TyreStewardship AUSTRALIA

Pyrolysis of end-of-life tyres

Review of pyrolysis technologies and product opportunities for Australia

Pyrolysis Products and Market Review

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The consultant who provided the technical information and market snapshot through a consultancy/research project funded by TSA:

Anthony (Tony) Campisi

Campisi Consulting – Fuel Technology and Chemistry

tony@campisiconsulting.com.au

+61 409 550 982

Melbourne, Australia

For a peer review of the document:

Robert Weibold GmbH (https://weibold.com)

sales@weibold.com

+43 1 997 10 50

Kalvarienberggasse 13/59,

1170 Vienna, Austria

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Executive Summary

Recovering Australia's end-of-life tyres

Recovery rates of Australia's end-of-life (EOL) tyres is well below the desired levels, and a one-size-fits-all approach to technology and markets is unlikely to enable 100% recovery. Until Australia can recover all its EOL tyres, operators in this market need to understand any emerging and alternative approaches, and receive up-to-date information to inform decision making.

The role of pyrolysis

One of these technologies is pyrolysis, by which we mean any technology that decomposes EOL tyres or similar rubber products in a closed system using heat and no oxygen or air. This thermal decomposition process produces oil, gas, and carbon-rich solid fractions. For organisations considering setting up pyrolysis operations, the potential markets for these materials is of critical importance.

Key aspects of the report

This report shows that not all EOL tyre pyrolysis operations are the same. It outlines the unique elements of different technologies and outputs so that industry can:

- identify the different types of tyre pyrolysis
- differentiate it from other thermal processing technologies
- understand the types of outputs tyre pyrolysis produces
- assess the markets for these outputs and any post-processing that might be needed to produce saleable products.

Thermal processing methods

Pyrolysis, Gasification, and Combustion are all thermal processes which have been explored for processing EOL tyres:

- Pyrolysis operates at moderate temperatures (400 to 600°C) and occurs in an inert atmosphere without oxygen/air
- Gasification operates at higher temperatures (800 to 1200°C) and includes steam and oxygen/air to decompose a tyre to produce a higher proportion of synthesis gas rich in CO and H_2
- Combustion uses the tyre as fuel using air and temperatures over 1200°C to produce heat for various applications.

Pyrolysis technology approaches

There are many technology approaches to tyre pyrolysis, varying in terms of feedstock inputs, reactor design, reactor operation, and processing conditions. The examples in this report are comprehensive but not exhaustive, and different approaches will affect the yield and composition of the outputs from the process.

The status of tyre pyrolysis in Australia and globally

Tyre pyrolysis technologies are still in early phases of development in Australia. Of the 12+ proposed pyrolysis projects from the last decade reviewed in this project, only five are beyond announced or proposed status, and of these, only two are close to a commercial scale operation. Currently, Australia processes around 1% of Australian EOL tyres through these operations each year.

Worldwide there are many operational pyrolysis facilities, but estimates suggest that less than 3-5% of all global EOL tyres are currently processed using pyrolysis. This low rate may reflect the challenges that the pyrolysis industry has been trying to resolve over the past few decades, including:

- technology development and product quality and variability
- market acceptance of products
- regulatory approvals, public perception and environmental & safety considerations
- the extra refining and processing often needed to establish stable and high-value outputs.

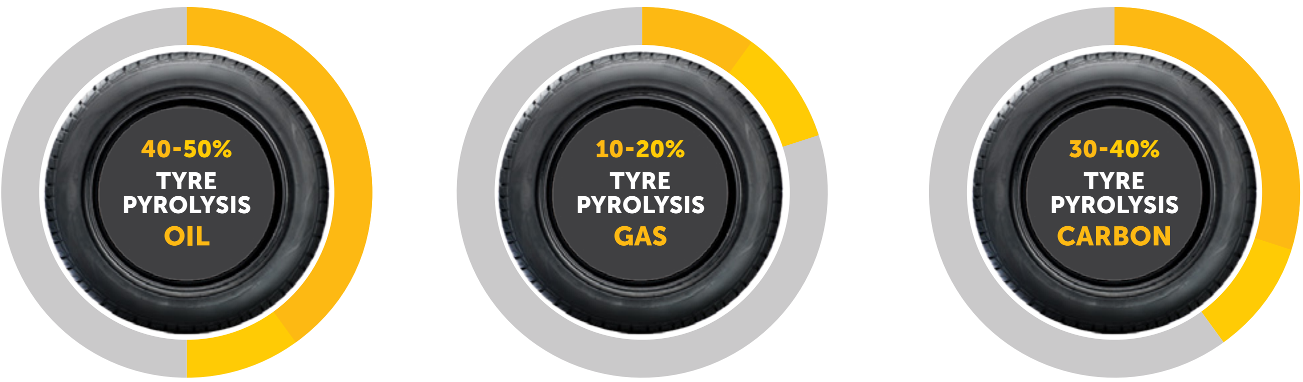
Pyrolysis output material from processing tyres

Given the variable composition of different tyre types and processing parameters, not all pyrolysis outputs are consistent between batches or technologies.

The approximate yield of outputs recovered from tyre pyrolysis on a steel-free basis are:

- 40-50% tyre pyrolysis oil
- 10-20% tyre pyrolysis gas
- 30-40% tyre pyrolysis carbon.

Figure 1: approximate yield of outputs on a steel-free basis



Steel wire is also recovered from EOL tyres during feed preparation or after pyrolysis and typically represents about 15% of the EOL tyre.

Tyre pyrolysis oil has similar properties as No. 6 Fuel Oil, and can be used as a fuel in bunkers, kilns and boilers, and be blended for use in heavy machinery. Tyre pyrolysis gas is a mixture of light hydrocarbons and other light gases, has a high calorific value and is typically used back into reactor heating.

Proposed applications and research and development for tyre pyrolysis carbon include use as:

- a replacement for lime in asphalt roads
- a carbon-rich soil conditioner
- a coke replacement in kilns and furnaces for energy recovery.

Refining pyrolysis outputs to produce higher-grade product applications.

Pyrolysis outputs can be processed and refined to produce outputs for a range of potentially higher-value applications.

Crude oil from tyre pyrolysis has a wide boiling point range and distillation can be used to separate the oil into different fractions. Each fraction has a unique composition and properties that determine how it can be used. A desulphurisation step may be needed to remove sulphur if the output is to meet fuel standards or other specifications. Other investigations for tyre pyrolysis oil include use as a feedstock for processing into sustainable carbon black, or recovery of valuable solvents and chemicals.

Tyre pyrolysis carbon is seen as valuable source of advanced carbon materials with adequate processing. Recent efforts in the tyre manufacturing industry to outline specifications for recovered carbon black, is guiding the pyrolysis industry. As well as milling and pelletising the char material, the rubber product industry has proposed other specifications within ASTM standards to use this material in their technical products.

As technologies, outputs, and products vary between pyrolysis operations, energy efficiency will also be specific to each process. To make accurate claims on the environmental impact of a pyrolysis technology, operators should conduct a process specific life cycle assessment or similar emissions accounting.

Conclusion

This report shows that there are applications for all three of the outputs of tyre pyrolysis (gas, oil and carbon), and that markets exist for the unrefined outputs. In Europe, America, and similar markets the oil can be sold to various industries and oil traders without post-treatment.

To be suitable for higher-value applications such as tyre manufacturing, the oil and carbon outputs need further processing to ensure they meet technical product requirements and fuel quality standards.

Further, as Australia has no onshore tyre manufacturing operations, operators will need to export or find alternate markets onshore, such as conveyor belt or retread markets. Tyres are not the only market though, recycled carbon black for example, can be used in various sectors including plastics, masterbatch, mechanical rubber goods, textiles, paints, and inks. To make this viable, Australia will likely need to develop secondary processing and quality standards, and research other high-performance applications.

There are other rubber product markets both onshore and offshore (conveyors, retreads etc, and other manufacturing markets) that are currently untapped. With research and development these could represent a big market opportunity.

It's worth noting that, with increasing global emphasis on achieving environmental goals, there is growing openness to using sustainable materials in every industry. There is definite value in conducting feasibility studies to explore the market conditions, desired product qualities, product demand and anticipated prices ranges within Australia and nearby countries.

When considering a pyrolysis project, operators should ensure there are suitable markets for their products and ideally have off-take agreements in place. Meeting the quality requirements and technical standards for carbon black for tyres and rubber products may be difficult, given there are already long established global markets and agreements in place.

The industry must also adhere to Australia's high safety and environmental standards that we outlined in our 2018 report. These measures are crucial for the successful integration of pyrolysis as a sustainable waste management solution in the Australian context.

Abbreviations

EOL	End-Of-Life (in reference to tyres, this is when they reach the end of their life on a vehicle. Globally this is commonly abbreviated to ELT)
EPA	Environmental Protection Agency
GHG	Greenhouse Gas
OTR	Off-The-Road (in the context of this report refers to the large tyres used in mining, agriculture and earth moving equipment)
rCB	Recovered Carbon Black (the processed, milled and pelletised material recovered from tyre pyrolysis)
sCB	Sustainable Carbon Black (carbon black processed and refined from tyre pyrolysis oil)
TDF	Tyre-Derived Fuel
TPC	Tyre Pyrolysis Carbon (solid residues/char obtained from pyrolysis process without any treatment)
TPG	Tyre Pyrolysis Gas (the non-condensable gas fraction from tyre pyrolysis)
TPO	Tyre Pyrolysis Oil (the condensable liquid hydrocarbon fraction from tyre pyrolysis)
TPSS	Tyre Product Stewardship Scheme
TSA	Tyre Stewardship Australia
vCB	virgin Carbon Black (from fossil oil)

1. Introduction

In 2018, TSA published an *Independent Guide on Thermal Processing Technologies*[1]. The guide aimed to increase industry knowledge and identify potential issues for bodies seeking funding or approval to build a thermal processing (pyrolysis) plant in Australia.

This report complements the Independent Guide, as a technical document covering different thermal processing technologies. Compiled from expertise provided by an independent consultant, this report gives an overview of various thermal processing technologies and markets worldwide.

Although pyrolysis is a global technology used to process various carbon-based materials, the tyre pyrolysis marketplace is fragmented and faces several challenges, including limited local information and relevance to the Australian market. While considering the impact of global marketplace dynamics, the report emphasises the need to gather accurate technical and market information relevant to Australia, to help people make informed decisions and implement effective local tyre management strategies.

The report covers:

- the different approaches to pyrolysis technology
- a snapshot of tyre pyrolysis in Australia and overseas
- tyre pyrolysis output materials
- post-processing of output materials and markets.

The role of Tyre Stewardship Australia (TSA)

TSA was established to implement the national Tyre Product Stewardship Scheme. This scheme promotes recovery of all end-of-life (EOL) tyres, and the development of viable commercial markets for tyre-derived materials. There are different recovery options for EOL tyres, and TSA is committed to providing accurate and up-to-date information on different tyre management options.

1.1 The tyre recovery challenge

Australia continues to grapple with the challenge of recovering all its EOL tyres. In recent years the industry has been making significant efforts to boost recovery rates and develop viable markets for tyre-derived materials. Despite this, it is estimated that every year less than two-thirds of Australia's used tyres will reach these sustainable outcomes, the remainder being dumped, stockpiled, buried or in landfills.

In recent years, Australia has produced over 500,000 tonnes of used tyres annually, with an estimated 545,000 tonnes generated in 2022-23[2]. Around 58% of the tyres generated in 2022-23 were recovered for use in domestic and international markets as either re-used tyres (as-is, or re-treaded and repaired), or as tyre-derived materials and products.

Yet recovery rates have declined over the past three years, standing at a 5-year average recovery rate of 65%. Passenger and truck tyres make up most recovered used tyres, with very limited recovery of off-the-road (OTR) tyres used in industries such as mining, agriculture and aviation.

1 Independent Guide on Thermal Processing Technologies
https://www.tyrestewardship.org.au/wp-content/uploads/2020/04/tyre-pyrolysis-and-gasification.pdf

2 Tyre Stewardship Australia (TSA) website:
https://www.tyrestewardship.org.au/handbooks/tyre-consumption-recovery-fact-sheet/

1.2 Methods of thermal processing

Thermal and *chemical* processing pathways can transform EOL tyres to create a new feedstock material for various products or fuel applications.

These approaches differ from *mechanical* processing, which reduces tyres into smaller usable forms such as chips, granules, or crumb rubber. Current markets for these size-reduced materials include road surfacing, recreational surfacing, concrete and advanced manufacturing.

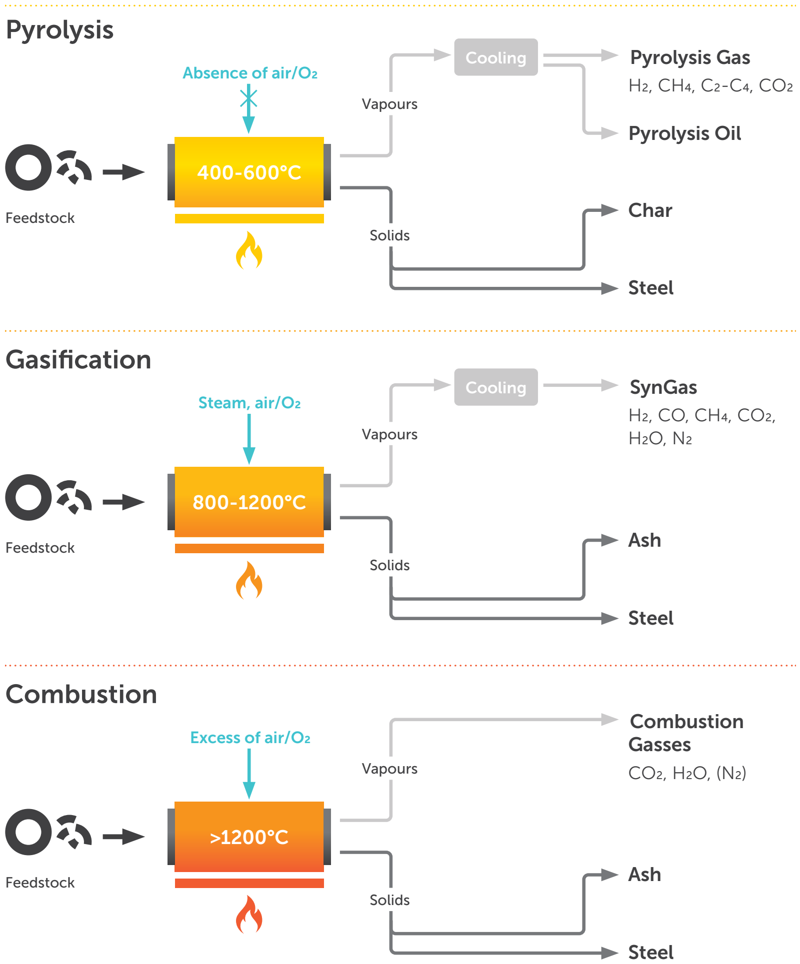
There are three main thermal processes that have been explored for processing waste tyres. The main differences between them are the temperatures at which they operate, and the amount of oxygen/air present (see Figure 2).

They are:

- Pyrolysis (moderate temperatures, no oxygen/air)
- Gasification (medium temperatures, oxygen/steam/air present)
- Combustion (high temperatures, excess air).

Pyrolysis is an established thermal pathway in which a tyre is thermally decomposed to oil, gas and carbon. Pyrolysis technologies are complex and variable, as are the materials they produce.

Figure 2: Simplified schematic of Pyrolysis, Gasification and Combustion processes (not exhaustive)



Pyrolysis

Pyrolysis is the reaction in the absence or near absence of air (or oxygen), with temperatures typically from 400 to 600°C, to thermally decompose the material.

Other terminology used to describe pyrolysis include:

- destructive distillation
- endothermic thermal desorption
- thermal decomposition
- thermal depolymerisation
- thermal desorption.

Pyrolysis has also been extensively investigated for many carbonaceous materials, including coals, biomass, plastics, as well as tyres.

Pyrolysis heats the material to 400-600°C, at which point it thermally decomposes to yield a volatile vapour. When this vapour cools it yields two fractions:

- hydrocarbon oil (tyre pyrolysis oil – TPO)
- non-condensable gas (tyre pyrolysis gas – TPG).

The residual carbon-rich solid (tyre pyrolysis carbon – TPC) remaining includes the carbon black, inorganics, fillers and steel used in the tyre. The steel can also be recovered before pyrolysis.

The thermal efficiency of tyre pyrolysis processes is high, because it needs only a small amount of energy to heat the waste tyres to the pyrolysis temperature. The pyrolysis gas produced in the process can provide the energy required to heat the reactor to the required temperatures, or can be used to generate electricity.

Gasification

Gasification is the reaction with a low ratio of oxygen (air) usually in the presence of steam, at temperatures of 800-1200°C to generate a synthesis gas (or syngas).

This syngas is high in carbon monoxide (CO) and hydrogen (H_2) and can be used for the synthesis of chemicals (hydrogen, ammonia, urea, methanol) or as a combustible gas to generate power (gas turbines, gas engines) or heat.

Gasification is a more complex process than combustion or pyrolysis, and there are no commercial examples of gasification plants exclusively using tyres. A comprehensive review of waste tyre gasification was conducted by Oboirien and North in 2017[3].

Combustion

Combustion is the reaction with excess air to produce heat in furnaces, boilers, and kilns, typically with peak temperatures above 1200°C.

Tyres in the form of Tyre-Derived Fuel (TDF) are used as fuel worldwide in cement kilns, paper mills and boilers to offset fossil fuels. Preparing TDF typically requires mechanically processing used tyres into smaller chip-sized chunks, with or without the steel wire, depending on the application.

[3] B O Oboirien and B C North (2017) A review of waste tyre gasification, Journal of Environmental Chemical Engineering, 5(5), 5169-5178. https://doi.org/10.1016/j.jece.2017.09.057

1.3 Pyrolysis technologies

There are many different approaches to pyrolysis, and the yield and composition of the pyrolysis outputs from each approach depend on:

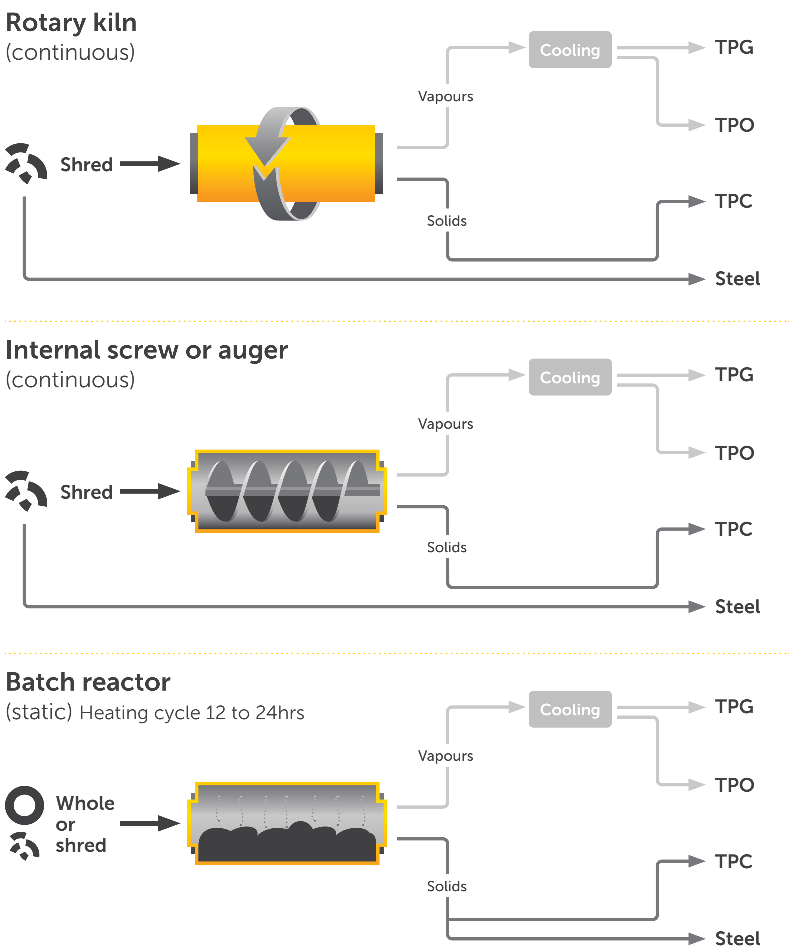
- the type of tyres fed into the reactor (OTR, truck or passenger tyres, conveyor belts)
- how the tyres are presented (whole, shredded, granules, crumbed tyres or belts)
- how the reactor is designed and operated (fixed bed, moving bed, rotary kiln or auger/screw)
- process conditions (heating rate, residence time, peak temperatures, pressure)[4 5 6].

The process conditions and feedstock types play a key role in the yield and product quality. On a commercial scale, the impact of reactor type on yield is minimal, and the process conditions and reactor design can be optimised to produce a desirable yield.

1.3.1 Different technology reactors and conditions

Figure 3 and Table 1 illustrate some of the different approaches to tyre pyrolysis.

Figure 3: Schematic representation of different configurations of tyre pyrolysis reactors



4 P T Williams, (2013) Pyrolysis of waste tyres: A review, Waste Management, 33(8), 1714-1728. https://doi.org/10.1016/j.wasman.2013.05.003

5 N Nkosi and E Muzenda, (2014) A Review and Discussion of Waste Tyre Pyrolysis and Derived Products, Proceedings of the World Congress on Engineering 2014 Vol II, WCE 2014, July 2 -4, 2014, London, U.K.

6 W M Lewandowskia, K Januszewicza, W Kosakowski, (2019) Efficiency and proportions of waste tyre pyrolysis products depending on the reactor type—A review, Journal of Analytical and Applied Pyrolysis, 140, 25–53. https://doi.org/10.1016/j.jaap.2019.03.018

Table 1: Different approaches to tyre pyrolysis

Aspect	Approach
Feed preparation/ pre-treatment	• whole car or truck tyre, or, with suitably sized reactors, large OTR tyres • shredded tyres, rubber granules or crumb rubber with or without the removal of steel wire and steel belts. • OTR tyres or conveyor belts cut to size to allow handling through the feed preparation system.
Reactor design	• horizontally-orientated reactors - static batch reactors - rotary batch reactors - continuous rotary reactors - continuous reactors with an internal screw • vertically-orientated batch or continuous reactors • semi-batch/semi-continuous reactors to reduce the overall pyrolysis batch cycle time.
Reactor heating	• commonly, indirect heating by combustion of tyre pyrolysis gas with natural gas or tyre pyrolysis oil used for start-up or for supplementary heating • in some examples, the pyrolysis reactor is electrically heated with a series of independently-controlled zones along the length of the reactor • hot inert gas or steam is sometimes injected to assist with feed heating.
Reactor operation	• feed heating rate • peak temperature • gas and solids residence time • operating pressure • use of catalysts (generally not at commercial scale).

The design and conditions in a pyrolysis reactor affect the output materials and this should be considered when making decisions about which approaches to take[4 5 7].

For example:

- smaller feed particle sizes can enable higher particle heating rates, more rapid thermal decomposition and shorter solids residence times
- operation at higher temperatures can increase thermal cracking of hydrocarbons to light gases and char
- operation under a vacuum can reduce the pyrolysis vapour residence time and reduce the potential for secondary reactions and decomposition of organic compounds to light gases
- long gas residence times can promote secondary gas phase reactions and increased decomposition of organic compounds to light gases.

[7] A T Hoang, T H Nguyen and H P Nguyen (2020) Scrap tire pyrolysis as a potential strategy for waste management pathway: a review, Energy Sources, Part A: Recovery, Utilization, and Environmental Effects. https://doi.org/10.1080/15567036.2020.1745336

1.4 The status of tyre pyrolysis operations in Australia

To assess the industry's current status we engaged with numerous stakeholders, including current, proposed, and past operators of pyrolysis plants.

In Australia, tyre pyrolysis technologies are still in the demonstration and early commercialisation phase of development, and the pyrolysis technology landscape in Australia has not made any significant advancements since TSA published the Independent Guide on Thermal Processing Technologies in 2018.

As of June 2023, there is:

- one commissioned tyre pyrolysis operation in Queensland, and one currently commissioning
- one commissioned tyre pyrolysis operation in Victoria running on a campaign basis
- one demonstration scale facility in New South Wales
- one plant under construction in Western Australia.

It's estimated that about 5,000 tonnes of tyres were processed through Australian pyrolysis facilities in 2021/22. This is expected to increase as existing plants increase throughput or new plants enter production.

Figure 4 shows the location of existing Australian tyre pyrolysis plants, and the location of proposed projects explored in this report. Most of the proposed projects are at the early development stage, with no construction timelines announced.

Figure 4: Location of tyre pyrolysis plants and project status in Australia (including proposed plants)

Table 2: Status of pyrolysis operations in Australia at either commissioning, demonstration and construction stage (as of April 2024).

Proponent	Location & Status	Feed	Reactor heating	Reactor type
Entyr Limited (Formerly Pearl Global)*	Stapylton, QLD (re-commissioning)	Shredded tyres with wire removed.	Electrically heated.	Continuous horizontal reactor with internal rotary screw. Four thermal processing units, each ~3,500 tpa.
Clean Energy Group	Dandenong South, VIC (demonstration)	Shredded tyres with wire removed.	Externally heated using natural gas/ pyrolysis gas.	Two batch rotary kilns, 8,000 kg per batch.
Green Distillation Technologies (GDT),	Warren, NSW (demonstration)	Whole passenger and truck tyres (up to 1.2 m diameter)	External heated using pyrolysis gas/oil.	Semi-batch vertical reactor, 420 kg per batch.
Waste Recovery & Energy Solutions (WRES)	New Chum, QLD (commissioning)	Whole car, 4WD, truck and forklift tyres with OTR cut to size.	Externally heated with pyrolysis gas	Commissioning 3x 10 tpd batch pyrolysers (capacity 10,000 tpa)
Elan Energy Matrix	Welshpool, WA (Under Construction)	Shredded tyres.	Externally heated using natural gas/ pyrolysis gas.	Continuous rotary kiln.

* At the time of publishing Entyr was in Voluntary Administration, and may not be operating after this report is released. Entyr Limited – Suspension of Approval ASX Code: ETR (Voluntary Administrators Appointed) (asxonline.com)

Table 2 demonstrates that each Australian tyre pyrolysis project has a different design and operational basis, including:

- **Feedstock preparation:** sites differ in the presentation of the tyre, some using whole tyres, others using shredded tyres and shredded tyres with steel removed
- **Tyre type:** sites vary in the tyre types they accept, some taking only passenger and truck, others taking OTR and conveyor belts
- **Reactor type:** there are examples of horizontal reactors and vertical reactors, which are a mix of continuous, semi-continuous, semi-batch, batch and internal rotary screw
- **Heating:** electrical heating, pyrolysis gas output heating or natural gas are all used
- **Plant size:** the number of reactors on site and daily throughput varies.

Considerations

TSA's 2018 Independent Guide on tyre pyrolysis lists issues for government and industry to consider when reviewing current and proposed tyre pyrolysis operations, such as:

- works approvals
- environmental approvals
- developing commissioning and operating procedures
- staff training.

Decision makers will also need to consider supply, economic modelling and off-take planning of outputs.

Hazards

Tyre recyclers will be familiar with the hazards associated with processing tyres, including the potential for large fires, manual handling issues, and hazards associated with rubber dust.

Pyrolysis introduces other safety and health hazards, mainly because it produces flammable liquids and gases at high temperatures. See Appendix 1: Safety considerations of pyrolysis technologies for more information on safety issues such as fires, dust, spills, handling and exposure.

These hazards should be addressed through proper engineering design, including (for example) HAZOP (HAZard and OPerability) studies of the plant during the design phase to implement appropriate engineering controls.

Proponents should seek technical guidance to ensure compliance with relevant health and safety legislation.

1.5 A snapshot of global tyre pyrolysis operations

Numerous pyrolysis facilities have also been established across other parts of Asia, Europe, and North and South America. Table 3 lists some examples of international operating tyre pyrolysis plants. This is a partial list to indicate the range of different plant configurations in operation.

Table 3: Examples of the configurations of international tyre pyrolysis plants

Proponent	Location	Feed	Reactor heating	Reactor type
Enrestec Inc	Taiwan	Shredded tyres, wire removed	Externally heated using tyre pyrolysis gas	Horizontal internal auger
Bolder Industries	Maryville, Missouri, USA	Shredded tyres, steel wire removed	Externally heated using tyre pyrolysis gas	Continuous process
Delta Energy	Natchez, Mississippi, USA	Shredded tyres, steel wire removed		Continuous process using catalysts
ReOil	Bukowno, Poland	Shredded tyres	Externally heated using tyre pyrolysis gas	Rotary kiln (continuous)
Pyrum Innovations AG	Dillingen, Germany	Shredded tyres, steel wire removed	Electrically heated	Vertical reactor (continuous)
Scandinavian Enviro Systems	Åsensbruk, Sweden	Shredded tyres	Electrical heating of pyrolysis gas injected into reactor	Vertical batch reactor (pressurised)
Contec S.A.	Szczecin, Poland	Shredded tyres, steel wire removed	Externally heated using molten salt as a heat transfer medium	Horizontal internal auger (continuous)
New Energy	Hungary	Shredded tyres, steel wire removed	Externally heated using tyre pyrolysis gas	Semi-batch vertical reactor with an internal stirrer
Kal Tyre	Antofagasta, Chile	OTR tyres, size reduced prior to loading reactor	Externally heated using tyre pyrolysis gas	Batch rotary kiln

Despite these many operational pyrolysis facilities, it is estimated that less than 3-5% of all EOL tyres are processed through pyrolysis operations[8]. Many pyrolysis technologies are often proven at prototype scale but remain unproven at industrial scale.

The low rate of processing tonnages reflects the challenges that the pyrolysis industry has been working to resolve over the past few decades, namely:

- developing the processing technology to suit the EOL tyres being processed (feedstock), the extent of primary processing required, and the consistency of outputs
- gaining regulatory approvals for the pyrolysis process, to establish facilities, and to use the outputs in product applications
- refining pyrolysis outputs (oils and carbon in particular) and establishing stable and profitable markets for the outputs.

Despite this, recent developments are showing strong signs of promising opportunities.

[8] Weibold Academy: Knowledge Base on Tire Recycling & Pyrolysis | Weibold – Tire Recycling & Pyrolysis Consulting - https://weibold.com/tire-recycling-and-pyrolysis-news?c=academy

2. Pyrolysis output material from processing tyres

Tyres are complex products composed of a blend of natural and synthetic rubbers, various grades of carbon black and fillers, additives and reinforcing materials. The specific composition varies for different tyre types to meet distinct performance requirements (see *Appendix 2: Structure and composition of a tyre* for information on trends in tyre compositions).

When tyres undergo a thermal decomposition process like pyrolysis, the commonality in the inputs (a blend of rubbers, carbon and others), is reflected in a trend in the outputs compared to other types of pyrolysis. Variability in these proportions will still create some variability in the outputs, but they will still have the key phases of solid, liquid and gases.

It's worth noting that if the steel in a tyre is not removed before pyrolysis, it can be recovered with the solids after pyrolysis by physical separation from the carbon. Magnetic separation may be required to remove fine wire.

The output fractions and approximate yield percentages recovered from EOL tyre pyrolysis, on both a steel-free mass basis and with steel.

Table 4: Approximate yield percentages recovered from EOL tyre pyrolysis

Output	Shredded tyres (steel-free)	Whole tyre (with steel)
Gas	10-20%	8-17%
Oil	40-50%	35-45%
Carbon	30-40%	25-35%
Steel wire	-	15-25%

2.1 Tyre Pyrolysis Gas

Tyre Pyrolysis Gas (TPG) is the non-condensable gas remaining after cooling and condensation of the pyrolysis oils from the vapour. TPG represents about 10-20% of the product yield on a steel-free basis.

Composition

The pyrolysis gas fraction is mainly composed of H_2, CH_4, C_2 to C_4 alkanes and alkenes, together with minor fractions of H_2S, CO and CO_2. The gas has a high calorific value and is typically used as a fuel for indirect (external) heating of the pyrolysis reactor.

Market options

Although TPG is commonly used for reactor heating, it can also be used in gas engines to generate electricity or supplied to boilers. To be used as a fuel in a gas engine, the pyrolysis gas has to be scrubbed to meet the H_2S fuel limit as set by the engine manufacturer (typically around 50 ppm).

Any un-used or post combustion gas can be flared off, which involves burning it in the same way the oil industry disposes of gas. The TPG can contain odorous sulphurous compounds including H_2S, which is a toxic, corrosive gas, and oxidises to sulphur oxides (SOx) when burnt. As SOx and other emissions to the atmosphere are limited by regulations, the TPG would have to be subjected to a series of treatments like thermal oxidation, scrubbing to remove sulphur and nitrous oxides, carbon sorbent and filters to remove particulates before flaring.

2.2 Tyre Pyrolysis Oil

Tyre Pyrolysis Oil (TPO) is the oil obtained when the pyrolysis vapour is cooled and condensed. On a steel-free basis, the yield of TPO is around 40-50% of the output.

Composition

The crude TPO is dark brown/black with an acrid smell, and consists of a complex mixture of chemical compounds (including hydrocarbons, aromatic compounds, and some organic compounds containing oxygen, sulphur, or nitrogen).

The properties of crude TPO are similar to No 6 Fuel Oil, also known as bunker oil (see Table 5), and the range of TPO properties reflects the combination of different feedstocks and process conditions. Before being used, the crude TPO would have to be filtered to remove fine char and ash.

The TPO can also be upgraded by distillation into two or more fractions. Upgrading of the TPO is discussed in *3.1 Upgrading Tyre Pyrolysis Oil.*

Table 5: Properties of crude TPO compared to Diesel[9]

Parameter	Unit	TPO	Diesel
Density @ 15°C	(kg/m3)	910 – 960	838
Carbon	(wt%)	79.6 - 88.3	87.4
Hydrogen	(wt%)	9.4 - 11.73	12.4
Oxygen	(wt%)	0.5 - 4.6	0.29
Nitrogen	(wt%)	0.4 - 1.05	0.037
Total Sulphur	(wt%)	0.6 - 1.6	0.29
Calorific Value	(MJ/kg)	38 - 42	45.5
Viscosity @ 40°C	(cSt)	3.22 - 6.3	2.1
Cetane Index		28.6	53.2
Flash Point	°C	20 - 65	50

When compared to diesel, crude TPO has a higher density, higher viscosity and a higher oxygen, nitrogen and sulphur content (0.6 to 1.6 wt%). This limits its uses as a direct fuel replacement in most applications.

The crude TPO also has a slightly lower calorific value and generally a lower flash point, which means it can ignite at lower temperatures. The higher nitrogen and sulphur contents of TPO also increase NOx or SOx formation in combustion processes, so emission control technologies may be required to meet environmental emissions limits.

Market options

TPO can be used as a heavy fuel (bunker) oil by filtering to remove fine carbon and ash. It can also be used as a fuel in furnaces, kilns, boilers, or suitable engines such as large marine engines or stationary engines to generate electricity.

At the time of this report, Australian pyrolysis operators can supply crude TPO for:

- combustion applications in boilers and furnaces, as a substitute for bunker fuel oil
- blending with diesel for use in heavy machinery
- blending and refining by oil companies.

9 M I Jahirul, F M Hossain, M G Rasul and A A Chowdhury, (2021) Review on the Thermochemical Recycling of Waste Tyres to Oil for Automobile Engine Application. Energies 14, 3837. https://doi.org/10.3390/en14133837

Further investigation is required to determine what percent of TPO can be blended to remain within acceptable emission limits.

See Section *3.1 Upgrading Tyre Pyrolysis Oil* for more details about potential markets.

Standards

The Australian Government applies fuel quality standards to regulate petrol, diesel and other fuels sold and supplied in Australia. Similar replacement fuels would need to meet these standards, or relevant alternate fuel standards if introduced (as with biodiesel)[10].

Currently, renewable and synthetic diesel fall under the Fuel Quality Standards (Automotive Diesel) Determination 2019.

2.3 Tyre Pyrolysis Carbon

Tyre Pyrolysis Carbon (TPC) is the residual solid fraction remaining after tyre pyrolysis. The typical yield of TPC is about 30-40% on a steel-free basis.

Composition

TPC is carbon-rich (~80% carbon) and includes the various grades of carbon black added to the natural and synthetic rubbers during tyre manufacturing, together with a small amount of carbon formed from thermal decomposition/cracking of organic vapour. The fillers and inorganics (zinc, silica (SiO_2), clay, etc) used during tyre manufacturing contribute to the ash content of TPC. This depends on the feedstock (20-25% for passenger tyres, 15% for truck tyres and lower for OTR tyres).

If the tyres processed through the pyrolysis facility are contaminated with soil, sand or other material, the contamination is also collected with the pyrolysis carbon. If steel wire is present, it can be removed by magnetic separation. TPC can be upgraded for use in other applications *(see Section 3.2 Upgrading Tyre Pyrolysis Carbon)*.

Market options

Some early demonstration of TPC applications include:

- in road making to enhance the binding of asphalt, substituting hydrated lime[11]
- as a source of slow-release zinc for soil conditioning[12].

Other proposed uses of TPC are:

- as a fuel in cement kilns or fluidised-bed combustors or as a reductant or coking coal substitute
- as a carbon in a blast furnace (iron ore reduction) or smelters to offset the use of coke/coal
- through gasification to produce syngas to generate electricity, or burnt in a fluidised-bed combustor to generate steam.

Compared to the revenues for oil and steel, current Australian pyrolysis operators show low revenue from carbon sales, suggesting poor market acceptance for TPC.

[10] Department of Climate Change, Energy, the Environment and Water: Regulating Australian fuel quality. Accessed 8th April 2024. https://www.dcceew.gov.au/climate-change/emissions-reduction/regulating-fuel-quality#toc_2

[11] NTRO: Beyond crumb rubber: New innovations using recycled tyres in transport construction. Accessed 8th April 2024. https://www.ntro.org.au/news/beyond-crumb-rubber

[12] K Greer, J Wiebe, E Bremer (2021) Repurposing Zinc from Mining Tire Waste to a Fertilizer Resource, Western Nutrient Management Conference, Proceedings, Vol 14, March 2-4, 2021, pages 12-16.

Less than 5,000 tonnes of used tyres were processed through Australian pyrolysis plants in 2021/22. Assuming a TPC yield of 40%, total TPC production would be less than 2,000 tonnes. As new tyre pyrolysis facilities enter the Australian market, production will increase and markets for the carbon will be needed to avoid stockpiling or disposal to landfill.

Further development is required to achieve commercialisation or market acceptance of the carbon product.

2.4 Steel wire

Depending on the set-up, the steel wire in tyres is separated either before or after pyrolysis. The steel wire represents 15-25% of the tyre mass and includes the wire bead bundle and steel belts. This is often linked to the type of tyres, for example passenger tyres may have 13 to 15% steel, whereas truck tyres 14 to 25%, and OTR tyres up to 30%. Magnetic separation can be used to remove residual fine wire from TPC.

Market options

The steel wire is sold into the scrap metal market.

3. Refining outputs to access higher grade product applications

This section examines some of the industry's efforts to upgrade oil and carbon pyrolysis products to produce higher-grade materials.

There has been some global market acceptance of tyre pyrolysis oils and carbon. Tyre manufacturers are showing interest in using them as part of commitments to sustainability and the circular economy.

While Australia doesn't have a tyre manufacturing industry to provide local demand, it does manufacture other rubber products such as conveyor belts and retreads, which could provide opportunities for local demand if explored.

3.1 Upgrading Tyre Pyrolysis Oil

As outlined in section 2.2, the properties of crude TPO are comparable to bunker oils. The difference is that crude TPO has a higher density, higher viscosity and a higher oxygen, nitrogen and sulphur content (0.6 to 1.6 wt%) compared to diesel.

This limits its uses as a direct fuel replacement in most applications. To be comparable with diesel, TPO would need to be upgraded into higher-value oils and solvents by processes such as distillation and desulphurisation.

3.1.1 Distillation

Crude TPO has a complex composition, a wide boiling point range (from <70°C up to 550°C), and a low flash point. Distillation (also called *fractionation*) can separate the TPO into fractions with narrower boiling point ranges, usually one or more lighter fractions and a residual, high-boiling point (heavy) fraction.

Some tyre pyrolysis operators sell distilled fractions of TPO as solvents. Table 6 shows an example of the fractions obtained after distillation of TPO.

Table 6: Distilled fractions of TPO[13]

Fraction	Boiling Point Range	Appearance
Light fraction	70 – 176°C	Yellowish, low viscosity, like gasoline fuel
Low-middle fraction	176 – 240°C	Dark brownish, slightly more viscous than the light fraction, compatible with diesel
High-middle fraction	240 – 285°C	Brownish, slightly more viscous than the low-middle fraction, compatible with distillate marine fuels
Heavy fraction	285 – 550°C	Black, with high viscosity at room temperature (barely flowing), like bitumen

[13] F Campuzano, A G A Jameel, W Zhang, A-H Emwas, A F Agudelo, J D Martínez, S M Sarathy, (2021), On the distillation of waste tire pyrolysis oil: A structural characterization of the derived fractions , Fuel, 290, 120041. https://doi.org/10.1016/j.fuel.2020.120041

The relative proportions of different fractions can depend on the pyrolysis technology used. High molecular weight sulphur compounds and polyaromatic hydrocarbons will concentrate in the heavy, higher-boiling-point fractions, improving the quality of the lighter fractions.

The lighter fractions will need to undergo further processing (hydrotreating and/or desulphurisation) to be comparable to the fuel quality standards.

3.1.2 Hydrotreating and desulphurisation

While distillation can separate out the different fractions of the oil, there may still be other contaminants that have to be removed for the oil to be suitable as a fuel. This can be done using processes such as hydrotreating and desulphurisation.

Hydrotreating

Hydrotreating is an established oil-refinery process used to remove sulphur, nitrogen and oxygen from organic feedstocks, and to hydrogenate unsaturated hydrocarbons such as olefins. It is expensive and requires hydrogen at high temperatures (300-400°C) and moderately high pressures (1.5-9.0 MPa).

Desulphurisation

Oxidative desulphurisation is a sulphur removal process that oxidises organosulphur compounds to sulphoxides and sulphones under mild conditions (50-100°C)[14 15]. Hydrogen peroxide (H_2O_2) is commonly used as a low-cost and readily available oxidant.

Sulphur removal of up to 86% has been reported with appropriate catalysts and process conditions. This method is generally cheaper than hydrotreating but can be expensive for small-scale applications[16].

3.1.3 Chemical and solvent production

TPO can also be a potential feedstock of chemicals such as benzene, toluene, ethylbenzene, xylene (BTEX chemicals) which have a market in the petrochemical industry[17]. Extracting this fraction is only possible with additional processing (distillation etc.) and refining, and the remaining fractions in the TPO would still require a market.

There has been some early investment in a few global markets[18 19].

Tyre pyrolysis oil can potentially be used as a substitute for fossil fuel oil to produce sustainable carbon black (sCB). A European consortium of pyrolysis and tyre industry companies have created a project called BlackCycle, to investigate the feasibility of the use of TPO for the production of a replacement for carbon black[20]. BlackCycle is an EU-funded project that aims to recycle EOL tyres into new

[14] R Serefentse, W Ruwona, G Danha and E Muzenda, (2019) A review of the desulphurization methods used for pyrolysis oil, Procedia Manufacturing, 35, 762-768https://doi.org/10.1016/j.promfg.2019.07.013

[15] V Toteva, and K Stanulov, (2020) Waste tires pyrolysis oil as a source of energy: Methods for refining. Progress in Rubber, Plastics and Recycling Technology, 36(2), 143-158. https://doi.org/10.1177/14777606198950

[16] M N Hossain, M K Choi, and H S Choi (2021) A Review of the Desulfurization Processes Used for Waste Tire Pyrolysis Oil. Catalysts 11, 801. https://doi.org/10.3390/catal11070801

[17] P T Williams, (2013) Pyrolysis of waste tyres: A review, Waste Management, 33(8), 1714-1728. https://doi.org/10.1016/j.wasman.2013.05.003

[18] BASF invests into Pyrum as part of its ChemCyclingTM project, September 21, 2020. https://www.basf.com/global/en/media/news-releases/2020/09/p-20-311.html

[19] Bolder Industries to supply Tauber with oil from tire pyrolysis, January 24, 2022. https://weibold.com/bolder-industries-to-supply-tauber-with-oil-from-tire-pyrolysis.

[20] BlackCycle website: https://blackcycle-project.eu/

tyres. It is coordinated by Michelin and includes several European industrial companies and research organisations as partners.

Under this programme, Orion Engineered Carbons[21] have announced production of N234, a sCB using tyre pyrolysis oil supplied by Pyrum Innovations AG, Germany[22].

3.2 Upgrading Tyre Pyrolysis Carbon

TPC is a potential carbon source for use in advanced materials, with proposed applications including:

- use in rubber and plastic products and epoxy resins[23]
- cleaning, milling and pelletisation to achieve the required fineness to be safely handled and called a recovered Carbon Black (rCB)
- producing activated carbons for use in gas and water treatment
- creating advanced materials for chemical treatment processes.

Operators in Australia are having difficulties identifying commercial markets for the carbon generated through pyrolysis, and none of the above applications have attained commercial status in the Australian market. These applications remain primarily in the research and development phase globally. The only exception is rCB, which is progressing toward international market acceptance, making it the primary focus of the following section.

3.2.1 Processing TPC into rCB

Carbon Black is a fine black powder composed of elemental carbon that has a high surface area. The global annual production of carbon black exceeds 10 million tonnes, and is expected to continue growing[24].

The most common use of carbon black is as a pigment and reinforcing filler in tyres (70% market share) and other rubber products (conveyor belts, hoses, other) (20%). Carbon black improves wear resistance and protects rubber against degradation from UV light.

Other uses for carbon black include printing inks, coatings, plastics (9%) and other applications (1%)[24].

It's worth noting that producing virgin carbon black (vCB) is energy intensive. There are also numerous grades of vCB which differ depending on the required properties (Figure 5).

[21] BlackCycle website, November 2022: https://blackcycle-project.eu/orion-engineered-carbons-is-moving-forward-on-the-road-to-sustainability-creation-of-sn234-able-to-be-used-as-a-drop-in-to-a-conventional-n234/

[22] Pyrum Innovations AG website: https://www.pyrum.net

[23] CRC Projects selection round outcomes, February 2024: https://business.gov.au/Grants-and-Programs/Cooperative-Research-Centres-CRC-Grants/CRC-grants-selection-round-outcomes

[24] What is Carbon Black? Orion Engineered Carbons GmbH, 2015

Figure 5: Example of different grades of Carbon Black used in Tyre Manufacture – Adapted from Martínez et al 2021[13]

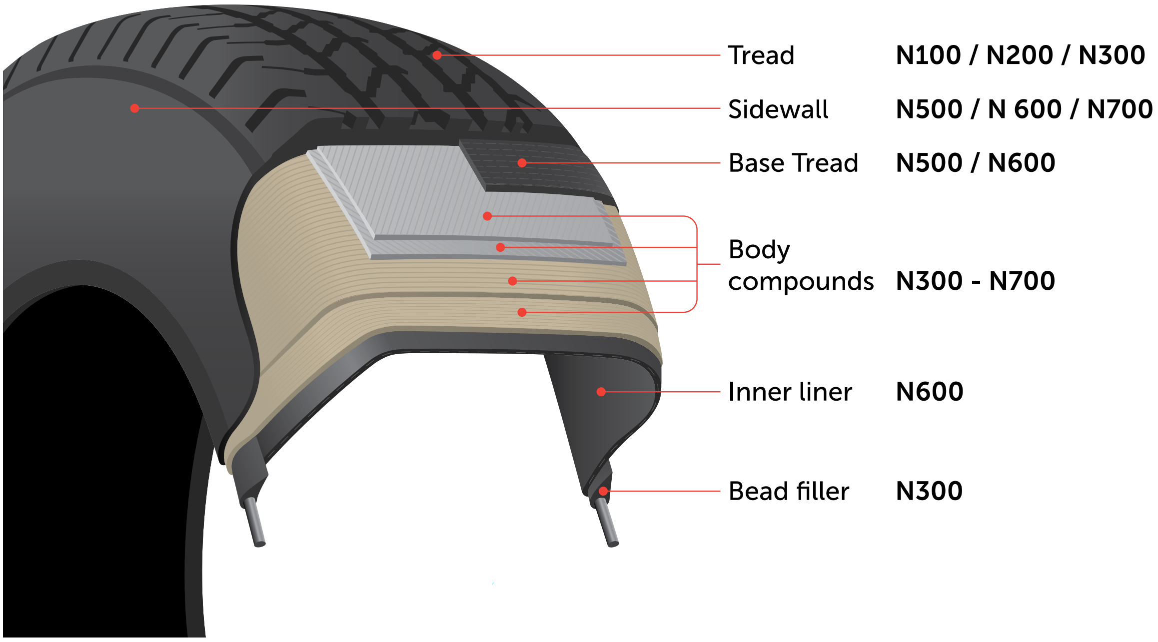


Table 7 shows the properties of the different carbon black grades, and their application in tyre manufacture.

Table 7: Properties and applications of some Carbon Black grades[25]

Carbon Black Grade	Properties	Application	Grade
N110	High reinforcement and abrasion resistance	Tyre treads, specialty and OTR tyres	Hard
N220	High reinforcement and tear strength	Tyre treads, specialty and OTR tyres	Hard
N330	Medium-high reinforcement, high elongation, good tear and fatigue resistance	Tyre treads, carcass, and sidewall, bicycle tyres	Hard
N550	Medium-high reinforcement, high modulus and hardness	Tyre inner liners, carcass, and sidewall, hoses and tubing	Soft
N660	Medium reinforcement and modulus, good flex and fatigue resistance	Tyre inner liners, carcass, and sidewall, sealing rings, cable jackets, hoses and tubing	Soft
N762	Medium reinforcement, high elongation and resilience, low compression set	Mechanical rubber goods (e.g. extruded profiles/mouldings), footwear; rubber flooring	Soft

rCB as a substitute

The Carbon Black used in tyres is seen as a highly desirable market for the rCB produced from tyre pyrolysis, and there are significant research efforts underway to improve the quality of rCB from tyre pyrolysis as a replacement for carbon black[25].

The American Society for Testing and Materials (ASTM) also has a working group to develop quality standards for rCB covering test methods, specifications, classifications, and nomenclature. Upgrading the TPC to rCB to meet the expectations of the tyre industry requires milling to a superfine product (<10 microns) and then pelletising to allow safe handling[26].

[25] Joint Bridgestone and Michelin rcbrubber website: https://rcbrubber.com
[26] ASTM D8178-22 Standard Terminology Relating to Recovered Carbon Black (rCB), Jun 2022 www.astm.org/d8178-22.html.

Applications

If the rCB has the required properties, it can be used as a part replacement of some of the lower grades of carbon black (N500, N600, N700 series) used in rubber or plastics. It has also been used to partially substitute Carbon Black in less demanding applications including tyre inner liners, footwear, industrial rubber goods, conveyor belts and hoses[27].

Even after upgrading, rCB has yet to meet the chemical and physical properties for tyre applications requiring high or medium-high reinforcement (N100 and N200 carbon black grades).

Differences

One of the reasons why rCB can only be substituted for the lower carbon black grades is the difference in composition between vCB and rCB.

vCB has high carbon and low ash (1%), whereas TPC (and therefore rCB), has a higher ash content and lower carbon due to the presence of fillers and additives in tyres. Good quality rCB will need to have an appropriate ash content, low volatiles (or oily residue), and be free of steel wire.

Table 8 shows the proximate and ultimate analysis for tyre pyrolysis carbons, rCB and carbon black.

Table 8: Reported analysis for tyre pyrolysis carbon, rCB and carbon black.

	Proximate Analysis, %db			Ultimate Analysis, %db			
	Volatile Matter	Fixed Carbon	Ash	Carbon	Hydrogen	Nitrogen	Sulphur
Tyre Pyrolysis Carbon	0.67 – 13.9	74.6 – 90.9	8.4 – 18.9	76.6 – 90.3	0.26 – 7.7	0.16 – 0.75	1.2 – 3.6
Commercial rCB	<5		14 – 22	>82			<3
Commercial Carbon Black	0.5 – 6.0	93.0 – 98.5	<1	96 – 99.5	0.2 – 1.3	0.0 – 0.7	0.1 – 1.0

Source: Carbon Black – Orion[28], Tyre Pyrolysis Carbon[29], Commercial rCB[27 30]

Tyre producers Bridgestone and Michelin aim to increase the use of rCB from pyrolysis of used tyres to achieve 100% sustainable materials in their products by 2050. They note that the lack of standards for rCB has hindered market development and that the tyre pyrolysis industry is fragmented with many different pyrolysis technologies at the prototype/demonstration scale and unproven at industrial scale. They have since have committed to provide support to the industry to improve this[26].

There is work currently underway to clarify characterisation and quality methods, along with an agreed specification towards an ASTM standard for rCB[27].

Global applications

Examples of international research and development efforts to increase the use of rCB from pyrolysis of used tyres include:

- Delta-Energy's[31] catalysis-based pyrolysis claims to produce an rCB product that retains the surface area and structure of the original carbon black. The rCB is claimed to compare well to medium reinforcing and low reinforcing carbon black grades (N700, N900, N600, N500 and N300).

[27] Black Bear Carbon Black website: https://blackbearcarbon.com/products-2-2/technical-rubber/conveyor-belts/

[28] BolderBlack Technical Specifications, https://www.bolderindustries.com/bb-technical-specifications-pdf

[29] Lawrence Industries (UK), Waverly Carbon Recovered Carbon Black Technical Datasheets. Website: https://www.l-i.co.uk/products/emerald-rcb

[30] Delta-Energy website: https://www.deltaenergy.com

- Birla Carbon[31] produce about 13% of global carbon black. A new tyre pyrolysis facility, under construction in the Netherlands, will produce 73,000 tpa of rCB from the pyrolysis of EOL tyres[32], to be used in new products, such as rubber compounds, plastics and coatings.
- Black Bear Carbon B.V.[33] has announced it will produce 12,000 tpa of rCB from pyrolysis of EOL tyre as a sustainable alternative to conventional carbon black. The rCB is to be used as a replacement for N330 and N660 carbon black grades.
- Researchers at Fraunhofer IBP (Germany) have developed an acid leaching process to remove ash impurities from rCB to allow replacement of virgin carbon black (vCB) in tyre manufacturing[34].
- UK-based Waverly Carbon have also developed technology to remove ash impurities from rCB and expect to produce 180 tpa of a rCB product with less than 1% ash from 2023[35].

These initiatives show that the industry is actively developing the rCB market. Ongoing collaboration is seen as essential to ensure the properties of rCB align with the technical specifications required for high-value rubber products, and to bridge gaps with the processes and testing methods outlined in current standards.

Australian applications

At the time of this report, there has been limited production of rCB from pyrolysis operations in Australia. This is possibly due to the lack of a local tyre manufacturing industry as a primary user.

Although local markets for rCB in products like conveyor belts and retreads offer opportunities, they may struggle to use the volume of output if tyre pyrolysis operations scale up.

While Australian pyrolysis proponents are able to explore international markets, these efforts are still in development. Producers will have to compete with global tyre pyrolysis initiatives, and further research and development may be needed to support the market.

3.3 Greenhouse Gas emissions savings potential

Australia is still some way from commercialising tyre pyrolysis products in fuel and carbon markets, but if it becomes commercially operational, it may become possible to make some greenhouse gas (GHG) emission savings.

TSA has issued some preliminary information on the GHG implications for processing and using EOL tyres[36]. Manufacturing new passenger tyres emits around 2,370 kg of CO_2 eq/tonne. Manufacturing truck tyres generates around 1,970 kg CO_2 eq/tonne. Disposing tyres to landfill doesn't recover the embedded energy content within the tyre or enable material recovery.

Pyrolysis of EOL tyres will enable recovery of steel, pyrolysis carbon, pyrolysis oils and pyrolysis gas. As established in previous sections, re-using these materials can provide a benefit by displacing virgin resources. For example:

[31] Birla Carbon website: https://www.birlacarbon.com
[32] https://www.birlacarbon.com/a-partnership-for-sustainability-between-circtec-and-birla-carbon/
[33] Black Bear Carbon B.V. website: https://blackbearcarbon.com
[34] Recovered Carbon Black: Major Step Toward Sustainable and Responsible Future, ChemAnalyst.News, 21-Oct-2022 https://www.chemanalyst.com/NewsAndDeals/NewsDetails/recovered-carbon-black-major-step-toward- sustainable-and-responsible-future-11697
[35] Waverly Emerald Pure. https://www.waverlycarbon.com/product/
[36] Tyre Stewardship Australia webiste: https://www.tyrestewardship.org.au/news/for-public-consultation-preliminary-findings-of-greenhouse-gas-emissions-analysis-of-waste-tyre-recovery/

- recovered steel can be recycled, offsetting the production of new steel from iron ore
- TPO can be used as a bunker fuel oil for combustion applications or in heavy marine engines, offsetting fossil oils, used as a chemical feedstock, displacing fossil fuel resources, or upgraded to higher-quality fuels and products
- TPG can be used to heat the pyrolysis reactor or other energy applications
- TPC can be upgraded to rCB and used as a part replacement for vCB in certain carbon black grades[37]. This could provide greenhouse benefits in offsetting the use of fossil oil required for carbon black production. Processes to produce vCB generate 2.5-3 tonnes of CO_2 per tonne of product. Production of vCB also requires 1.5-2 tonnes of oil per tonne of vCB. Some studies have suggested production of rCB has around 80% lower CO_2 emissions compared to vCB.
- TPO has the potential to be used to produce sCB instead of using petroleum-derived oils[38].

Australian EOL tyre pyrolysis technologies vary with the types of tyres, pre-processing, transport distances and logistics, both between states and compared to global operators.

This makes it premature to develop generic numbers on emission savings for Australian operations. General trends from international data can be drawn upon, but there's a gap in verifiable data in Australia, so EOL tyre pyrolysis processors will need to calculate their own unique emission assessments to make environmental claims.

[37] Press Release Scandinavian Enviro Systems AB dated 21-03-2019. Life-cycle analysis of recovered carbon black Enviro's rCB reduces CO_2 emissions by over 79%, better than earlier estimates. https://mb.cision.com/Main/9805/3100575/1239033.pdf (accessed 9-Apr-2024)

[38] News Release Orion Carbons dated 01-12-2021 The BlackCycle consortium announces the world's first production of sustainable carbon blacks https://orioncarbons.com/the-blackcycle-consortium-announces-the-worlds-first-production-of-sustainable-carbon-blacks/ (accessed 9-Apr-2024)

4. Conclusion

Within Australia, and overseas, there is a wide range of approaches to EOL tyre pyrolysis for materials recovery. Many of these approaches are at the early demonstration or commercialisation stages. As the technologies are still under development and scale-up, it is not clear which approach will dominate the sector in the future.

By outlining the unique elements of different technologies and their outputs, the report aims to enable the industry to identify the important aspects of tyre pyrolysis, and so differentiate it from other thermal processing of carbon-based materials. Pyrolysis provides an energy-efficient means to recover valuable materials from EOL tyres and other rubber products.

The process flow diagram in Figure 5 summarises the key elements of this report.

Tyre Pyrolysis Oil (TPO)

TPO can be used in furnaces, kilns, and boilers or engines such as large marine engines, or as feedstock for chemicals production. The oil has around 1% sulphur and may need to be blended with lower sulphur fuels in some applications. The oil can also be upgraded by distillation/desulphurisation to produce higher-value light oils or solvents.

Tyre Pyrolysis Gas (TPG)

TPG has a high heating value and is usually used to heat the pyrolysis reactor, but generally requires scrubbing to remove contaminants such as H_2S.

Tyre Pyrolysis Carbon (TPC)

Finding markets for TPC has been difficult. Recent use in road making has been trialled, using TPC as a substitute for hydrated lime to enhance the binding of asphalt. Internationally, some tyre pyrolysis producers are starting to find high-value markets for the pyrolysis carbon by upgrading it to rCB to partly replace medium-quality carbon black in rubber products.

Tyre wire

Tyre wire can be sold into the scrap metals market.

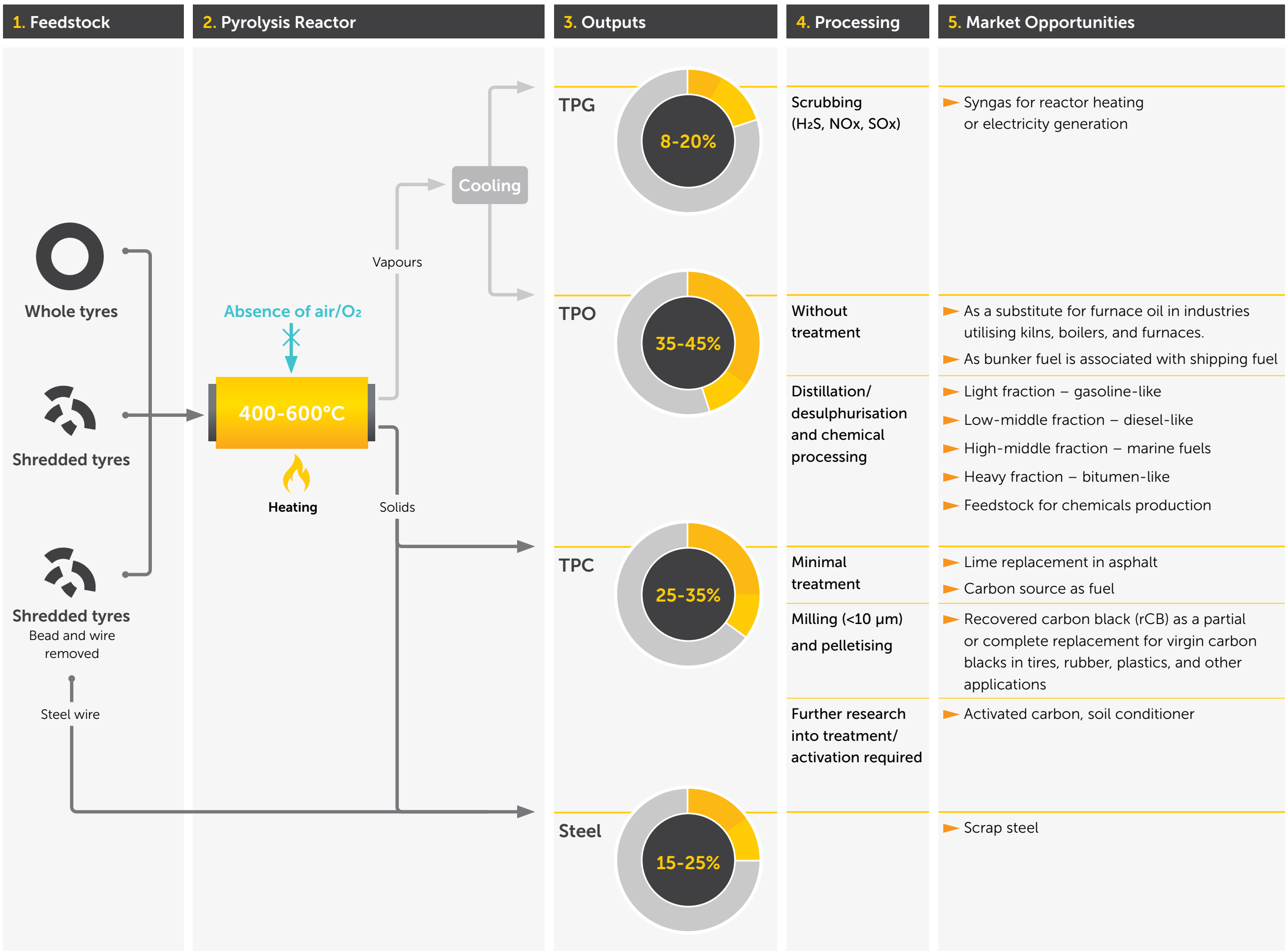
Finding markets

Success of EOL tyre pyrolysis plants requires value markets for the products, and specifically the TPO and TPC. When considering new projects, operators need to review potential markets and ensure their products can meet market the quality and quantity expectations. Ideally, off-take agreements for the TPO and TPC should be obtained before committing to a project.

High-value circular economy markets, such as raw materials for tyres and rubber products, have high technical standards, and pyrolysis operations will need to adapt to fit these long-established global markets.

The industry has seen innovation in developing new product markets, such as projects in roads, fuels and advanced materials, but these are still in development and will face scrutiny for technical specifications to achieve market acceptance.

Figure 6: Summary of different tyre pyrolysis inputs, outputs, processing and market opportunities.



Meeting standards

The industry must also adhere to high safety and environmental standards. This involves secure storage practices, fire prevention, emission controls, and compliance with relevant Australian regulations. These measures are crucial for the successful integration of EOL tyre pyrolysis as a sustainable waste management solution in the Australian context.

Industry investment

While the development of commercial facilities and markets in Australia has been moving slowly, recent global developments show significant investment and interest from the tyre industry in tyre pyrolysis technology.

A recent white paper by Michelin and Bridgestone relating to rCB shows that the tyre industry has not provided the right guidance to pyrolysis proponents about their capacity, demand and technical requirements. A commitment to provide this guidance may increase the quality and quantity and acceptance of materials being produced from tyre pyrolysis.

Local limitations

Without a local Australian tyre manufacturer, there is a limited market for carbon black onshore, which may be why there is currently little upgrading and production of rCB in Australia.

For Australian pyrolysis facilities to access a global rCB market, Australia will need to develop rCB secondary processing and quality standards, and research other high-performance applications (such as conveyor belts and retreads). A similar approach would be needed for producing sCB from tyre pyrolysis oil. To gain access to global markets for rCB, industry support for research, development and marketing will be required.

Pyrolysis is one of the options to increase the recovery of EOL tyres in Australia. Currently in Australia and overseas, there are many approaches to pyrolysis with no single technology achieving market dominance. This report provides an overview on the topic of thermal processing technologies, as requested by TSA stakeholders. While Australia still falls short in recovering all its tyres, any emerging and alternative management approaches warrants consideration, and up-to-date information to inform decision making.

5. Appendices:

5.1 Appendix 1: Safety considerations of pyrolysis technologies

Like all waste processing technologies, there are hazards associated with processing EOL tyres through pyrolysis plants which need to be considered and managed. This list is not exhaustive.

These hazards should be addressed through proper engineering design, including (for example) HAZOP (HAZard and OPerability) studies of the plant during the design phase to implement appropriate engineering controls. Proponents should seek technical guidance to ensure compliance with relevant health and safety legislation.

Fire

- Correct storage of waste tyres and shredded material is required to minimise risks of fire[39].
- Risks of leaks of flammable pyrolysis vapour from the pyrolysis plant and the potential for fires and explosions when mixed with air. Hot surfaces and electricals can provide an ignition source. Appropriately rated equipment (e.g. ATEX-rated explosion-proof motors) may be required.
- Risks associated with leaks and spills from the pyrolysis liquids, handling equipment and storage systems including potential for fires. Australian Standard AS1940 covers the safe storage and handling of flammable and combustible liquids.

Dust and explosions

Risks associated with handling of pyrolysis carbon and the potential for carbon dust explosions. Smouldering carbon will release CO, a poisonous gas. Milling circuits for upgrading pyrolysis carbon to an rCB product will generate ultrafine carbon dusts and potential for carbon dust explosions. Good housekeeping practice is to avoid the accumulation of carbon dusts on horizontal surfaces that could be disturbed to form a dust cloud with increased risks of ignition and dust explosions. The dust explosibility and self-heating potential for the carbon product should be evaluated.

Occupational exposure

Control of occupational exposure to pyrolysis oils, odours, and dusts. There are occupational exposure limits for airborne dusts. The Australian occupational exposure limit for carbon black dusts is 3 mg/m^3 [40]. Pyrolysis oils should not come into contact with skin. Appropriate personal protective equipment should be worn.

Control of odours and exposure from sulphurous gases including H_2S. Vents on pyrolysis oil storage tanks are commonly fitted with carbon filters to adsorb vapours and control emission of odorous sulphur compounds to the environment. H_2S has an odorous and offensive 'rotten egg' smell at low

39 Tyre Stewardship Australia, Best Practice Guidelines for Tyre Storage and Fire and Emergency Preparedness. Update May 2022. https://www.tyrestewardship.org.au/guidelines/stockpile-guideline/

40 Safe Work Australia, www.safeworkaustralia.gov.au, Workplace Exposure Standards for Airborne Contaminants. Date Of Effect: 1 October 2022/

concentrations 0.01-1.5 ppm. The Australian Time Weighted Average workplace exposure limit to H_2S is 10 ppm[41]. Exposure to concentrations, above 100 ppm, can be fatal[42].

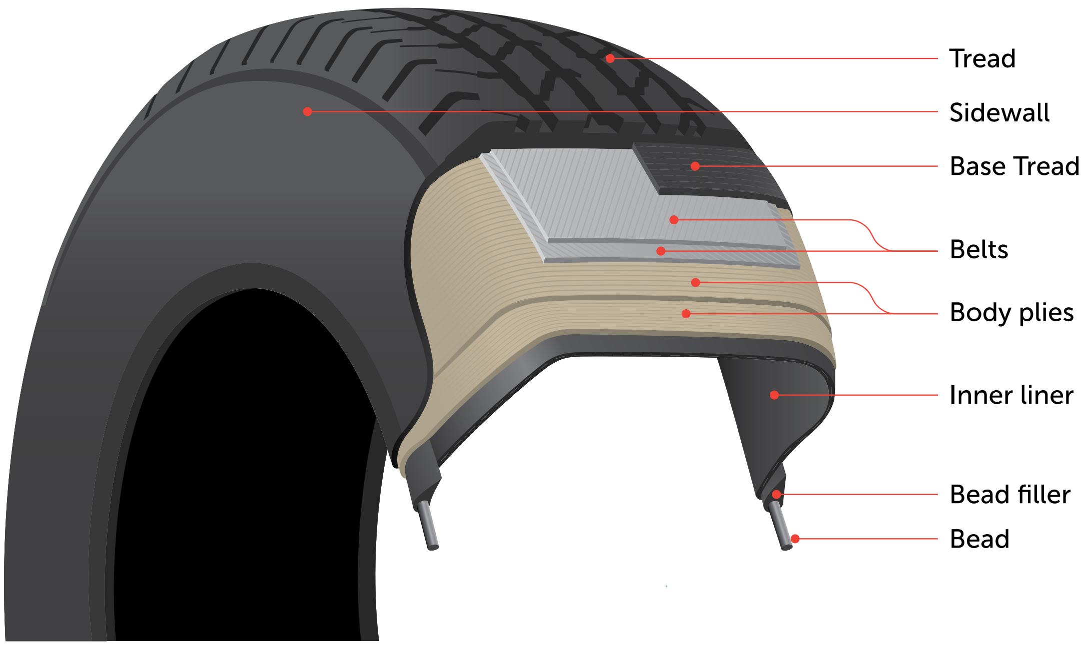
Meeting standards

Where equipment has been imported into Australia, the vessel design and auxiliary equipment (motors, electricals, burners, safety installations) may not meet Australian Standards. Additional engineering and modifications may be required for the plant to be compliant.

5.2 Appendix 2: Structure and composition of a tyre

Figure 7 shows the basic structure of a passenger tyre. Natural and synthetic rubbers are used in the tread, shoulder, sidewall, carcass and inner liner. The main source of natural rubber is tapped from *Hevea brasiliensis*, colloquially termed rubber trees. The most common synthetic rubbers are polymers of butadiene or styrene butadiene. Carbon black is added to reinforce the rubber, making it stronger and more resistant to abrasion. The reinforcing plies are often made from textiles, like nylon in the case of passenger tyres, but are generally not used in truck tyres. The belts and bead are made from steel wire and help to reinforce and strengthen the tyre.

Figure 7: Structure of a passenger car tyre. Adapted from Harrison et al and USTMA[44 47]



Truck tyres generally have higher levels of natural rubber compared to passenger tyres. Passenger tyres have higher levels of synthetic rubber as well as nylon (or rayon or polyester) textile belts and braided steel belts. Various chemical additives, pigments, and fillers (silicas, clays) are also added to the rubber compound for different performance attributes.

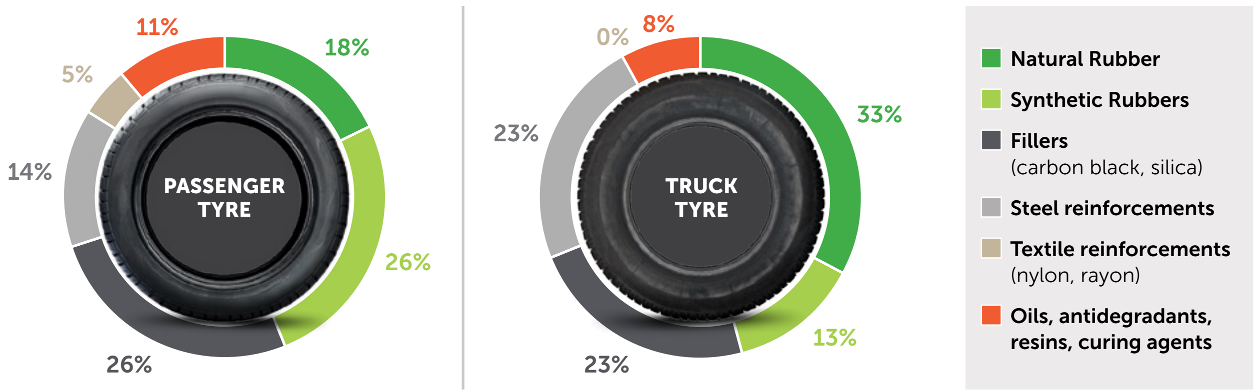
During rubber compounding, sulphur is added to the process to enable the rubbers to undergo vulcanisation, which improves structural integrity by crosslinking individual polymers of natural rubber. Zinc oxide is added as an accelerant to speed the vulcanisation process.

[41] Safe Work Australia Exposure Standard Documentation Hydrogen sulphide http://hcis.safeworkaustralia.gov.au/ExposureStandards/Document?exposureStandardID=327

[42] https://www.osha.gov/hydrogen-sulfide/hazards

Figure 8 shows the approximate material composition of passenger and truck tyres. This data is taken from various USA and European Union sources. Exact tyre compositions will depend on the unique tyre type and brand and the below numbers are a combination of average compositions gathered from various international sources. The average composition of Australian tyres may be different and reflect the mix of tyres imported into the domestic market.

Figure 8: Average material composition of passenger and truck tyres[43 44 45 46 47 48]



Information on OTR composition is not widely available in the literature, although it is widely accepted in the industry that the composition of OTR tyres is more like truck tyres.

Table 9 shows the elemental composition of passenger and truck tyres (C, H, S, N, Cl), which is from a European study[49]. The average composition of tyres in the Australian market may be different.

Table 9: Elemental composition by % mass of car and truck tyres (C, H, S, N, Cl) (dry basis)

Element	Passenger car	Truck
Carbon (C)	64 - 68%	61.5 - 68%
Hydrogen (H)	5.8 - 6.4%	5.5 - 6.4%
Sulphur (S)	1.3 - 1.4%	1.4 - 1.8%
Nitrogen (N)	0.5 - 0.6%	0.3 - 0.45%
Chlorine (Cl)	0.01 - 0.02%	0.007 - 0.01%

[43] J Harrison, M Lyons, G O'Connor and L Thomas (2019) Literature Review on the Use of Passenger Vehicle Tyres in Bitumen. Technical Report TR 216 prepared for Vic Roads. ISBN 978-0-7311-9178-9. www.vicroads.vic.gov.au/business-and-industry/technical-publications/technical-publications-a-to-z

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[46] U.S Tire Manufacturers Association. What's In A Tire. https://www.ustires.org/whats-tire-0 (2020).

[47] European Tyre & Rubber Manufacturers' Association (ETRMA). Guidance on the use of VULCANIZED-RUBBER PSEUDO SUBSTANCES in IMDS declarations of tyres. (2013).

[48] Continental. Tire Mixture: What's in your tires? https://www.continental-tires.com/car/tire-knowledge/tire-basics/tire-mixture (2021).

[49] Aliapur - Technical Datasheet Powergom A (Car Tyres, 2019) https://www.aliapur.fr/uploads/pdfs/fiche-technique-aliapur-powergom-a.pdf
Aliapur - Technical Datasheet Powergom B (Truck Tyres, 2019) https://www.aliapur.fr/uploads/pdfs/fiche-technique-aliapur-powergom-b.pdf

TyreStewardship AUSTRALIA

ABN: 44 164 971 939

Address: Suite 101, 271 Bridge Road, Richmond, VIC 3121

Phone: 03 9977 7820

Email: getonboard@tyrestewardship.org.au

Website: tyrestewardship.org.au

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