability gains.</td></tr>
<tr><td>Applicability to Producers and Purchasers</td><td colspan="5">For producers, it will be advantageous to ensure their products are well positioned in light of the ratings scheme and may include developing EPDs or being accredited under certification schemes.

Purchasers will be seeking to understand the environmental impact of TDP for inclusion into the IS ratings for large infrastructure projects.</td></tr>
<tr><td>Governing Body</td><td colspan="5">Infrastructure Council of Australia</td></tr>
<tr><td>Applicable Region</td><td colspan="5">Australia</td></tr>
<tr><td>Recognition with other schemes</td><td colspan="5">Revisions have been made to v2.0 of the scheme to align with EPD impact assessment methodology and EN 15804.</td></tr>
<tr><td>Assessment Process</td><td colspan="5">The process involves registration with the council, assessment, independent third-party verification and finally certification.</td></tr>
<tr><td>Assessment Criteria</td><td colspan="5">IS ratings can be applied to projects with a total value greater than $50 million or where the project falls under a set of defined categories (including roads, waste to energy, parks and other open spaces). The framework consists of 17 categories across governance, resource use, emissions and pollution, ecology, people and place, innovation, workforce and economic.</td></tr>
<tr><td>Accreditation Model</td><td colspan="5">One off, except for the IS Operations rating which is reviewed annually.</td></tr>
<tr><td>Applicable fees</td><td colspan="5">Fees will vary based on whether the organization has membership with the council, the project value and the rating scheme sought. Fees range from $9,500 - $131,500.</td></tr>
<tr><td>Further information</td><td colspan="5">https://www.iscouncil.org/is-ratings/</td></tr>
<tr><td rowspan="2">Rating</td><td>Robustness</td><td>Uptake</td><td>Impact</td><td>Eligibility</td><td>Total</td></tr>
<tr><td>1</td><td>1</td><td>1</td><td>0</td><td>3/4</td></tr>
</table>

9.2.2 Voluntary Reporting

Voluntary reporting schemes relate to initiatives that allow producers/purchasers to publish their GHG emissions and related activities to provide transparency and reputability to industry stakeholders and/or end users. Relevant schemes to EOLT/TDP producers/purchasers in the Australian landscape are identified in Table 52 through to Table 62 below.

Table 56 | Science Based Targets

	Scheme Details				
Summary	Global mechanism for private sector to commit to targets to limit GHG emissions in line with the Paris Agreement. Targets include a near-term target and a net-zero long term target, aiming to align an organisations' activities to help achieve a global warming of less than 1.5C or less than 2C compared to pre-industrial levels.				
Applicability to Producers and Purchasers	Relevant to all applications of EOLT/TDP. A **Producer** or **Purchaser** can choose to pursue and commit to science-based targets at an organisation level. EOLT processing, TDP production and TDP purchase will be accounted for within the Science-based target commitment of a producer or purchaser respectively.				
Governing Body	Science Based Targets initiative (SBTi); a partnership between CDP, UN Global Compact, World Resources Institute and WWF.				
Applicable Region	Global				
Assessment Process	The producer or purchaser organisation must submit a letter establishing intent to set target to commence the process. Once a commitment is formalized, organisations develop a target for emissions reduction in accordance with criteria set out by the SBTi. Targets can be near-term and/or net zero targets. The target will need to be presented to the SBTi for validation, and once validated, must be communicated to stakeholders. Ongoing reporting and monitoring of emissions must occur annually.				
Assessment Criteria	The validation process assesses target boundary, scope (1, 2, 3) boundary, GHG scope, emissions coverage, method validity (for calculating emissions), target formulation, ambition, sector-specific guidance. Assessment is undertaken by a team of 'technical experts' employed by SBTi.				
Accreditation Model	On-going.				
Applicable fees	Validations fees are $2,000 for small & medium enterprises, and $14,500 for large businesses. Associated costs may include target setting advisory and calculation, and communication fees.				
Further information	https://sciencebasedtargets.org/				
Rating	**Robustness**	**Uptake**	**Impact**	**Eligibility**	**Total**
	1	1	1	1	**4/4**

Table 57 | Carbon Disclosure Project

<table>
<tr><th></th><th colspan="5">Scheme Details</th></tr>
<tr><td>Summary</td><td colspan="5">Global disclosure system for public and private sector to manage environmental impacts. Carbon Disclosure Project (CDP) is a not-for-profit charity that provides advisory and data to support companies and cities in disclosing their environmental impacts. The CDP disclosure process is aligned with TCFD (Task Force on Climate-Related Financial Disclosures) requirements.</td></tr>
<tr><td>Applicability to Producers and Purchasers</td><td colspan="5">Relevant to all applications of EOLT/TDP.

If requested/required by end users and investors, Producers and Purchasers can utilize CDP to calculate their impacts, leverage the CDP data set to identify and implement risk mitigation initiatives, and disclose this information to their end users, investors and public.</td></tr>
<tr><td>Governing Body</td><td colspan="5">CDP – not-for-profit charity</td></tr>
<tr><td>Applicable Region</td><td colspan="5">Global</td></tr>
<tr><td>Assessment Process</td><td colspan="5">Organisations prepare and collate data on environmental impacts in their organizational activities and submit to the CDP for feedback and advisory on how to reduce impact and risk. The CDP provides a questionnaire to assist in the solution identification process. Organisations can choose to implement mitigation activities based on the CDP advice. Data submitted to CDP can also be shared with investors and end users, and the public.</td></tr>
<tr><td>Assessment Criteria</td><td colspan="5">CDP provides advisory on opportunities for reducing impact and risk.

CDP undertakes an annual scoring and ranking of companies on their disclosure process and demonstrated environmental leadership. These are accessible only by CDP disclosure participants.</td></tr>
<tr><td>Accreditation Model</td><td colspan="5">On-going</td></tr>
<tr><td>Applicable fees</td><td colspan="5">Free; organisations may choose to engage third parties to assist with the disclosure process.</td></tr>
<tr><td>Further information</td><td colspan="5">https://www.cdp.net/en</td></tr>
<tr><td rowspan="2">Rating</td><th>Robustness</th><th>Uptake</th><th>Impact</th><th>Eligibility</th><th>Total</th></tr>
<tr><td>0</td><td>1</td><td>1</td><td>1</td><td>3/4</td></tr>
</table>

Table 58 | MECLA (Materials & Embodied Carbon Leaders' Alliance)

<table>
<tr><th></th><th colspan="5">Scheme Details</th></tr>
<tr><td>Summary</td><td colspan="5">Materials & Embodied Carbon Leaders' Alliance is driving the reduction of embodied carbon in the building and construction industry. This is not a reporting scheme but a collaboration of organisations working together to reduce embodied carbon in the built environment.</td></tr>
<tr><td>Applicability to Producers and Purchasers</td><td colspan="5">Potentially relevant to all applications of EOLT/TDP; more so for crumb rubber applications however pyrolysis fuel applications may be relevant dependent on intended use.

There is an opportunity for EOLT processors, and TPD Producers and Purchasers to join MECLA as a collaborating organisation to contribute to efforts that can assist in the uptake of their product by end-users. For example, contribute to schemes that will help demonstrate demand for their product, capture and communicate best practice case studies, accelerate material supply, standardize procurement guidelines, and manage risk.</td></tr>
<tr><td>Governing Body</td><td colspan="5">NSW Government, WWF Australia, and Climate-KIC Australia</td></tr>
<tr><td>Applicable Region</td><td colspan="5">Australia-wide</td></tr>
<tr><td>Assessment Process</td><td colspan="5">N/A</td></tr>
<tr><td>Assessment Criteria</td><td colspan="5">N/A</td></tr>
<tr><td>Accreditation Model</td><td colspan="5">N/A</td></tr>
<tr><td>Applicable fees</td><td colspan="5">$10,000</td></tr>
<tr><td>Further information</td><td colspan="5">www.Mecla.org.au</td></tr>
<tr><td rowspan="2">Rating</td><td>Robustness</td><td>Uptake</td><td>Impact</td><td>Eligibility</td><td>Total</td></tr>
<tr><td>0</td><td>1</td><td>1</td><td>1</td><td>3/4</td></tr>
</table>

Table 59 | GHG Protocol

	Scheme Details
Summary	GHG Protocol is a global framework for measuring emissions and mitigation actions; global accounting standard for GHG reporting. It can be used together with reporting frameworks as a way to complete the calculation. GHG Protocol also offers a range of tools to enable companies and cities to develop comprehensive and reliable inventories of their GHG emissions and track their progress. These range from cross sector tools to country specific and specific tools, plus tools for countries and cities to track their progress. For example, there are tools for calculation of the GHG emissions from stationary combustion, cement, and aluminium. The aluminium tool is an example that was jointly developed by the International Aluminium Institute and the GHG protocol. While the current standards are generally to identify hot spots in a product life cycle, the intention is that in the future, industries will be able to build off the product standard to develop industry specific product rules. Note these standards are voluntary, developed based on the need for global standards and developed with a broad range of stakeholders across private, public, and academic sectors.
Applicability to Producers and Purchasers	**Producers** should publish credible and transparent information on the GHG emissions of EOLT/TDP to attract purchasers who are wishing to reduce their carbon footprint under these standards. **Purchasers** of EOLT/TDP whom use the GHG Protocol corporate accounting standards will find it useful if there is easy access to information pertaining to the GHG emissions of the products they have purchased. They may also use this information to make an informed judgment on the products they should purchase to reduce their overall footprint.
Governing Body	World Resources Institute (WRI) and World Business Council for Sustainable Development
Applicable Region	Global
Recognition with other schemes	The Climate Active Carbon Neutral Standard for organisations is based on the principles outlined in the GHG Protocol – Corporate Standard. EPDs can be used to calculate emissions under the GHG protocol.
Assessment Process	The standards and tools can be adopted and used as desired by the organisation. WRI does offer a verification process where a 'Build on GHG Protocol' mark can then be used once approved. Currently, WRI is not accepting new applications for the mark.
Assessment Criteria	The GHG protocol standards can be found at https://ghgprotocol.org/standards and the criteria for the mark at https://ghgprotocol.org/guidance-built-ghg-protocol.
Accreditation Model	Ongoing
Applicable fees	All GHG Protocol resources, including standards, guidance reports and calculation tools, are free to download and use. The cost of attaining a 'Built on GHG Protocol' mark with verification by WRI will vary based on the size and complexity of the project or organisation.
Further information	https://ghgprotocol.org/about-us

Rating	Robustness	Uptake	Impact	Eligibility	Total
	1	1	0	0	**2/4**

Table 60 | Declare Product Labelling

	Scheme Details				
Summary	Scheme that generates industry recognised product labels declaring key product information including whether it includes materials on the Living Building Challenge Red List, part of the International Living Future Institute's Living Future Challenge philosophy and tools.				
Applicability to Producers and Purchasers	Relevant to all applications of EOLT/TDP. **Producers** can use this scheme to disclose information about their EOLT/TDP product including product ingredients, any chemicals of concern, assembly locations, life expectancy, and end-of-life options. This can contribute to further circularity of the product and improved supply chain tracking of the material. N/A to **Purchasers** however pursuit of a Declare label by producers can provide confidence and transparency in product for purchasers when making purchasing decisions.				
Governing Body	International Living Future Institute				
Applicable Region	Global				
Assessment Process	Producers to submit an application with required product information (e.g. final assembly locations, life expectancy, end-of-life options, product description, product 'ingredients'), for review by the International Living Future Institute. Third-party review is optional.				
Assessment Criteria	Assessed for compliance against the Living Building Challenge Red List (compliant or not).				
Accreditation Model	Annual				
Applicable fees	$1,000 USD per label plus annual ILFI membership (POA).				
Further information	www.Living-future.org.au/declare				
Rating	**Robustness**	**Uptake**	**Impact**	**Eligibility**	**Total**
	0	1	0	1	**2/4**

Table 61 | Global Reporting Initiative Standards

	Scheme Details				
Summary	An independently established set of global standards for best practice sustainability reporting to encourage transparency in organisation operations. The standards provide a common language and template for organisations to report their impact and actions being taken to mitigate or reduce these impacts.				
Applicability to Producers and Purchasers	Relevant to all EOLT/TDP applications. **Producers** and **Purchasers** can leverage the Global Reporting Initiative (GRI) Standards to develop globally recognised reports on GHG emissions, either as stand-alone reporting activities or in conjunction with other reporting or quantification schemes.				
Governing Body	Global Reporting Initiative – independent international organisation				
Applicable Region	Global				
Assessment Process	Modular standard guidelines are provided for free by GRI. Organisations can choose to use the standards to guide reporting unofficially, or choose to align with standards in completeness, and register their report(s) with GRI.				
Assessment Criteria	N/A - GRI does not verify, check or 'pass judgement' on quality of disclosures; organisations self-declare that their report aligns.				
Accreditation Model	On-going				
Applicable fees	Free				
Further information	https://www.globalreporting.org/				
Rating	**Robustness**	**Uptake**	**Impact**	**Eligibility**	**Total**
	0	1	0	1	**2/4**

Table 62 | Construction Materials: Sustainability Accounting Standard

<table>
<tr><th></th><th colspan="5">Scheme Details</th></tr>
<tr><td>Summary</td><td colspan="5">Sustainability Accounting Standards Board (SASB) produce a set of standards that guide organisations in communicating potential impact of sustainability issues on a businesses' finances, and governance & management requirements. These standards can be used as a tool for implementing the framework provided by the TCFD and are designed for reporting requirements to capital stakeholders and investor audiences.</td></tr>
<tr><td>Applicability to Producers and Purchasers</td><td colspan="5">Relevant to crumb rubber applications of EOLT/TDP.

Applicable standards to EOLT and TDP products include Construction Materials and Chemicals.

Producers and purchasers can choose to refer to SASB standards to guide reporting and communication of sustainability issues to end users, investors and other stakeholders. Production or purchasing of EOLT/TDP will affect (likely decrease impact) the environmental data for an organisation, providing an opportunity for organisations to demonstrate the benefit of EOLT/TDP product.</td></tr>
<tr><td>Governing Body</td><td colspan="5">SASB</td></tr>
<tr><td>Applicable Region</td><td colspan="5">Global</td></tr>
<tr><td>Assessment Process</td><td colspan="5">Producers/purchasers should identify the relevant standard to their organisation’s activities, sector and size. Once identified, disclosure reports are to be developed in accordance with the standards. These can be published via SASB or via selected platforms chosen by the organisation.</td></tr>
<tr><td>Assessment Criteria</td><td colspan="5">No assessment undertaken. Organisations self-declare disclosures in accordance with SASB Standards.</td></tr>
<tr><td>Accreditation Model</td><td colspan="5">N/A</td></tr>
<tr><td>Applicable fees</td><td colspan="5">N/A</td></tr>
<tr><td>Further information</td><td colspan="5">https://www.sasb.org/wp-content/uploads/2018/11/Construction_Materials_Standard_2018.pdf</td></tr>
<tr><td rowspan="2">Rating</td><th>Robustness</th><th>Uptake</th><th>Impact</th><th>Eligibility</th><th>Total</th></tr>
<tr><td>0</td><td>1</td><td>0</td><td>0</td><td>1/4</td></tr>
</table>

9.3 Compliance Considerations

Processing of EOLT and the production and/or purchasing of TDP may be subject to compliance with compulsory standards and regulations for manufacture, design, and application of TDP products. These may stipulate specific requirements for TDPs such as crumb rubber or establish minimum/maximum specifications for an application that TDP can be used as a substitute to virgin material.

Table 63 refers to standards and regulations that specifically refer or relate to TDP products or primary applications of TDP, such as crumb rubber, in civil & construction projects. The table includes a number of road application standards that regulate the use of TDP. However, it is important to note that this is not an exhaustive list, and there are standards for concrete, fuel quality and other applications that may also regulate the use of TDP that are not quoted in this table.

Additional standards and regulations may be relevant in determining the current industry standard for applications that TDP could be applied to in future, and for requirements for recycled content generally. A summary of these supplementary standards is provided by the Department of Agriculture, Water and the Environment.

Table 63 | Standards and Regulations with specification implications for TDP applications

Standard/Regulation	Summary	Governing Body	Region	Year
AS 2758 Aggregates and rock for engineering purposes	Specifies requirements for aggregates used in sprayed bituminous surfacing, including aggregate quality and properties.	Standards Australia	Australia	2021
AS 3727:2016 Pavements	Specifies requirements for design and construction of pavements.	Standards Australia	Australia	2016
ATS-3110 - Test Methods & Specifications	Sets out the requirements for the supply of polymer modified binders and crumb rubber.	AustRoads	Australia	2020
Specification Framework for Polymer Modified Binders, Publication No. AGPT-T190-19	Specification for polymer modified binders and crumb modified binders used in spray sealing and asphalt.	AustRoads	Australia	2019
Crumb Rubber Modified Open Graded and Gap Graded Asphalt Pilot Specification	Pilot specification for use of crumb rubber modified open graded asphalt, including testing requirements, mix design, manufacture and storage, and application.	Australian Asphalt Pavement Association	Australia	2018
408 Sprayed Bituminous Surfacings 421 High Binger Crumb Asphalt 422 Low Binder Crumb Asphalt	Sets out the requirements for sprayed bituminous surfacings and asphalt applications where the crumb rubber is sourced from waste tyres.	Vic Roads	Vic	2019 2020 2019
Section 421 - High Binder Crumb Asphalt	Sets out the requirements for High Binder Crumb Rubber Asphalt, where the crumb rubber is sourced from waste tyres.	Tasmanian Department of State Growth	TAS	2021
Specification 516 Crumb Rubber Open Graded Asphalt	Specification for supply and application of crumb rubber modified open graded asphalt for pavement, including material properties, mix design, manufacture, testing and application. Informed by Australian Standards, Austroads & Mainroads test methods and specifications.	Mainroads WA	WA	2020
The Recovered Tyres Order 2014	Outlines requirements for suppliers of recovered tyres for use in civil construction projects. Requirements relate to sampling criteria, chemical concentration criteria, testing methods, and associated reporting.	NSW EPA	NSW	2014

Standard/Regulation	Summary	Governing Body	Region	Year
Transport and Main Roads Specifications MRTS18 Polymer Modified Binder (including Crumb Rubber)	Outlines requirements for use of TDP (and other crumbed rubber sources) in polymer modified binder used in asphalt applications (road construction and maintenance). To be read in conjunction with ATS-3110	QLD Government	QLD	2020
NSW EPA Eligible Waste Fuels Guidelines	Stipulates tyre-derived fuels are only considered an eligible fuel when used in a cement kiln. The kiln needs to be approved by the EPA, and appropriate environmental protection license in place.	NSW EPA	NSW	2016

In addition to standards/regulations that stipulate requirements for TDP quality and application, there are standards established to guide and enforce suitable reporting of GHG emissions.

Table 64 to Table 67 outline relevant standards for quantification and reporting of GHG emissions.

Table 64 | European Parliament Product Environmental Footprint (PEF) Standard

<table>
<tr><th></th><th colspan="5">Scheme Details</th></tr>
<tr><td>Summary</td><td colspan="5">The European Parliament Product Environmental Footprint (PEF) is a criteria-based assessment of a product or service's environmental performance. The standard provides guidance for calculating the performance/impact over the full life cycle of a product or service. The technical guidance includes a method (the Circular Footprint Formula) for calculating performance of products/services in circular life cycles, e.g., how to distinguish the primary and secondary product phases. The intent of the PEF is to allow organisations to calculate environmental impacts for internal information, and not designed for public claims or comparative assessments with external products.

Note: this is currently a voluntary compliance standard in the European Union (EU), however the intent is for mandatory adoption of this standard[10].</td></tr>
<tr><td>Applicability to Producers and Purchasers</td><td colspan="5">Potentially relevant to all EOLT/TDP applications.

Producers may choose to use this model to calculate the environmental performance of their organisation or TDP specifically. The process outlined by the PEF standard can be undertaken to provide insights for an organisation to direct efforts to reduce environmental impact.

N/A to Purchasers</td></tr>
<tr><td>Governing Body</td><td colspan="5">European Commission</td></tr>
<tr><td>Applicable Region</td><td colspan="5">Europe (for all products entering EU Common Market)</td></tr>
<tr><td>Assessment Process</td><td colspan="5">N/A</td></tr>
<tr><td>Assessment Criteria</td><td colspan="5">N/A</td></tr>
<tr><td>Accreditation Model</td><td colspan="5">N/A</td></tr>
<tr><td>Applicable fees</td><td colspan="5">May incur fees if external technical experts are engaged to assist in undertaking calculations (particularly for applying the Circular Footprint Formula).</td></tr>
<tr><td>Further information</td><td colspan="5">https://ec.europa.eu/environment/publications/recommendation-use-environmental-footprint-methods_en</td></tr>
<tr><td rowspan="2">Rating</td><th>Robustness</th><th>Uptake</th><th>Impact</th><th>Eligibility</th><th>Total</th></tr>
<tr><td>1</td><td>1</td><td>1</td><td>1</td><td>4/4</td></tr>
</table>

[10] European Commission (n.d.) *The Environmental Footprint transition phase*, accessed via https://ec.europa.eu/environment/eussd/smgp/ef_transition.htm

Table 65 | International Standard ISO 14064-1 - Greenhouse gases - Part 1 Specification with guidance at the organization level for quantification and reporting of greenhouse gas emissions and removals

<table>
<tr><th></th><th colspan="5">Scheme Details</th></tr>
<tr><td>Summary</td><td colspan="5">Specification for quantification and reporting of GHG emissions and removals including design, development, management, reporting and verification of an inventory at the organisation level.

This standard is a tool used in both mandatory and voluntary schemes, such as emissions trading schemes, within the CDP, and carbon credit schemes.</td></tr>
<tr><td>Applicability to Producers and Purchasers</td><td colspan="5">Relevant to all EOLT/TDP applications.

Producers/purchasers can choose to become accredited against this ISO standard by undertaking a third-party audit and verification process of its activities and reporting against this standard. EOLT processing, TDP production and TDP purchasing would all be accounted for within the calculation of emissions at the organisation level.</td></tr>
<tr><td>Governing Body</td><td colspan="5">International Organisation for Standardisation - independent non-governmental international organisation</td></tr>
<tr><td>Applicable Region</td><td colspan="5">Global</td></tr>
<tr><td>Assessment Process</td><td colspan="5">Producers/purchasers may seek technical expertise to assist in the development of an inventory(ies), including undertaking a life cycle assessment, reporting on environmental and technical information, relevant product comparisons, and impacts. This will inform preparation of organization-wide reporting mechanisms in accordance with ISO 14064-1. Once the organisation deems itself compliant with the ISO 14064-1 criteria, an audit is undertaken by a certified ISO 14064 auditor to verify the data and claims made are in compliance with ISO 14064-1. If deemed compliant, the organisation is considered certified against ISO 14064-1.</td></tr>
<tr><td>Assessment Criteria</td><td colspan="5">Organisations are audited against the ISO 14064 –1 Standard.</td></tr>
<tr><td>Accreditation Model</td><td colspan="5">Generally, audits for compliance against an ISO standard is three-yearly, however may differ depending on the organisation.</td></tr>
<tr><td>Applicable fees</td><td colspan="5">Producers/purchasers may incur costs related to engaging technical experts to assist in inventory development and data gathering/calculation unless completed in-house, where costs will be incurred internally. Fees will apply for third-party auditing services.</td></tr>
<tr><td>Further information</td><td colspan="5">https://www.iso.org/standard/66453.html</td></tr>
<tr><td rowspan="2">Rating</td><th>Robustness</th><th>Uptake</th><th>Impact</th><th>Eligibility</th><th>Total</th></tr>
<tr><td>1</td><td>1</td><td>0</td><td>1</td><td>3/4</td></tr>
</table>

Table 66: National Greenhouse and Energy Reporting (NGER) Scheme

	Scheme Details
Summary	The NGER scheme is the national scheme for reporting GHG emissions, energy production and energy consumption. Australian corporations that meet a certain threshold are required to report their emissions and energy information annually under this scheme. The scheme is in accordance with the National Greenhouse and Energy Reporting Act 2007.[11]
Applicability to Producers and Purchasers	Relevant to all EOLT/TDP applications. If **producers** or **Purchasers** exceed the threshold for emissions generation, it will a requirement to report information annually under the scheme.
Governing Body	Australian Government Clean Energy Regulator
Applicable Region	Australia-wide
Assessment Process	Corporations must check whether they meet the threshold for reporting and register under the scheme. Once registered, annual reporting through the NGER scheme Emissions and Energy Reporting System must be undertaken on a yearly basis. Reports will include scope 1 and scope 2 emissions, energy production, and energy consumption. These are submitted to the Clean Energy Regulator (Australian Government). Reporting is due by October 31 of each reporting year. Guidelines on how to measure emissions is provided by the governing body and is publicly available, e.g., Measurement Determination and technical guidelines can be found on the Clean Energy Regulator web page[12].
Assessment Criteria	Reporting must comply with the NGER Reporting Act 2007[13] and associated regulations, determinations and technical guidelines. The Clean Energy Regulator is responsible for regulating report compliance for up to five years after submission.
Compliance Model	Annual reporting required.
Applicable fees	Organisations may incur costs associated with data collection, gathering and reporting activities.
Further information	http://www.cleanenergyregulator.gov.au/NGER
Rating	N/A – mandatory

[11] National Greenhouse and Energy Reporting Act 2007, accessed via https://www.legislation.gov.au/Series/C2007A00175

[12] 2021, *Measurement Determination,* Australian Government, accessed via http://www.cleanenergyregulator.gov.au/NGER/Legislation/Measurement-Determination

[13] National Greenhouse and Energy Reporting Act 2007, accessed via https://www.legislation.gov.au/Series/C2007A00175

Table 67: IPCC Guidelines for National GHG Inventories

	Scheme Details
Summary	Originally prepared in 2006, and subsequently updated in 2019, the IPCC guidelines provide a methodology for calculating national GHG inventories, establishing a globally accepted framework for calculating GHG emissions for national reporting. These guidelines are used in calculating annual emissions in Australia as part of the NGER scheme.
Applicability to Producers and Purchasers	Relevant to all EOLT/TDP applications. If **Producers** or **Purchasers** exceed the threshold for emissions generation, it will a requirement to report information annually under the NGER scheme, which relies on these guidelines.
Governing Body	Intergovernmental Panel on Climate Change
Applicable Region	Global
Assessment Process	Assessment/compliance is captured within the NGER scheme requirements. Refer above.
Assessment Criteria	Assessment/compliance is captured within the NGER scheme requirements. Refer above.
Compliance Model	Annual reporting required under the NGER scheme.
Applicable fees	Organisations may incur costs associated with data collection, gathering and reporting activities.
Further information	https://www.ipcc.ch/report/2019-refinement-to-the-2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/
Rating	N/A - mandatory

9.4 Fiscal Opportunities

9.4.1 Carbon Trading Mechanisms

Carbon trading aims to reduce GHG emissions by establishing carbon markets in which registered emissions reduction projects are sold as carbon credits, with companies able to purchase these credits to offset their own emissions. There are currently no mandates to purchase carbon credits in Australia, however, there is growing demand from businesses wishing the voluntarily reduce their emissions profile.

EOLT processing and TDP projects both generate emissions reductions that can potentially be eligible as carbon credits, from diverting waste from landfill and avoiding fossil-derived virgin materials. These credits are an opportunity to generate an addition revenue stream. Note, however, that credits are generally issued on a project basis, and therefore financial viability will need to be considered on a case-by-case basis with consideration of potential certification costs against potential revenue.

Carbon credits must be reviewed and verified by a recognised carbon offset scheme operator. Post verification, they are made available for purchase by companies and individuals who wish to offset their emissions through various online platforms. This includes through carbon neutrality certification schemes such as Climate Active (Table 53).

Recognised carbon offset schemes include:

- **Australian Carbon Credit Units (ACCUs)** – this is governed by the Clean Energy Fund as an initiative of the Australian Government. Projects are only eligible for carbon credits if they fall into a prescribed category, which are determined based on current government priorities. Unfortunately, EOLT and TDP are unlikely to be eligible under the existing categories.
- **Certified Emissions Reduction (CERs)** – these are issued to projects under the Clean Development Mechanism (CDM), which operates in predominately developing countries. EOLT and TDP are unlikely to be eligible for CERs.

- **Verified Carbon Units (VCUs)** – these are issued by the organisation VERRA under their Verified Carbon Standards (VCS).
- **Voluntary Emissions Reduction (VERs)** – these are issued through a voluntary certification process governed by Gold Standard.

Of these schemes, EOLT and TDP are likely only eligible for VERs and VCUs, through emissions avoidance from the diversion of EOLT waste from landfill and the avoidance of high carbon virgin materials. These schemes are summarised in Table 68 and Table 69.

Table 68 | VERRA Verified Carbon Standard

	Scheme Details				
Summary	VERRA manages the Verified Carbon Standard (VCS) offset certification program. VCS is focused on removing and reducing GHG emissions, issuing voluntary carbon units (VCUs) to approved programs per one tonne of GHG emissions abated. The program currently has over 1,700 certified projects with 907 million tonnes of CO_2 eq offset so far.				
Applicability to Producers and Purchasers	**Producers** need to demonstrate their EOLT processing and TDP manufacturing activities are reducing GHG emissions compared to the baseline landfill scenario. Carbon credits are usually issued on a project basis; however, projects can potentially be aggregated. Not applicable to **Purchasers** of EOLT/TDP				
Governing Body	VERRA				
Applicable Region	Global				
Assessment Process	Producers are required to submit a methodology for verification if an existing methodology does not exist for the project type. Once approved, the required documentation for the project can be submitted for verification and the credits issued. At this stage there is no existing methodology for alternative waste processing that covers EOLT and TDP.				
Assessment Criteria	The criteria are outlined in the VCS but requirements include that the project is real, measurable and additional. 'Additional' refers to the requirement that the GHG emission reductions must be additional to what would have happened under a business-as-usual scenario if the project had not been carried out.				
Accreditation Model	Ongoing audit requirements				
Applicable fees	One off account fee of $500, registration fees of $0.10 per credit, capped at $10,000. Methodology approval fees of $2,000 for the application and $13,000 once approved. Annual validation fees of $2,500. All fees are quoted in USD. Note this does not include any third-party fees such as consultants. The purchase price of credits issued will depend on the verifying agency and the supply and demand mechanisms of the carbon market.				
Further information	https://verra.org/				
Rating	**Robustness**	**Uptake**	**Impact**	**Eligibility**	**Total**
	1	1	1	1	**4/4**

Table 69 | Gold Standard Verified Emissions Reduction

	Voluntary Emissions Reduction – Gold Standard				
Summary	Gold Standard is an international offset program developed by the WWF in 2003. The Gold Standard program has more stringent requirements compared to the VCS program when certifying a project for carbon credits. The program currently has over 2,300 certified projects with 191 million tonnes of CO_2 eq offset so far. It is particularly well regarded by NGOs due to its rigour.				
Applicability to Producers and Purchasers	**Producers** need to demonstrate their EOLT processing and TDP manufacturing activities are reducing GHG emissions compared to the baseline landfill scenario. They will also need to prove additional benefits as per the assessment criteria. Carbon credits are usually issued on a project basis; however, projects can potentially be aggregated. Not applicable to **purchasers** of EOLT/TDP				
Governing Body	Gold Standard Foundation				
Applicable Region	Global				
Assessment Process	Producers are required to submit a methodology for verification if an existing methodology does not exist for the project type. Once approved, a monitoring report and plan can be submitted for verification and the credits issued.				
Assessment Criteria	The criteria required includes the same criteria as for VCUs, however, the project must also prove benefit to the local community by contributing to at least 3 Sustainable Development Goals (SDGs). That is, the project must benefit local economic, social and/or environmental outcomes in addition to reducing or removing GHG emissions.				
Accreditation Model	Ongoing audit requirements				
Applicable fees	$1,000 for registration, and $0.15 per credit issued. Methodology approval fees are not disclosed. Additional costs include consultant and third-party auditor fees. The purchase price of credits issued will depend on the verifying agency and the supply and demand mechanisms of the carbon market.				
Further information	https://www.goldstandard.org/				
Rating	**Robustness**	**Uptake**	**Impact**	**Eligibility**	**Total**
	1	1	1	TBD	**3/4**

Issued carbon credits can be purchased by businesses and individuals through a broker or a carbon trading platform. Brokers can be more costly and complex due to the need to engage intermediary parties. Trading platforms represent a simpler, more cost-effective solution. The Clean Energy Regulator, funded by the Australian government, is intending to operate a platform called the Australian Carbon Exchange, like an online stock exchange platform. The platform is due to be launched in 2023. In the interim, there are private platforms that also provide a similar service.

It may also be worthwhile to consider potential co-benefits of EOLT and TDP activities. In addition to carbon abatement, projects may achieve a range of other environmental, social and economic benefits, known as co-benefits. These co-benefits offer additional value to purchasers in meeting their sustainability commitments beyond emissions reduction.

There is also potential to aggregate carbon credits on behalf of smaller projects. The role of the aggregator is to assemble tradable amounts by combining carbon credits from several organisations. Note, however, that as with all financial instruments, an aggregation is a complex arrangement with financial and legal risks and considerations. An example of an organisation that assists with aggregation is the Carbon Farmers of Australia, a regionally based carbon trading advisor with the objective to establish a farm-based carbon offset industry. In addition to providing aggregation services for farmers wishing to enter the carbon market, the organisation has generally provided support and advocacy services for the farming industry including submitting the first soil carbon methodology, developing a carbon handbook and training program and facilitating the sale of carbon credits.

9.4.2 Funding Mechanisms

TDP producers and purchasers may be eligible for government grants (at the federal, state/territory, or local level), that support industry innovation and implementation of schemes that enable recycling of problem wastes and application of the secondary product.

The most prominent funding mechanism relevant to TDP producers and purchasers is the Recycling Modernisation Fund[14] (RMF) established by the federal government. This fund seeks to enable the transition to onshore recycling that Australia must undergo by mid-2024 in response to the ban on waste exports for problem wastes by the Council of Australian Governments in 2019[15]. Funding via the RMF is distributed to state and territory governments for allocation to grant programs that collectively work towards improving and expanding Australia's waste and recycling sector.

In addition to the RMF, TDP producers and purchasers may be able to access funding from state-based recycling or circular economy initiatives such as the NSW Waste Less, Recycle More[16] initiative, or Green Industries SA Circular Economy Market Development initiative[17].

Table 69 summarises grants available within each state or territory, that TDP producers and purchasers may be eligible to receive. Note, the table includes grant schemes that are already closed to applications, or imminently due to close to applications, however these are included for information to demonstrate the scope and scale of potential future grants at the state/territory level that may be implemented in future, e.g., as part of the RMF. Currently open grants can be found on sites such as the government 'Grants and program finder' at business.gov.au.

Table 70 | Summary of State-based grants applicable to TDP producers and/or purchasers

	Grant Details
Recycling Victoria – Recycling Modernisation Fund	
Summary	Supports projects that seek to expand capacity and capability of resource recovery and quality of recovered materials in Victoria. Projects must demonstrate outcomes specific to the waste export bans, including addressing waste whole used tyres and baled tyres. Bus, truck, and aviation tyres exported for re-treading are excluded.
Eligible Applicants	Businesses, not-for-profit organisations, local government
Governing Body	Sustainability Victoria
Applicable Region	Victoria
Value	No cap, requires a co-contribution of 1:1:1 (Sustainability Victoria: Australian Government: Applicant) or 1:2 (Sustainability Victoria: Applicant) for local government applicants
Further information	https://www.sustainability.vic.gov.au/grants-funding-and-investment/grants-and-funding/materials-recycling-infrastructure-funding
Recycling Victoria- Infrastructure Fund – Materials stream	
Summary	Supports projects that seek to expand capacity and capability of resource recovery and quality of recovered materials in Victoria. Six problem waste materials are nominated to be addressed in recovery projects, including tyres.
Eligible Applicants	Businesses, not-for-profit organisations, local government

[14] DAWE, 2021, *Investing in Australia's waste and recycling infrastructure,* accessed via https://www.awe.gov.au/environment/protection/waste/how-we-manage-waste/recycling-modernisation-fund

[15] DAWE, 2022, *Waste exports*, accessed via https://www.awe.gov.au/environment/protection/waste/exports

[16] NSW EPA, 2021, *Waste Less, Recycle More, accessed via https://www.epa.nsw.gov.au/your-environment/recycling-and-reuse/waste-less-recycle-more*

[17] Green Industries SA ,2022 , *Circular Economy Market Development Grants*, accessed via https://www.greenindustries.sa.gov.au/funding/ce-market-development-funding

	Grant Details
Governing Body	Sustainability Victoria
Applicable Region	Victoria
Value	No cap, requires a co-contribution of 1:3 (Sustainability Victoria: Applicant)
Further information	https://www.sustainability.vic.gov.au/grants-funding-and-investment/grants-and-funding/materials-recycling-infrastructure-funding
Remanufacture NSW	
Summary	To fund streams, infrastructure and trials, to support projects that seek to address the waste export bans and find solutions for recycling and reuse of plastic, tyre, and paper & cardboard wastes onshore in Australia.
Eligible Applicants	Councils, industry, business, state government, not-for-profit, research institutes
Governing Body	NSW Government
Applicable Region	NSW
Value	$100,000 to $3 million for infrastructure projects, $50,000 to $1 million for trial projects.
Further information	https://www.epa.nsw.gov.au/working-together/grants/infrastructure-fund/remanufacture-nsw
Plastics & Tyres Processing Infrastructure Fund	
Summary	Provides funding to projects that increase capacity to process and recycle plastic and tyre waste in WA.
Eligible Applicants	Industry
Governing Body	WA Government
Applicable Region	WA
Value	$350,000 to $10 million
Further information	https://www.wa.gov.au/service/environment/environment-information-services/plastics-and-tyres-processing-infrastructure-fund
Queensland Recycling Modernisation Fund	
Summary	Funds to support projects that can expand processing capacity and markets for recycling in QLD, namely infrastructure to improve sorting, processing, recycling and manufacturing of problem wastes, including plastic, paper, cardboard, tyres and glass.
Eligible Applicants	Private sector
Governing Body	QLD Government
Applicable Region	QLD
Value	Unknown
Further information	https://www.statedevelopment.qld.gov.au/industry/priority-industries/resource-recovery/queensland-recycling-modernisation-fund
Northern Territory Recycling Modernisation Fund	
Summary	Fund to support projects that respond to the waste export bans and improve recovery and recycling of problem waste materials, namely plastics, paper & cardboard, glass and tyres.

	Grant Details
Eligible Applicants	Profit and not-for-profit private organisations
Governing Body	Northern Territory Government
Applicable Region	NT
Value	>$50,000, co-contribution required of 1:1 (NT Government: Applicant)
Further information	https://nt.gov.au/industry/business-grants-funding/nt-recycling-modernisation-fund
Circular Economy Market Development Grants	
Summary	Funds for projects based on developing and implementing circular economy applications that contribute to increased supply and demand of recycled material and recycled-content product in South Australia.
Eligible Applicants	Councils, industry associations, not-for-profit organisations, research institutes, businesses
Governing Body	Green Industries, South Australian Government
Applicable Region	SA
Value	Up to $100,000
Further information	https://www.greenindustries.sa.gov.au/funding/ce-market-development-funding
Recycling Infrastructure Grants	
Summary	Funds projects that support the recovery, and reprocessing of recyclable materials in South Australia.
Eligible Applicants	Businesses, local government
Governing Body	Green Industries, South Australian Government
Applicable Region	SA
Value	$25,000 to $200,000. Larger values (up to $500,000) will be considered pending demonstrated impact and co-contribution.
Further information	https://www.greenindustries.sa.gov.au/funding/recycling-infrastructure-grants
RMF Regional and Remote Communities	
Summary	Funds to support projects that improve recycling capacity and capability and address current gaps in onshore recycling infrastructure.
Eligible Applicants	Small & medium enterprises, not-for-profit organisations, local government, community groups, regional research institutes, Traditional Custodians
Governing Body	Green Industries, South Australian Government
Applicable Region	SA
Value	$20,000 to $500,000, co-contribution required of 1:1:1 (South Australian Government: Commonwealth Government: Applicant)
Further information	https://www.greenindustries.sa.gov.au/funding/commonwealth-rmf-regional
Circulate, NSW Industrial Ecology Program	

	Grant Details
Summary	Provides funds to support innovation in the industrial ecology space, including projects that divert materials from landfill and use in commercial, industrial or construction applications.
Eligible Applicants	Business, not-for-profit organisations, government agencies/organisations, industry bodies, product stewardship groups
Governing Body	NSW EPA, NSW Government
Applicable Region	NSW
Value	$20,000 to $150,000
Further information	https://www.epa.nsw.gov.au/working-together/grants/business-recycling/circulate-grant

9.5 Summary of schemes and regulations

Table 71 | Summary of schemes and regulations relevant to EOLT/TDP producers and purchasers

Type	Category	Key schemes	Rating	Recommendation for TSA action
Reporting and certification schemes	Environmental Labels	GECA ecolabel	★★★★	TSA should consider developing sector wide EPD. This encourages the use of TDP as a product category, but also supports members to develop their own EPDs. EPDs recognised by a range of schemes including GECA, Climate Active and the ISCA Rating Scheme. TSA can also develop an industry wide tool to allow comparison of existing products with TDP alternatives. The tool allows producers to understand how to market their products and gives purchasers confidence in the products they buy. The voluntary reporting standards are more relevant at the organisation and product level and provides opportunity to educate TSA members on how to position their TDP products.
		EPD	★★★☆	
		ANZ EPD Climate Declaration	★★★★	
		Climate Active	★★★★	
	Other tools and schemes	AfPA LCA Calculator for Asphalt	★★☆☆	
		ISCA Rating Scheme	★★★☆	
	Voluntary reporting	Science Based Targets	★★★★	
		Carbon Disclosure Project	★★★☆	
		GHG Protocol	★★★☆	
		MECLA	★★★☆	
		Declare Product Labelling	★★☆☆	
		GRI Standards	★★☆☆	
		SASB	★☆☆☆	
Compliance considerations	Compulsory standards and regulations	State-based and national standards	N/A – mandatory	TSA should explore the need and potential to lead the development of state/territory-based or Australia-wide standards for pyrolysis fuels to ensure quality of this new stream and generate confidence in the new market entrant to foster strong uptake by industry.
		European Parliament PEF		
		ISO 14064-1 GHG specification		
		NGER scheme		
		IPCC Guidelines for National GHG Inventories		

Fiscal opportunities	Carbon trading mechanisms	VCUs	☆☆☆☆	While TSA should not be providing financial advice, TSA can provide some general information on schemes relevant to producers.
		VERs	☆☆☆☆	
	Funding mechanisms	State-based grants	N/A – consider eligibility and availability at time of application	TSA can proactively seek funding grants that producers may be eligible for and use their knowledge and resources to support their applications.

10 Recommendations for Delivering Benefits of EOLT & TDP

TSA has the opportunity to accelerate the transition towards a circular economy in sectors that can benefit from EOLT and TDP. Armed with quantitative data demonstrating the benefits of EOLT and TDP outputs in GHG emissions reduction, TSA is well-positioned to leverage this information as momentum to influence sector-wide change.

Key recommendations for next steps by TSA to accelerate and support the uptake of EOLT and TDP by industry and end-users are:

1. Develop a tool to assist companies, which can include Marginal Cost Curves, similar to the tool developed for a local council (for roads and buildings). This will allow the comparison of existing products in the markets with TDP alternatives, to provide an indication of the GHG saving. If other impact categories are included, these can also be included in the tool.
2. Develop a sector-wide EPD on selected TDPs using input data from member companies. A verified sector-wide EPD would help encourage the use of the TPD compared to alternatives in the same category. It can also be provided to TSA members who provided the input data to allow development of their own specific EPDs. Edge is currently developing a sector-wide EPD with Cement, Concrete and Aggregates Australia to encourage the use of clinker, cement and concrete products compared to alternatives in those categories.
3. Undertake a feasibility study to assess the current market capacity to collect & process EOLT, and manufacture and produce TDP across Australia. This will identify gaps in capacity, and/or areas of inefficiency to be addressed. Market review could include review of existing infrastructure in alternative uses that could potentially be leveraged for EOLT/TDP applications.
4. Commission a comparative LCA of TDPs in typically cementous applications, against new carbon neutral/ low carbon concrete products, such as ECOPact – Low carbon concrete by Holcim, to understand the GHG emissions and cost comparison of these two alternatives to traditional materials. This will proactively address queries from producers/purchasers who may be considering emissions-reducing initiatives, however are unsure which alternatives are most appropriate for their business activities.
5. Prioritising the EOLT/TDP applications with the largest potential demand (e.g. crumb rubber), undertake a cost-benefit analysis of the EOLT/TDP life cycle, to calculate the cost savings (and potentially, a different cost distribution profile) of recycled content over virgin materials. This will allow producers/purchasers to present a business case for transitioning to EOLT/TDP and inform discussions with key business stakeholders. There is opportunity to develop a tool for calculating costs for select EOLT & TDP uses or sectors to allow producers/purchasers to apply business specific cost data.
6. Translate GHG emissions data into public-facing marketing and communications collateral to allow industry and community to rapidly digest the benefits of EOLT/TDP applications. This will accelerate the transition to EOLT/TDP by mitigating effort required by producers/purchasers to create buy-in from end-users.
7. Establish a partnership with national and international research institutions and circular economy associations such as CSIRO, and the Victorian Circular Activator, to understand future direction of pyrolysis technology and potential application to new TDP products in the energy and thermal use sectors. Partnerships may provide the opportunity for TSA or industry stakeholders to participate in trials or pilot programs for innovative applications of EOLT.
8. Explore potential to apply blockchain technology to create digital ledgers of EOLT/TDP outputs to establish transparency of supply chain, product/ content and quality, and contribute to improving the collection and management of data in the circular economy in Australia.
9. Develop or commission training material for the internal TSA team to educate them on the content of this project and its outcomes, to improve their understanding and empower them to communicate the outcomes to stakeholders.

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Appendix A – Background data

The following background data sources were used to model the product life cycles:

- Ecoinvent v3.8: The ecoinvent Centre holds the world's leading database with consistent and transparent, up-to-date LCI data. The ecoinvent database contains LCI data from various sectors such as energy production, transport, building materials, production of chemicals, metal production, and fruit and vegetables. The entire database consists of over 10,000 interlinked datasets, each of which describes an LCI on a process level.
- Australian National Life Cycle Inventory Database (AusLCI v1.39): A major initiative currently being delivered by the Australian Life Cycle Assessment Society (ALCAS). The aim is to provide and maintain a national, publicly-accessible database with easy access to authoritative, comprehensive and transparent environmental information on a wide range of Australian products and services over their entire life cycle.
- Australasian Unit Process LCI 2014.09: The main Australasian database in SimaPro, which has been developed for use with LCA in Australia over the past 12 years. The original database was developed as part of a project funded by the four state-based environmental protection authorities', the commonwealth government and the Cooperative Research Centre for Waste Management and Pollution Control. The project partners were the University of New South Wales and the Centre for Design at RMIT University. The database has been added to over time by different public projects and its upkeep is coordinated by Life Cycle Strategies.

Item	Process	Database	Year
Bitumen binder	Bitumen adhesive compound, hot {RER}| production | Cut-iff, U	Ecoinvent v3.8	2021
Bitumen	Bitumen, at consumer/AU U	Australasian Unit Process LCI v2014.09	2014
Carbon black	Carbon black {GLO}| production | Cut-off, U	Ecoinvent v3.8	2021
Coal	Thermal coal, at mine/AU U	AusLCI unit process v1.39	2022
Concrete	Concrete 20 MPa, at batching plant/AU U	AusLCI unit process v1.39	2022
Diesel	Diesel {RoW}| diesel production, petroleum refinery operation | Cut-off, U	Ecoinvent v3.8	2021
Electricity from grid	Electricity, low voltage, Australian/AU U	AusLCI unit process v1.39	2022
Gravel/crushed rock	Gravel, crushed {RoW}| production |Cut-off, U	Ecoinvent v3.8	2021
Landfill	Waste treatment, rubber and leather, at landfill/AU U	AusLCI unit process v1.39	2022
Landfill	Landfill, steel products/AU U	Australasian Unit Process LCI v2014.09	2014
Landfill	Waste treatment, inert waste, at landfill/AU U	AusLCI unit process v1.39	2022
Light fuel oil	Light fuel oil {RoW}| petroleum refinery operation | Cut-off, U	Ecoinvent v3.8	2021
LPG	LPG, at consumer/AU U	Australasian Unit Process LCI v2014.09	2014
Lubricating oil	Lubricating oil {RER}| production | Cut-off, U	Ecoinvent v3.8	2021
Natural gas	Natural gas, low pressure, Australia/AU U	AusLCI unit process v1.39	2022

Item	Process	Database	Year
Polyurethane additive for binder	Polyurethane adhesive {GLO}| market for polyurethane adhesive | Cut-off, U	Ecoinvent v3.8	2021
Sand	Sand, river, at mine/AU U	Australasian Unit Process LCI	2014
SBS	Acrylonitrile-butadiene-styrene copolymer, {RER}| production | Cut-off, U	Ecoinvent v3.8	2021
Steel	Steel, unalloyed {RER}| steel production, converter, unalloyed | Cut-off, U	Ecoinvent v3.8	2021
Tap water	Tap water, at user, Australia/AU U	AusLCI unit process v1.39	2022
Thermal oil	Heavy fuel oil {RoW}| heavy fuel oil production, petroleum refinery operation | Cut-off, U	Ecoinvent v3.8	2021
Transport	Transport, truck, 40t load/AU U	AusLCI unit process v1.39	2022
Transport	Transport, truck, 16 to 28t, fleet average/AU U	AusLCI unit process v1.39	2022
Transport	Transport, truck, 3.5 tp 16t fleet average/AU U	AusLCI unit process v1.39	2022
Transport	Transport, freight, rail/AU U	AusLCI unit process v1.39	2022
Transport	Transport, truck, 16 – 28t, fleet average/AU U	AusLCI unit process v1.39	2022

Appendix B – Biogenic Carbon

Biogenic carbon contained in the EOLT was calculated as per the following formula (One Click LCA, 2022).

$$P_{CO_2} = \frac{44}{12} \times cf \times \frac{\rho_\omega}{1+\frac{\omega}{100}}$$

Where:

P_{CO_2} is the biogenic carbon oxidized as carbon dioxide emission from the product system into the atmosphere (e.g. energy use at the end-of-life);

$\frac{44}{12}$ is the ratio between the molecular mass of CO_2 and C molecules;

cf is the carbon fraction of rubber biomass, assumed to be 39.2% (Kunioka, 2014);

ϖ is the moisture content of the product, assumed to be 0.33% (TA Instruments, n.d.);

ρ_ω is the mass of rubber biomass of the product at that moisture content (kg).

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