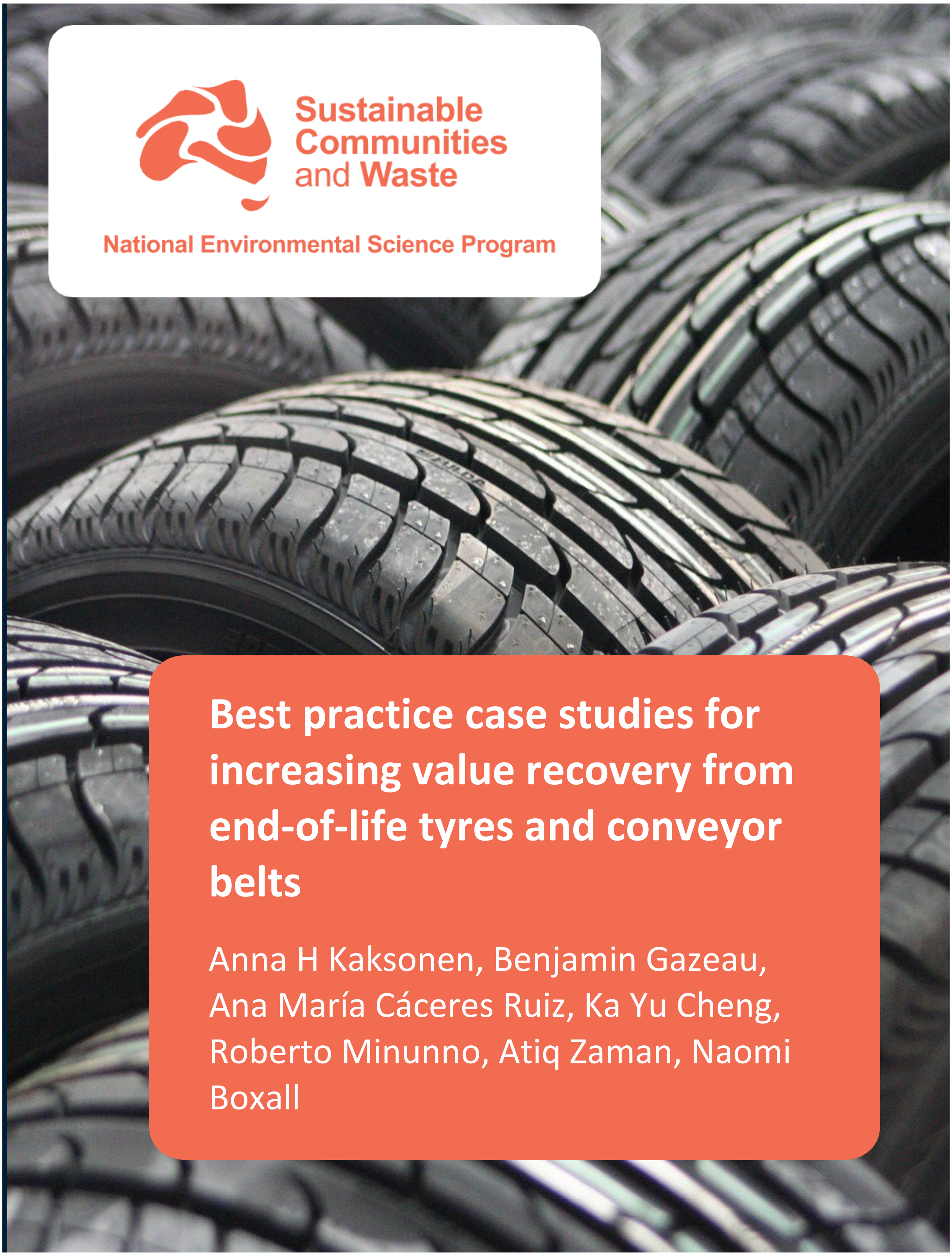

Sustainable Communities and Waste

National Environmental Science Program

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Anna H Kaksonen, Benjamin Gazeau, Ana María Cáceres Ruiz, Ka Yu Cheng, Roberto Minunno, Atiq Zaman, Naomi Boxall

UNSW SYDNEY · CSIRO · MONASH University · Curtin University · UNIVERSITY of TASMANIA

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1	May 2024	AHK, BG, AMCR, KYC, RM, AZ, NJB	Version 1 submitted to NESP2 Sustainable Communities and Waste Hub and Australian Government Department of Climate Change, Energy, the Environment and Water (DCCEEW) for review
2	September 2024	AHK, BG, AMCR, KYC, RM, AZ, NJB	Version 2 amended based on feedback received

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Abbreviations

AAC	Autoclaved aerated concrete
ABS	Australian Bureau of Statistics
ACT	Australian Capital Territory
AGPT	Austroads Guide to Pavement Technology
AIATSIS	Australian Institute of Aboriginal and Torres Strait Islander Studies
ANIR	La Asociación Nacional de la Industria del Reciclaje
ATRA	Australian Tyre Recyclers Association
AV	Aviation
BCN	Biblioteca del Congreso Nacional de Chile
BOF	Basic oxygen furnace
CATRA	Canadian Association of Tire Recycling Agencies
ChCl	Chloromethylene
CRMOGA	Crumb Rubber Modified Open Graded Asphalt
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CUSP	Curtin University Sustainability Policy Institute
CWTS	Controlled Waste Tracking System
DA	Devulcanisation aid
DD	Diphenyl disulfide
DES	Deep eutectic solvents
dGTR	Ddevulcanized ground tyre rubber
DWER	Department of Water and Environmental Regulation (WA)
EAF	Electric arc furnace
EDX	Energy dispersive X-ray analysis
EOL	End-of-life
EOLT	End-of-life tyre
EOW	End-of-waste
EPA	Environment(al) Protection Authority
EPDM	Ethylene propylene diene monomer rubber
ERA	Environmentally relevant activities
ETRMA	European Tyre & Rubber Manufacturers’ Association
ETRTO	European Tyre and Rim Technical Organisation
EU	European Union

FAA	Federal Aviation Administration
FCC	Fluid catalytic cracking
FEM	Foreign end markets
FESEM	Field emission scanning electron microscopy
FTIR	Fourier-transform infrared spectroscopy
GDP	Gross domestic product
GHG	Greenhouse gas
GT	Ground tyre
GTR	Ground tyre rubber
HDV	Heavy duty vehicle
IP	Intellectual Property
LCO	Light cycle oil
LDV	Light duty vehicle
LPG	Liquified petroleum gas
NEPC	National Environment Protection Council
NEPM	National Environment Protection Measure
OHS	Occupational health and safety
OTR	Off-the-road
NR	Natural rubber
NSW	New South Wales
NT	Northern Territory
POEO Act	Protection of the Environment Operation Act
QLD	Queensland
SA	South Australia
SBR	Styrene-butadiene rubber
$scCO_2$	Supercritical CO_2
SMA	Superintendencia del Medio Ambiente
SR	Synthetic rubber
SUV	Sport utility vehicle
TAS	Tasmania
TBR	Truck, bus and radial (tyres)
TDF	Tyre derived fuel
TDP	Tyre-derived polymer
TGA	Thermogravimetric analysis

TPO	Tyre pyrolysis oil
TPV	Thermoplastic vulcanisate or rubber
TSA	Tyre Stewardship Australia
TSBC	Tyre Stewardship British Columbia
TTR	Truck-tyre rubber
UHPWJ	Ultra-high pressure water jet
UNCTAD	United Nations Trade & Development
UNSW	University of New South Wales
US	United States
VIC	Victoria
WA	Western Australia
WARR Act	Waste Avoidance and Resource Recovery Act
WEEE	Waste electrical and electronic equipment
Wt-%	Weight percent

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Additional information

This report is prepared for Stage 2 of a two-year project and is a continuation of the research presented in Stage 1 report. The content of this Stage 2 report should be taken in consideration of the previous work captured in Stage 1 report:

Boxall NJ, Tobin S, Minunno R, Cheng KY, Zaman A, Kaksonen AH (2023) Exploring opportunities for increasing value recovery from end-of-life tyres and conveyor belts in Western Australia. CSIRO, Australia. https://doi.org/10.25919%2Fcan7-md68.

Executive summary

As part of the Australian Government's National Environmental Science Program Sustainable Communities and Waste Hub, CSIRO and Curtin University reviewed a set of best practice case studies for overcoming barriers identified in a previous report by Boxall et al. (2023) and increasing value recovery from end-of-life tyres and conveyor belts in Australia. The case studies included product stewardship schemes implemented in various jurisdictions in Canada, Chile, some European countries (Denmark, Finland, France, Italy) and New Zealand; enablers for recycling, such as waste classifications, quality standards and recycling business hubs; reverse logistics; technologies for value recovery from EOLTs and conveyor belts, and end markets of tyre-derived products; and strategy for communicating with indigenous communities.

Product stewardship schemes

One of the identified barriers to increasing value recovery from end-of-life tyres and conveyor belts in Australia was the lack of a regulated product stewardship for tyres and conveyor belts. Therefore, examples of compulsory tyre stewardships from selected jurisdictions in Canada, Chile, selected European countries (Denmark, Finland, France and Italy) and New Zealand were reviewed as case study examples for possible learnings to Australia. Based on the review of the examples of overseas stewardship schemes, the following recommendations were made for an Australia:

- Including rubbery conveyor belts into the stewardship scheme
- Enacting a regulated stewardship scheme to capture all tyre and conveyor belt importers and all stakeholders that sell new tyres and conveyor belts and collect, transport, and/or process EOLTs
- Import levies to be extended to all tyre and conveyor belt imports (including tyres fitted on vehicles and equipment) to cover costs of EOLT and conveyor belt recycling
- Implementing a recycling fee as part of the price of new tyres and conveyor belts instead of charging a fee for returning EOLTs or conveyor belts for recycling. Moreover, an additional bond fee could be charged as part of the price of new tyres/conveyor belts to allow a refund to be paid upon returning the used tyres/CB for recycling, to further incentivise material recovery. These fees (import levies passed to consumers, recycling fees and bond) could be bundled into a single fee to consumers paid at the point of purchase. More complete economic modelling of fee disbursements across the value chain needs to be completed.
- Banning landfilling and on-site disposal of EOLTs and conveyor belts in all states and territories to complement the compulsory stewardship regulations
- Extending auditing to all stakeholders that carry out tyre and conveyor belt imports and all stakeholders that sell new tyres and conveyor belts and collect, transport, and/or process EOLTs
- Setting clear targets and timeframes to provide a roadmap for all stakeholders, and unifying collection and valorisation targets over a specific timeframe to enable building recycling capacity, but preventing excessive stockpiling
- Separating tyres based on categories and recognising the logistical and economic differences between categories to allow for tailored collection and valorisation strategies

- Incentivising remote, geographically isolated industries (e.g., mining companies) and allowing them flexibility to valorise EOLTs and conveyor belts themselves rather than having to deal with long-distance transport
- Proactively developing policies, incentive mechanisms and research and development initiatives to encourage retreading, collection and processing of EOLTs, and manufacturing and use of tyre-derived products

Enablers for recycling

Currently, classification systems for EOLTs vary across Australia, and waste conveyor belts are not classified as controlled waste in Australia, leading to inadequate monitoring and lack of data on arisings, transport, and the fate of waste conveyor belts. Moreover, the alignment of jurisdictional hazardous waste codes remains poor, and there is a lack of regulatory consistency across borders, diminishing the capacity to develop a consistent national system for waste management. Classifying waste tyres and conveyor belts consistently is crucial for enabling their recycling. Moreover, establishing comprehensive tracking mechanisms is necessary to monitor the movement of these waste streams accurately. Standardising the units of measurement (mass or volume) across stakeholders is essential for reliable data collection and analysis. Without standardised units, meaningful insights from the data become challenging to derive. Standards should also be implemented for imported tyres, to ensure that they are of good enough quality to allow retreading. Enablers including consistent waste classifications, quality standards, coordinated tracking and traceability, data related to material flows and feedstock composition, and collaboration across the value chain are all critical to the successful development of EOLT and conveyor belt management technology and development of market pathways. Moreover, the creation and support of recycling hubs or ecosystems, where tyre recyclers and industries that consume tyre-derived products and fuels co-exist, allows technology development and conversion of rubber waste to valuable products to support circularity.

Reverse logistics

Reverse logistics, including the adoption of Industry 4.0 (4^{th} Industrial revolution that includes advanced information technologies and robotics) technologies, plays a crucial role in managing rubber waste, particularly tyres and conveyor belts, in Australia. By repurposing these waste materials and minimizing landfilling, reverse logistics can contribute to a more sustainable waste management system. To enhance reverse logistics for rubber waste in Australia, it is recommended to explore opportunities and challenges faced in the reverse logistics of other materials, e.g. in relation to the application of technologies, supply chain logistics, and economic systems supporting effective waste management. Addressing the complexity of Australia's geography by drawing lessons from global examples and applying them to both urban and rural settings is essential. A regulatory framework that mandates waste separation and diversion to collection points should be established and can ensure effective waste management and resource recovery. Considering Industry 4.0 technologies to improve reverse logistics operations is also important, but their implementation should be approached cautiously, considering their feasibility and economic viability in the rubber waste industry.

Value recovery and end-markets

Products derived from EOLTs and conveyor belts have versatile applications across industries, promoting waste reduction, resource efficiency, and environmental sustainability. The increasing recognition of the economic and environmental benefits of recycling, coupled with technological advancements, is driving the expansion of the market for recycled rubber products. However, to foster circular economy solutions effectively, it is crucial to maximize the material value of EOLTs and prioritize waste hierarchy in product markets, thus ensuring the achievement of sustainability goals. End-markets need to be created or reinforced in Australia for retreading, upcycling, recycling of EOLTs and conveyor belts.

Improving the value recovery of EOLTs and conveyor belts in Australia is unlikely to result from the uptake of a single technology or market pathway. Many technologies have been demonstrated, and when considered against the waste management hierarchy and circular economy principles have various benefits and impacts for recovery of value from rubber materials. Prioritisation and investment into technologies should be aligned to circular economy principles, enabled through wholistic value chain assessments such as Value Retention Models (VRM), cost/benefit comparison, Life Cycle Assessment (LCA) and Material Circular Indicators (MCI). Enablers including product stewardship, tracking and traceability, data related to material flows and feedstock composition are all critical to the development of EOLT and conveyor belt management technology. Technology assessments should also consider contextual elements such as location, supply chain dynamics, market conditions, policy mechanisms in place, process efficiency, as well as impacts on the local and broader community and the environment. A comprehensive assessment will enable informed, unbiased decisions and ensure that sustainable development of EOLT and conveyor belt management is implemented in Australia.

Strategy for communicating with indigenous communities

This project considers communication as a part of the dissemination of the research findings and engagement of Indigenous communities. The governance structure of the NESP2 project includes Hub representatives, including the Senior Indigenous Facilitator, ensuring that project findings are effectively shared with Indigenous communities and organizations. To facilitate meaningful engagement, key actions will be taken, such as engaging with Hub Senior Representatives and the Department for dissemination, establishing communication channels with Indigenous communities actively involved in NESP projects, and collaborating with cross-hub programs. This strategic approach aims to promote transparent and inclusive communication, ensuring that project outcomes are effectively communicated and foster meaningful engagement and collaboration with Indigenous communities for potential future co-design and Indigenous-led research projects.

1 Introduction

End-of-life Tyres (EOLT) are one of the largest hazardous waste categories by weight in Australia (Latimer, 2019). In 2018-19, a total of 465,000 t of EOLTs were generated in Australia. Historically, large quantities of EOLTs have been stockpiled, disposed on-site, or exported from Australia. However, EOLTs were targeted by the Waste Export Ban under the Recycling and Waste Reduction Act 2020, and from the 1st of December 2021, tyre exports from Australia were restricted, with various conditions and exclusions. Passenger car, bus and truck tyres have contributed to approximately 70-75% of EOL tyre arisings whereas OTR tyres have contributed the remaining 25-30%. While the recovery rates for passenger car, bus and truck tyres has been approximately 90%, the OTR recovery rate has been only approximately 10%. Therefore, the overall recovery rate for all EOL tyres has been in the order of 60-70% across all types of EOL tyres. Closing the gap between the 60-70% and the 80% target set in the National Waste Policy Action Plan prepared by Commonwealth, state and territory governments and the Australian Local Government Association in 2019 requires major improvement in recovering OTR tyres (Tyre stewardship Australia, 2023). In addition to EOLTs, conveyor belts are another notable rubbery waste stream produced by the mining industry. Waste conveyor belts have similar properties to waste tyres in terms of their rubber composition and means of on-site disposal (Boxall et al., 2023).

CSIRO produced a Circular Economy Roadmap in 2021 that identified key gaps in the management, reuse and recovery of plastic, glass, paper, and tyres (Schandl et al., 2021). It identified collection, remanufacturing and reuse, recycling, and use of recovered materials as key opportunities for the development of a circular economy for these materials. Following this, CSIRO and Curtin University produced another report *Exploring opportunities for increasing value recovery from end-of-life tyres and conveyor belts in Western Australia* (Boxall et al., 2023), which reviewed the data on tyre and conveyor belt arisings and processing infrastructure in WA. Moreover, the report identified challenges and strategies to enable higher value recovery from EOLTs and conveyor belts in Western Australia (WA) by redirecting waste to resource recovery and addressing challenges related to logistics and cost, to guide investment and policy decisions (Boxall et al., 2023). A summary of the barriers identified in the report is shown in Table 1.

Using the previously identified barriers, CSIRO and Curtin University reviewed international practices for EOLT and conveyor belt management and value recovery. Learnings and solutions to identified barriers for the EOLT and conveyor belt market in Australia are drawn from this review. The international practices covered in this report include:

- Product stewardship schemes implemented in various jurisdictions in Canada, Chile, some European countries (Denmark, Finland, France, Italy) and New Zealand
- Enablers for recycling, such as waste classifications, quality standards and recycling business hubs
- Reverse logistics
- Technologies for value recovery from EOLTs and conveyor belts
- Usage and end markets of tyre-derived products
- Strategy for communicating with indigenous communities

Table 1. Summary of key findings on current barriers for value recovery from end-of-life tyres and conveyor belts in Western Australia (Boxall et al., 2023).

Inconsistency of classification of end-of-life tyre (EOLT) arisings and related data This results in a lack of understanding about the types of EOLTs being generated, the fate of these arisings and the processing requirements (e.g., technology, capacity) for recycling at the end of life.	**Conveyor belts are not currently classified as controlled wastes** Therefore, there is no existing mandate for the reporting of conveyor belt transports, and thus no data about conveyor belt arisings, which makes it impossible to determine the required processing capacity for the possible feedstock or develop markets for the end products.
No quality standards for imported tyres and conveyor belts in Australia As a result some tyres are not suitable for retreading, and impact the efficiency of current recycling processes due to low quality tyres in feedstocks.	**No regulated product stewardship for tyres and conveyor belts** As a result, some imported tyres and conveyor belts are not captured under the voluntary product stewardship scheme, reducing the funding available for value recovery.
Regional landfilling and on-site disposal by burial of EOLTs and conveyor belts is not restricted in WA This results in the permanent loss of materials from our economy and has unknown impacts on the Australia's unique biodiversity and the health of ecosystems, as well as co-located Indigenous communities.	**No incentives for returning EOLTs and conveyor belts for value recovery** This can lead to illegal dumping, or on-site disposal or management of these materials (e.g., EOLTs used on farms for silage).
No incentives for retreading EOLTs in WA The market demand for retreading has decreased because it is considered cheaper to purchase new tyres than extend the life of in-use tyres.	**The regulatory ecosystem of WA does not preference the use of products derived from EOLTs and conveyor belts for energy recovery** The WA regulations do not preference the use of EOLT- and conveyor belt-derived products for energy recovery, unless EOLTs and conveyor belt feedstocks are classified as residual waste.
Approval processes for the use of land for the development of recycling facilities can be slow This limits the recycling capacity for end-of-life tyre materials within a certain timeframe.	**Lack of EOLT and conveyor belt collection, processing, and recycling infrastructure for regional areas** This is where many OTR tyre and conveyor belt generators operate.
Mismatch between product specifications and capabilities of recycling facilities There is a mismatch between product specifications and capabilities of recycling facilities planned and approved for of the generation of recovered rubber materials.	**Need for greater efforts to engage Aboriginal Corporations for EOLT recycling initiatives in regional WA** Greater efforts are needed to engage Aboriginal Corporations for EOLT recycling in regional WA where communities are impacted by improper disposal and handling of these materials and the impact on human and environmental health are largely unknown.

2 Methods

This report was generated to identify best practice case studies for increasing value recovery from EOLTs and conveyor belts. Methods included a review of scientific and grey literature and semi-structured interviews with key government and industry stakeholders. A total of 26 and 20 stakeholders (Appendix 1) were engaged in Stages 1 and 2, respectively of the project through interviews and/or email communication. Each interview generally lasted between 30 and 90 minutes. The de-identified insights from the interviews are presented in this report throughout the relevant sections and cited as "Personal communication" and year. To support the semi-structured interview process, some stakeholders provided quantitative data or other information via email. Ethics Approvals were obtained for this project from CSIRO (005/22) and Curtin University (HRE2022-0102) prior to conducting the interviews or asking for information from stakeholders.

3 Product stewardship schemes

One of the identified barriers to increasing value recovery from end-of-life tyre (EOLT) and conveyor belts in Australia was the lack of a regulated product stewardship for tyres and conveyor belts. Because of the voluntary nature of the stewardship scheme, some imported tyres and conveyor belts are not captured under the scheme, reducing the funding available for value recovery (Boxall et al., 2023). The following sections review examples of compulsory tyre stewardship schemes (or as in some countries called extended producer responsibility schemes) from selected jurisdictions in Canada, Chile, selected European countries (Denmark, Finland, France and Italy) and New Zealand as case study examples for possible learnings to Australia.

3.1 Canada

Managing waste tyres in Canada is governed by a decentralised regulatory framework, where hazardous materials fall under federal jurisdiction. However, waste tyres are categorised as non-hazardous, subjecting their regulation to the provincial authority. Despite this classification, inter-provincial export of waste tyres remains prohibited, necessitating each region to devise strategies for converting this waste into acceptable sub-materials or end-products suitable for internal consumption or export. The approach to conversion is contingent upon the local manufacturing infrastructure within each province, presenting opportunities for developing high-value products, such as closed-loop systems where EOLTs are recycled back into tyre manufacturing processes. However, the feasibility of such scenarios is constrained by the uneven distribution of tyre producers across provinces. A national framework would allow material to cross borders if the receiver can fully and transparently demonstrate that the material will be recycled in a way that complies with regulation. Such development would allow the development of technology which need volume to make sense economically.

The transformation of waste tyres into sub-materials (e.g., crumb rubber, tyre-derived fuel products) or end-products for export faces challenges stemming from international market dynamics, where factors such as price, quality, and volume competitiveness are important. The logistical aspects of reverse logistics, including transportation costs from remote areas and the requirement for specialised reprocessing equipment for large-scale tyres, further complicate market entry for end products.

The variability in composition among different tyre types and brands poses a significant hurdle to efficient waste tyre management, necessitating sorting processes based on composition to yield high-quality output streams. Composite tyres present additional challenges to achieving a closed-loop ideal. Unless decomposition techniques, such as devulcanisation or pyrolysis, are used to avoid sorting steps with the goal of high-end value material, unsorted mixed tyres will result in different kinds of end-products. Off-the-road (OTR) tyres, which typically contain higher concentrations of natural rubber compared to passenger car tyres, hold promise for closed-loop scenarios due to their potentially more significant value and quality. However, the viability of such initiatives hinges on the availability of reverse logistics infrastructure and reprocessing capacity.

Each province of Canada operates autonomously within their tyre stewardship programs, but each stewardship tries to harmonise their practices to have a Canadian model, focusing on traceability to track the origins and destinations of waste tyre products (Figure 1). However, a notable gap exists in monitoring the second life cycle of these products, as regulation primarily pertains to tyre rubber, thereby needing more oversight over waste derived from tyres if not reintegrated into new tyre manufacturing processes.

Addressing this issue is imperative to ensure comprehensive waste tyre management and sustainable resource utilisation. The following sections review examples of tyre stewardship schemes from selected jurisdictions in Canada highlighted with green boxes in the map shown in Figure 2.

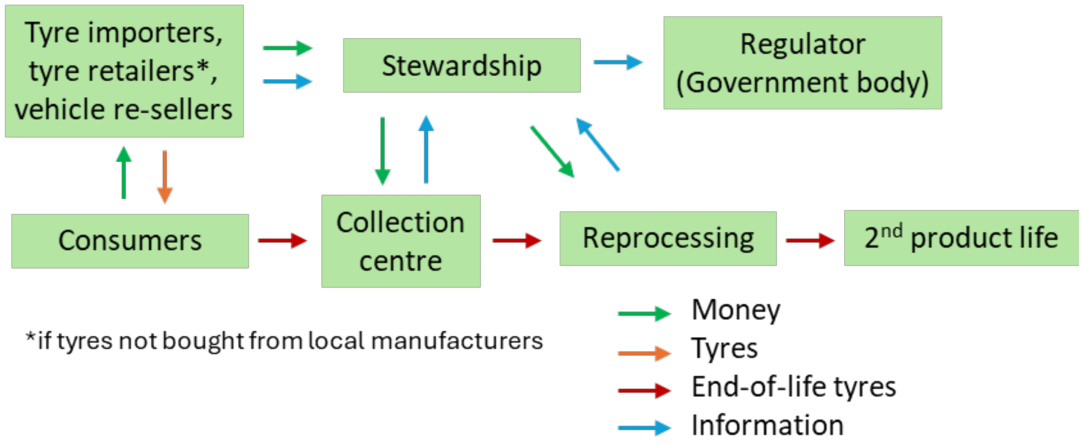

Figure 1. Flow of materials, money and information in most of the tyre stewardship schemes in Canada.

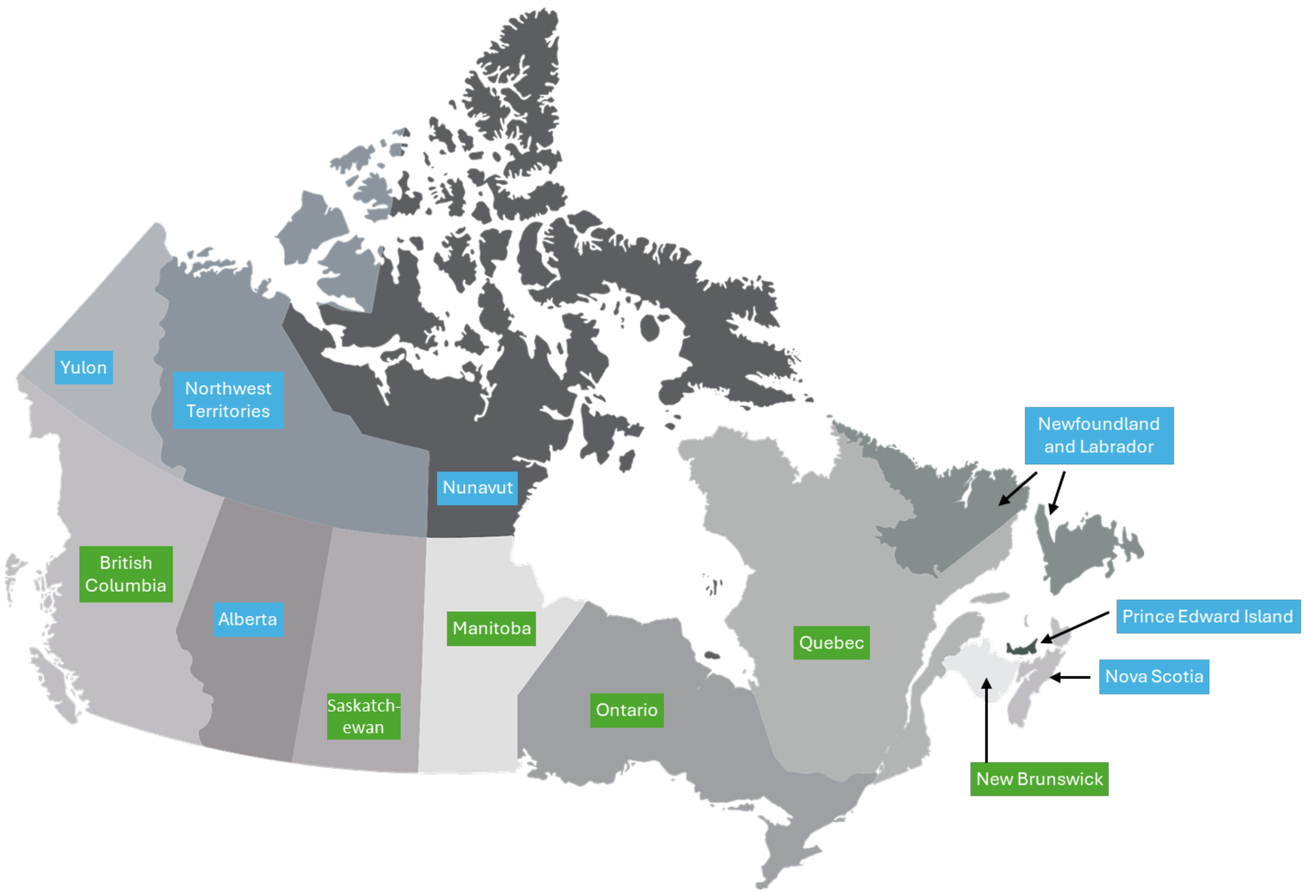

Figure 2. Canadian map with jurisdictions for which tyre stewardship schemes were shown highlighted with green background (Adapted using a map created by Craig Clark and sourced from Pixabay).

3.1.1 British Columbia

The tyre stewardship program in British Columbia underwent a notable evolution, transitioning from a government-operated initiative from 1991 to 2006 to being incorporated into recycling regulations under the designation of Tyre Stewardship by the ministry in 2006. This transition marked the adoption of principles aligning with Extended Producer Responsibility (EPR), officially taking effect in January 2007.

In British Columbia, the term "producer" is attributed to retailers, thereby designating them as responsible entities within the province's tyre stewardship framework. However, this definition raises questions, particularly compared to a national model wherein tyre manufacturers, brand owners, and first importers assume primary responsibility, as observed in Ontario. The proliferation of retailers, numbering approximately 2000, in contrast to a relatively more minor pool of tyre manufacturers, complicates the identification of liable parties and revenue collection processes.

British Columbia employs an incentive system based on distances travelled for tyre disposal, whereby greater distances yield higher incentives (Table 2), encouraging extensive tyre collection efforts across diverse geographic regions. This approach aims to foster widespread participation and efficient tyre management practices. Furthermore, incentive rates within the British Columbia program are contingent upon utilising derived products and fuels, reflecting a commitment to incentivise environmentally sustainable disposal methods and the conversion of waste tyres into valuable resources (Table 3). Recyclers are mandated to register with the stewardship program, with higher incentives tied to producing higher-end products. Traceability within the program is facilitated through financial audits conducted by the stewardship program, focusing on tracking the flow of funds and waste throughout the reprocessing cycle. While annual audits are conducted, there is limited focus on tracking the final destination of the recycled materials (Tyre Stewardship British Columbia, 2023).

Table 2. Subsidy for end-of-life tyre transporters based on distance range in British Columbia, Canada (Tyre Stewardship British Columbia, 2023)

Distance range (km)	Subsidy (CAN$ per km/per t)
0 – 30	3.860
31 - 75	2.695
76 - 125	1.784
126 - 200	1.289
201 - 300	0.630
301 - 400	0.502
401 - 500	0.444
501 - 600	0.377
601 - 700	0.338
701 - 800	0.313
801 - 900	0.292
901 - 1000	0.275
1001 - 1100	0.264
1101 - 1200	0.250
1201 - 1300	0.240
1301 - 1400	0.225
1401 - 1500	0.224
1501 - 1600	0.218
1601 - 1700	0.215
1701 - 1800	0.210
1801 - 1900	0.201
1901 – 2000+	0.198

Table 3. Subsidies for producing or using tyre-derived products (TDP) and tyre-derived fuels (TDF) in British Columbia, Canada (Tyre Stewardship British Columbia, 2023).

Category	Rate (CAN$ per t)	Description
TDP 1	348.15	For scrap tyres processed into a crumb rubber or powder form, having a particle size up to approximately 5/16" and free of steel and fibre
TDP 2	140	For scrap tyres that are utilized essentially in their original form (e.g., blasting mats)
TDP 3	6	For high-volume applications such as coarse shred used as road-fill (commonly known as tyre-derived-aggregate (TDA))
TDP 4	0	For products made from the whole tyre in its original form or where the tyre will be sold as a used tyre
TDP 5	140	For the shearing and disposal of BC generated program scrap tyres that cannot be processed but have received an Advance Disposal Fee
TDP 6	0	For medium truck (MT) tyres received for processing into either TDP 1 or TDP 7
TDP 7	284.94	For coloured rubber granules with a particle size range of >5/16 to 3/4" and free of steel, for use as recycled rubber mulch typically used as landscape cover (For uncoloured granules, the rate is $214.24 per t).
TDP 8	158.54	For steel (bead wire and fines) extracted from the scrap tyre during the recycling process and sold to an end market
TDF 1	131.76	For shred processed for energy recovery
TDF 2	60	For whole tyres processed for energy recovery
TDF 3	158.54	For fibre extracted from the scrap tyre during the recycling process and sold for energy recovery

3.1.2 Manitoba

The Manitoba Tyre Stewardship program, operated by a nonprofit industry organisation known as the Tyre Stewardship Manitoba (TSM), is tasked with comprehensively managing EOLTs within the province. Under this program, all new tyres sold in Manitoba must be part of an approved tyre recycling program, effectively making TSM the province's sole governing body for tyre stewardship. The entity responsible for the initial sale or importation of tyres assumes stewardship obligations.

Substantial financial resources, approximately CAN$6 million, are allocated annually by TSM towards tyre collection and processing efforts. Municipalities and communities registered with TSM receive a CAN$0.50 per tyre incentive to offset storage costs, with additional funding opportunities provided for tyre-derived product utilising projects such as playgrounds, rubber mats for sports arenas, and road construction, with grants of up to CAN$10,000 and CAN$20,000 for storage and tyre-derived product utilisation, respectively. Moreover, tyres may be repurposed for applications such as sewage lagoon filtration, demonstrating their versatility in various projects.

Financial oversight is conducted through regular audits to ensure transparency and accountability in fund allocation. TSM operates under a retail-based system, where tyre sellers are required to register with the organisation and remit steward fees based on tyre type. These fees vary depending on the tyre category, ranging from CAN$4 for passenger and light truck tyres to CAN$30 for rear agricultural and large OTR tyres.

Despite the absence of tyre manufacturing facilities and limited local markets in Manitoba, efforts are directed towards maximising opportunities within the province rather than pursuing high-value product manufacturing or market creation initiatives. TSM collaborates with designated processors responsible for tyre collection, processing, and product sales. The recent addition of a second processor, focusing on the aggregate and road markets, is expected to benefit rural and northern communities by utilising a portable shredder to process tyres at waste disposal sites.

Currently, most of the recycled tyre material, approximately 60%, is utilised in aggregate applications, primarily for road construction. The resulting mulch and crumb rubber products serve various purposes, including potential certification for backfilling around residential and commercial buildings. Despite the absence of landfill bans for tyres in Manitoba, the incentive-based approach implemented by TSM has proven effective in diverting tyres from landfills over the program's nearly three-decade existence (Personal communication, 2023).

3.1.3 New Brunswick

In the context of tyre stewardship in New Brunswick, two distinct systems are observed within Canada: traditional stewardship and Extended Producer Responsibility (EPR), with the latter representing a more contemporary approach. While New Brunswick's program initially followed the stewardship model, there is a gradual transition towards EPR, a trend observed in many Western provinces. Despite being the second tyre program established, implementing EPR regulations has been comparatively slower in New Brunswick.

Under the stewardship framework, the recycling operations, including collection and processing, are managed indirectly through subcontracting to a third party. Tyre Recycling Atlantic Canada Corporation (TRACC), the sole contractor responsible for collections and recycling, has been integral to the program since its inception. This relationship operates symbiotically, with TRACC facilitating operations while the stewardship entity maintains a hands-off approach to business management.

The recycling industry faces significant financial and market challenges, leading to numerous business failures. While quality remains a crucial aspect, the stewardship program does not actively pursue regulatory changes, as it refrains from involvement in operational matters. The emphasis, instead, is placed on the performance of end products utilising recycled materials, reflecting a pragmatic perspective on material efficacy.

Mechanical recycling processes are predominantly utilised within the program, yielding products such as rubber mats tailored for agricultural applications. This focus on mechanical recycling underscores the program's commitment to sustainable practices and using recycled materials in practical contexts, such as farming (Personal communication, 2023).

3.1.4 Ontario

The Ontario province tyre stewardship program operates through a service provider akin to an industry association known as E-track. Despite its professional status as an independent entity from the public sector, E-track represents approximately 85% of the overall obligation in Ontario. Its clientele primarily comprises significant tyre manufacturers and automotive companies.

The primary mission of E-track encompasses the establishment of contracts, collection management, and recycling oversight. Ontario's producers are responsible for collecting and recycling tyres based on their market contributions. These tyre producers are entities selling equipment containing tyres, selling replacement tyres, or importing tyres into the market.

In addition to E-track, five other competitors exist in the Ontario tyre stewardship landscape. Producers under E-track's management are mandated to collect and recycle 100% of the tyres they introduce into the market, with a further obligation to recycle new products equivalent to 85% of the weight of the collected tyres. This obligation encompasses many tyres, including aviation, solid, resilient tyres (e.g., forklifts, pump trucks), agricultural, skid steer loaders, and mining tyres.

The utilisation of tyres as fuel or landfill cover does not contribute towards meeting the 85% recycling target mandated by provincial law—failure to achieve this recycling rate results in fines for the producers. E-track oversees various recycling initiatives, including producing moulded rubber products, blast mats for road construction, tyre-derived aggregate for civil engineering applications, and backyard tiles.

The program operates under a yearly audit system, in which the stewardship scheme audits the recyclers, to ensure compliance with regulatory requirements. Quality control measures are not rigorously enforced due to local re-processors' diverse end-applications of recycled materials. Processors are incentivised to produce high-quality materials, as processing fees are only incurred once the recycled products are sold as end products.

Market-driven forces dictate the acceptability of reprocessed products, yet compliance with recycling targets remains paramount to avoid penalties. This necessitates a collaborative approach between businesses to ensure adherence to quality standards and effective tracking throughout the recycling process. Ultimately, the responsibility for meeting recycling targets falls squarely on the industry, incentivising proactive solutions to achieve sustainability objectives (Personal communication, 2023).

3.1.5 Quebec

The Quebec tyre stewardship program, initiated in the 1990s, operates through a structured system involving registered tyre retailers and other entities responsible for tyre disposal within the province. Retailers are enlisted as the primary entry point into the program, offering a free service for tyre pickup and transportation to processing facilities. Additionally, entities involved in contracting or regional administration of tyre disposal must also register with the program, with registration being cost-free, thereby facilitating seamless participation.

The program significantly emphasises collection efficiency, targeting all tyres measuring under 48 inches in height. The program recently adjusted its fee structure to sustain operational costs, raising fees from $3 to $4.50 for car tyres and $6 for truck tyres, effective last July 2023. This adjustment was necessary to mitigate deficits from insufficient funding to cover transportation and processing expenses.

Regular audits of the recyclers are conducted every three years by the stewardship scheme to ensure program compliance and effectiveness. Expansion of recycling capacity is facilitated through financial support from government schemes and private investments. The program incentivises recycling through a volume-based approach, where processors receive higher compensation based on the number of tyres processed.

The program's key focus is the conversion of tyre waste into products such as Animat, Dynamat, and Royal Mat, primarily used in flooring applications. Most of these products are exported, mainly to industries such as agriculture. Quality control is limited, as the end application dictates the standards maintained by local re-processors. Mechanical recycling methods, including crushing and pelletising, are predominantly employed due to the absence of petrochemical plants within Quebec. However, a demonstration plant near the Ontario border specialises in pyrolysis, with no devulcanisation processes currently in place.

Partnerships within the program are structured one-on-one, lacking a collaborative space for broader knowledge exchange among stakeholders. Instead, re-processors are afforded the autonomy to expand their businesses, enhance product quality, and drive innovation. Notably, the program boasts a 100% tyre collection rate, reflecting its comprehensive approach to tyre waste management and recycling (Personal communication, 2023).

3.1.6 Saskatchewan

In Saskatchewan, the tyre stewardship initiative was initiated in the mid to late 1990s as an environmental program to address recycling scrap tyres. Over the ensuing decades, the province has grappled with the legacy of accumulated tyres, some of which date back several years, necessitating ongoing management efforts. The persistence of these "legacy piles" underscores the region's enduring challenges associated with tyre waste management.

The province has encountered setbacks, notably in 2014 when a processor declared bankruptcy, leaving behind environmental liabilities associated with on-site materials that required remediation efforts. Completing this cleanup endeavour occurred as recently as 2021, marking the resolution of these lingering environmental concerns.

Currently, Saskatchewan relies on a single processor to manage tyre recycling activities within the province. Approximately 21% of the processed output consists of moulded goods derived from crumb rubber, utilised for various applications such as driveway material. In contrast, the majority, accounting for 74% of the output, comprises tyre-derived aggregate (TDA), commonly utilised for road projects or as fill material. The remaining percentage primarily consists of steel tyre wire.

The province implements a payment system based on outbound material, wherein incentives are tied to processing material delivery. However, this approach has raised concerns regarding its effectiveness in fostering sustainable business practices, as it primarily incentivises tyre collection rather than the development of value-added ventures utilising recycled materials.

Efforts to promote sustainability within the tyre industry extend to initiatives such as utilising rubber for rubber-modified asphalt, which displaces virgin concrete use. This application addresses environmental concerns and contributes to the circular economy by repurposing tyre-derived materials in infrastructure projects (Personal communication, 2023).

3.2 Chile

According to studies conducted by the Chilean Ministry of the Environment, Chile generates approximately 140,000 t of tyre waste per year, but only 17% of it is properly disposed of in compliance with environmental standards. This means that over 112,000 t of tyres end up in landfills and illegal dumping sites every year (Chile sin basura, 2021). To resolve this, in 2016 the Chilean government has formulated the Law 20.920 which provides the framework for the waste management system, extended producer responsibility (EPR) and recycling promotion in Chile and it is based on the polluter pays principle (Ministerio Del Medio Ambiente, 2021). The Ministry of the Environment (MMA) sets recovery targets, administers the registration system, authorises management plans, and promotes environmental education. Producers, whether manufacturers or importers, must finance waste collection through a waste management system, register and declare their activities on the electronic platform (Registro contaminantes (RETC)), and meet the established targets. Waste management systems are individuals, organisations or companies dedicated to managing tyre waste. They must be duly authorised by the MMA, and they are responsible for all aspects of the recycling chain, from collection, storage, transportation, and waste treatment. They must also ensure traceability by declaring the nature, volume, costs, origin, treatment, and destination of the waste. Municipalities, on their part, can enter into agreements with management systems and informal recyclers and apply for a new Recycling Fund.

Extended producer responsibility (EPR) law 20.920.

The extended producer responsibility (EPR) law 20.920 (Ministerio Del Medio Ambiente, 2016) is based on the polluter pays principle, where the generator of waste is responsible for it, from its generation to its valorisation or disposal, as well as for internalising the costs and negative externalities associated with its management (Ministerio Del Medio Ambiente, 2016). The Chilean EPR law applies for the following priority products: lubricating oils, electrical (Ministerio Del Medio Ambiente, 2016) and electronic devices, batteries, packaging, tyres and batteries (Ministerio Del Medio Ambiente, 2016).

Being potentially valuable in the generation of by-products such as rubber, energy, among others, tyres are part of the priority products of the Chilean EPR Scheme due to their large-scale consumption and the significant amount of waste they generate at the end of their useful life. The EPR law aims to achieve two key objectives: 1) collecting waste and 2) creating value from it (Ministerio Del Medio Ambiente, 2016). To accomplish this, the law sets collection targets and valorisation targets, which must be achieved by utilising a management system (Figure 3). This system is described as the "functional mechanism for producers, whether individually or collectively, to meet the responsibilities set forth in the REP Law" (Ministerio Del Medio Ambiente, 2016). Producers are required to achieve this by implementing a management plan that receives approval from the Ministry of the Environment (MMA) (Ministerio Del Medio Ambiente, 2016). The targets and other specifications for tyres were established by Supreme Decree No. 8 (published on the 20th of January, 2021). Titles III and IV of this regulation, which concern targets and obligations, came into effect 24 months after the decree's publication, which was the 20th of January, 2023. By that date, all management systems for this priority product must be approved (Caballero, 2022).

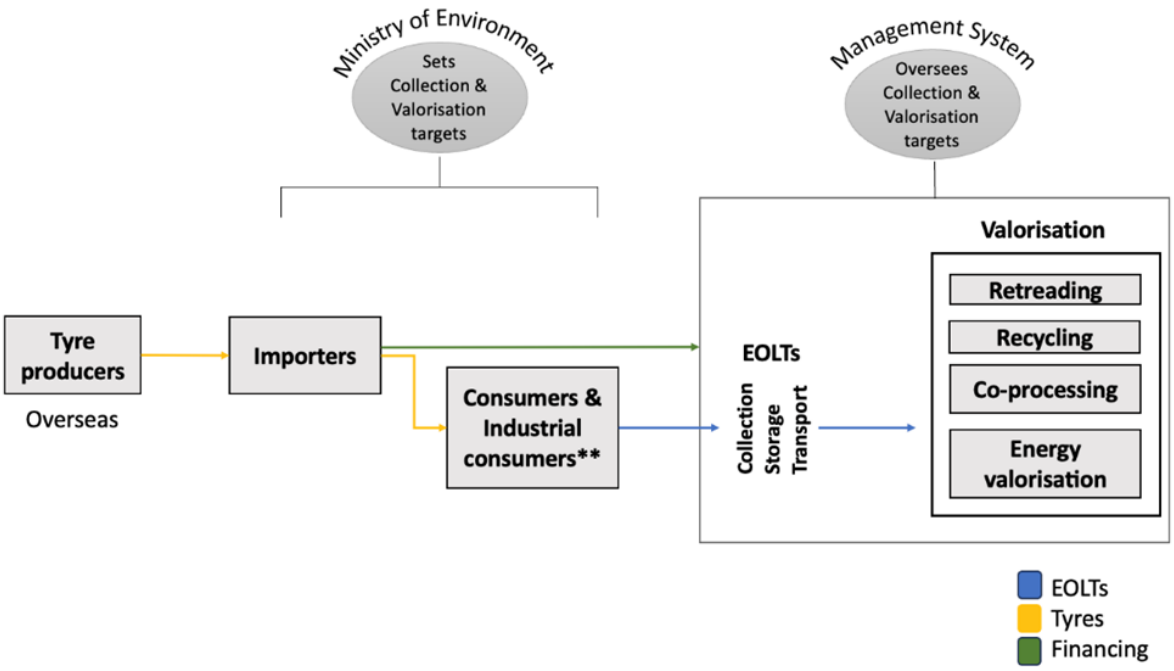

Figure 3. Lifecycle of tyres and money flows under the Chilean EPR Scheme. Adapted using information from (Ministerio Del Medio Ambiente, 2021).

EPR law stakeholders and responsibilities

Producers: A producer of tyres, as defined, refers to an entity engaged in the commercialisation of tyres in the national market. This encompasses various aspects of product introduction, branding, and importation of tyres. The EPR applies to those who introduce tyres into the Chilean market. This applies regardless of whether the tyres are an integral part of a vehicle or machinery of any kind (original equipment tyres) or if they have been introduced into the national market separately as replacement tyres (Ministerio Del Medio Ambiente, 2021). Producers subject to the EPR must comply with the following obligations (Ministerio Del Medio Ambiente, 2021):

a) Register with the RETC, in accordance with the regulations of said registry, and provide the requested information, directly to the RETC if it is an individual management system or through the relevant collective management system. This registration is compulsory and failing to do so leads to high penalties. Complying with the EPR law targets is then compromised and the registration on the RETC is the first step that producers must take when requesting approval from the MMA on the management system (Superintendencia del Medio Ambiente (SMA) Gobierno de Chile, 2022).
b) Organise and finance the collection of EOLTs throughout the national territory, as well as their storage, transportation, and treatment in accordance with current regulations.
c) Meet the collection and valorisation goals for EOLTs for each category through a management system.
d) Ensure that the management of EOLTs is carried out by authorised by the MMA and registered on the RETC management system entities (Superintendencia del Medio Ambiente (SMA) Gobierno de Chile, 2022)

Additionally, to import tyres into the country, producers must submit a sworn statement to the National Customs Service, a document that includes a section to indicate which management system they subscribe to or if the process is still pending (Gallardo, 2023).

Management system (or producer responsibility organisations): Management systems can be individual or collective. They are responsible for complying with the collection and valorisation obligations established within the framework of extended producer responsibility through the implementation of a management plan. Among other aspects, the Management Plans must include:

a) An estimate, for each year of the plan's duration, of the total quantity of tyres to be introduced into the market, in units and mass (t).
b) The average lifespan and estimation of EOLTs generated within the same period.
c) The strategy to achieve compliance with goals and associated obligations throughout the national territory for the duration of the plan, including:
    - Collection strategies
    - A specific schedule
    - Coverage
    - Consumer information
    - An estimation of the cost for managing EOLTs
    - The financing mechanism for management operations during the plan's duration

Municipalities (local government areas): The management systems may enter into agreements with municipalities or associations of municipalities, aimed at source separation, selective collection, the establishment, and operation of facilities for receiving and storing EOLTs (Ministerio Del Medio Ambiente, 2021). Thus, municipalities must create ordinances (local laws) to implement waste source separation that support recycling (Chile sin basura, 2019). In addition, municipalities must promote environmental education for the population, and design and implement communication and awareness strategies (Ministerio Del Medio Ambiente, 2021).

Informal waste collectors: Informal waste collectors can participate in waste management after official registration.

Superintendency of the Environment (environmental regulatory body): Through the regional environmental authorities (Seremías de Medio Ambiente), the Superintendency monitors the compliance with the collection and valorisation targets for each priority product's waste, as well as the associated obligations contained in the Decree 8. The responsibility for inspection and penalties also falls under the regional environmental authorities. Additionally, they oversee the operation of the management system, the fulfillment of reporting duties, and other obligations established in the Law 20.920 (EPR Law).

Household Consumers: Household consumers must deliver their waste to the respective local management system. According to Decree 8, EOLTs are not considered household waste. Therefore, this actor is not taken into account in the tyre waste management model in Chile.

Industrial Consumers: Industrial consumers are any industrial establishments that generate waste from a priority product. Industrial consumers can either deliver their waste directly to the management system or carry out authorised valorisation processes.

Collection and valorisation

In the Chilean EPR system, collection is defined as an operation consisting of collecting waste, including its initial storage, with the purpose of transporting it to a storage facility, a valorisation facility, or a disposal facility, as applicable (Ministerio Del Medio Ambiente, 2016). Decree 8 considers the processes below as valorisation operations for tyres (Ministerio Del Medio Ambiente, 2021) (Ministerio Del Medio Ambiente, 2016):

- ***Retreading:*** Retreading is the operation of reconditioning used tyres by replacing the tyre's tread, with or without the sidewall rubber, to extend its service life.
- ***Material recycling:*** Material recycling includes a set of actions aimed at recovering one or more of the materials that make up a tyre waste, excluding processes that use it, either wholly or partially, as a source of energy or for fuel production.
- ***Co-processing:*** Co-processes is the operation of managing EOLTs in an industrial process, in which both the energy and materials present in this waste are utilised.
- ***Energy valorisation:*** Energy valorisation is the use of waste with the purpose of harnessing its calorific value.

The EPR law applies to the EOLT categories listed in Table 4. These categories include motorcycle, car, truck, agricultural and OTR tyres (Scott, 2020). The categories do not include bicycle tyres, wheelchair and solid tyres which are not covered by the EPR law (Ministerio Del Medio Ambiente, 2021).

Table 4. EOLT categories subject to the expended producer responsibility law in Chile (Ministerio Del Medio Ambiente, 2021)

Category A	**Category B – mining tyres**
Rim size: < 57" ≠ 45", 49", 51"	Rim size: 45", 49", 51" or ≥ 57"

Targets for EOLT Category A collection and valorisation

Collection: Producers of Category A tyres are required to meet collection targets, through a management system, concerning the overall number of tyres they introduce to the national market in the immediately preceding year (Ministerio Del Medio Ambiente, 2021). As of the initiation of Decree No. 8's validity, commencing on the 20th of January, 2023, these producers must ensure the collection of a minimum of 50% of the tyres introduced to the national market. From the fourth calendar year of the decree's validity, in 2026, the collection target increases to a minimum of 80%. From the eighth calendar year, namely 2030, producers must collect at least 90% of the tyres introduced to the national market in the immediately preceding year (Ministerio Del Medio Ambiente, 2021). Additionally, from the third calendar year of the decree's validity, collective management systems must meet a minimum collection percentage per region, concerning the total number of tyres introduced to the national market by the participating producers (Figure 4).

Valorisation: Producers of Category A tyres must comply, through a management system, the valorisation targets for EOLTs, concerning the total number of tyres they introduce to the national market in the immediately preceding year (Figure 5). Starting from the first calendar year of the validity of Decree No 8, that is 2023, they must valorise at least 25% of the tyres introduced to the national market (Ministerio Del Medio Ambiente, 2021). By the second, third and fourth calendar years Category A producers must valorise 30%, 35% and 60% respectively of tyres that they introduce in the market. The sixth calendar year of the validity of Decree No 8, that is 2028, must have a valorisation increase from 60% from the year before to 80% of the tyres. Lastly, from the eighth calendar year of the validity of Decree No 8, namely 2030, producers must valorise at least 90% of the tyres introduced to the national market in the immediately preceding year (Ministerio Del Medio Ambiente, 2021). It is worth mentioning that of valorisation percentages of EOLT category, a minimum of 60% must correspond to EOLTs subjected to material recycling or retreading (Ministerio Del Medio Ambiente, 2021).

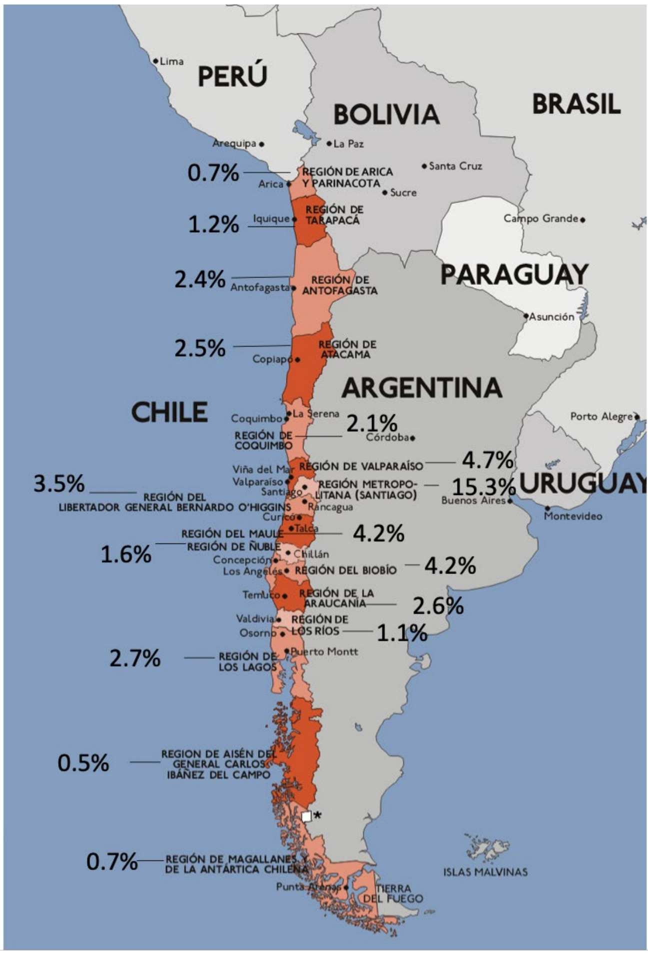

Figure 4. Minimum regional collection targets from the third calendar year after the EPR law comes into effect. *Note:* based on (Ministerio Del Medio Ambiente, 2021), adopted from (Kal Tire Mining Tire Group, 2021; Tirebuyer, 2023). Adapted from https://zu.m.wikipedia.org/wiki/File:Mapa_administrativo_de_Chile.png. CC BY-SA 3.0.

Targets for EOLT Category B collection and valorisation

Collection and valorisation: Producers of EOLT Category B must adhere to collection and valorisation goals through a management system (Figure 5). In the initial calendar year of Decree's validity, they are required to valorise a minimum of 25% of the tyres introduced to the national market in the preceding year. Subsequently, by the fifth year, the target escalates to 75%, and by the eighth year, producers must achieve valorisation for 100% of the tyres introduced in the previous year. It is crucial to note that the fulfillment of the collection targets for Category B tyres is deemed accomplished at the moment of their valorisation. In other words, achieving the valorisation target is interpreted as having simultaneously met the collection target for Category B tyres. The graph below depicts the collection and valorisation targets per EOLT category.

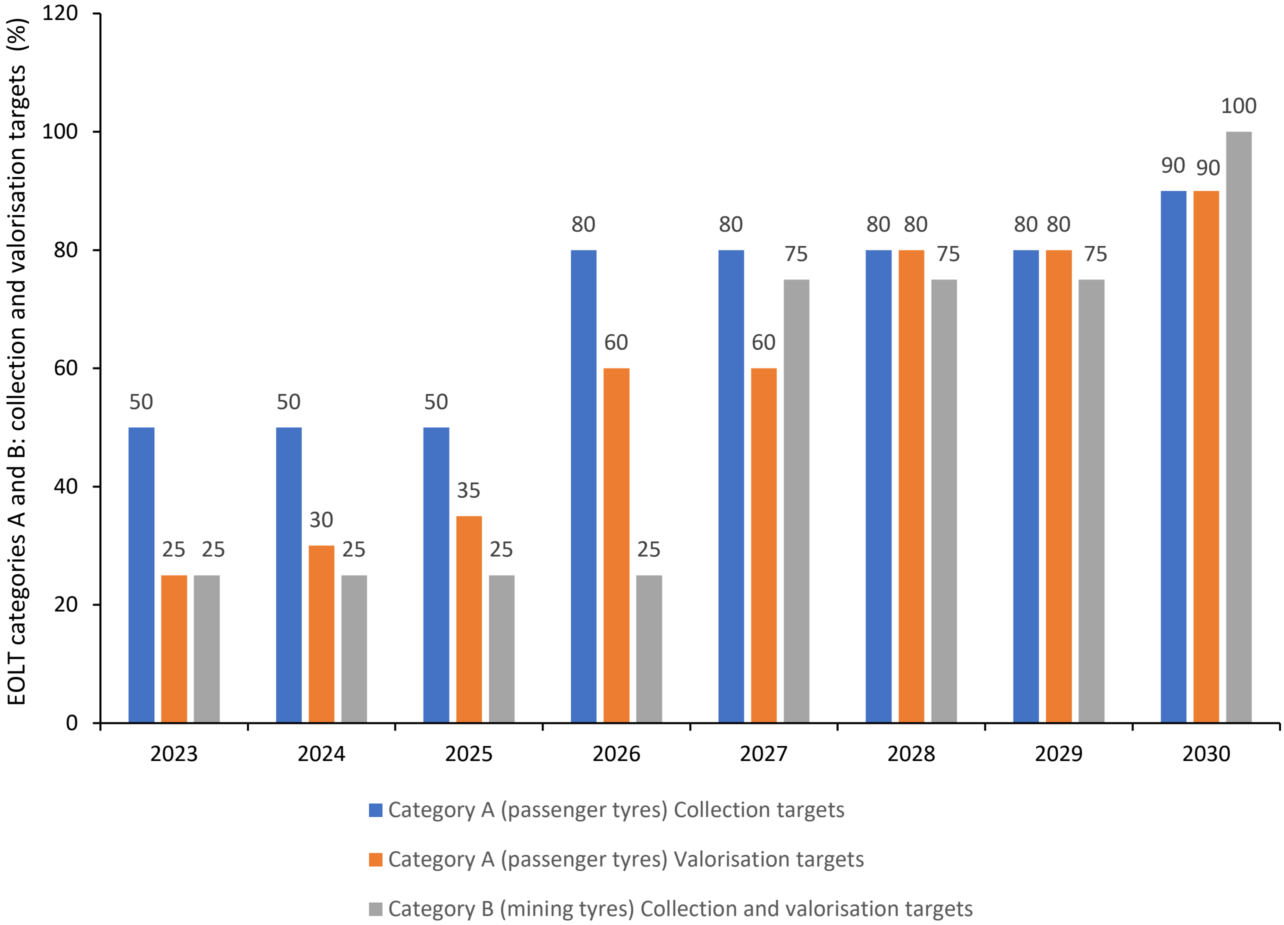

Figure 5. Collection and valorisation targets of EOLT categories A and B. Drawn using data from (Ministerio Del Medio Ambiente, 2021).

In terms of the tyre categories, an interviewed participant shared that the individual management systems primarily deal with large tyres, especially those used in mining, while the collective ones mainly focus on the other type of tyres, such as those used in cars. This is because individual systems have a very significant restriction and can only operate with their own waste. This is due mainly to the fact that tyres belonging to category B are easier to identify, track and are found in remote areas such as mining sites, whereas category A tyres can be more easily accessed and managed in metropolitan areas, such as car service centres. The participant commented that the service centres will accumulate tyres of different types, and it would be expensive and messy if each producer had to collect them. That is why all the category A tyres or car tyres are covered by the collective systems for that segment, but not other tyres, such as mining tyres. The large mining tyres are well identifiable, and the tyre collectors probably have long-term contracts with mining companies, knowing exactly where they are and when EOLTs will be generated for pick up. That is why it makes more sense for individual systems for large tyres and hence more individual systems have emerged for larger tyres (Ministerio Del Medio Ambiente, 2021).

The EPR Law, however, also includes another avenue for EOLTs valorisation that does not involve management systems. Industrial facilities that generate EOLTs may valorise these, either independently, meaning themselves, or through authorised and registered management systems. In this case, they must report to the Ministry, through the Emissions and Pollutant Transfers Registry, regarding the valorisation carried out (Ministerio Del Medio Ambiente, 2021). This is particularly the case for mining companies in Chile. According to an interview, it may not be easy for a management system to collect tyres from remote mining companies. The law also contemplates the possibility that industrial facilities valorise on their own and then simply report what they valorise to the management systems or directly to the ministry, and it is counted towards the valorisation goals (Ministerio Del Medio Ambiente, 2021; Ministerio Del Medio Ambiente 2023; Personal communication, 2023). There are also business models where the mining companies are financially benefitted from conducting EOLTs valorisation processes. Some of the options are shown in Figure 6 and include:

a) A management system that operates under a model called full cost. The management system hires operators with trucks who collect tyres, and entities to receive that material and valorise it.

b) Large mining companies or other industrial facilities valorise by themselves. They hire an operator, and then just report it. In this case, there is even a model where the management system can offer incentives to the mining company by paying money per kilo of material valorised and the industrial facility provides proof that they have valorised the materials in a particular way. They sign an agreement that the company valorises, and then bills the management system based on actual valorisation. In this case, the management system is still tallying the kilos, but they do not hire any operators. This means that industrial facilities can both generate and valorise EOLTs in an agreement with a management system (Personal communication, 2023). The mass of EOLTs that the industrial facility valorised is then assigned to the management system whom the facility signed the agreement with (Ministerio Del Medio Ambiente, 2021). Should the industrial facility opt for reporting directly to the Ministry, the mass of EOLTs valorised by the facility will be allocated to all collective management systems proportionally to the mass introduced into the market by their members during the previous year (Ministerio Del Medio Ambiente, 2021). The Figure 6 provides an overview of the EOLTs management options that industrial facilities have.

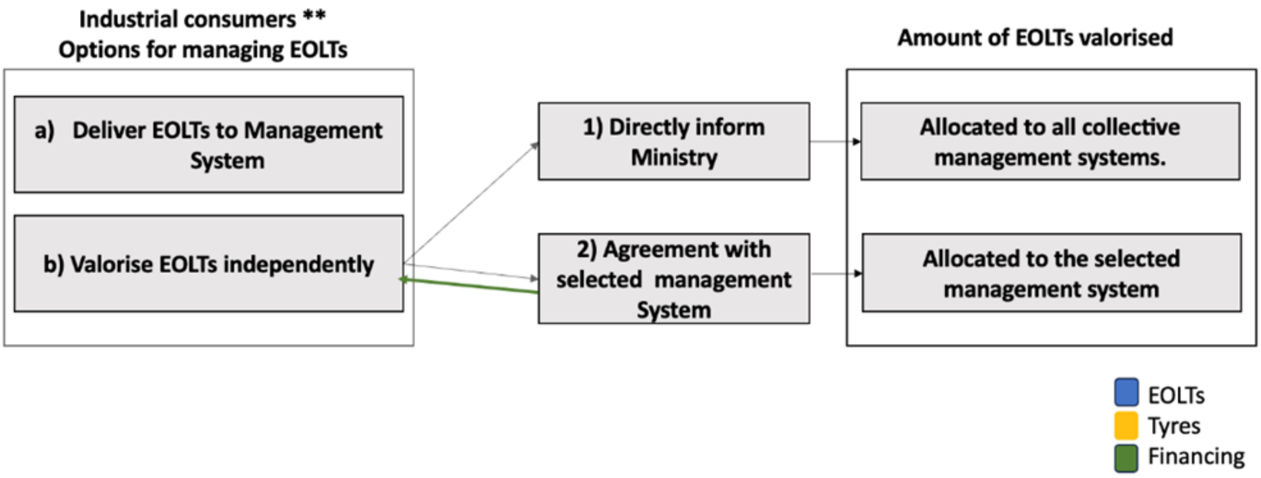

Figure 6. EOLTs management options for industrial consumers that generate EOLTs. Own elaboration, based on (Ministerio Del Medio Ambiente, 2021).

Funding of collective management systems

Even though the Chilean government does not charge a fee to the tyre importers, producers must pay a fee to the collective management systems they belong to, and the fee depends on their tyre imports. The EPR law states that producers who are part of a collective management system must finance the system proportionally based on the quantity of tyres introduced to the market by each producer. The fee is set by the collective management system. The criteria for determining fees include factors such as size, weight, composition, or design of tyres, along with considerations for the potential for retreading the tyres in Chile (Ministerio Del Medio Ambiente, 2021). According to one of the interviewed people, "The management system charges a fee to each tyre producer based on the quantity of tyres they introduce into the country.

Therefore, someone who brings in 10,000 tyres in a year will obviously have to pay a larger fee to the management system than someone who introduces only 1,000 tyres. The management systems define their fees based on weight. With this financing, the management systems hire waste management entities to collect tyres and send them to valorisation plants" (Personal communication, 2023).

Collection and valorisation rates

For each management system, the percentage of collection and valorisation needed to determine goal achievement will be determined by the following formula (Ministerio Del Medio Ambiente, 2021):

$$P_i = \left(\frac{NG_i \ x \ 100}{NC_{i-1} \ FD}\right)$$

Where (Ministerio Del Medio Ambiente, 2021):

P_i represents the percentage of collection or valorisation for the year i;

NG_i is equivalent to the total mass (t) of EOLTs collected or valorised, in the year i;

FD is the wear factor due to tyre usage, corresponding to 0.84 for Category A tyres and 0.75 for Category B tyres, as the case may be; and

NC_{i-1} is equivalent to the total mass (t) of tyres introduced into the national market in the year immediately preceding the one in which the collection or valorisation operations referred to in NG_i were carried out.

In the case of an individual management system, the value of NC_{i-1} will coincide with the producer's own value. In the case of a collective management system, the value NC_{i-1} will be the sum of the NC_{i-1} values of each of the producers within it.

In the case of industrial facilities opting to valorise EOLTs independently (i.e. option b in Figure 6), the percentage of collection or valorisation will be (Ministerio Del Medio Ambiente, 2021):

$$P_i = \left(\frac{\left(NG_i + N_{CONSIND\,i}\right) x \ 100}{NC_{i-1} \ x \ FD}\right)$$

Where (Ministerio Del Medio Ambiente, 2021):

P_i, NG_i, FD represent same as above; and

$N_{CONSINDi}$ is equivalent to the sum of mass (t) of relevant category EOLT valorised in year i.

Impacts of the scheme to recycling rates

Given that the EPR law for tyres started to roll in 2023, to date, there are still no data available to track the performance of the first year. As a baseline, the latest data shows that in 2022 (before EPR law) in Chile out of 178,647 EOLTs, 23,471 were valorised. The data also suggested that in 2022 there was a reprocessing capacity of 96,740 EOLTs (La Asociación Nacional de la Industria del Reciclaje, 2023).

Challenges

Tyre recycling in Chile has several challenges. These are briefly discussed below.

Time constrains and free competition. Delays in processing approvals, particularly before the Antitrust Court (TDLC) and the need for MMA (Ministry of the Environment) approval to commence the collection of EOLTs, have created challenges for the management systems, such as Econeu (a collective management system). As a result, these delays may limit the time available for the systems to operate effectively within the specified timeframes and consequently there is a risk of stockpiling (Gallardo, 2023). There may be issues regarding free competition; the tribunal does not behave in the same manner, especially in matters related to sunk costs and membership quotas. Corporations could have different ways of conducting themselves (Superintendencia del Medio Ambiente (SMA) Gobierno de Chile, 2022).

Traceability of EOLTs valorised by industries. Concerning industrial generators, which can valorise either independently or through authorized managers, there is an apprehension about how to ensure traceability in the management of EOLTs from industrial consumers who opt for individual management models. In other words, when introducing a tyre to the market for the first time, the associated integrated management system should be established, defining the value of its management. Allowing industrial consumers, the choice of management alternatives could potentially jeopardise the traceability of the chain.

Stockpiling risk. Given that the goals set by the Decree 8 of law EPR for tyres falling into category A differentiate between collection and valorisation goals, with the former being higher, unwanted temporary storage of this waste could occur. Although EOLTs are not classified as hazardous waste in Chile, they exhibit characteristics that complicate their storage for extended periods, such as the risk of fires and the potential proliferation of disease vectors (e.g. mosquitos carrying Dengue and Zika viruses) due to the accumulation of moisture and water, especially in the northern regions of the country (Personal communication, 2023).

Products from EOLTs. The development of the EPR law did not consider strategies to identify markets for these recycled products. One of the interviewed participants stated that the laws themselves did not establish many mechanisms or provide detailed information regarding the promotion of demand for these products (Personal communication, 2023). Other complexities were acknowledged, including the need for technical standards for certain byproducts like pyrolysis oil. Despite this regulatory gap, the Chilean government is actively finding ways to address this concern. Various actions have been taken by both the private and public sectors to foster demand in secondary material markets. For example, there are ongoing efforts with the Ministry of Public Works to promote the use of recycled rubber in road construction. Chilean reports on the sustainability of EOLTs have suggested that there is a need identified for an agreement between the Ministry of the Environment and the Ministry of Public Works so that part of future contracts involve asphalt mixtures with recycled rubber powder content (Sánchez and Río, 2017). This would mobilise the demand for this type of product. Additionally, the participant noted the importance of conversations with other ministries, such as Housing and Urbanism, and the Ministry of Energy, particularly in addressing challenges related to the valorisation of tyres through mechanical processes. As a matter of fact, the Ministry of Housing, has established sustainability criteria in the areas of housing and public spaces by updating Sustainable Construction Standards and publishing a Manual of Sustainable Urban Elements, respectively (Personal communication, 2023). These guidelines are voluntary and do not constitute compulsory standards, but they set a precedent for determining the sustainability of a construction. Both documents promote the use of materials with recycled content and the management of construction waste. However, the Ministry lacks direct experience in the application of recycled rubber in public construction (social housing) (Sánchez and Río, 2017). Through private sector initiatives, these products could be validated and certified to potentially open up a market for recycled rubber in public housing (Sánchez and Río, 2017).

Information on how to ensure a constant demand for the remaining byproducts obtained in recycling lines through mechanical treatments namely textile and steel was not available. Finally, as a byproduct of pyrolysis, carbon black is obtained which would serve as a raw material for the rubber industry (for example, tyre manufacturing). Although there is only one national manufacturing plant, and the demand for this carbon black is expected to be low, mostly directed towards international markets, Kal Tyre is currently reutilising this co-product in to conduct tyre repairs and retreading processes (Kal Tire Mining Tire Group, 2023b). This indicates a market for the product.

EOLTs disposal in mining sites. Chile has a ban on landfilling tyres. Decree 189 of 2008 "Approves regulation on basic sanitary and safety conditions in sanitary landfills" puts forward Article 57 which states that only non-hazardous industrial solid waste that does not affect the normal operation of the final disposal of household solid waste under stable conditions can be disposed of. Even though tyres are considered non-hazardous waste in Chile, their disposal is not allowed. Article 57 lists the types of industrial residues that are banned from landfills: a) liquid waste; b) demolition waste; c) tyres. During an interview on this topic, a participant indicated that tyres are mostly banned because they may pose stability threats in the landfills, tyre piles may collapse and this could lead to accidents. The participant added that before the EPR law came into effect for EOLTs (i.e. until last year, when there was no obligation to valorise), there have been specific industrial landfills where tyres could be received. The participant had seen aerial photographs of mining operations with receival areas that had thousands of tyres piled up (Personal communication, 2023).

3.3. European Union

European Council Landfill Directive (1999/31/EC) has prohibited sending EOLTs to landfills (European Commission, 1999). European Union member states are free to set national initiatives to reach European Union (EU) targets on the development of waste management policies at the national level. In the European Union there are three different models for managing EOLTs (Figure 7). These include (European Tyre and Rubber Manufacturers' Association, 2024):

1. Extended Producer Responsibility (EPR)
2. Liberal system (free market)
3. Tax system (Government responsibility, financed through a tax)

The Extended Producer Responsibility (EPR) means that the producer's full or partial operational and / or financial responsibility for a product is extended to the post-consumer state of a product's life cycle. Therefore, the original manufacturer has a duty of care to ensure that the waste from its products is disposed of responsibly, in an environmentally-sound manner. This has led to the setting-up of not-for-profit companies financed by tyre producers aiming to manage the collection and recovery of EOLTs through the most economical solutions. A reporting obligation towards the national authorities provides a good example of clear and reliable traceability (European Tyre and Rubber Manufacturers' Association, 2024).

Under the **free market system**, the legislation sets the objectives to be met but does not designate those responsible. Therefore, all the operators in the recovery chain contract under free market conditions and act in compliance with the legislation. This may be backed up by voluntary cooperation between companies to promote best practice. Free market systems operate for example in Austria, Switzerland, Germany, and the United Kingdom (UK). The UK operates a "managed free market" system as EOLT collectors and treatment operators must report to national authorities (European Tyre and Rubber Manufacturers' Association, 2023).

Under the tax system model, each country is responsible for the management of EOLTs. It is financed by a tax levied on tyre producers and subsequently passed on to the consumer. The tax system model is applied in Denmark and Croatia (European Tyre and Rubber Manufacturers' Association, 2023).

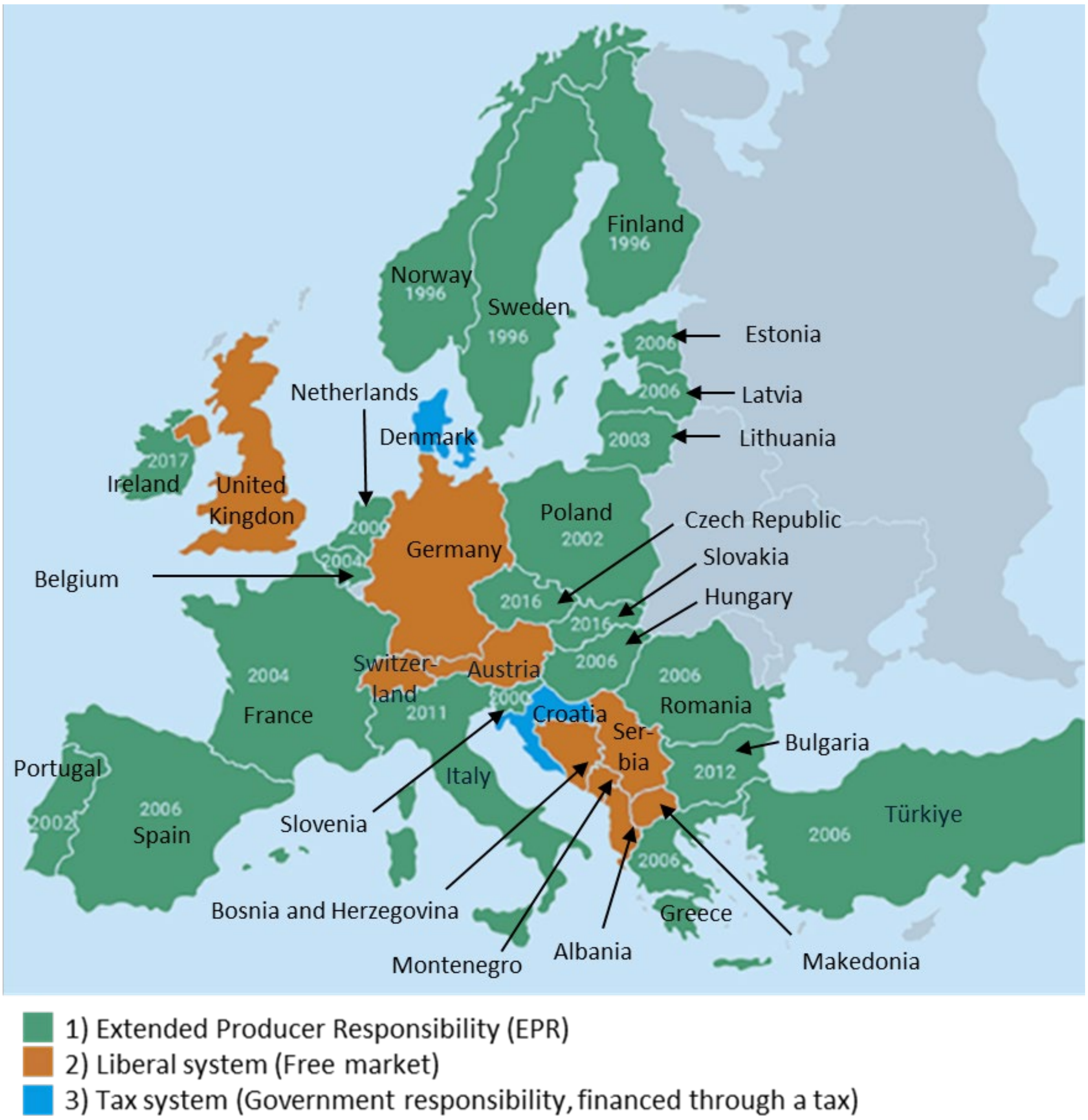

Figure 7. Models used for managing end-of-life tyres in Europe (Adapted from European Tyre and Rubber Manufacturers' Association, 2024).

Examples of organisations responsible for extended product stewardship schemes for EOLT management in European Union countries are shown in Table 5. The following sections will summarise key aspects of stewardship schemes in Denmark, Finland, France and Italy.

Table 5. Examples of organisations responsible for extended product stewardship schemes for end-of-life tyre management in European Union countries (Adapted from European Tyre and Rubber Manufacturers' Association, 2024).

Country	Organisation	Web site
Belgium	RECYTYRE	https://www.recytyre.be/fr
Czech Republic	eltma	https://www.eltma.cz
Finland	SUOMEN RENGASKIERRÄTYS	https://www.rengaskierratys.com
France	ALIAPUR COLLECTE ET RECYCLAGE DE VOS PNEUS	https://www.aliapur.fr/fr/
Greece	ecoelastika USED TIRES MANAGEMENT	https://www.ecoelastika.gr
Ireland	circol ELT	https://circolelt.ie
Italy	ECOPNEUS	https://www.ecopneus.it/en/
Netherlands	RecyBEM B.V. BAND & MILIEU	https://www.recybem.nl/nl
Norway	Norsk Dekkretur	https://www.dekkretur.no
Poland	CUO CENTRUM UTYLIZACJI OPON ORGANIZACJA ODZYSKU S.A.	https://utylizacjaopon.pl
Portugal	valorpneu Porque existe Amanhã	https://www.valorpneu.pt
Romania	eco anvelope	https://ecoanvelope.ro
Slovakia	eltma	https://www.eltma.sk
Spain	SIGNUS	https://www.signus.es
Sweden	SVENSK DÄCKÅTERVINNING	https://www.sdab.se
Turkey	LASDER® Lastik Sanayicileri Derneği	https://www.lasder.org.tr

3.3.1 Denmark

Denmark's tyre value chain includes no new tyre producers, several tyre importers (7 of which are in the tyre importers' association), 2 bus/truck tyre retreaders, 2 registered EOLT collectors and 2 approved EOLT processors. In 2022, a total of 2,012,724 passenger/motorcycle tyre units, 54,509 van tyre units (load index above 123), 216,791 truck/bus tyre units and 28,219 OTR tyre units were imported to Denmark. In 2022 a total of 45,976 t of EOLTs were recycled in Denmark, and of these 62% (28,713 t) were car tyres, 27% (12,344 t) bus/truck tyres and 11% (4,918 t) OTR tyres (Danish Tyre Trade Environmental Foundation, 2023c).

The first Danish Executive Order with economic incentives for EOLTs was introduced in 1995 to collect and recycle EOLTs in an environmentally sustainable way. Currently applied Executive Orders are no. 1660 dated 13 November 2020 and Executive Order no. 637 dated 24 May 2023 that amends the Executive Order 1660 (Danish Tyre Trade Environmental Foundation, 2023a).

Organisations that import tyres to Denmark must be registered by the taxation authorities (Danish Tyre Trade Environmental Foundation, 2023c) and pay a levy to the Customs and Tax Administration (Skat). The levy ranges from 12 DKK to 250 DKK excluding value added tax per tyre depending on the size and type of tyre as shown in Table 6 (Danish Tyre Trade Environmental Foundation, 2023a). Import levies are not applied to tyres that are imported as part of vehicles, such as cars (Danish Tyre Trade Environmental Foundation, 2023c).

Table 6. Fee rates for organisations that produce or import tyres to Denmark as of the 1st of July 2023 in accordance with Executive Order no. 1660 of the 13th of November 2020 on fees and subsidies for the recovery of tyres and amendments by the Executive Order no. 637 of the 24th of May 2023 (Danish Tyre Trade Environmental Foundation, 2023a).

Group	Fee (DKK)	Tyre types*
1	12	Moped, Load index (LI) ≤ 123 Motorbike, LI ≤ 123 Passenger car, LI ≤ 123 Van, LI ≤ 123 Trailer, LI ≤ 123 Other motorised vehicles, rim diameter ≤ 10 inches
2	12	Retreaded tyres as mentioned in group 1
3	28	Passenger car, LI ≥ 123 Van, LI ≥ 123 Trailer, LI ≥ 123 Other motorised vehicles, rim diameter > 10 inches and < 19.5 inches
4	28	Retreaded tyres as mentioned in group 3
5	84	Motorised vehicle other than mopeds, motorcycles, passenger cars, vans and trailers, rim diameter ≥ 19.5 inches and < 24 inches
6	84	Retreaded tyres as mentioned in group 5
7	250	Motorised vehicle other than mopeds, motorcycles, passenger cars, vans and trailers, rim diameter ≥ 24 inches
8	250	Retreaded tyres as mentioned in group 7

*The following tyres are exempted from the fee:

- Tyres with section width < 5 inches and rim diameter < 8 inches
- Tyres fitted on new vehicles from abroad
- Tyres used for fitting in the manufacture of new vehicles
- Used tyres with fees already paid
- Retreaded tyres with fees already paid

The levies are transferred from the Skat to the Danish Environmental Protection Agency (EPA). EOLTs are collected from car dealers, tyre shops and garages by EPA-registered tyre collectors free of charge. The administration and supervision of the payment of subsidies for tyre collection are exercised by the EPA and Danish Tyre Trade Environmental Foundation (Dækbranchens Miljöfond) (Danish Tyre Trade Environmental Foundation, 2020). Levies to be used for subsidy payment are transferred four times a year from EPA to The Danish Tyre Trade Environmental Foundation. The transferred amount is based on a forecast which is based on the payment for the previous three years. The transferred amount is not equal to the levies (Personal communication, 2023). The Danish Tyre Trade Environmental Foundation pays a subsidy to the tyre collectors on behalf of the EPA for EOLTs delivered to approved recycling plants. Only collectors registered by the EPA can get a subsidy for EOLT collection and they need to deliver the EOLTs to EPA approved EOLT processors (Personal communication, 2023) and the information needs to be endorsed by stage-authorised or registered auditor (Danish Tyre Trade Environmental Foundation, 2020). Collectors must report the origin (waste producer) of the EOLTs either in units (pieces) or weight (kg) delivered to a processor in order to receive a subsidy from The Tyre Trade Environmental Foundation (Personal communication, 2023). The subsidy depends on the size of tyres as shown below and is graduated according to the extent of recycling at the plant where the collected tyres are delivered (Danish Tyre Trade Environmental Foundation, 2023b):

- Max 1.59 DKK for tyres with rim diameter < 24 inches
- Max 2.20 DKK for tyres with rim diameter ≥ 24 inches

Consumers can return EOLTs to municipal recycling points free of charge (but not to tyre distributors or importers). There are no refunds for returning EOLTs (Danish Tyre Trade Environmental Foundation, 2023c). Bus and truck tyres that are suitable for retreading are delivered to retreading companies. There are no legal standards or rules about the quality of imported tyres to ensure that they can be retreaded, but retreaders normally only choose to retread quality casings. There are no incentives for retreading tyres (Danish Tyre Trade Environmental Foundation, 2023c). Other tyres are delivered to EPA-approved recycling plants for either granulation of pyrolysis treatment (Danish Tyre Trade Environmental Foundation, 2023b). Landfilling is banned for tyre shreds and whole tyres with an outer diameter of <1.4 m (Danish Tyre Trade Environmental Foundation, 2023c). For each reprocessing process, material and energy balances are conducted, and the intended use of the products is determined. Based on this, the products from the process are assigned to reuse and recovery, respectively depending on if they are used for materials recovery or recovery for energy. Components from pyrolysis processes can be assigned to reuse if they are used as chemicals. Reuse requirements are further specified in Appendix 2 of the Executive Order no. 1660 dated 13 November 2020 in terms of maximum allowable content of polycyclic aromatic hydrocarbons (PAHs), phthalates and eluted Zn in rubber granules, and PHA in oils and carbon black produced from pyrolysis (Danish Tyre Trade Environmental Foundation, 2020).

The recycling rate is calculated based on the following equation (1) (Danish Tyre Trade Environmental Foundation, 2020):

$$G = N_{GA}/Dækt_{tot} \qquad (1)$$

Where:

G = the reuse rate expressed in %

N_{GA} = The mass of tyre materials reused in kg

$Dækt_{tot}$ = The mass of tyres converted in kg (total)

The amount of subsidy is determined using equation (2) (Danish Tyre Trade Environmental Foundation, 2020):

X% reuse = X% subsidies (2)

As the subsidies encourage EOLT processors to utilise EOLTs as material rather than energy, most EOLTs are directed to material use and only a small volume of EOLTs that are not suitable for material recovery are utilised for energy recovery. Currently there are two active plants that conduct granulation and no active pyrolysis plants in Denmark. Other processors of EOLTs do not qualify for subsidy and therefore are not largely used. The two granulation plants also process most large OTR tyres. In rare cases it is not possible to granulate some tyres and they must be incinerated (Danish Tyre Trade Environmental Foundation, 2023c). The responsibilities of various stakeholders in the EOLT system in Denmark are summarised below (Danish Tyre Trade Environmental Foundation, 2023c) and an overview of the material and money flows in the Danish tyre recycling are shown in Figure 8:

- **Tyre importer:** Pay levy to taxation authorities for each imported tyre.
- **Taxation authority:** Receive levy from importers and enforce levy regulations.
- **EPA:** Make the regulations, receive levy payments from taxation authorities, and pay The Tyre Trade Environmental Foundation for operations and subsidies payment.
- **EOLT collector:** Voluntary collection of scrap tyres. Can apply for subsidy at The Tyre Trade Environmental Foundation for tyres delivered to a EOLT processor.
- **EOLT processor:** Voluntary acceptance of scrap tyre from collectors.
- **Tyre Trade Environmental Foundation:** Pay subsidy to collectors for tyres delivered to EOLT processor.

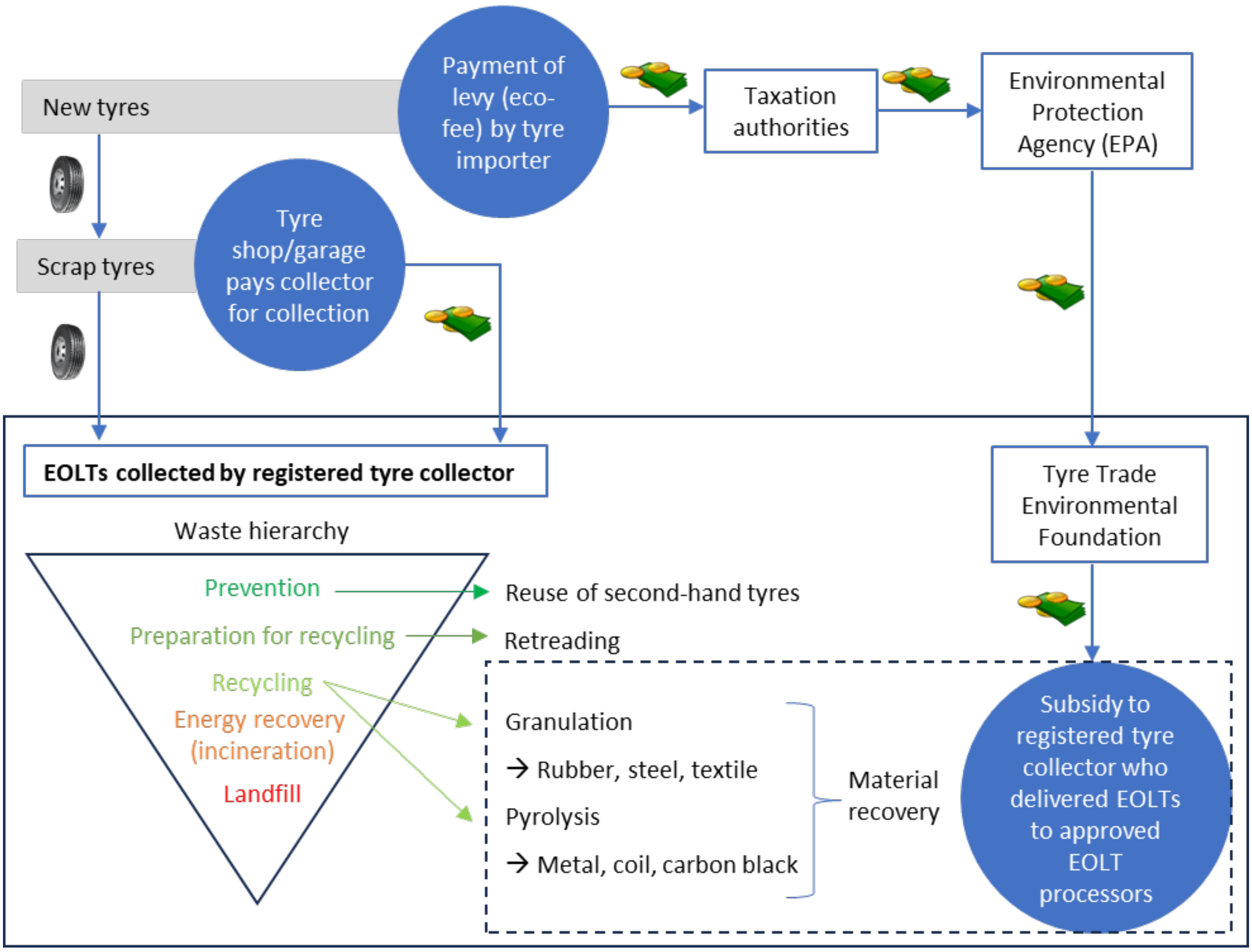

Figure 8. A summary of the material and money flows in the Danish tax-financed tyre stewardship scheme (redrawn from a diagram received from Danish Tyre Trade Environmental Foundation through personal communication, 2023).

One barrier in capturing EOLTs for value recovery has been that the processors can decide their gate-fee for receiving EOLTs from collectors. The level of the gate-fee isn't regulated in any way. Recently the gate-fee has been too high compared to the subsidy given to the collectors by The Tyre Trade Environmental Foundation, which has caused a shutdown of almost all EOLT collection. To overcome this the EPA has allowed the collectors to charge the tyre shops, garages, etc. for the EOLT collecting. This has previously not been allowed, as the subsidy should be sufficient to cover the collection costs. Many tyre shops, garages, etc. are very upset about the new rules, as consumers now end up paying both a levy when buying a new tyre and a waste management surcharge when scraping a tyre. The original idea was that the levy should cover all scrap management costs. Reverse logistics is not currently being used for new and EOLT transport as the transports are organised by two different stakeholders. There are currently no plans to extend the EOLT stewardship scheme to conveyor belts or other rubbery products or otherwise modify the scheme (Danish Tyre Trade Environmental Foundation, 2023c).

3.3.2 Finland

In Finland, producer responsibility is based on waste law (646/2011) and State Council tyre regulation (8527/2013) (Tuominen, 2024). The term "tyre producer" refers to the professional manufacturer, importer, and retreader of tyres and importers of vehicles and equipment equipped with tyres. The producer responsibility concerns tyres of vehicles, construction machinery and equipment designed to be used on land. Tyre producers must either take care of the recycling of the tyres they supply to the market independently or by transfer their producer responsibility on agreement to the producer association. (Finnish Tyre Recycling, 2024e).

The key stakeholders in the tyre industry in Finland established Suomen Rengaskierrätys Oy (Finnish Tyre Recycling) in 1995 to meet the tyre recycling obligation based on producer responsibility (Finnish Tyre Recycling, 2024a). Tyre recycling commenced the year after, 1996 (Tuominen, 2024). In Finland, tyre producers can carry out their collection and recycling responsibilities by (Tuominen, 2024):

1) Joining an accepted producer association, in which case the responsibility is transferred to the association; or
2) Registering to Pirkanmaa Ely-Keskus producer register, in which case the producer carries out collection, recycling, reporting and information sharing themselves.

Finnish Tyre Recycling is currently the only tyre producer association in Finland. It is owned by ARL-Palvelut Oy, Bridgestone Europe NV/SA, Finland, Continental Rengas Oy, Goodyear Dunlop Tyres Finland Oy, Nokian Renkaat Oyj and Oy Suomen Michelin Ab (Tuominen, 2024). The organisation offers their producer members a full producer responsibility service. The rights and responsibilities of the parties are stipulated in a shared producer agreement (Finnish Tyre Recycling, 2024e). The Finnish Tyre Recycling operates as a non-profit organisation. Any surplus must be used for further developing the recycling system or reducing the recycling fees (Personal communication, 2024).

Currently, approximately 410 tyre producers and 3,400 collection points have joined the recycling system organised by the Finnish Tyre Recycling (Finnish Tyre Recycling, 2024a; Personal communication, 2024). The collection points are labelled with "Renkaat Kiertoon" (Translated as "Tyres for Recycling") sign (Figure 9). EOLTs can be returned to any of the collection points free-of-charge without a purchase obligation. People can find the nearest collection point on the Finnish Tyre Recycling Map Service using either postcode or their location. The ownership of the tyres transfers to Finnish Tyre Recycling when the tyres are handed over to the producer association. The collection points take care of storing the tyres and arranging for collection and transfer to a local temporary storage location, known as a terminal. The terminal may only hand the tyres over to selected companies that have joined the recycling system (Finnish Tyre Recycling, 2024h).

Figure 9. Renkaat Kiertoon (Translated as "Tyres for Recycling") sign used in Finland to indicate tyre collection points operated by the Finnish Tyre Recycling (The Finnish Tyre Recycling, 2024h), and photos of tyres collected without or with rim and a container for tyre collection in Finland (Photos: Anna Kaksonen).

Before 2023 Finnish Tyre Recycling subcontracted many of its functions to other organisations. However, from the 1st of January 2023 Finnish Tyre Recycling started to carry out most collection and recycling operations directly. Finnish Tyre Recycling carries out logistics planning, operates recycling centre in Loppi, operation of movable cutter and marketing of tyre-derived products. Transport companies carry out tyre collections and the Tyre terminal network is implemented in collaborative agreement with Encore/Stena Recycling Oy (Tuominen, 2024).

The Pirkanmaa Centre for Economic Development, Transport and the Environment (ELY Centre) can assign a penalty payment for negligence to a company that has failed to fulfil its tyre producer responsibilities. The penalty payment is 1% of the annual turnover of the company for the previous financial period, or a maximum of €500,000 (Finnish Tyre Recycling, 2024e). Approximately 50,000 t of tyres reach their end of life in Finland annually (Finnish Tyre Recycling, 2024a), and in 2022 a total of 64,571 t of tyres were collected for recovery (Tuominen, 2024). According to Finnish Tyre Recycling, all EOLTs are collected and close to 100% recovered for various purposes (Finnish Tyre Recycling, 2024a). In the last few years, the collection has been over 100% of those known to be put on market, and in 2019 the recovery was 120%, which means that some tyres enter Finland through unofficial routes through free riders (Tuominen, 2024). There is currently no producer responsibility for conveyor belts in Finland. Nor does the producer responsibility cover motor sledge and all-terrain-vehicle belts (Personal communication, 2024).

The material and money flows for tyre recycling in Finland are shown in Figure 10. Tyre manufacturers and importers bring new tyres to market. Tyre retailers change tyres to vehicles, ensure that tyres meet regulations and receive tyres at the end-of-life. Finnish Tyre Recycling collects EOLTs from collection locations to large containers and transfers them to terminals (temporary storage facilities) for sorting. Then the EOLTs are reduced in size for various applications (Finnish Tyre Recycling, 2024f).

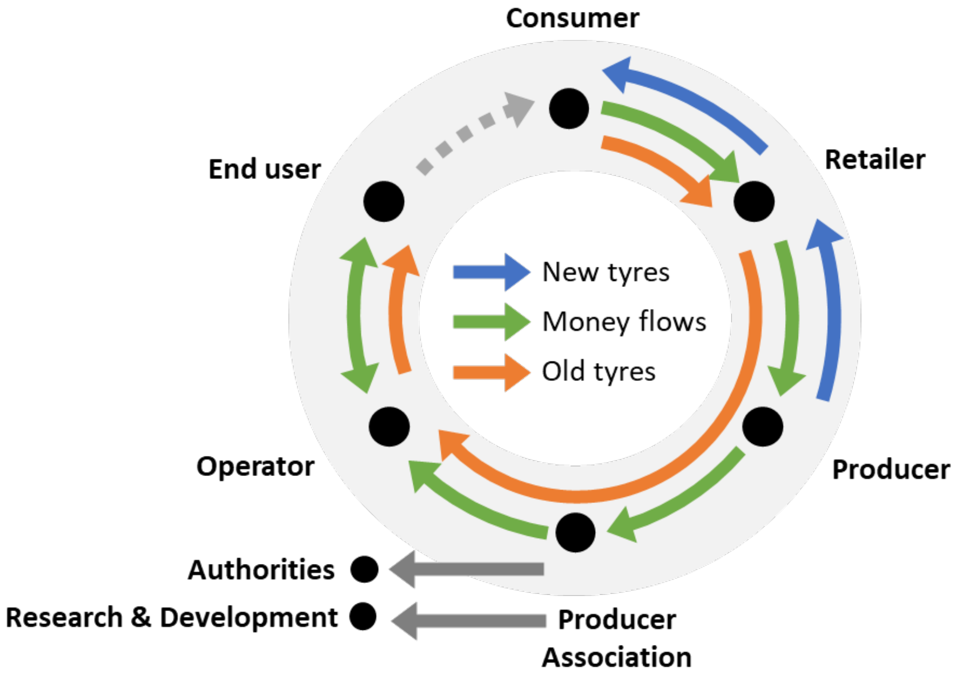

Figure 10. Material and money flows for tyre recycling in Finland (Adapted from Finnish Tyre Recycling, 2024g).

On average, passenger car tyres are used for approximately six years (Finnish Tyre Recycling, 2024f). The average lifespan of tyres in Finland is 6.5 years, 6.37 years for winter tyres and 6.15 years for summer tyres. It is to be noted that due to the use of two sets of tyres (winter and summer), the tyres are not used for a full 12 months each year (Tuominen, 2024). By law, car and van summer tyres must have a minimum of 1.6 mm tread depth, but the safety recommendation for wet weather is 4 mm treat depth. For winter tyres the minimum required tread depth is 3 mm, but for demanding winter conditions, the recommended minimum tread depth is 5 mm (Finnish Tyre recycling, 2024b).

Consumers can return old tyres to any of the collection points for recycling free of charge (Finnish Tyre Recycling, 2024a) as the recycling of tyres is funded with a recycling fee collected in connection with the purchase of new tyres (Figure 10). Tyres can be returned with or without rim, but rim removal may be subjected to a charge (Finnish Tyre recycling, 2024b). The tyre recycling fee is dependent on the size and type of tyres as shown in Table 7. The recycling fee for retreaded truck tyres is lower than for new truck tyres to promote the use of retreaded truck tyres in Finland, and thereby supporting circular economy for tyre materials (Finnish Tyre Recycling, 2024c).

Table 7. Tyre recycling fees in Finland in 2024 (Finnish Tyre Recycling, 2024c).

Tyre class	Tyre type	Tyre size	Recycling fee (Euros before GST)	Recycling fee (Euros after GST 24%)
101	Moped, scooter and motor cycle tyres	≥ 10.0 inches	1.26	1.56
102	Passenger car tyres	NA	1.40	1.74
103	Delivery van tyres	< 17.5 inches	1.40	1.74
104	Truck and bus tyres	≥ 15.0 inches	6.89	8.54
105	Industrial tyres	≥ 15.0 inches	6.89	8.54
106	Freely rolling front tyres of tractors, trailer tyres, small machines, all-terrain vehicles (quad bike) tyres, industrial tyres (except for riding lawn mowers and wheelbarrows < 10”)	< 15.0 inches	1.79	2.22
107	Agricultural machinery tyres	< 20.0 inches	3.83	4.75
108	Agricultural machinery tyres	≥ 20.0 inches	8.64	10.71
109	Work- and forestry machinery tyres	< 300 kg	13.73	17.03
110	Work- and forestry machinery tyres	≥ 300 kg	64.08	79.46
111	Retreaded truck tyres	NA	2.07	2.57
112	Retreaded passenger car tyres	NA	0.00	0.00
113	Large machinery tyres	> 2000 kg	500	620

NA = Not applicable

The recycling of EOLTs in Finland follows the waste hierarchy of the European Union waste framework Directive 2008 (European Union, 2024) and Finnish Waste law (Ympäristöministeriö, 2012), according to which the prevention of waste generation is of priority, followed by processing for reuse, recycling of material or utilisation as energy (Figure 11, Table 8). Good quality truck and bus tyre casings can be retreaded for reuse after careful inspection process. Heavy tyres are retreaded on average twice in Finland. Tyres are usually retreaded to the customer’s casings, and therefore retreaded tyres appear in recycling statistics only at the end of life of the tyres (Finnish Tyre Recycling, 2024d). Retreading is done by baking/vulcanisation rather than glueing (Personal communication, 2024). The bulk of EOLTs are utilised as whole, shred or crumb for road and civil works (Finnish Tyre Recycling, 2024d).

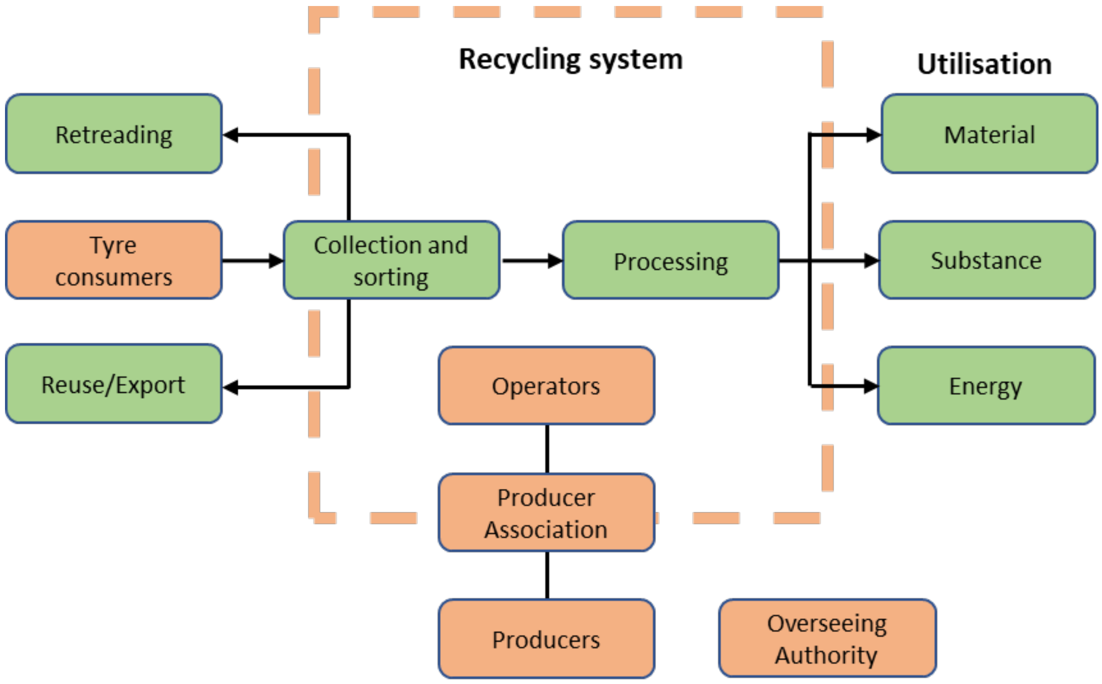

Figure 11. The life cycle of tyres from consumers to utilisation (Adapted from Finnish Tyre Recycling, 2024d).

Table 8. Fate of tyres between 2019 and 2023 in Finland (Tuominen, 2024).

Parameter	**Mass of tyres (t)**				
Year	**2019**	**2020**	**2021**	**2022**	**2023**
Collection	61,436	61,089	64,999	64,571	59,341
Retreading	376	147	47	100	11
Material use	56,802	51,949	50,281	63,601	56,220
Other use	10,733	5,743	5,893	2,802	1,200
Energy recovery	5,958	3,061	2,137	9,460	9,027
Export	67	32	13	32	19
Total utilisation	73,935	60,933	58,371	75,998	66,477

The tyre recycling centre in Loppi (which processes about one third of EOLTs in Finland) has a capacity and permit for processing 20,000 t of tyres per year and operates in two shifts. Incoming trucks are weighed to document flows for reporting to regulators (Tuominen, 2024). Tyres are sorted based on type and size, with capability to do video-assisted sorting based on the label on the side of tyres (Personal communication, 2024). Tyres are then processed using a pre-cutter (20 t/h) which cuts tyres to 50-350 mm size and removes impurities such as soil, rocks and ice, granulation line (6 t/h) and grinder (1.5 t/hour). The annual products include 16,000 t rubber products (25-400 mm shred, 0.7-8 mm granules and 0.2-0.7 mm powder), 2,800 t iron and 1,200 t fibre (Tuominen, 2024).

Steel is used for steelmaking and fibre goes to incineration (Personal communication, 2024). Rubber granules are utilised for applications that require flexibility, such as artificial lawns and sport and soft-fall playgrounds. Small particle size rubber material is used as binder in asphalt to reduce tyre noise and increase durability. In 2023, 84.57% of EOLTs were utilised for civil works, 13.58% for energy and pyrolysis, 0.82% for explosion mats, 0.02% were retreaded, 0.99% for other materials use and 0.03% exported for retreading (Finnish Tyre Recycling, 2024d). Approximately, 4,000 t of tyres have been used for cement industry and the remaining energy use is for heating. Pyrolysis has been trialled in three projects, but large-scale pyrolysis has not been considered profitable as it would require 20,000 t feedstock annually. Carbon black produced from pyrolysis would have markets, but the annual amounts of pyrolysis oil would need to be 20,000-30,000 t to get oil refiners interested (Personal communication, 2024).

Examples on new applications include the use of tyre-derived products in spray-moulding of shoe soles by Lenkki Oy. The tolerance of the soles to ultraviolet radiation and bending has improved because of the use of the recycled material. The Finnish Tyre Recycling has also suggested that the same material can be used over time for multiple purposes. For example, bus tyres can be retreaded for 3-4 times and thereafter cut and used as explosives mats. When no longer usable, the mats can be used for manufacturing granules for sports fields. For professional football fields the artificial lawn is typically used for 4 years and can thereafter be moved for use by juniors and amateurs for another 10-15 years. After that the granulate can be collected and used again e.g. as asphalt binder, soft fall surfaces or shoe soles (Tuominen, 2024).

Finnish Tyre Recycling operates movable cutters that are taken to mine sites and that are used to cut large mining tyres in 5-6 pieces, which are used for civil construction and as protective barriers at shooting ranges. The use of the movable cutter requires a minimum mass of 500 t of EOLTs to be available to make its use economical. Reverse logistics is not utilised as the transport infrastructure needs are different for EOLTs (Personal communication, 2024).

Challenges raised by Finnish Tyre Recycling include self-sealing tyres, as the glue sticks to everything and causes the rubber to form balls during the processing. Another consideration is the fact that electric cars are heavier and thus tyres used in electric cars wear out faster than those used for conventional cars (Personal communication, 2024).

3.3.3 France

Aliapur, the principal entity overseeing tyre stewardship in France (Figure 12), plays a pivotal role in collecting and recycling EOLTs within the nation. It annually collects approximately 400,000 t of tyres across France, with major tyre manufacturers actively participating as members of Aliapur's board. The primary applications for recycled tyre rubber in France include utilization in the cement industry and as infill material for synthetic turf. Although in niche sectors, additional applications include asphalt and various specialized applications. The regulatory landscape significantly influences the viability of recycled tyre rubber markets. Recent regulations addressing microplastics have restricted tyre shreds in synthetic turf, affecting a significant portion of the market. Considering evolving regulations mandating digital passports and certified sourcing, traceability and adherence to quality standards are increasingly imperative. Aliapur can address these requirements through its robust sorting and tracking processes. Despite the potential benefits of recycled tyre rubber, its adoption remains limited to niche markets, primarily due to prohibitive investment costs and challenges in achieving economies of scale. Pyrolysis, a critical technology for rubber reclamation, is poised to revolutionize the sector. However, its successful implementation necessitates large-scale operations managed by major manufacturers. Accurate characterization of material composition is essential to ensure that recycled rubber meets customer specifications and functions effectively in various applications.

Aliapur is committed to exploring new uses and markets for recycled rubber. However, it acknowledges the inherent challenge of competing with low-cost virgin materials on price, underscoring the need for innovative strategies to enhance competitiveness and market penetration. Aliapur perceives its role as a pivotal facilitator within the tyre recycling ecosystem of France, aiming to establish connections among various stakeholders, including manufacturers, grinders, and cement plants. The organization collaborates closely with Michelin, a prominent tyre manufacturer, on regulatory matters and initiatives such as the Blackcycle project. However, Aliapur's board structure, including all manufacturers, prevents its leadership in projects that benefit only one manufacturer. Recognizing the growing significance of life cycle assessment in evaluating recycling pathways and establishing carbon reduction objectives, Michelin utilizes this framework to assess its carbon footprint. Standardization efforts at the European level have played a crucial role in fostering collaboration and harmonizing practices across different industry players, facilitating adequate networking opportunities.

Despite its pivotal role, Aliapur encounters challenges from a perceived lack of leadership and understanding within the French government. Ministries primarily delineate roles only by actively engaging with Aliapur's needs, impeding project development and removing obstacles.

Aliapur adopts a pragmatic approach, prioritizing operational efficiency over innovation, given its responsibility for managing continuous waste flows and controlling the entire supply chain.

The organization undertakes initiatives to educate cement plants on tyre quality, transforming them from mere customers into active buyers through the assurance of quality control and delivery standards. Emerging pyrolysis projects promise to extract additional value from byproducts such as oil, offering potential benefits beyond traditional carbon black. However, the scalability of such projects is contingent upon proximity to refineries, posing logistical challenges.

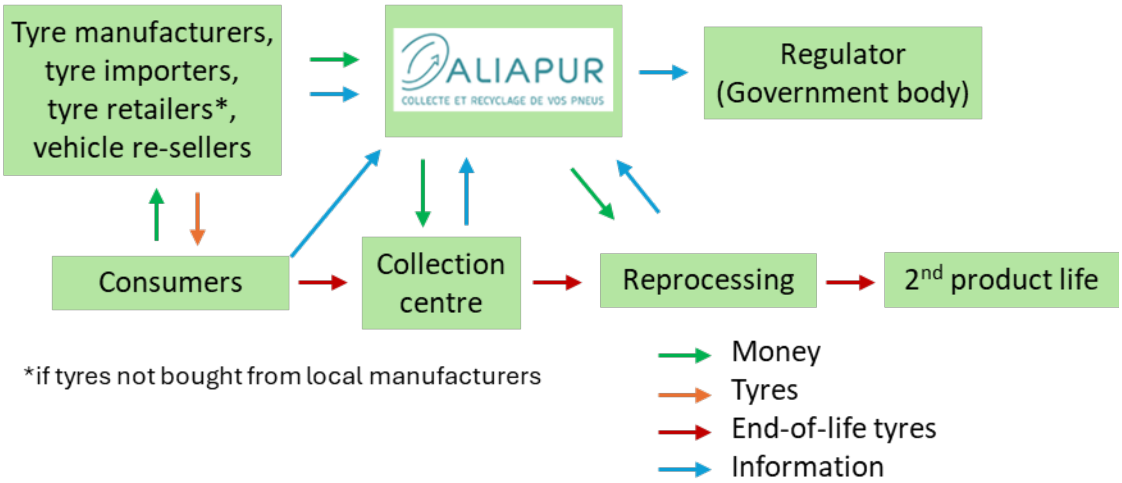

Figure 12. Material, information and money flows in the French tyre recycling scheme (Adapted based on info from Aliapur, 2024).

Several prominent global applications of recycled rubber have been discussed:

Article I. Recycled rubber finds significant utilization in the cement industry, serving as a crucial raw material. In France, particularly, the cement industry emerges as the primary consumer of recycled rubber.

Article II. Another notable application lies in road construction, specifically in asphalt rubber production. This innovative practice involves incorporating recycled rubber into asphalt for road construction purposes, representing a growing trend in the industry.

Article III. Previously, rubber was extensively employed as an infill for synthetic turf fields. However, recent regulations enacted by the European Union targeting microplastics have constrained this usage, marking a shift in the industry dynamics.

Article IV. The manufacturing of "green doors," comprising recycled rubber and plastic obtained from shredded tyres, has emerged as a significant avenue. Companies specializing in this manufacturing process are identified as major consumers of recycled rubber.

Article V. Additionally, recycled rubber sourced from shredded truck tyres finds utility in the steel industry. It serves as a viable substitute or supplement for anthracite in electric arc furnaces, demonstrating the versatility of recycled rubber in various industrial applications.

Apprehensions have been expressed regarding the predominantly niche nature of current markets and projects involving recycled rubber. The imperative for large-scale technologies like pyrolysis was emphasised to process larger volumes on a commercial scale worldwide effectively. Nonetheless, the considerable financial investments required to implement such technologies was noted. It was highlighted that the devulcanisation process for rubber remains a niche market. Reservations were voiced regarding the market potential for devulcanised rubber, citing a lack of enthusiasm among manufacturers towards its utilization. Despite the capability of the process to generate high-quality rubber, there exists scepticism surrounding the demand and application of the product. These observations underscore the necessity for enhanced educational initiatives and demonstrations to fully unlock the technology's potential and facilitate its widespread adoption.

Several successful partnerships have been discussed, including:

Article I. The Blackcycle project in Europe, spearheaded by Michelin tyre manufacturer, aimed at developing tyre recycling technologies. Aliapur, the French recycling organization, was pivotal in ensuring access to used tyre deposits.

Article II. Partnerships between Aliapur and Michelin in France are characterized by regular exchanges focusing on tyre waste status and regulatory issues.

Article III. Collaborations between Aliapur and cement manufacturers in France, wherein Aliapur contributed to educating cement companies on the value and quality of recycled tyre material. This initiative led to a reversal in the relationship, with cement companies now procuring the material from Aliapur.

European standardization endeavours, led by recycling organizations like Aliapur, have aimed at establishing common standards. This collaborative effort facilitated the convergence of various industry and government stakeholders. Projects funded by the European Union and national governments involved both major tyre manufacturers and recycling organizations. Government funding has been provided for such initiatives, while manufacturers have assumed leadership roles in project execution. In essence, these successful partnerships capitalize on the complementary strengths of each sector. Manufacturers contribute funding, scale, and technological expertise while recycling organizations offer access to materials and logistical support. Conversely, governments provide funding, regulatory frameworks, and standards, thus fostering collaborative endeavours. Conveyor belts are not currently included to the French product stewardship scheme due to composition issues (Personal communication, 2023).

3.3.4 Italy

Under Article 228 of Legislative Decree 152/2006 (the Environmental Consolidated Act (ECA)), tyre manufacturers and importers were obliged to ensure the management of a quantity of EOLTs equal in weight to that which is placed on the replacement market in the preceding calendar year, based on the Extended Producer Responsibility (Ecopneus, 2024f). However, until 2011 Italy did not have a national system for the management of collection, recovery, and monitoring of tyre flows. On the 7th of September 2011, a national system became operational under Ministerial Decree 82/2011 (Ecopneus, 2024i). The management of EOLTs was redefined later in Ministerial Decree 182/2019 (Ecopneus, 2024c). The main changes introduced by MD 182/2019 included (Ecopneus, 2024c):

- Classification of online tyre sales from abroad directly to Italian consumers

- Better definition of the parties who can take on responsibility in a consortium both as constituting parties and as associates
- A more careful definition of the obligations of the parties authorised to act on all the national territory and on all typologies of EOLTs, with similar quotas per geographical areas, carrying on the collection based on the sequence of received requests, and without making any connection with brands and sales activities – thus guaranteeing the most complete separation between tyre sales and EOLT management
- Fairer and clearer identification of "individual" parties that operate on the national system of EOLT management
- Wider, more articulate, and precise reporting to increase transparency towards the many stakeholders involved

Ecopneus scpa is the non-profit company responsible for tracking, collecting, processing and destination of EOLTs created by the major tyre manufacturers operating in Italy (Bridgestone, Continental, Goodyear-Dunlop, Marangoni, Michelin and Pirelli). Many other companies have also joined Ecopneus over time (Ecopneus, 2024f). Currently Ecopneus has 50 shareholders: tyre manufacturers and importers that have chosen to become shareholders of Ecopneus (Ecopneus, 2024h).

Ecopneus is also entrusted with the duty of reporting to the Authorities on behalf of its business partners as provided for by Ministerial Decree 82/2011 which implements Article 228. For reporting, Ecopneus utilises an appropriate IT system to certify the quantitative flows of tyres placed on the market, the quantities of EOLTs from the source to collection and use and economics. If manufacturers and importers do not meet targets they are subjected to a system of sanctions (Ecopneus, 2024f).

Approximately 350,000 t of tyres reach their end of life in Italy each year based on the replacement of tyres in vehicles. This includes approximately 30 million car tyres, 2 million truck tyres, 3 million tyres for 2-wheeled vehicles and over 300,000 tyres for industrial and agricultural vehicles (Ecopneus, 2024i). On average, approximately 200,000 t (or approximately 60% of the national production) of EOLTs are collected, transported, processed, and recovered by Ecopneus (Ecopneus, 2024h). Additionally, Ecopneus promotes the applications of recycled rubber and initiatives of information and awareness raising to create a recycling culture (Ecopneus, 2024e). The mass and share of various types of tyres collected by Ecopneus in Italy in 2023 is shown in Table 9. According to Ecopneus, the number of tyres recovered is higher than that legally put on the market which indicates that some operators operate illegally and do not pay eco-fees. Therefore, better traceability of tyres is required. Ecopneus also recommended more control by authorities and ministry and higher fines for illegal tyre selling. The stakeholders are also currently not audited (Personal communication, 2024).

Table 9. The mass and share of various types of end-of-life tyres (EOLTs) collected by Ecopneus in Italy in 2023 (Ecopneus, 2024j).

Tyre type	Mass collected (t)	Share (%)
Small EOLTs (< 33,25 kg): e.g. from motorbikes, scooters (including tilting 3-wheeled scooters, i.e. MP3s), quads, enduros, automobiles, sports utility vehicles (SUVs), light commercial vehicles (LCVs), caravans	146.045	77.91
Medium EOLTs (from 33,25 kg to 147,25 kg): e.g. from trucks, buses, traction units, trailers	38.392	20.48
Large EOLTs (> 147,25 kg): e.g. from industrial, agricultural and earth work	3.008	1.60
Total	187.445	100

Tyre recycling in Italy is financed with an “eco-fee”, which is an environmental contribution that tyre purchasers pay when buying new or second-hand imported tyres. The fee depends on the tyre type and weight. The fee must be specified in the sale document and is used exclusively to ensure the correct management of EOLTs (Ecopneus, 2024h). The eco-fees for Ecopneus shareholders are shown in Table 10 (Ecopneus, 2024b) and the flow of eco-fees, new and EOLTs and information is shown in Figure 13. Ecopneus has created an external, independent, and specialised network which is entrusted with the activities of collection, transportation and recovery of EOLTs. This network is controlled by a managerial structure for waste traceability (Ecopneus, 2024f).

Table 10. Eco-fees for Ecopneus shareholders for various types of tyres in Italy (Ecopneus, 2024b).

Size category	Fee category	Weight range of tyres placed in the market (kg)	Eco fees before GST (Euros)/tyre
Small (P)	1	0 – 4.999	1.00
	2	5 – 7.999	1.80
	3	8 – 12.999	2.60
	4	13 – 15.999	3.70
	5	16 – 24.999	4.70
	6	25 – 34.999	7.70
Medium (M)	7	35 – 64.999	14.50
	8	65 – 104.999	18.70
	9	105 – 154.999	32.70
Large (G)	10	155 – 224.999	56.30
	11	225 – 314.999	79.70
	12	315 – 424.999	112.30
	13	425 – 554.999	148.00
	14	555 – 704.999	184.30
	15	> 705	266.60

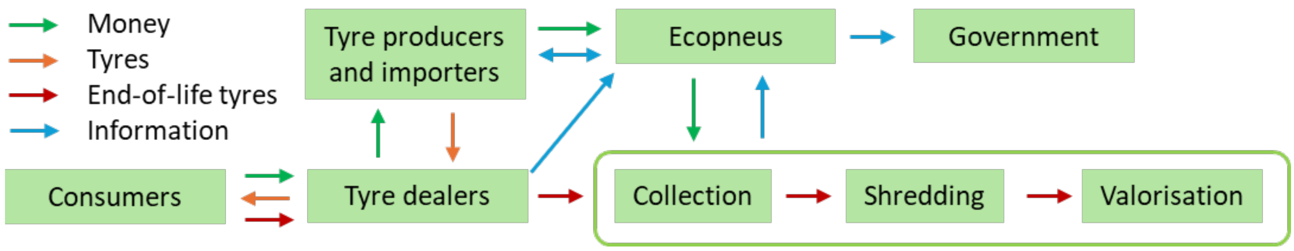

Figure 13. Flow of eco-fees (money), new and end-of-life-tyres and information in Italian tyre stewardship scheme operated by Ecopneus (Adapted from Dossena, 2023).

The Ministerial Decree 82/2011 forces the current EOLT management bodies, such as Ecopneus to destine a minimum of 30% of their end of the year fiscal surplus (if present) to collect historical stocks of tyres that were accumulated before September 2011. Since 2012 Ecopneus has collected tyres from 15 different historical stocks across Italy and handled over 84,000 t of EOLTs (Ecopneus, 2024a). The Italian Ministry has only set targets for the collection of EOLTs and the legislation does not mandate the recycling of conveyor belts. Therefore, the Ecopneus consortium only manages tyre waste, and has no plans to expand recycling to cover end-of-life conveyor belts. Currently bicycle tyres are also not on the list for recycling, and hence they cannot be collected for recycling. Retreading is also not part of the recycling scope and hence no data is available on retreading. However, some partners are trialling the use of water cutters for conveyor belt processing and to remove material from tyres before retreading (Personal communication, 2024).

EOLTs are allocated to the various recovery options with respect to the European waste hierarchy and preferring recycling to energy recovery (Ecopneus, 2024f). The percentage share of EOLTs utilised for materials and energy recovery in Italy in 2021-2023 is shown in Table 11, which shows that the percentage of energy recovery has increased during the past few years. Uses of tyre shred include the generation of electrical power, cement factories and civil engineering. Rubber granules are used for football fields, sport floorings and acoustic insulation. Rubber powder is utilised for asphalt, sealants, and other rubber items (Ecopneus, 2024h). The actual production volumes depend on the availability of EOLTs and processing plants as well as markets and can vary throughout the year. The main market for tyre-derived materials in Italy is currently sport applications, but new applications are being developed for example for rubber in plastic products, injection moulding, and asphalt rubber. Moreover, there is interest to expand processing capabilities from the predominantly used mechanical treatment to chemical recycling, such as devulcanisation and pyrolysis. So far chemical treatment has been mainly trialled in lab- and pilot scale and only 1-2 plants are able to carry out devulcanisation. The Italian Government does not provide financial incentives for the development of new tyre recycling technologies or retreading tyres. European Union funding can be applied for research and development projects (Personal communication, 2024).

Table 11. Percent share of end-of-life tyres utilised for materials and energy recovery in Italy 2021-2023 (Ecopneus, 2024d).

Year	Fate (%)	
	Material recovery	Energy recovery
2021	48	52
2022	41.7	58.3
2023	34	66

Ecopneus has adopted a Quality and Environmental Integrated Management Systems according to the International Standards ISO 9001 for quality management and ISO 14001 for Environmental Management System. With the implementation and keeping of the Integrated Management System, Ecopneus possesses a new strategic tool for the consolidation of the following objectives (Ecopneus, 2024g):

- Annually **intercepting**, collecting, and recovering EOLTs in all national territories for an amount equal at least to the amount put on the market by the Partners during the previous year.
- **Actuating** the principle of proximity for the operative and managerial optimisation of the activities and the limitation of the associated environmental impact.
- **Sending** the maximum amount possible of EOLTs to material recovery as opposed to energy recovery.
- **Preventing** situations that may cause damage to health and the environment.
- **Promoting** activities of communication, information and awareness raising towards Public Administration, Citizens, and Companies with the objective of supporting the consolidation of a culture of legality and sustainability in EOLT management.
- **Promoting** the consolidation and development of applications and of the recycled rubber markets, towards solutions likely to deliver the most benefits to Society.
- **Monitoring** and controlling the environmental aspects connected to activities and processes carried out directly and/or by the means of third-party companies.

Ecopneus organises an annual chain convention to improve the qualification of the industrial sector, share common strategies and objectives, activate synergies, and identify strengths and development perspectives. Participation has also been extended to companies that use rubber granules and powder. This facilitates the matching of the supply with demand (Ecopneus, 2024f).

3.4 New Zealand

EOLT volumes generated in New Zealand are approximately 40,000 t on the North Island and 15,000 t on the South Island, i.e. 55,000 t in total (Rose, 2023). The regulation in New Zealand is gazetted under the Waste Minimisation Act 2008 Priority Product legislation (Tyrewise, 2024d). The waste minimisation regulations for tyres come to effect in 2024 (New Zealand Government, 2023). Tyrewise is Aorearoa New Zealand's first regulated and the only Ministry for the Environment-accredited product stewardship scheme to manage regulated EOLTs. It is operated by Auto Stewardship New Zealand, a not-for-profit trust which acts as the Product Stewardship Organisation. Tyrewise aims to minimise the environmental impacts of EOLTs by managing all tyres from collection through to processing and ensures that EOLTs will not end up dumped, stockpiled, or landfilled. The scheme is funded by tyre stewardship fees which are collected by the Ministry for the Environment on regulated tyres entering the Aotearoa New Zealand market as loose tyres or fitted on vehicles. Tyrewise and Auto Stewardship New Zealand are responsible for publicly reporting on the scheme's performance. Tyrewise reports on how funds are spent and its achievement of targets. It must also maintain a chain of custody for all collected and processed tyres using Tyrewise's bespoke tracking software. The Ministry for the Environment is responsible for monitoring the stewardship scheme (Tyrewise, 2024a).

The stewardship fee will cover the costs of the management of the scheme, tyre collection services, incentive payment for processing and tyre-derived product manufacture for the New Zealand market, research and development grants and monitoring of the scheme by Ministry for the Environment (0.48% of the fee) (Tyrewise, 2024a). From 1st September 2024 Tyrewise will also be responsible for ensuring that

EOLTs are not stockpiled to an extent that causes problems. However, Tyrewise cannot use fees paid on regulated tyres to manage existing tyre stockpiles. Instead, Tyrewise will work with central and local governments to manage existing stockpiles using the National Environmental Standard for the Outdoor Storage of Tyres as guidance (Tyrewise, 2024e).

The benefits of Tyrewise scheme include (Rose, 2023):

- Visibility of scheme performance and harm reduction
- Level playing field as fees are consistent
- Stable cash flow to collection sites and transporters as well as local government
- Free tyre collections from tyre retailers, generators, collection sites
- Reduced administrative burden to EOLT transporters, processors, and manufacturers
- Audited standards for participants
- Reduction in illegal stockpiles and dumping, and thus environmental harm and clean-up costs
- Subsidies to processors and manufacturers for incentivising higher value products
- Supporting development of processors and manufacturers through grants
- Contribution to emission reduction targets
- Investment in developing solutions for difficult to recover tyres from mining and forestry
- Enhanced reputation from industry-led solution

The flow of tyres, money and information in the New Zealand tyre stewardship scheme are shown in Figure 14 and the roles and responsibilities of various stakeholders and described in the following sections.

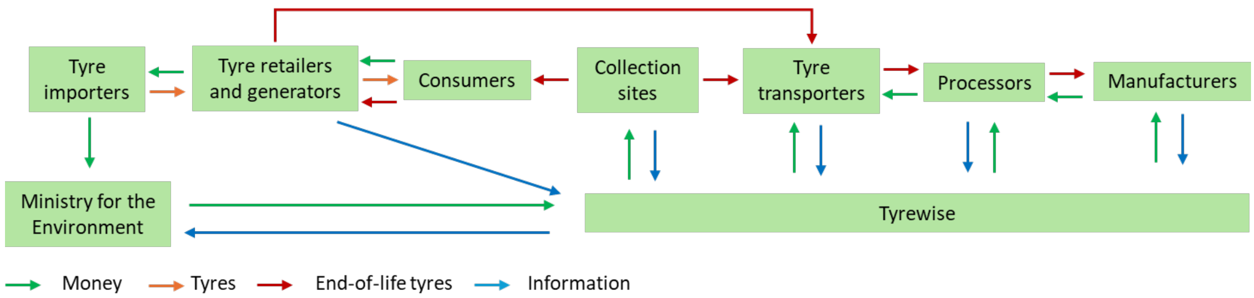

Figure 14. The flow of tyres, money and information in the New Zealand tyre stewardship scheme (created based on information available in Tyrewise, 2024c).

Importers pay tyre stewardship fees for all imported regulated tyres (i.e., pneumatic and/or solid tyres either loose or for use on motorised vehicles for cars, trucks, buses, motorcycles, aircraft, and off-road vehicles, which are scope one tyres) (Tyrewise, 2024c). The fees are listed in Schedule 2 of the Waste Minimisation (Tyres) Regulations 2023 (New Zealand Government, 2023). Imported retreaded aircraft tyres are exempt under the regulation. Scope two tyres for bikes and non-motorised equipment such as prams or retread components will be brought into the stewardship scheme later. Importers pass the stewardship fee through the supply chain to consumers and must transparently declare the fee in invoices. There is no exemption or refund of the tyre stewardship fee for exporting from New Zealand new or used tyres for which the fee has already been paid. Importers that store tyres outside need to comply with National Environmental Standard for Outdoor Storage of Tyres (Tyrewise, 2024c).

Tyre retailers on-charge a tyre stewardship fee at point of sale. All tyre retailers charge their customers the same fee on new tyres at point of sale irrespective of their location and are not allowed to charge a disposal fee for taking back old tyres. Tyre retailers do not pay for the collection of EOLTs from their site, but instead Tyrewise pays registered transporters to collect tyres. Tyre retailers can book tyre collection through Tyrewise software and verify the collection as it takes place. Registered EOLT processors verify the receipt of the EOLTs upon delivery. Thus, EOLTs are tracked through the Tyrewise software from collection through to processing. Collected tyres can be reported based on tyre sizes and volumes (Tyrewise, 2024c).

Collection Sites need to register with Tyrewise to get approved and receive EOLTs from consumers who do not want to purchase new tyres. Collection Sites may be transfer stations or community recycling networks. Registered collection Sites are paid a nominal service fee by Tyrewise for acting as an aggregation point for tyres to be collected from the public. The payments depend on how large or busy the collection site is. Collection Sites can book a collection of tyres from their site for free using the Tyrewise software and verify the collection as it takes place by tyre size and volume (Tyrewise, 2024c).

Consumers pay a tyre stewardship fee as part of the price of new tyres and the fee will be disclosed to the consumers at the time of purchase on the sales receipt. The fee is the same everywhere in New Zealand. Consumers can return EOLTs to the companies who fit new tyres. Additionally, they can return other old tyres to registered Collection sites, with a maximum of five tyres at a time. Consumers do not receive any money for returning old EOLTs for recycling, but do not pay any fee for disposing them either (Tyrewise, 2024c).

EOLT generators are organisations which have sites where large numbers of tyres are replaced (e.g. a fleet owner/operator) or which sell/fit tyres and take old tyres back when selling new ones (e.g. a garage). Depending on business type, EOLT generators either pay the fee on fitted or loose tyres they import directly for using in their own fleet, or they will transparently on-charge the fee to their customers at the point of sale of the tyre or vehicle they are fitted to. If the EOLT generators sell or fit any tyres, they must take used tyres from customers for recycling by Tyrewise. EOLT generators cannot charge disposal fees to customers for taking their old tyres, and Tyrewise will pay registered transporter to collect the tyres from EOLT generators for free. EOLT generators can book tyre collection through Tyrewise software and verify the collection as it takes place (Tyrewise, 2024c).

Tyre transporters collect tyres from registered retailers, generators and/or collection sites and deliver them to registered processors. Tyre transporters must be registered with Tyrewise as an approved transporter and can only deliver tyres to registered processors. Tyre transporters do not charge for collecting tyres from registered retailers, generators, or collection sites, but instead will be paid either by Tyrewise or the Processor (normal commercial arrangements apply). The size and volume of transported EOLTs will be tracked through the Tyrewise software from collection to processing (Tyrewise, 2024c).

Tyre processors transform old tyres for value recovery. From 1st September 2024, Tyrewise will pay for the transport of EOLTs. Tyrewise can pay registered transporters to deliver the tyres the processors need, or processors pay the registered transporters directly (normal commercial arrangements apply). In addition to the revenue tyre processors earn for selling tyre-derived products, Tyrewise pays the processors based on what products they produce, upon receiving evidence of the sale. The payment depends on the end use of the products. Tyrewise can audit tyre processor reports to ensure payments are made correctly. Processors must also comply with local and health and safety regulations and be subjected to audit (Tyrewise, 2024c).

Manufacturers purchase tyre-derived products from registered processors to use in their business and pay a market price for the products they receive (normal commercial arrangements apply). If manufacturers purchase whole tyres directly from registered transporters they are classified as processors as well as manufacturers. From 1st September 2024, Tyrewise may pay an incentive to registered manufacturers based on eligible sales of products made from tyre-derived product or fuels in the domestic market. The manufacturers may need to be part of a verified end market process. They need to provide evidence to Tyrewise of what they manufacture and what volumes of tyre-derived products fuel they use as this may affect the incentives paid. Manufacturers must also comply with local, and health and safety regulations and the manufactured products must comply with any safety standards (Tyrewise, 2024c).

Tyre stewardship fees are listed in Table 12-Table 15. Tyre stewardship fees for importers have been modelled on NZ$6.65 (excluding GST) per equivalent passenger unit (EPU). An EPU is based on a new standard passenger tyre of approximately 9.5 kg. All tyre types have been grouped based on their size and function and assigned an average EPU value. For imported tyres, this is based on a tyre type that corresponds to the tariff item. Tyre importers can pass the stewardship fee on to their customers, who can pass it on to the final tyre buyer (Tyrewise, 2024e).

The way the stewardship fee is charged depends on whether tyres are sold loose or as fitted tyres on road registered vehicles or off-the road vehicles. The fee for loose tyres is initially paid by the importer of the tyres. The importer must pass the fee to consumers. Importers, retailers and tyre fitters (generators) must ensure that the fee is transparently declared at each sale process. The fee for tyres fitted on road registered vehicles is charged at the point of first registration by NZTA/Waka Kotahi and the fee will be part of the on-road costs (ORC) of a vehicle. The amount of the fee must be transparently disclosed as part of the on-road costs. Importers of off-road vehicles will declare imports directly to Tyrewise (Tyrewise, 2024e).

Imported and regulated second-hand tyres will attract tyre stewardship fees in the same way as new regulated tyre imports. Second-hand tyres which originated in Aotearoa New Zealand do not require a stewardship fee at point of sale. Tyres that are considered suitable for sale on the second-hand market should be stored separately by tyre generators and retailers as their management is not covered by Tyrewise (Tyrewise, 2024e).

Table 12. Fees for loose tyres imported to New Zealand (New Zealand Government, 2023).

Tariff item	Fee per type (NZ$)
4011.70.00 39K	2.00
4011.40.00 00C	3.33
4011.10, 4011.20.03 01C, 4011.20.03 09J, 4011.20.03 11L, 4011.20.03 19F, 4011.20.12 01B, 4011.20.12 09H, 4011.20.12 11K, 4011.20.12 19E, 4012.11.11 00G, 4012.11.19 00H, 4012.20.01 01J	6.65
4011.30.00 00K, 4012.13.00 00D	12.64
4011.90.10, 4011.90.20, 4011.90.30, 4011.90.40, 4011.90.50, 4011.90.90 00L, 4012.19.11 00C, 4012.19.19 00D, 4012.20.01 09D, 4012.20.09 00A	13.30
4011.70.00 10A, 4011.70.00 23C	17.29
4011.20.03 21H, 4011.20.03 29C, 4011.20.12 21G, 4011.20.12 29B	21.28
4012.90.00 01H, 4012.90.00 09C, 4012.90.00 19L	23.94
4011.20.07 01J, 4011.20.07 09D, 4011.20.18 01L, 4011.20.18 09F, 4012.12.00 00K	27.93
4011.70.00 19E, 4011.70.00 21G, 4011.70.00 35G	29.26
4011.80.00, 4012.19.29 00K, 4012.20.19 00G	33.92
4011.70.00 11K, 4011.70.00 25K	53.87
4011.70.00 13F, 4011.70.00 29B	154.28
4011.70.00 15B, 4011.70.00 31D	420.95

Table 13. Tyre stewardship fees for all tyres on vehicles with a standard number of tyres imported to New Zealand (New Zealand Government, 2023).

Motor vehicle class or vehicle type as described in Part 2 of the Land Transport Rule: Vehicle Standards Compliance 2002	Fee per vehicle (NZ$)
Moped with two wheels (Class LA)	6.65
Motor cycle (Class LC)	6.65
All-terrain vehicle	8.00
Moped with three wheels (Class LB 1, LB 2)	9.98
Motor cycle and side-car (Class LD)	9.98
Motor tricycle (Class LE 1, LE 2)	9.98
Very light trailer (Class TA)	13.30
Passenger vehicle (Class MA, MB, MC)	33.25
Light trailer (Class TB)	39.90
Light omnibus (Class MD 1, MD 2)	66.50
Light goods vehicle (Class NA)	66.50

Table 14. Tyre stewardship fees for each tyre on vehicles with a variable number of tyres imported to New Zealand (New Zealand Government, 2023).

Motor vehicle class as described in Part 2 of the Land Transport Rule: Vehicle Standards Compliance 2002	Applicable gross vehicle mass range	Fee per tyre (NZ$)
Medium goods vehicle (NB)	≥3.5 t to 6.0 t	13.30
	> 6.0 t to 9.0 t	21.28
	>9.0 t to 12.0 t	27.93
Heavy goods vehicle (NC)	>12.0 t	27.93
Medium trailer (TC)	≥3.5 t to 6.0 t	13.30
	>6.0 t to 10.0 t	21.28
Heavy trailer (TD)	>10.0 t	27.93
Medium omnibus (MD 3)	≥3.5 t to 4.5 t	13.30
Medium omnibus (MD 4)	>4.5 t to 5.0 t	13.30
Heavy omnibus (ME)	>5.0 t	27.93

Table 15. Tyre stewardship fees for all tyres on vehicles not specified in Table 13 or Table 14 imported to New Zealand (New Zealand Government, 2023).

Applicable gross vehicle mass range	Fee per vehicle (NZ$)
≤1.5 t	31.26
>1.5 t to 3.5 t	63.18
>3.5 t to 6.0 t	142.31
>6.0 t to 9.0 t	237.41
>9.0 t to 12.0 t	333.17
>12.0 t to 15.0 t	428.26
>15.0 t to 18.0 t	523.36
>18.0 t to 21.0 t	619.12
>21.0 t to 24.0 t	714.21
>24.0 t to 27.0 t	809.31
>27.0 t to 30.0 t	904.40
>30.0 t to 33.0 t	1,000.16
>33.0 t to 36.0 t	1,095.26
>36.0 t to 39.0 t	1,190.35
>39.0 t to 42.0 t	1,286.11
>42.0 t to 45.0 t	1,381.21
>45.0 t to 48.0 t	1,476.30
>48.0 t	1,540.14

The domestic incentives for processing EOLTs and manufacturing tyre-derived products and fuels are shown in Table 16.

Table 16. Tyrewise domestic incentive schedule for processing end-of-life tyres and manufacturing tyre-derived products (TDP) and fuels (TDF) (Tyrewise, 2024b).

Type of processing/manufacturing	Code	Description	Processing/manufacturing incentive per t for eligible sale (NZ$)
Whole tyres in engineering solutions	TW1	Whole tyres used essentially in their original form for civil engineering: baled – retailing walls, temporary roads, sea embankments, blasting mats	165
Feedstocks as tyre-derived fuel	TDF1	Primary shred for further use in a destructive process or secondary process, typically irregular shape. Cut tyres or portions of 100-300 mm	365
	TDF2	Whole tyres for energy recovery	70
Tyre-derived products processed from feedstock as raw material for a secondary process, e.g., mulch, landfill or civil engineering, equestrian arenas, tyre derived aggregate	TDP1	Rubber powder free of steel and fibre (mesh size 30; 0 micron-0.9 mm)	390
	TDP2	Rubber granulate uncoloured, free of steel and in accordance with playground standard (mesh size 1-29 mm)	365
	TDP3	Rubber chip, typically cubical in shape for high volume applications, used as road fill – commonly known as tyre-derived aggregate (TDA) (mesh size 30-299 mm)	85
	TDP4	End use/fabricated products (use 75% by weight of TDP 1-3) (Incentive negotiated per application type)	Up to 160
	TDP5	Rubber granulate coloured, free of steel, in accordance with playground standard (mesh size 1-29 mm)	365
	TDP6	Carbon black derived from tyre pyrolysis undertaken within New Zealand (Incentive negotiated per application type)	TBA

3.5 A comparison of tyre stewardship schemes

A comparison of the reviewed tyre stewardship schemes and the Australian scheme is shown in Table 17, and some key background information for these countries is shown in Appendix 2 Table A1. The reviewed overseas tyre stewardships were all compulsory and most countries had bans for landfilling and on-site disposal of tyres. Many of the reviewed countries (including Australia) had implemented auditing of the companies that carry out EOLT collections and processing. It should be noted that auditing is only conducted for participants of the stewardship schemes. Import levies or fees were used for tyres in Australia, Denmark, Finland, and New Zealand.

In most countries except for Australia, recycling fees were included to the purchase price of new tyres, whereas in the Australian stewardship scheme, disposal fees are charged when disposing EOLTs. The latter does not encourage returning tyres for recycling and can result in illegal dumping or stockpiling. Some of the overseas countries have implemented incentives to support tyre recycling. Incentives exist e.g., in the form of lower recycling fees for retreaded tyres, subsidies provided to end-of-life collectors or incentive payments for EOLT processing and manufacturing of tyre-derived products. None of the reviewed stewardship schemes included conveyor belts to the scheme.

Table 17. A summary of product stewardship schemes for end-of-life tyres (EOLTs). None of the reviewed countries have stewardship schemes for conveyor belts.

Country (region)	**Scheme type (compulsory /voluntary)**	**Bans for landfilling and on-site disposal**	**Auditing**	**Import levies/fees to companies**	**Recycling fees for consumers (at the time of purchase or disposal)**	**Incentives for recycling**
Australia	Voluntary	No	Yes: Companies	Yes	Disposal	No
Canada						
British Columbia	Compulsory	Yes	Yes: Companies	Yes	Purchase	Yes, for processing EOLTs and manufacturing tyre-derived products
Manitoba	Compulsory	Yes	Yes: Companies	Yes	Purchase	Yes, for collection and reprocessing
New Brunswick	Compulsory	Yes	Yes: Companies	Yes	Purchase	No
Ontario	Compulsory	Yes	Yes: Companies	Yes	Purchase	No
Quebec	Compulsory	Yes	Yes: Companies	Yes	Purchase	Yes, to help re-processor maintain equipment
Saskatchewan	Compulsory	Yes	Yes: Companies	Yes	Purchase	Yes, for reprocessing
Chile	Compulsory	Yes	Yes: Stewardship scheme and companies	No (but waste management fee that is based on tyre import volumes)	Purchase	Yes, only when industrial consumers perform valorisation processes
Denmark	Compulsory	Yes	Yes: Companies	Yes (tax)	(only import levy (tax))	Yes, subsidy for collectors
Finland	Compulsory	Yes	No	Yes	Purchase	Yes, lower recycling fee for retreaded tyres
France	Compulsory	Yes	Yes: Companies	Yes	Purchase	Yes, for reprocessing
Italy	Compulsory	Yes*	No	No	Purchase	No
New Zealand	Compulsory	Unknown	Yes: Stewardship scheme and companies	Yes	Purchase	Yes, for processing EOLTs and manufacturing tyre-derived products

* Except for some applications such as the civil construction use as base for landfills.

The EOLT arisings in Australia are larger in the overseas countries for which tyre stewardship schemes were reviewed. France and Italy have the highest populations. Australia's land area is somewhat smaller than that of Canada's, but larger than those of other reviewed countries. Gross domestic product (GDP) was in the same order of magnitude in Australia as has been in Canada, France, and Italy, whereas Chile, Denmark, Finland, and New Zealand have had an order of magnitude lower GDP. Mining has been a major contributor to the GDP in Chile and Australia, and to some extent also in Canada, whereas the share of agriculture was higher in Canada, New Zealand, and Chile than in Australia. The mining industry and agriculture contribute to the generation of large OTR tyres.

3.6 Summary of stewardship lessons in the Australian context

Australia can adopt several approaches from countries such as Canada, Chile, Finland, France, Italy and New Zealand to improve the stewardship of tyres and conveyor belts. Including rubber conveyor belts into the stewardship scheme would support the recovery of a larger portion of rubbery end-of life products than tyre recycling alone. Moreover, enacting a regulated stewardship scheme to capture all tyre and conveyor belt imports (including tyres fitted on vehicles and equipment) under import levies would be important to capture all stakeholders that sell new tyres and conveyor belts and collect, transport, and/or process EOLTs and to support the recycling of EOLTs.

To further increase the recovery of value from EOLTs and conveyor belts, Australia could implement a recycling fee that is part of the price of new tyres (and conveyor belts) instead of charging a fee for returning EOLTs (and conveyor belts) for recycling. Moreover, an additional bond fee could be charged as part of the price of new tyres/conveyor belts to allow a refund to be paid upon returning the used tyres/CB for recycling, to further incentivise material recovery. These fees (import levies passed to consumers, recycling fees and bond) could be bundled into a single fee to consumers paid at the point of purchase. More complete economic modelling of fee disbursements across the value chain needs to be completed.

Banning the landfilling and on-site disposal of EOLTs and conveyor belts would also increase recovery rates as long as there are viable recycling options available. As waste is managed on the state and territory level, tyres and conveyor belt wastes would need to be restricted to landfill in each jurisdiction to complement the compulsory stewardship scheme. Harmonisation would require all states and territories to restrict and regulate in the same way. Identification of relevant stakeholders in the supply chain and assigning clear responsibilities is important to ensure accountability. Moreover, auditing could be extended to all stakeholders that carry out tyre and conveyor belt imports and all stakeholders that sell new tyres and conveyor belts and collect, transport, and/or process EOLTs (and that are free riders in the current voluntary scheme) to ensure that sustainable practices are followed.

Setting clear targets and timeframes can provide a roadmap for all stakeholders, and unifying collection and valorisation targets over a specific timeframe can enable the building of recycling capacity but preventing excessive stockpiling. Separating tyres based on categories and recognising the logistical and economic differences between categories allows for tailored collection and valorisation strategies.

Australia could also consider incentivising remote, geographically isolated industries (e.g., mining companies) and allowing them flexibility to valorise EOLTs and conveyor belts themselves rather than having to deal with long-distance transport. It is also important to proactively develop policies, incentive mechanisms and research and development initiatives to encourage retreading, collection, and processing of EOLTs and manufacturing and use of tyre-derived products in Australia.

4. Enablers for EOLT and conveyor belt recycling in Australia

To enable the recycling of end-of-life tyres (EOLTs) and conveyor belts, it is imperative to classify these materials as categorised waste consistently across Australia. Additionally, comprehensive tracking mechanisms should be established to accurately monitor the movement of these waste streams across jurisdictions in Australia, thereby generating reliable data on their material flows and overall disposal. Currently, waste conveyor belts are not classified as controlled waste in Australia, and there is no compulsory requirement to report movement of these materials. This results in inadequate data on the import, material flow and generation of end-of-life conveyor belts (Boxall et al., 2023). To establish reliable databases for EOLT and conveyor belt arisings, it is crucial to ensure uniformity in units across all stakeholders involved in tracking the material-flows. Consistent units, such as those based on mass or volume, need to be agreed upon and adopted. Without standardised units, it becomes impossible to derive meaningful insights from the data, as values measured in inconsistent units are not directly comparable.

4.1 Waste classifications

4.1.1 Australia

Waste classification systems vary across jurisdictions in Australia. There are differences in the classifications used for quantifying and reporting landfill activities, as well as those employed for recycling activities, among different jurisdictions within Australia. In the Commonwealth of Australia, the legislation that governs waste management is the Hazardous Waste (Regulation of Exports and Imports) Act 1989. This Act is administered by the Department of Climate Change, Energy, the Environment and Water. The main purpose of this Act is to regulate the export and import of hazardous waste to ensure that hazardous waste is disposed of safely so that human beings and the environment both within and outside Australia, are protected from the harmful effects of the waste.

According to this Act, waste is defined as a substance or objects that:

(a) is proposed to be disposed of; or

(b) is disposed of; or

(c) is required by a law of the Commonwealth, a State, or a Territory to be disposed of.

At the Commonwealth level, “Hazardous waste” is defined as:

(a) waste prescribed by the regulations, where the waste has any of the characteristics mentioned in Annex III to the Basel Convention (Basel Convention, 1989); or

(b) wastes covered by paragraph 1(a) of Article 1 of the Basel Convention; or

(c) household waste; or

(d) residues arising from the incineration of household waste; but does not include wastes covered by paragraph 4 of Article 1 of the Basel Convention.

Waste tyres contain various substances listed as hazardous under the Basel convention (refer to Table 18). However, for processed waste tyres to be considered 'hazardous waste' under the Basel Convention, they must exhibit "hazardous characteristics" as outlined in Annex 3 of the Convention (Basel Convention, 1989).

Table 18. Basel Convention hazardous waste constituents found in waste tyres (Basel Convention, 2000).

Chemical name	Remarks	Content (% weight)
Copper Compounds	Alloying constituent of the metallic reinforcing material	Approximately 0.02%
Zinc Compounds	Zinc oxide, retained in the rubber matrix	Approximately 1%
Cadmium	On trace levels, as cadmium compounds attendant substance of the Zinc oxide	Maximal 0.001%
Lead; Lead Compounds	On trace levels, as attendant substance of the zinc oxide	Maximal 0.005%
Acidic solutions or acids in solid form	Strearic acid, in solid form	Approximately 0.3%
Organohalogen compounds other than substances in Annex 3	Halogen butyl rubber (tendency: decreasing)	Content of halogens maximal 0.10%

According to the Revised Basel Technical Guidelines, components of tyres are devoid of intrinsic hazardous properties (Basel Convention, 2000). Nevertheless, inadequate management and improper disposal of these components can pose risks to public health and the environment. Primary hazardous risks identified in the Basel Convention revolve around the transportation and storage of intact tyres, which can create ideal breeding grounds for disease-carrying mosquitoes and larvae. Moreover, accumulated stockpiles of tyres present a significant risk of fire. If processed and handled properly, it is possible that processed waste tyres are not classified as 'hazardous waste' under the Hazardous Waste Act 1989.

In 1998, Australia established a national framework for managing hazardous waste materials with the initiation of a National Environment Protection Measure (NEPM) by the National Environment Protection Council. This measure aimed to regulate the transport of controlled waste between Australian states and territories. The cornerstone of this framework is the National Environment Protection (Movement of Controlled Waste between States and Territories) Measure 2004, commonly known as the Controlled Waste NEPM. It provides a basis for ensuring that controlled wastes which are to be moved between States and Territories in Australia are properly identified, transported, and otherwise handled in ways which are consistent with environmentally sound practices for the management of these wastes. It is designed to establish a comprehensive national system for monitoring and reporting all interstate movements of controlled waste, ensuring compliance with Australia's international commitments under the Basel Convention.

All Australian jurisdictions (Australian Capital Territory (ACT); New South Wales (NSW); Northern Territory (NT); Queensland (QLD); South Australia (SA); Tasmania (TAS); Victoria (VIC); and Western Australia (WA)) have incorporated provisions of the Controlled Waste NEPM into their respective state and territory legislation. This integration enables the monitoring of controlled waste production, movement, and treatment/disposal across borders. Moreover, most jurisdictions have statutory powers to regulate the movement of hazardous waste materials within their own borders. These regulations may cover materials beyond those listed under the Controlled Waste NEPM, reflecting jurisdiction-specific concerns and priorities.

Generators, transporters, and facility operators handling controlled wastes, as defined under the NEPM, are obligated to adhere to data management, tracking, and other stipulations outlined in relevant legislation. On the 1st of May 2017, all jurisdictions had signed an agreement, which sets out the administrative matters on which agreement between jurisdictions is required to facilitate a cooperative and integrated approach to implementation of the NEPM throughout Australia (National Environment Protection Council (NEPC), 2017). Key features of this Agreement are the mutual recognition of waste transport licences for the purposes of controlled waste movements between States and Territories, and the development of a national tracking system.

Table A2 in Appendix 3 details the waste codes and descriptions of materials that must be tracked when crossing any state or territory border under the National Environment Protection (Movement of Controlled Waste between States and Territories) Measure 2004 (Schedule A, List 1). These waste codes correspond to either the contaminants or the source of the waste. As shown in Appendix 3, only Tyres (T140) are included as Controlled Waste. Conveyor Belts or other rubber wastes are not included.

Australian Capital Territory

Waste regulation and policy in the Australian Capital Territory (ACT) are primarily governed by the Environmental Protection Act 1997. Additionally, the Waste Minimisation Act 2001 supplements legislation concerning waste management in the ACT. The ACT Environment Protection Agency (EPA), operating under the Department of Territory and Municipal Services, serves as the regulatory authority for waste matters and is empowered to enforce legislation. Legislative authority resides with the ACT Government, which, in the formulation of legislation, seeks policy advice from the EPA, NO Waste, and the ACT Commission of the Environment. The ACT EPA possesses statutory powers, including the authorization of commercial landfills for specific activities.

In ACT, waste is defined under the Environment Protection Act 1997 as follows: "Waste means any solid, liquid, or gas, or any combination of them, that is a surplus product or unwanted by-product of an activity, whether the product or by-product is of value or not."

In ACT there are four classifications of solid waste, namely (1) inert, (2) solid, (3) industrial, and (4) hazardous, as outlined in the Environmental Standards: Assessment and Classification of Liquid and Non-liquid Wastes June 2000:

1. Inert: This includes natural wastes, building and demolition materials, asphalt, biosolids, tyres, office and packaging waste.
2. Solid: This includes municipal waste, biosolids, cleaned pesticide, biocide, herbicide, or fungicide containers, drained and mechanically crushed oil filters, rags, and oil absorbent materials (without free liquids) from automotive workshops, disposable nappies, incontinence pads, sanitary napkins, food waste, vegetative waste from agriculture or horticulture, and non-chemical waste from manufacturing and services (including metal, timber, paper, ceramics, plastics, and composites).
3. Industrial: This includes stabilized asbestos and asbestos fiber and dust waste.
4. Hazardous: This includes waste meeting the criteria for assessment as dangerous goods under the Australian Code for the Transport of Dangerous Goods by Road and Rail (categorized into one or more of nine types), pharmaceuticals and poisons (waste generated by activities for business or commercial purposes containing specified substances listed under the Poisons and Therapeutic Goods Act 1966 (NSW)), clinical waste, cytotoxic waste, sharps waste, and quarantine waste.

New South Wales

In New South Wales (NSW), the regulatory framework for waste management is governed by the primary legislation, the Protection of the Environment Operations Act (POEO Act, 1997, amended in 2008)(NSW Government, 1997), and the Waste Avoidance and Resource Recovery Act (WARR Act) 2001 (NSW Government, 2001). The governmental department responsible for waste oversight is the Office of the

Premier. The Waste Avoidance and Resource Recovery Strategy (WARR) 2007 delineates the waste management strategy for NSW. Under the POEO Act, waste is defined as:

(a) any substance (whether solid, liquid or gaseous) that is discharged, emitted or deposited in the environment in such volume, constituency or manner as to cause an alteration in the environment, or

(b) any discarded, rejected, unwanted, surplus or abandoned substance, or

(c) any otherwise discarded, rejected, unwanted, surplus or abandoned substance intended for sale or for recycling, processing, recovery or purification by a separate operation from that which produced the substance, or

(d) any processed, recycled, re-used or recovered substance produced wholly or partly from waste that is applied to land, or used as fuel, but only in the circumstances prescribed by the regulations, or

(e) any substance prescribed by the regulations to be waste.

There are five categories of solid waste: special, hazardous, restricted solid, general solid (putrescible), and general solid (non-putrescible). Each category has various sub-classes, as follows:

- Special waste includes three classes: clinical and related wastes, asbestos wastes, and waste tyres.
- Hazardous wastes are divided into six classes.
- Currently, there are no sub-classes for restricted solid waste.
- General putrescible waste comprises eight classes.
- General non-putrescible waste is further classified into 22 classes.

Used tyres are classified as special waste in NSW, whereas used conveyor belts are not classified as special waste in NSW.

Northern Territory

The Northern Territory Environment Protection Authority (NT EPA) regulates key aspects of waste management in the Northern Territory. Waste tyres are classified as prescribed wastes listed in Schedule 2 of the Waste Management and Pollution Control (Administration) Regulations 1998. Like other jurisdictions, waste conveyor belts are not classified as prescribed wastes in the Northern Territory.

Under the Waste Management and Pollution Control Act 1998 (WMPC Act), all Territorians have the following legal requirements for waste tyres in the Northern Territory:

- Have a General Environmental Duty (GED).
- Are responsible for preventing environmental harm.
- Require a licence to collect, transport, store, recycle, treat, or dispose of waste tyres on a commercial or fee for service basis.
- Performing licenced activities without an appropriate licence is an offence.

The broader community shares in the responsibility of ensuring proper management of waste tyres. Certain tyre retailers hold accreditation from Tyre Stewardship Australia, allowing them to accept waste tyres and guarantee lawful disposal on behalf of their customers. Additionally, some local landfills offer designated collection points where members of the public can safely dispose of their waste tyres.

Queensland

In Queensland, environmentally relevant activities (ERA) are defined as industrial activities with the potential to release contaminants into the environment. Waste-related ERAs are managed in Queensland under the Environmental Protection Act 1994 and Environmental Protection Regulation 2019.

Under the Environmental Protection Act 1994, 'waste' is made up of general waste, such as household waste, and regulated waste which requires a higher level of management to prevent harm to the environment or human health. Under the Waste Reduction and Recycling Act 2011, a waste can be approved as a resource under the end of waste (EOW) framework if the Department of Environment, Science and Innovation considers that it has a beneficial use and it meets the specified resource quality criteria for specific use under a code or an approval (Queensland Government, 2024).

The Environmental Protection Regulation 2019 (the Regulation) includes a risk-based waste classification framework where regulated waste is classified as either:

- Category 1 regulated waste (highest risk)
- Category 2 regulated waste (moderate risk)
- Not-regulated waste/general waste (lowest risk)

The regulated waste classification provisions in the Regulation are used to identify and appropriately manage the risks associated with various wastes and related waste management activities.

Schedule 9 of the Regulation provides a list of regulated wastes and their default category, wastes that are not regulated waste, and categorisation thresholds for solid and liquid tested waste.

It is noteworthy that in Queensland, tyres fall under the classification of category 2 regulated waste, reflecting their potential environmental and health risks. However, waste conveyor belts, despite sharing similarities in material composition and potential hazards, are not currently classified as regulated waste in the region.

South Australia

In South Australia (SA), waste is classified in accordance with the “Current criteria for the classification of waste- including Industrial and Commercial Waste (Listed) and Waste Soil” (Environment Protection Authority South Australia, 2024).

The types of waste that must be tracked during transport are listed in Schedule 1 of the Environment Protection Act 1993. For these wastes that must be tracked, the following waste characteristics must be determined and recorded:

1) Form of waste
2) Waste classification (as stipulated in the abovementioned Current criteria)
3) Waste code (the waste codes used in SA are from the Controlled Waste National Environment Protection Measure)
4) Waste description (more specific information about the waste than is usually provided by the waste code)
5) Dangerous goods properties (if the hazardous waste is classed as 'dangerous goods', then the dangerous goods information should be included on the waste transport certificate. Both a Dangerous Goods Licence and an Authorisation to transport waste under the Environment Protection Act 1993 is required)

In SA, waste tyres are classified as a waste stream that must be tracked when transported within the state or interstate. Waste conveyor belts are not subject to this requirement.

Tasmania

The Environment Protection Authority (EPA) of Tasmania regulates key aspects of waste management in Tasmania. This includes the regulation of Tasmania's larger waste depots; and of controlled waste (sometimes referred to as hazardous waste). The EPA assesses compliance with, and enforces, relevant rules and laws. Tasmania has adopted the terminology of the National Environment Protection (Movement of Controlled Waste between States and Territories) Measure 1998 (Controlled Waste NEPM) which uses the term "controlled waste" to classify waste streams that are of similar nature as hazardous waste or prescribed waste used by other jurisdictions.

The definition and classification of controlled waste are outlined in the Environmental Management and Pollution Control Act 1994 (EMPCA) and the Environmental Management and Pollution Control (Waste Management) Regulations 2020. Controlled wastes are specifically identified in List 1, Schedule A of the Controlled Waste National Environment Protection Measure (NEPM) and are presumed to possess one or more characteristics listed in List 2, unless proven otherwise. The waste classification codes of controlled waste used in Tasmania are based on List 1, Schedule A of the Controlled Waste NEPM but include several other wastes prescribed in the Regulations.

Interstate movements of controlled waste (including the Tasmanian leg of such movements) are controlled under the National Environment Protection (Movement of Controlled Waste between States and Territories) Measure (2004) (the Controlled Waste NEPM). As stated by the EPA, the responsibility for accurately describing controlled waste falls upon the controlled waste producer, agent, transporter, or receiving facility operator for any handling or transport documentation. Thus, it is imperative to select the appropriate waste code and description from the controlled waste list. In Tasmania, waste or used tyres are classified as controlled waste, whereas waste conveyor belts are not classified as controlled waste.

Victoria

Victoria's main legislation for environmental protection, waste management, and resource recovery is the Environment Protection Act 1970. The administration of this act falls under the jurisdiction of the Environment Protection Authority Victoria (EPA Victoria). The Environment Protection (Industrial Waste Resource) Regulations 2009 became effective on July 1, 2009. These regulations introduce a set of controls governing the management of industrial and hazardous wastes, referred to as prescribed industrial wastes in Victoria. The rules categorise specific wastes as 'prescribed wastes' and 'prescribed industrial wastes' in alignment with the provisions of the Act. Additionally, the regulations outline stipulations for the transportation of prescribed waste, incorporating a tracking system and a permit system for vehicles transporting such waste. The aim is to maintain consistency with controls in related domains and facilitate the regulated movement of hazardous wastes across borders.

In Victoria, waste is defined according to the Environment Protection Act 1970, and classified into three main categories, namely municipal, industrial, and prescribed waste. Municipal waste refers to any waste arising from municipal or residential activities, and includes waste collected by, or on behalf of, a municipal council, but does not include any industrial waste. Industrial waste refers to: a) any waste arising from commercial, industrial or trade activities or from laboratories; or b) any waste containing substances or materials which are potentially harmful to human beings or equipment. Prescribed industrial waste means any industrial waste or mixture containing industrial waste other than industrial waste or a mixture containing industrial waste that: a) is a Schedule 1 industrial waste; or b) has a direct beneficial reuse and has been consigned for use; or c) is exempt material; or d) is not category A waste, category.

Used tyres are classified as prescribed industrial waste in Victoria, whereas waste conveyor belts or other rubber wastes are not included.

Western Australia

In Western Australia (WA), the key legislation that governs waste and resource recovery in WA is The Waste Avoidance and Resource Recovery Act 2007, which is supported by The Waste Avoidance and Resource Recovery Regulations 2008. Under the act, waste is defined as matter whether useful or useless, which is discharged into the environment; or matter which is prescribed by the regulations to be waste. In WA, there are three waste classification types, namely (1) municipal solid waste, (2) commercial and industrial waste and (3) construction and demolition waste.

In WA, used tyres are classified as one of the 15 broad waste groups of controlled wastes as listed in the Schedule 1 of the Environmental Protection (Controlled Waste) Regulations 2004, and that is within the definition of waste in the National Environmental Protection (Movement of Controlled Waste between States and Territories) Measure as varied November 2010 (the NEPM) (Table A3 in Appendix 3). Tyres are classified as controlled waste (Category Group T: Miscellaneous; Waste Code T140) and are subject to regulations, even if they are legally permissible for acceptance at Class I, Class II, or Class III landfill facilities.

Used conveyor belts are not classified as controlled wastes in WA, and therefore the movements of used conveyor belts are not tracked making it impossible to collect information on their arisings. In WA, The Department of Water and Environmental Regulation (DWER) regulates the transportation of controlled waste on roads in Western Australia (WA) by administering the Environmental Protection (Controlled Waste) Regulations 2004 (the Regulations) under the Environmental Protection Act 1986 (Government of Western Australia, 2024).

For transportation of used tyres in WA, a Controlled Waste Carrier Licence is required as used tyres fall under the regulations as packaged controlled waste, which is transported in any manner other than in a tank. DWER manages an electronic Controlled Waste Tracking System (CWTS) designed to streamline the tracking of controlled waste on roads in WA.

4.1.2 European Union

Europe maintains a commendable recovery rate (~95%) for waste tyres, owing to strict legislative measures (Valentini and Pegoretto, 2022). The EU Commission imposes regulations to manage waste with the aim of minimising negative effects on the environment and human health. The Waste Framework Directive 2008/98/EC establishes fundamental principles for waste management. It mandates that waste should be managed without:

- endangering human health and harming the environment
- risk to water, air, soil, plants or animals
- causing a nuisance through noise or odours
- adversely affecting the countryside or places of special interest

The European strategy for managing used tyres and rubber products is primarily governed by the Landfill Directive 1999/31/EC. This directive mandates the prohibition of whole tyres in landfills by the 16th of July, 2003, and shredded tyres by the 16th of July, 2006. However, there are exemptions for specific uses, such as employing whole tyres for engineering purposes, bicycle tyres, and tyres exceeding 1,400 mm in diameter. However, despite the existence of the Directive on the Landfill of Waste 1999/31/EC, which expressly prohibits tyres disposal in landfills, a notable proportion (8%) still finds its way into landfill sites (Valentini and Pegoretto, 2022).

The EU's Waste Framework Directive also delineates criteria for when waste transitions into secondary raw materials and how to differentiate between waste and by-products. It also introduces two key concepts: the "Polluter Pays Principle" and "Extended Producer Responsibility (EPR)", which affirm that waste importers or producers must be responsible and bear the costs of waste management. The introduction of these systems resulted in notable success across most of the member states in Europe. For instances, the implementation of EPR in Portugal has significantly boosted waste recycling rates from 69% to 98%, although there remains a need for improvements in the consistency of waste management practices (Niza et al., 2014). A comparative study on waste tyres management between Italy and Romania revealed that different management pathways were influenced by varying regulations and economic contexts. The adopted EPR systems led to the collection of 403,000 t of used tires in Italy and 46,000 t in Romania in 2012. In Italy, 18.1% of collected EOLTs were reused, while the rest were recycled (36.1%), used for energy recovery (57.9%), and landfilled (6%). In Romania, EOLTs were directed to recycling (43.5%) and energy recovery (56.5%) (Torretta et al., 2015). Another comparative study of the EPR systems in Belgium, The Netherlands, and Italy also demonstrated that EPR increases resource efficiency, reduces illegal stockpiling, and promotes advancement up the waste hierarchy (Winternitz et al., 2019).

Indeed, central to EU waste management is the five-step "waste hierarchy," as outlined in the Waste Framework Directive (Figure 15). This hierarchy prioritizes methods to prevent waste formation, followed by preparation for reuse, recycling, recovery, and finally disposal. It lays a useful foundation for promoting circular economy.

Figure 15. European Union Waste Hierarchy. Source: https://ec.europa.eu/environment/topics/waste-and-recycling/waste-framework-.Directive_en

Additionally, the EU Directive introduces the concept of "End-of-waste status", whereby a waste stream, meeting specific criteria post-recycling or recovery, can cease to be classified as waste. For this, Member States in the EU shall take appropriate measures to ensure that waste which has undergone a recycling or other recovery operation is considered to have ceased to be classified as waste if it complies with the following conditions:

1. the substance or object is to be used for specific purposes;
2. a market or demand exists for such a substance or object;

3. the substance or object fulfils the technical requirements for the specific purposes and meets the existing legislation and standards applicable to products; and
4. the use of the substance or object will not lead to overall adverse environmental or human health impacts.

A key difference between the Australian waste classification systems and that of the EU is that, in the EU waste tyres and EOLTs are classified as "Rubber wastes" under "Item 19" listed in the EUROSTAT Guidance on EWC-Stat Waste Categories (Figure 16). As such, waste conveyor belts are also classified as "Rubber wastes". As mentioned above, the disposal of rubber waste in landfills is highly regulated according to the EU Landfill Directive. Therefore, waste tyres and waste conveyor belts are required to be handled using alternative waste management practices to ensure environmental compliance (e.g. recycling or energy recovery), which support the transition towards a circular economy.

Clearly, it is imperative to reconsider the policies for the management of waste tyres and conveyor belts to bolster recycling rates in Australia. Embracing the rubber waste management models and pertinent legislations that have proven effective in several EU member countries could be beneficial for enhancing recycling rates in Australia.

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Rubber wastes (Item 19)

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Code	Description,	Definition	Includes	Source branches (nomenclature of LoW is bold, NACE is non-bold)	Excludes
07.3	Rubber wastes Only non-hazardous	**Kind of waste:** End-of-life-tyres **Origin:** Maintenance of vehicles, end-of-life-vehicles **Hazardous:** Rubber wastes are non hazardous		Only waste tyres. • **Separately collected fractions** (38.1 Waste collection; 45.20 Maintenance and repair of motor vehicles)	All other wastes containing rubber Plastic and Rubber -> see cat. 07.4

Extract Regulation (EC) 2150/2002 ANNEX III: Table of equivalence

Rubber wastes

07.3 Rubber wastes
07.31 Used tyres
0 Non-hazardous
16 01 03 end-of-life tyres

Figure 16. Classification of end-of-life tyres as "Rubber wastes" in EUROSTAT Guidance on EWC-Stat Waste Categories

4.2 Traceability and tracking of materials

The review of international EPR schemes showed that the implementation of robust tracking systems is essential to effectively monitor EOLTs and conveyor belts. This includes also those that are valorised independently by industries, where they must report directly to the government and not through waste management systems (producer responsibility organisations).

In some Canadian jurisdictions, such as British Columbia, traceability of EOLTs is facilitated through financial audits conducted by the stewardship program, focusing on tracking the flow of funds and waste throughout the reprocessing cycle. However, while annual audits are conducted, there is limited focus on tracking the final destination of the recycled materials (Tyre Stewardship British Columbia, 2023). In France, the evolving regulations mandating digital passports and certified sourcing, traceability and adherence to quality standards are increasingly imperative. Aliapur can address these requirements through its robust sorting and tracking processes. In Italy, Ecopneus scpa is the non-profit company responsible for tracking EOLTs created by the major tyre manufacturers operating in Italy (Bridgestone, Continental, Goodyear-Dunlop, Marangoni, Michelin and Pirelli) (Ecopneus, 2024h), whereas in New Zealand, Tyrewise maintains a chain of custody for all collected and processed tyres using Tyrewise's bespoke tracking software (Tyrewise, 2024a).

In Australia, generators, transporters, and facility operators handling controlled wastes, as defined under the NEPM, are obligated to adhere to data management, tracking, and other stipulations outlined in relevant legislation (National Environment Protection Council (NEPC), 2017). The agreement features the mutual recognition of waste transport licences for the purposes of controlled waste movements between States and Territories, and the development of a national tracking system. For example, in Victoria, the regulations outline stipulations for the transportation of prescribed waste, incorporating a tracking system and a permit system for vehicles transporting such waste. For transportation of used tyres in WA, a Controlled Waste Carrier Licence is required as used tyres fall under the regulations as packaged controlled waste, which is transported in any manner other than in a tank. DWER manages an electronic Controlled Waste Tracking System (CWTS) designed to streamline the tracking of controlled waste on roads in WA. Technological developments such as automated weighing of shipments, intelligent tracking devices, and information technologies can advance the traceability and tracking of EOLTs and conveyor belts and enable effective reverse logistics (Agnusdei et al., 2022).

4.3 Quality standards

Interviews with EOLT re-processors indicated that the quality of feedstocks is critical for the technical and economic feasibility of recycling processes. The following sections discuss standard for new and retreaded tyres as well as tyre-derived products.

3.2.1 Quality standards for new tyres

Currently, there are no quality standards for imported tyres and conveyor belts in Australia (Boxall et al., 2023). The import of low-quality passenger tyres is a hindrance for extending the life of passenger tyres through retreading.

In Europe, tyres are considered to play a crucial role in both the environmental footprint of road transportation and ensuring road safety. In response to these concerns, the EU implemented Regulation 1222/2009 aimed at enhancing these aspects. This regulation encourages the use of more fuel-efficient tyres with reduced noise levels while upholding stringent safety standards. By employing labels like those found on domestic appliances, the regulation categorizes tyres based on their fuel efficiency, wet grip and external rolling noise levels, empowering consumers to make well-informed purchasing choices. The European Commission introduced, starting from 2012, labelling rules for tyres (Figure 17). The labelling rules provide a clear and common classification of tyres performance in terms of rolling resistance, braking on wet surfaces and external noise for passenger cars, light-duty vehicles (LDVs) and heavy-duty vehicles (HDVs). Apart from promoting fuel efficiency, the new labelling system also helps to extend the lifespan of tyres, thereby reducing the amount of waste (Valentini and Pegottini, 2022).

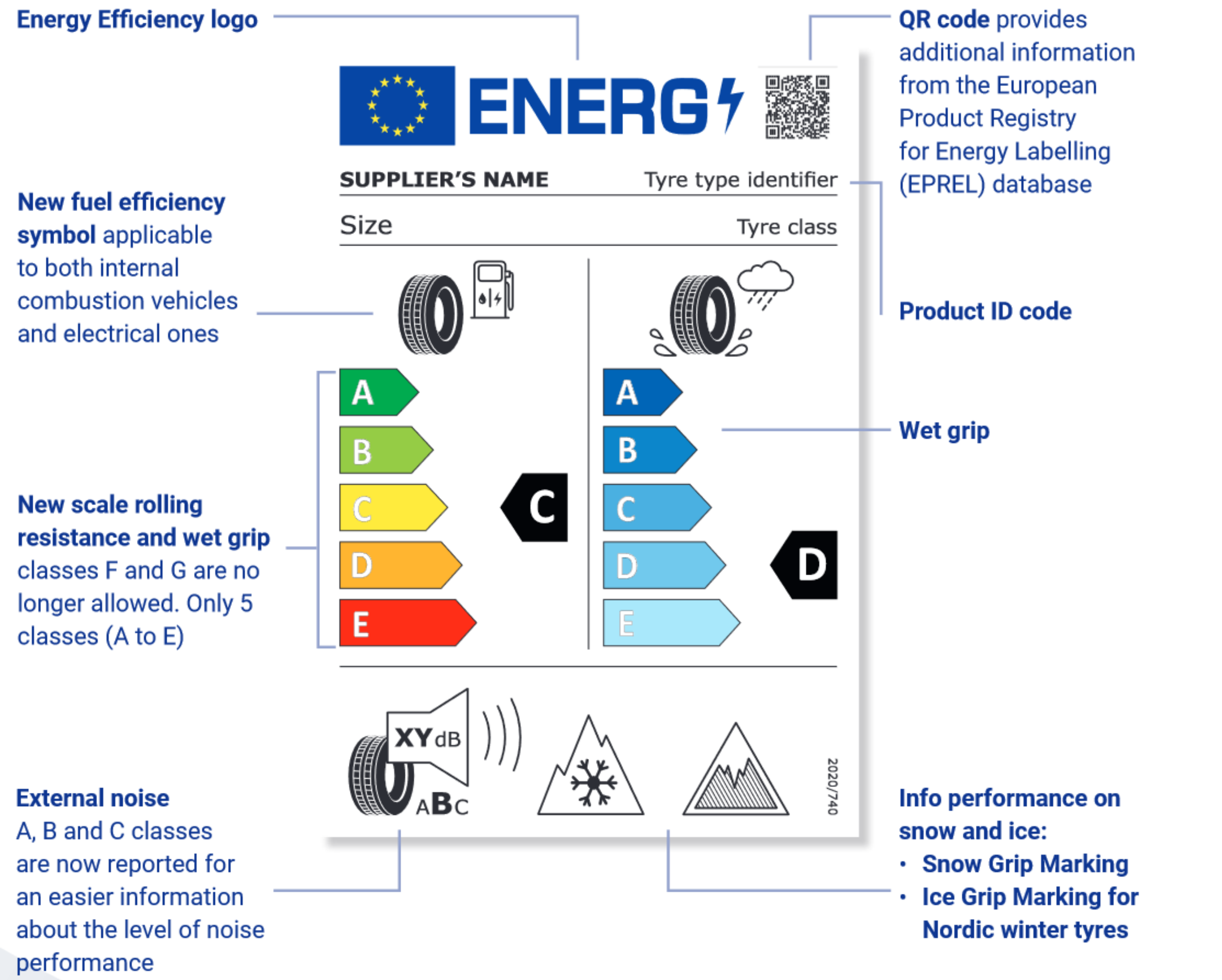

Figure 17. New EU tyre labelling introduced by European Tyre & Rubber Manufacturers' Association (ETRMA) in accordance with Regulation (EU) 2020/740 (European Tyre & Rubber Manufacturers' Association, 2021).

Tyre suppliers (including manufacturers, authorized representatives, and distributors) bear the responsibility of accurately labelling tyres. Each member state is tasked with ensuring compliance through market surveillance efforts. The European Tyre & Rubber Manufacturers' Association (ETRMA) conducts investigations into tyre labelling to verify regulatory adherence. These inspections are commissioned by the relevant market surveillance authority and must be thorough to ensure complete compliance (European Tyre and Rubber Manufacturers' Association, 2019).

It should be noted that the labelling regulations do not apply to all types of tyres, with the following tyre types are exempted:

1) Tyres manufactured before the 1st of July, 2012
2) Retreaded tyres

3) Off-road professional tyres

4) Tyres designed only for vehicles first registered before the 1st of October, 1990

5) T-type temporary use spare tyres

6) Tyres with a speed rating of less than 80 km/h

7) Tyres with nominal rim diameters of less than 254 mm or more than 635 mm

8) Tyre fitted with additional devices to improve traction properties such as studded tyres

9) Tyres designed only to be fitted on vehicles which are exclusively for racing

Where applicable, this regulation applies to class C1 (passenger car tyres), C2 (van tyres) and C3 (truck and bus tyres).

In Europe, tyre standards are primarily regulated by the European Union (EU) through the European Tyre and Rim Technical Organisation (ETRTO, Website: http://www.etrto.org/Home). It establishes standards and specifications to ensure the safety, performance, and compatibility of tyres and vehicles. Specifically, it sets standards to specify and harmonise sizes of rims and their associated pneumatic tyres across the EU. ETRTO sizes apply to rims and tyres for vehicles of all types, including bicycles. ETRTO provides standardized information on tyres sizes, load capacity, and inflation pressure. For example, the ETRTO standard for passenger car tyres might be expressed as a series of numbers and letters, such as "205/55 R16 91V," where each component denotes a specific aspect of the tyre. The ETRTO sizing is unambiguous, whereas previously nominal dimensions were used which were interpreted in different ways by different countries and manufacturers, which was problematic for the end-users.

3.2.2 Quality standards for retreaded tyres

Retreading of used tyres in Australia must meet the Australian Standard AS1973-1993 “Pneumatic tyres - Passenger Car, Light Truck and Truck/Bus - Retreading and Repair Process”. According to MRA Consulting Group (2021), nearly all tyre casings can undergo retreading to comply with the Australian standard for retread tyres, although the process is often deemed economically unfeasible. In Australia, there is one company engaged in domestic tyre retreading. It operates a facility in Wacol, Queensland, which manufactures pre-treated treads, and oversees 19 company-owned and franchised locations responsible for applying treads to tyre casings. All tyres retreaded by this company adhere to the Australian Standard AS1973-1993 for truck and bus tyres. According to this standard, the tyre must have markings specifying the identity of the retreader, the date it is retreaded, the words ‘RETREAD’ or ‘REMOULD’ as applicable, and the tyre’s speed limit. However, some stakeholders involved in the MRA Consulting Group’s study have noted that the AS1973-1993 standard is relatively lenient.

It is mandatory for all tyres retreaded within Australia or imported into the country to conform to the AS1973-1993 standard. The retreaded tyre must comply with the appropriate specifications or standards before being put into service. Table 19 outlines some of the essential specifications and standards.

Table 19. Specifications and standards for retread tyres.

Specification/standard title	Publisher	Location	Material Type
AS1973-1993 Pneumatic Tyres - Passenger Car, Light Truck and Truck / Bus - Retreading and Repair Processes [a]	Standards Australia	Australia	Retread truck waste tyres
AS4457.2-2008 Earth-moving machinery - Off-the-road wheels, rims and tyres - Maintenance and repair Tyres[b]	Standards Australia	Australia	Retread waste tyres
NZS 5423:1996 Specification for repairing and retreading car, truck and bus tyres[c]	Standards New Zealand	New Zealand	Retreading waste tyres
SAE ARP4834B Aircraft Tyre Retreading Practice - Bias and Radial[d]	SAE International	International	Retread aviation (AV) tyres
ISO 83.160.10 Road vehicle tyres Including cycle tyres, and tyre retreading and repair processes [e]	International Organization for Standardization	International	Retreading waste tyres
AC145-4A : AC Inspection, Retread, Repair, and Alterations of Aircraft Tyres [f]	Federal Aviation Administration	United States of America	Retread aviation (AV) tyres

[a] Standards Australia (1993)
[b] Standards Australia (2008)
[c] Standards New Zealand (1996)
[d] SAE International (2020)
[e] International Organisation for Standardization (2024)
[f] Federal Aviation Administration (2006)

In the aviation (AV) tyre sector in Australia, regulations are stringent due to the limited number of manufacturers and a constrained customer base. The international standard governing retreaded AV tyres is SAE ARP4834B. According to MRA Consulting Group (2021), retreaders utilise this standard along with AC145-4A as references, crafting a retread specification tailored to their specific processes. These specifications undergo approval by a recognised airworthiness authority, such as the US Federal Aviation Administration (FAA), with access regulated by intellectual property (IP) restrictions.

According to MRA Consulting Group (2021), Australia recognises FAA certification for retreads, and retreading facilities are subject to independent audits by national airworthiness authorities. However, there lacks an international verification or standard that retreading facilities must adhere to. The prevalent method of assessing overseas retread tyre facilities domestically is through the Tyre Stewardship Australia (TSA)'s Foreign End Markets (FEM) verification process (https://www.tyrestewardship.org.au/accreditation/foreign-end-market-verification/). This process, optional for both TSA members and non-members, entails an on-site inspection conducted by the global auditing firm Intertek (https://www.intertek.com/inlight/).

3.2.3 Quality standards for tyre-derived products

There are some international specifications and standards for waste tyres processed into commodity products such as shred, crumb, granules and buffings. These international specifications and standards include (Table 20):

- ISRI Scrap Specifications Circular Guidelines for Tyre Scrap
- ASTM D6270 Standard Practice for the Utilization of Scrap Tyres in Civil Engineering Applications
- ASTM D6114/D6114M Standard Specification for Asphalt-Rubber Binder
- ASTM D6700-19 Standard Guide for the Utilization of Scrap Tyres as Tyre-derived Fuel.

However, none of these international standards are widely used in Australia. Table 21 lists several national standards or specifications that are commonly used in Australia (MRA Consulting Group, 2021).

Table 20. International waste tyre specifications and standards (adapted from MRA Consulting Group, 2021).

Standard/ Specification	Waste tyres	Publisher
ISRI Scrap Specifications Circular Guidelines for Tyre Scrap	Rubber crumb, rubber shred, rubber granules	Institute of Scrap Recycling Industries, Inc.
ASTM D6270 Standard Practice for the Utilization of Scrap Tyres in Civil Engineering Applications	Whole tyres for use in civil construction	ASTM International (formerly American Society for Testing and Materials)
ASTM D6114/D6114M Standard Specification for Asphalt-Rubber Binder	Rubber crumb for use in asphalt	ASTM International (formerly American Society for Testing and Materials)
ASTM D6700-19 Standard Guide for the Utilization of Scrap Tyres as Tyre-derived Fuel.	Tyre shred for use as TDF	ASTM International (formerly American Society for Testing and Materials)

Table 21. Standards and specifications for processed tyres used by Australian processors (adapted from MRA Consulting Group, 2021).

Specification/ Standard	Tyre Stewardship Australia (TSA)/Australian Tyre Recyclers Association (ATRA) recommended minimum standard	AGPT/T190 - Size #16 [a]	AGPT/T190 - Size #30 [a]	CRM OGA - Pilot Specification [b]
Publisher	TSA/ ATRA	Austroads/ Standards Australia	Austroads/ Standards Australia	Australian Asphalt Pavement Association
Material type and size	TDF shred <150 mm, rubber crumb	Rubber crumb 0.6-1.18 mm	Rubber crumb (powder) 0.3-0.6 mm	Rubber crumb (granule) 10-14 mm
Likely end uses	TDF for industrial processes	Bitumen road spray	Bitumen road spray and tile adhesive glue	Asphalt mix
Operations/ machinery required to meet specification	Primary shredders	Primary shredders, secondary shredders, grinding mill	Primary shredders, secondary shredders, grinding mill	Primary shredders, secondary shredders, grinding mill

[a] Austroads (2008)
[b] Australian Asphalt Pavement Association (2018)
AGPT = Austroads Guide to Pavement Technology
CRMOGA = Crumb Rubber Modified Open Graded Asphalt

EOLT-derived products are processed to a size depending on individual customer requirements (MRA Consulting Group, 2021). There are no specific mandatory standards to guide the manufacture of products derived from waste tyres in Australia. Tyre Stewardship Australia (TSA) and the Australian Tyre Recyclers Association (ATRA) have proposed a processing standard that must be adhered to for export. As per TSA/ATRA, mandating processors to meet this standard would serve as a preventive measure against the emergence of a secondary or illegitimate market that might redirect Australian waste materials to unsustainable offshore applications. Nonetheless, the likelihood of Australian exporters or waste tyre processors adopting these standards is primarily determined by the intended end-use rather than specific importer requirements or industry standards.

4.4 The concepts of recycling business hubs and industrial symbiosis

In a previous study that aimed at exploring opportunities for increasing value recovery from waste tyres and conveyor belts in WA, several opportunities have been recommended as enablers for promoting recycling of waste tyres and conveyor belts (Boxall et al., 2023) (Table 22). To facilitate these opportunities, it is essential to incentivise businesses throughout the material supply chain to coordinate and collaborate closely, establishing a unified platform for the sharing of materials and resources across industries. Improved collaboration and coordination can be achieved through the formation of a consortium comprising tyre and conveyor belt producers, users, recyclers, resource extractors, road builders, and civil work operators. This consortium can be facilitated by leveraging existing networks established by TSA, which works across the value chain, government and local communities to reduce barriers and encourage investment in the sector. Policies should be enacted to endorse and facilitate such cross-sector resource flow, prompting a shift in stakeholders' mindsets.

Table 22. Recommendations for enabling waste tyre and conveyor belt recycling in WA (adapted and modified from Boxall et al., 2023)

Recommendation	Rationale
Consider prioritising future funding for the development of recycling facility capacity in regional areas, close to mine sites and populated centres where EOLT (including OTR tyre) and conveyor belt arisings are occurring, and future growth is identified.	Synergies amongst waste producers, recyclers, waste-derived products end-users and other relevant stakeholders should be established in close proximity, particularly with the constraints associated with long transportation distances between recycling facilities and waste tyres/conveyor belts arisings.
Seek the development of technologies and investment in facilities for used conveyor belt recycling.	The products (e.g. rubber) derived from waste tyres/conveyor belts can be used more easily by other businesses for the manufacture of other products. Transportation routes of waste tyres/conveyor belts or the products derived from these wastes within a closely located hub/region can be more streamlined/efficient, facilitating symbiosis of various industries.
Seek to tie market technical demands and product specifications to the application and approval of funding for new recycling facilities.	This integrated approach ensures that investments in recycling infrastructure yield tangible benefits for both the environment and the economy, driving positive change and creating lasting value for society. This helps maximising the effectiveness of recycling initiatives and accelerate the transition towards a circular economy.
Consider reviewing permitting and approvals processes for the use of land for recycling and waste management.	To streamline and enable the development of new and additional capacity for EOLT and conveyor belt management, the involvement of government would be beneficial.

To amplify these opportunities, fostering collaboration among businesses and various stakeholders along the material supply chain is critical. By establishing a recycling business hub, a centralised platform can be created where industries can converge to exchange materials and resources. This hub would serve as a focal point for tyre and conveyor belt producers, users, recyclers, and other stakeholders to connect and synergise their efforts. Moreover, this concept aligns closely with the principles of industrial symbiosis, wherein different industries collaborate to share resources, waste streams, and expertise, thereby maximising efficiency and minimising environmental impact. Industrial symbiosis has been defined as engaging "traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and by-products" (Chertow, 2000). The keys to this operation are collaboration and the synergistic possibilities offered by geographic proximity.

From an economic standpoint, rubber waste management presents significant challenges, including high capital investment, substantial operating costs, and uncertain returns on investment (Leong et al., 2022). These factors often deter industry players and investors from active participation. To address this, governments may implement incentives to stimulate industry involvement and encourage increased participation. Conducting studies to assess the cost-effectiveness of rubber waste management may be a good approach to generate valuable insights for governments in formulating frameworks that maximize profits from rubber waste recycling (Leong et al., 2022). With these insights, governments may take a lead to drive the establishment of waste recycling business hubs based on the concept of industrial symbiosis. Stakeholders involved (directly/indirectly) in the tyre/conveyor-belt circularity chain may collectively work towards sustainable end-of-life operations for rubber products, promoting circularity and resource conservation across sectors.

Case Study: EcoPark of Hong Kong

The EcoPark, with a land area of approximately 20 hectares, was established in 2007 by the Environmental Protection Department (EPD) of the Hong Kong Government. It is a significant initiative by the Hong Kong Government aimed at fostering the development of the local recycling industry. It was set up to promote the reuse, recovery, and recycling of various waste resources. The park offers long-term land leases at affordable rental costs, with a variety of basic utilities provided, including sea and land transport access, water and electricity supply, sewerage system, and telecommunication facilities. Additionally, common facilities like internal road networks, berthing spaces, and meeting rooms are available to tenants, reducing their capital expenditure and encouraging investments in advanced recycling technologies. The total quantity of recyclables processed in EcoPark exceeded 1 million t (over 200,000 t/year on average) in the last 5 years (Hong Kong SAR Government, 2023). Currently, EcoPark has 10 tenants, engaging in various recycling businesses including recycling of wastes including, cooking oil, metals, wood, waste electrical and electronic equipment (WEEE), plastics, batteries, construction and demolition waste, glass, EOLTs and paper.

These tenants are operating within the local recycling sector, benefit from competitive advantages in rental rates, land tenure, and available infrastructure compared to recyclers primarily focused on exporting recyclables. Additionally, any regulated waste destined for export from Hong Kong must obtain approval from the authorities of both exporting and importing jurisdictions in line with Basel Convention requirements. Moreover, such waste must be transported to government-recognized facilities for appropriate handling. In the implementation of various producer responsibility schemes, priority is given to local stakeholders, including suppliers, retailers, collectors, and recyclers, to play a more active role, provided it proves to be more cost-effective.

By drawing inspiration from the strategies employed at EcoPark, Australia may enhance its EOLT and conveyor belt recycling industry development. Assessing the adequacy of ancillary facilities, optimising operations, encouraging job creation, streamlining processes, and prioritising local waste recycling are key areas for consideration.

Lessons for Australian context

Tailoring support to industry needs: The government of Hong Kong proactively communicates with the recycling industry to understand its needs and adjusts EcoPark's operation strategy accordingly. Similarly, government agencies in Australia, could take a lead role in coordinating communication with stakeholders and recyclers, tailor support policies and ensure the recycling facilities meet their requirements effectively.

Encouraging advanced recycling technologies: To encourage the adoption of advanced and value-added recycling technologies, the EPD in Hong Kong has increased the technical/rental weighting of tenders to favour such developments. Similarly, Australian authorities can prioritise tenders that incorporate innovative recycling technologies and value addition, helping to drive technological advancements in the industry driving toward circular economy.

Flexibility in site leasing: EcoPark offers flexible site leasing based on market demand, allowing different types of recyclers to enter and operate within the park. In Australia, adopting a similar approach, where leasing areas can accommodate various recyclers (including small-medium scale/ innovative start-up companies relevant to the supply-demand chain of tyres/conveyor belt-derived materials), can foster diversity and inclusivity in the industry.

Supporting businesses to promote their establishment within the hub: The concept of constructing a multi-storey factory in EcoPark to facilitate smaller recyclers with fewer specific requirements is worth. Currently, there is a waste tyre recycling company located in the EcoPark. The Fund subsidised the company with approximately HKD$8 million (~AUD 1.6 million) in 2021 to enhance its operational efficiency and transformational upgrade by purchasing equipment for shredding waste tyres, separating steel wires, granulating rubber, and separating fibres, for turning waste tyres into rubber powder, steel wires, paving blocks, and rubber mats. Besides, the Fund has also subsidised the business and operation of other two local waste tyre recyclers. The total subsidy to the three recyclers amounts to approximately HKD$10.6 million (~AUD 2.1 million). Such initiatives can reduce operating costs for smaller businesses and encourage their start-up and growth.

Prioritising Local Recycling: While maintaining a fair competitive environment, the Hong Kong Government gives priority to local recycling to relieve the burden on landfills and foster a circular economy. Similarly, in Australia, adjusting policies to prioritize local/regional recycling may create more opportunities for local stakeholders and contribute to a sustainable waste management approach.

4.5 Summary of enablers in the Australian context

Currently classification systems for EOLTs vary across Australia, and waste conveyor belts are not classified as controlled waste in Australia, leading to inadequate monitoring and lack of data on arisings, transports and fate of waste conveyor belts. Moreover, the alignment of jurisdictional hazardous waste codes remains poor, and there is a lack of regulatory consistency across borders, diminishing the capacity to develop a consistent national system for waste management. Classifying waste tyres and conveyor belts consistently is crucial for enabling their recycling.

Australia can draw valuable insights from the European Union's approach to managing rubber waste. In the EU, waste tyres and EOLTs are classified as "Rubber wastes". Rubbery waste conveyor belts are similarly classified as "Rubber wastes". According to the EU Landfill Directive, the disposal of rubber waste in landfills is strictly regulated, compelling the use of alternative waste management practices, such as recycling or energy recovery, to ensure environmental compliance. This regulatory framework supports the transition towards a circular economy by reducing landfill dependency and promoting sustainable waste management practices. Adopting similar regulations in Australia could enhance recycling initiatives and contribute to environmental sustainability.

Moreover, establishing comprehensive tracking mechanisms is necessary to monitor the movement of these waste streams accurately. Standardising the units of measurement (mass or volume) across stakeholders is essential for reliable data collection and analysis. Without standardised units, meaningful insights from the data become challenging to derive. Standards should also be implemented for imported tyres, to ensure that they are of good enough quality to allow retreading.

Enablers including an improved product stewardship scheme, quality standards, coordinated tracking and traceability, data related to material flows and feedstock composition, and collaboration across the value chain are all critical to the successful development of EOLT and conveyor belt management technology and development of market pathways. Moreover, the creation and support of recycling hubs or ecosystems where tyre recyclers and industries that consume tyre-derived products and fuels co-exist allows technology development and conversion of rubber waste to valuable products to support circularity.

5 Applying reverse logistics to tyres and conveyor belts in Australia

5.1 Reverse logistics: definitions and research approach

Reverse logistics refers to the entirety of logistical processes involved in repurposing products that users no longer need into market-ready items. In an environmental context, reverse logistics has proven effective in reclaiming, recycling, and reintroducing waste electrical and electronic equipment (WEEE)(Uriarte-Miranda et al., 2018; Barker and Zabinsky, 2011).

Reverse logistics of tyres and conveyor belts is defined as the process that sees the implementation of a flow of materials from the point of consumption to their point of origin (Rogers and Tibben-Lembke, 2001). The goal of reverse logistics is to minimise waste through landfill diversion by bringing it back to locations where it can be put to better use, typically to extend its life. A special mention is required to highlight that the classical definition of reverse logistics is shifting to include the adaptation to Industry 4.0. For this report, however, Industry 4.0 and the related definition of reverse logistics will be considered in linking sustainable management to the value recovery of end-of-life products using smart technologies (Sun and Solvang, 2022). How Industry 4.0 revolutionises reverse logistics operations can help integrate innovative logistic transformation by including intelligent tracking systems, information technologies and robotics. Integrating these technologies into the reverse logistics of tyres and conveyor belts might be far-fetched. Despite initial considerations showing that the first mile of innovative reverse logistics supply chains is under-researched (Agnusdei et al., 2022), Industry 4.0 and related technological advancement are essential to future-proof the rubber waste industry. With the broad definition of reverse logistics and the narrower link with Industry 4.0, we can draw relevant lessons in three ways. Notwithstanding the influence of technologies typical to the Industry 4.0 concept, a reverse supply chain exploits the orchestration of a network of operators, including suppliers, users, collection centres, reprocessing plants, landfills and movers to increase the mass of waste brought back to the producer for remanufacturing or waste processing. This generic definition of reverse logistics can be applied to most product categories, including tyres (Banguera et al., 2018).

Firstly, exploring opportunities, challenges, benefits, and *modii operandi* for reverse logistics operations in Australia can be drawn from observations from global case studies and prime examples to evaluate how these can be adopted in the Australian context. Secondly, lessons can be learnt from reverse logistics operations of other materials; these investigations are essential to understanding the technologies, supply chains, and economic systems in place to support reverse logistics. Finally, a tactful consideration is required due to the complexity linked to the geography of Western Australia, which sees the most significant production of tyre and conveyor belt waste being accumulated in remote locations. To bridge this gap, lessons from the literature will be drawn. In summary, observations of reverse logistics will be applied to the Western Australian context, highlighting their feasibility, final products, economic and environmental benefits, and potential in urban and rural settings. Notably, these definitions of reverse logistics must, however, include a regulatory framework that forces the users to separate and divert to collection points their waste for collection and transportation, which can be carried out by third-party companies or even the original producers. When the final products are valuable, the benefit of recycling or other value-adding operations is allocated among the network (Banguera et al., 2018).

5.2 Reverse logistics from global case studies

Reverse logistics aims to bring back materials and resources to the source or resource extraction facilities to be primarily diverted from landfills, reducing environmental impact, and concurrently creating a market for their second life. Therefore, it is essential to ensure that the returned materials are reused if in good condition or in the context of tyres rethreaded and recycled otherwise. If neither of these options is available in the destination of the reverse chain, other mechanisms, such as energy recovery, should be carried out as aligned with the waste hierarchy (Sienkiewicz et al., 2012). Since in Western Australia, the application of reverse logistics of tyres from remote locations is scant; we turn our attention to global case studies to learn how these operations are conducted elsewhere. Various countries employ diverse strategies for managing tyre waste. In Chile, legislation holds waste generators accountable for waste management costs, resulting in 17% of tyres being treated sustainably. Finland implements strong Extended Producer Responsibility (EPR) schemes, aiming for 95% tyre recovery. In Russia, regions outsource tyre transportation, but economic feasibility remains challenging. These examples offer valuable insights into Western Australia's tyre waste management.

5.2.1 Reverse logistics in Chile

In 2016, the Chilean Government established that the waste generator is responsible for its generation (Ministerio del Medio Ambiente de Chile, 2016; Rodríguez et al., 2023), and as such, the generator has to cover the costs and consequences of the waste management of products, including tyres. Because of this legal action, of the nearly 200,000 t of tyres (more than 6.5 million) wasted every year, it is considered that about 17% are treated sustainably (Ministerio del Medio Ambiente de Chile, 2016). As part of this initiative, the producer was responsible for collecting no less than 50% of the tyres sold in 2023, and the ratio should increase to 90% in 2031. One of the mainstream treatment options in Chile is pyrolysis for energy and resource recovery (Rodríguez et al., 2023), which, albeit low on the waste hierarchy, helps recover gas, oils and char from tyres (Chang, 1996). To increase the efforts towards waste recycling instead of pyrolysis, EPR laws dated January 2023 require companies that import tyres in Chile to collect and recycle at their end of life, in a gradual yearly pathway, commencing in 2023 and by 2030, sees them targeting 100% for passenger cars and 90% for mining tyres (Ministerio Del Medio Ambiente, 2016; Moore, 2023). Much like Western Australia, Chile struggles to manage mining in vast regions, and the regulatory bodies adopted in Chile to foster internal production and import of tyres could be similarly adopted in the Australian state.

5.2.2 Policy instruments for reverse logistics in Finland

In Finland, strong extended-product responsibility (EPR) schemes enforce, through policy instruments, reporting obligations for tyres, ensuring that all products are separated and collected free of charge whilst the producer monitors and reports the operations to the Finnish authority (Mayanti and Helo, 2024). The objective of these political instruments is recovery via reuse, recycle, or energy recovery of at least 95% of tyres, and leaves the total responsibility of taking back the waste to the producers. Tyres will be returned through drop-off schemes. The main scope of these instruments seems to be car tyres, which is arguably a smaller concern in Western Australia compared to truck tyres used in remote locations, and another critical difference in Finland is their obligation to fulfil the European Union’s directive in terms of reporting and management. Still, an important lesson is the existence of several tyre recycling centres, which if they existed in Western Australia would facilitate the waste recovery and make tyre reverse logistics profitable.

5.2.3 The division of responsibility in Russian regions

Despite Russia's many difficulties in applying reverse logistics of tyres, their main attempt is to outsource the transportation to external companies, which would be entitled to move the EOLTs across the country. Yet again, since Russian regions tend to be independently managed, these strategies might differ across the country. However, the reason for this outsourcing is linked to the fact that neither producers nor users specialise in waste moving, making a third-party company a necessary addition to the reverse logistics network. Problematically, in Russia, most regions have not succeeded in making this network process economically feasible. Hence, they rely on government subsidies, which are often missing (Uriarte-Miranda et al., 2018). Then again, at the time of this writing, the Russian-Ukrainian war makes information sourcing complex. A lesson that Australia can learn from the Russian context is the regional management of the reverse logistics of tyres. Australia has a vast territory, remote locations could be forced to manage their own waste as long as they meet predefined waste recovery targets.

5.2.4 Summary of reverse logistics lessons in the Australian context

Australia can adopt several strategies from countries including Chile, Finland, and Russia to improve tyre reverse logistics. Firstly, introducing legislation that holds waste generators responsible for tyre waste management, like in Chile, can drive sustainable treatment and recycling efforts. Secondly, implementing Extended Producer Responsibility (EPR) schemes, as seen in Finland, can ensure that producers take full responsibility for tyre collection and recycling, aiming for high recovery rates. Additionally, Australia can learn from Russia's regional management approach by incentivising local waste management, especially in remote areas, and setting clear targets for waste recovery. Like in Finland, establishing tyre recycling centres can facilitate waste recovery and make tyre reverse logistics economically viable. By aligning policies with broader waste management objectives and international standards, Australia can efficiently manage tyre waste in line with global best practices.

Translating lessons from reverse logistics of products other than tyres

Examining the implementation of reverse logistics operations across various waste types reveals several lessons that can be applied to managing tyre waste in Australia. For example, the financial cost and environmental impacts of food waste reverse logistics significantly affect the total food waste management chain. While more significant expenditure is necessary, using mid-size electric vehicles for food waste collection and transportation could help reduce environmental impacts. This highlights the importance of investing in environmentally friendly vehicles for waste collection (Li et al., 2023). A circular economy can also boost economic growth and bring environmental and social benefits. Implementing efficient reverse logistics plays a decisive role in achieving sustainability targets. Combining reverse and forward flows can contribute to waste reduction. This emphasises the importance of strategic partnerships and technological investments in achieving circular economy goals (Butt et al., 2023). Problematically, however, the first-mile reverse logistics system involves voluntary return behaviour and complements selective collection programs, which is arguably complex to translate into remote tyre waste production. Still, the main contribution is a simulation model predicting the materials' volume returned through a distributed system. This highlights the importance of data-driven decision-making and simulation tools in optimising reverse logistics systems (Labelle and Frayret, 2023). When it comes to e-waste, particularly from the medical sector, many businesses consider outsourcing their recycling due to limitations in infrastructure and expertise. A benchmarking approach for selecting and evaluating third-party reverse logistics providers is proposed. Lessons include the need for rigorous supplier evaluation and the importance of considering economic, environmental, and social sustainability criteria (Singh et al., 2023). In this context, lessons from these diverse waste types underscore the importance of investing in environmentally friendly transportation, strategic partnerships, data-driven decision-making, and rigorous supplier evaluation processes. These principles can be applied to managing tyre waste in Australia or highlight the need for sustainable practices, efficient logistics, and strategic collaborations to achieve circular economy goals.

6 Value recovery from end-of-life tyres and conveyor belts and end markets for derived products

Products derived from end-of-life tyres (EOLTs) and conveyor belts have versatile applications across industries, including construction, automotive, and agriculture, contributing to environmental sustainability and fostering innovation. The increasing recognition of the economic and environmental benefits of recycling, coupled with technological advancements, is driving the expansion of the market for recycled rubber products. To foster circular economy solutions, the material value of the end-of-life tyres (EOLTs) needs to be as high as possible to promote circulation. Thus, the market for products derived from EOLTs should be prioritised, using both the waste hierarchy and circular economy principles. As such end-markets need to be created or reinforced in Australia for retreading, upcycling, recycling and tyre-derived fuels as shown in the Figure 18.

Figure 18. Possible usages and markets for end-of-life tyres.

Retreading involves refurbishing worn-out tyres by replacing the tread and sidewalls, extending their life cycle and reducing the demand for new tyre production. Tyre re-grooving involves removing rubber from the layer of existing rubber to restore tread pattern depth. These processes extend tyre life, conserve valuable resources and reduce the environmental impact of tyre disposal.

Upcycling EOLTs involves repurposing tyre components into higher-value products with improved functionality. This approach focuses on extracting valuable materials, such as steel and rubber, from discarded tyres to create new, useful items. For instance, recycled rubber from tyres can be transformed into playground surfaces, athletic tracks, or construction materials (Moreno, et al., 2023; Xiao et al., 2022). There are various examples of using recycled tyre rubber crumbs in the noise barriers (Figure 19). The traditional and commonly used autoclaved aerated concrete (AAC) is carbon intense. The research suggests that there is potential for replacing approximately 40% of the coarse aggregate with rubber which will make the noise wall lighter, save overall cost and reduce emissions (Roadline, 2022).

Figure 19. Tyre-based noise walls (Roadline, 2022).

Recycling, perhaps the most common approach, involves breaking down tyres into their constituent materials and reusing them in various applications. This can include extracting steel for manufacturing, using shredded rubber in road construction or as an additive in asphalt and concrete (Saqib et al., 2018; Kumar and Gupta, 2018). The study conducted by TSA (Tyre stewardship Australia, 2019b) claimed that crumb rubber-modified binder showed higher benefits against bitumen for the road. The benefits include increased service life, improved durability, resistance against reflective cracking and improvements in waterproofing (Tyre stewardship Australia, 2019b). Effective recycling initiatives contribute to reducing landfill waste and conserving raw materials, while also addressing the environmental hazards associated with tyre incineration.

Tyre-derived fuel refers to the use of tyres or their parts as a fuel for energy generation. Rubbery tyres have a high energy content (Ruwona et al., 2019) which can be utilised to generate electricity or heat, reducing the reliance on fossil fuels and mitigating environmental impacts associated with landfilling.

6.1 Potential market pathways in Australia

Products derived from EOLTs and conveyor belts find versatile and sustainable applications across various industries (Doe, 2023). Recycling these materials not only addresses environmental concerns but also fosters innovation. In construction, shredded rubber is utilized for rubberized asphalt, enhancing road durability and reducing noise pollution, while rubber mulch serves as a sustainable landscaping solution. The automotive sector benefits from recycled rubber products for noise dampeners and seals, contributing to vehicle comfort and environmental sustainability. In agriculture, recycled conveyor belts are repurposed for barn flooring and erosion control. With growing recognition of the economic and environmental benefits of recycling, coupled with technological advancements, the market for these products continues to expand, driving innovation and meeting diverse industry needs. Figure 20 shows a simplified schematic of EOLTs potentially being used to produce new materials (green arrow) in local market and the residual waste could be used in the waste-to-energy sector (red arrow) as feedstock. In addition, depending on the context, after processing locally the recovered material can be exported as commodity in the international market (blue arrow).

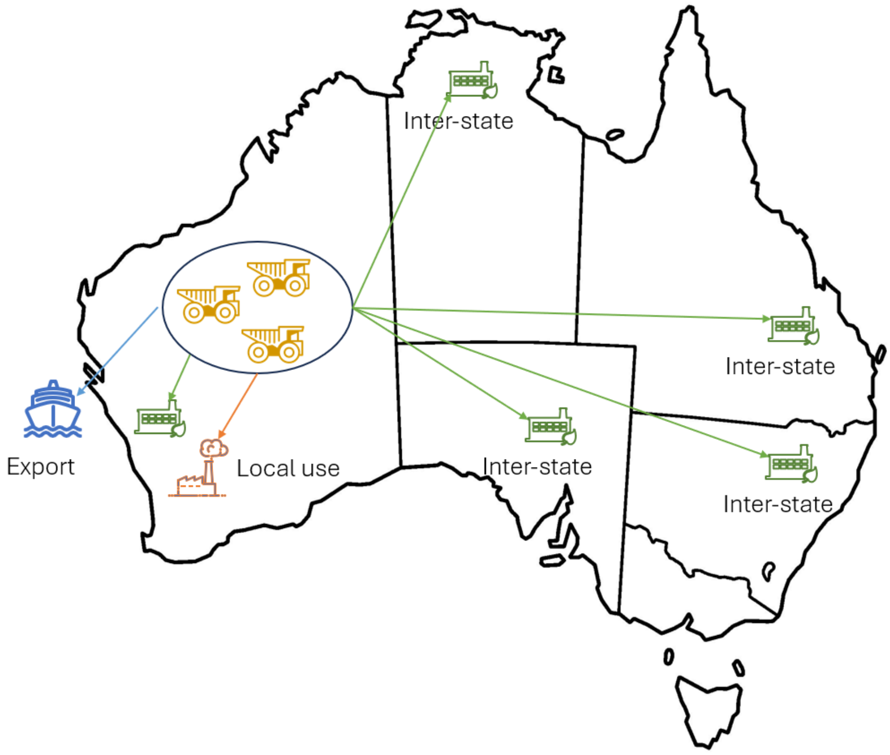

Figure 20. Possible various pathways of local, interstate and international application of products and fuels derived from end-of-life tyres.

The following sections review some examples of technologies that can enable the value recovery from EOLTs and conveyor belts.

6.2 Example technologies for EOLT and conveyor belt management in Australia

6.2.1 Re-grooving and retreading

Tyre re-grooving and retreading extend tyre life by removing rubber to restore tread pattern depth and replacing the whole tread, respectively. Thus, they support the real circularity of tyres as shown in Figure 21. According to Marangoni (2024, the truck, bus and radial (TBR) tyre retreading markets is estimated to cover 0.8 million tyres in Australia, 17 million tyres in North America, 9.6 million tyres in South America, 5 million tyres in Europe, 1.3 million tyres in Africa and 18.5 million tyres in Asia. Bridgestone (Bandag), Michelin (Recamic and Michelin Retread), Goodyear and Dunlop along with some smaller independent companies retread in Australia, which provides higher mileage and longer casing life, as well as both quality and cost savings for non-passenger vehicles (Bridgestone, 2024). According to the TSA Retread Fact Sheet (Tyre stewardship Australia, 2019a), retreading a truck tyre can increase its lifespan by up to 3 times and only requires 1/3 of the oil to manufacture it compared to a new truck tyre. Up to 80% of jet plane tyres are retreaded up to 6 times. Moreover, retreading can save up to 70% of raw materials (natural and synthetic rubber, oil, steel), up to 65% of energy used for manufacturing, 64% of CO2 emissions, 21% air pollution and 19% of water for TBR tyres, and reduce waste (Marangoni, 2024). Additionally, retreading supports the local economy and in times of logistic disruptions (e.g., during COVID) provides security for countries that do not have domestic tyre manufacturing (Personal communication, 2024). The retreading industry has evolved to incorporate advanced technologies and quality control measures, such as imaging technologies and automation, making it a viable and environmentally responsible alternative to manufacturing new tyres. Retreading may be cold or hot retreading and include approaches such as mould retreading or vulcanisation in an autoclave followed by tread pattern cutting (Marangoni, 2024; Personal communication, 2024). As an example, the retreading process used by Bandag is shown in Figure 22. Some retreaders are also utilising circular economy business models such as providing tyre products as a service in which customers pay per km of tyres used instead of per tyre Figure 23 (Marangoni, 2024). Tyre retreading requires trust and acceptance by the users. Some countries incentivise retreading e.g. by discounts on high-way tolls or other fiscal advantages (Personal communication, 2024).

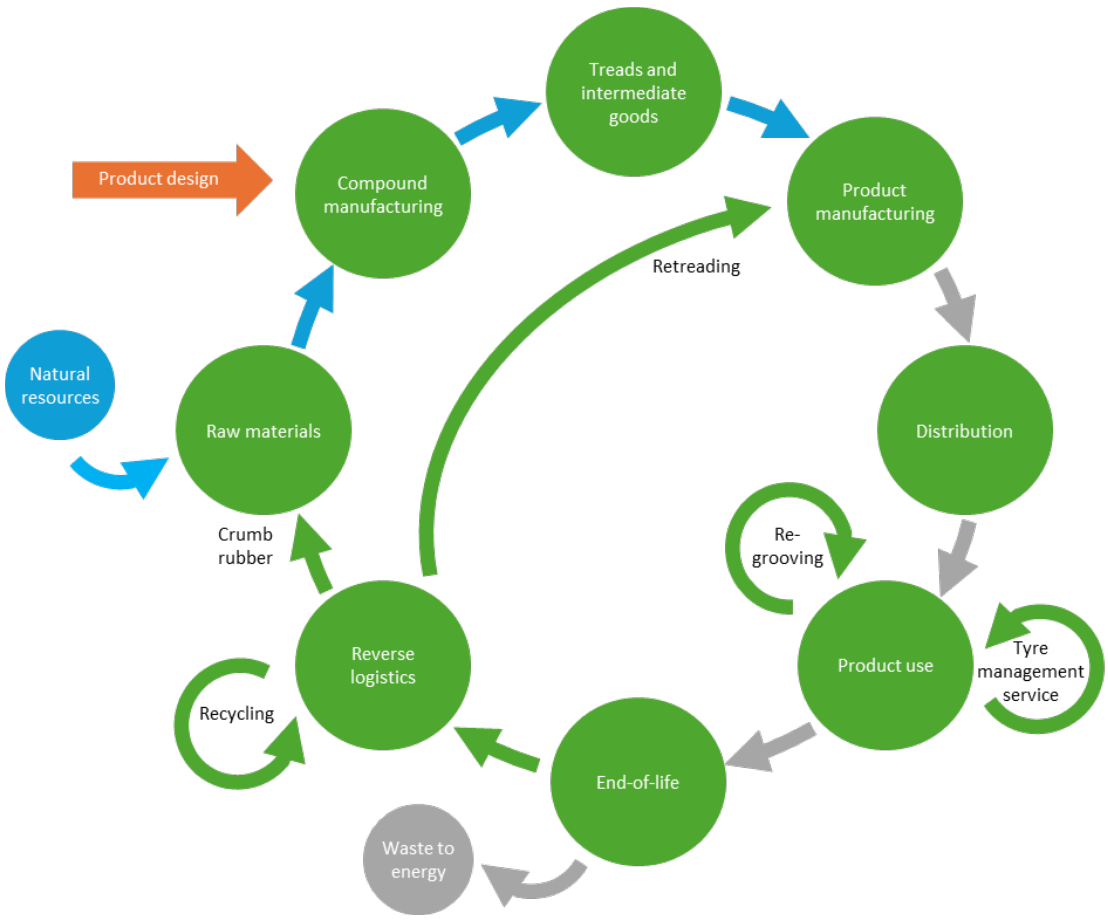

Figure 21. Circular economy for tyres (Adapted from Marangoni, 2024).

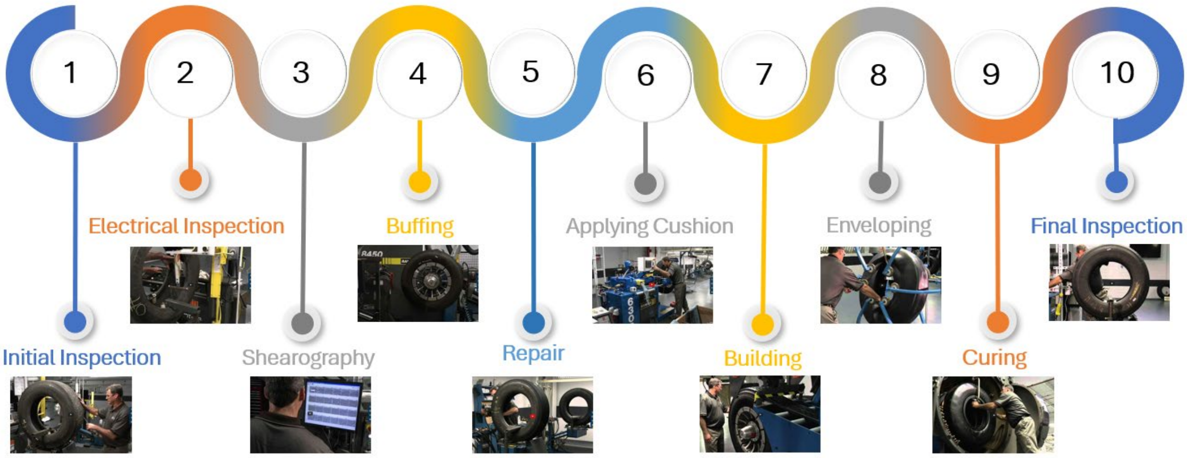

Figure 22. Retreading process used by Bandag (Adapted from Bridgestone, 2024).

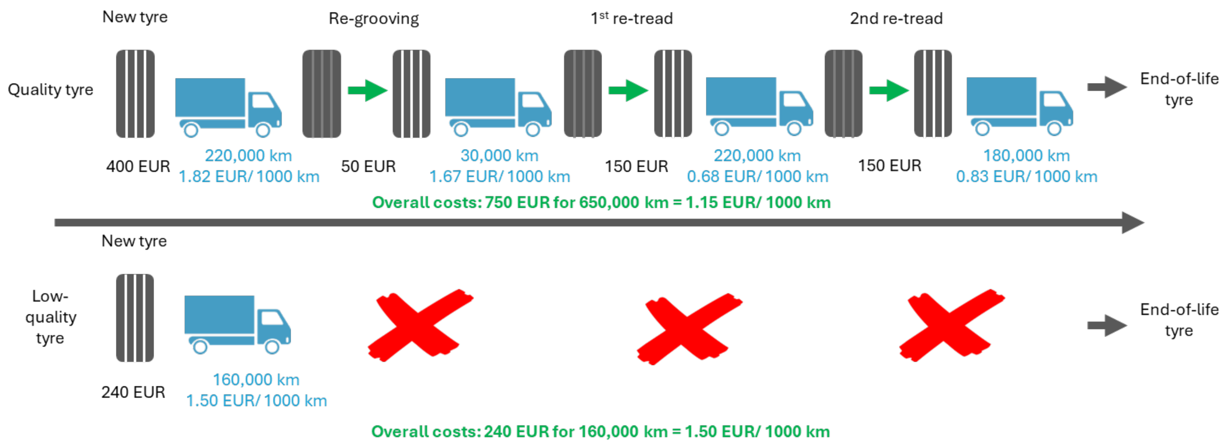

Figure 23. Tyre as a service business model that utilises tyre re-grooving and retreading (Marangoni, 2024).

Advantages and disadvantages of tyre re-grooving and retreading are shown in Table 23.

Table 23. A summary of advantages and disadvantages of regrooving and retreading

Advantages	Disadvantages
- Aligned with waste hierarchy priorities for enabling tyre reuse - Extend the tyre life and improve circularity - Reduce virgin material consumption, waste generation, energy consumption and emissions - Potential for economic savings for good quality tyres - Creates local jobs and thus support local economy	- Poor quality tyres are not suitable for retreading

Key messages: Regrooving and retreading help to extend tyre life, improve circularity, reduce virgin material and energy consumption and offer potential savings for good quality tyres. However, import of poor-quality tyres that are not suitable for retreading is a barrier for retreading.

Recommendations: Quality standards for imported tyres and circular economy business models such as providing tyre products as a service could be considered to increase tyre regrooving and retreading in Australia. Collaboration among stakeholders (e.g., recyclers, manufacturers, researchers) should be encouraged to enhance knowledge sharing of lessons learnt and best practices.

6.2.2 Rubber devulcanisation

Vulcanised rubber, known for its superior mechanical properties, is integral to various automotive industries (Saputra et al., 2021). The rubber industry, driven by global tyre demands, has evolved, with tyres now comprising approximately 19% natural rubber, 24% synthetic rubber, and the remainder comprising plastic polymer, metal, filler, and additives. EOLTs contain valuable rubber hydrocarbon, motivating efforts for its recovery or regeneration. Conventional EOLT recovery methods often yield undesirable products, such as the destruction of the polymeric chain and exponential degeneration of the vulcanisates' physical properties, compromising vulcanisate physical properties and quality. To address this, various devulcanisation processes have been developed to reverse the vulcanisation of rubber so that it can be vulcanised again. Devulcanisation aims to selectively break the sulfur cross-links (carbon-sulfur and sulfur-sulfur bonds) while leaving the carbon-carbon bonds intact. Devulcanisation methods include chemical, thermomechanical, irradiation (ultrasound, microwave), and biological approaches, sometimes combined for enhanced efficacy (Saputra et al., 2021). The thermomechanical devulcanisation based on extrusion is more suitable to be applied on an industrial scale. Supercritical CO_2 has been proposed as having the potential to improve this type of devulcanisation (Personal communication, 2023).

An example of a flow sheet for tyre devulcanisation is shown in Figure 24. The flow sheet itself can be used for lots of various applications, where the diversification would happen after the devulcanisation step where the material could be pelletised instead of micronized, then reconverted into a blended formula for other products necessitating other conversion technologies (Personal communication, 2023). Devulcanisation has not yet been applied widely in Australia. However, East-West Pilbara Rubber Recycling Pty Ltd received recently $675,000 of land allocation to establish a dedicated off-the-road tyre recycling and devulcanization facility in Port Hedland, WA capable of processing 12,000 tonnes each year (Pittorino, 2024).

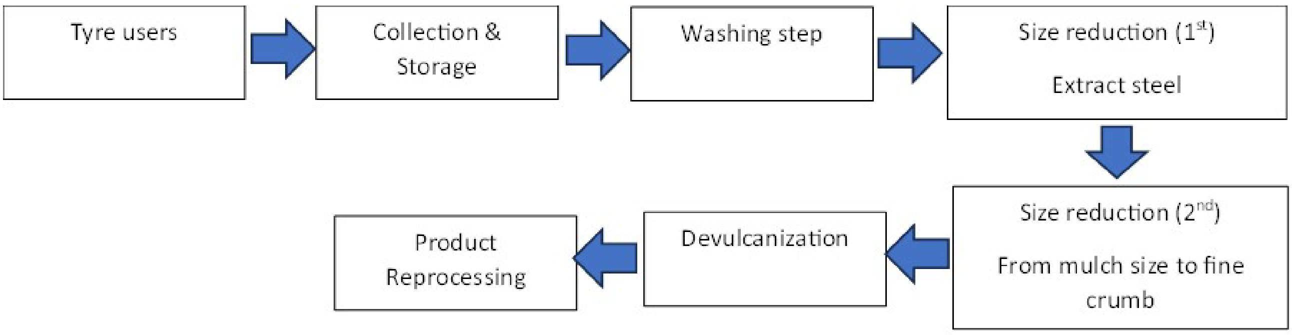

Figure 24. Process flow for devulcanisation technology (Drawn based on personal communication, 2023).

Use of devulcanized rubber

Devulcanised rubber performs better than rubber granules, micronised rubber, or other compounds. Test results have validated the potential to replace up to 90% of virgin material. The versatility of devulcanised rubber extends to its compatibility with natural rubber and various polymer types (such as styrene-butadiene rubber (styrene-butadiene-rubber (SBR), ethylene propylene diene monomer rubber (EPDM) and thermoplastic vulcanizates (TPV), allowing the creation of new compounds without substantially reducing mechanical and physical properties. The replacement concentration will vary upon the end application and the material requirements established by industry standards and quality levels. The main barrier to overcome is the resistance to change, which is the unwillingness to adapt to new circumstances or ways of doing things, from the converter, which needs education workshops and demonstration set ups. Due to the composition variability from one brand to another, tyre manufacturers would be more inclined to receive back their own product from devulcanisation plant than unknown mix. This issue can be addressed by implementing an accurate traceability system, guided by robust feedstock characterization according to mandatory standard practices (Personal communication, 2023).

Recycled rubber can be integrated into various market applications and products (from large a concentration to a minimum concentration), and it is always linked to its quality level or properties and price. To incorporate recycled materials, a market is needed. The first thing needed is manufacturers who use the recycled materials as a feedstock. So, who are the rubber manufacturers in Australia, what do they produce, and how do they make their products; implementing recycled rubber from devulcanised plants should match their requirements. If the manufacturing ecosystem needs to be more robust (requiring several stakeholders, various applications and markets, or volume), exporting the material is the alternative. It becomes a challenge to overcome the threshold of resistance, which is the perceived barriers between the material from devulcanisation plants to potential customers; this is based on the quality level and the demonstration of property requirements that the material needs to achieve using testing reporting (including origin certificate, composition details, and other key traceability attributes). Recycled rubber can be used as is or blended into other materials (Personal communication, 2023).

Policies could play an important role in adopting the technology at scale. For example, the extended producer responsibility (EPR) system is a great tool, but most of the barriers to unlock its full potential are determined by its boundaries. In Canada, EPR for waste tyres is implemented in some provinces. They can only include the retailers as leading contributors to the EPR while the tyre manufacturers are not incorporated into the scheme. When stopping at tyre manufacturers, the automotive industry should also be included because they could not sell their product (car, bus, off-road vehicle and more) without tyres attached to it. However, when stopping there, the chemical plant producing the materials should also be part of the scheme as well as the mining and extraction companies. So EPR would reach its full potential if all stakeholders in the supply chain were included; the traceability system would be more accurate if required within recycling practices, and partnerships among industries along the supply chain could also be more impactful.

Research on devulcanisation technologies

In the case of EOLTs, there is an ongoing demand for the continual advancement of methods and processes capable of devulcanising rubber vulcanisates into products possessing qualities and properties closely resembling those of virgin rubber (Gumede et al., 2022). The following sections review examples of research efforts on developing devulcanisation technologies.

Chemical devulcanisation

Mondal et al. (2023) have focused on devulcanising ground tyre rubber (GTR) using a multifunctional **devulcanising agent, bis(3-triethoxysilylpropyl)tetrasulfide**. This chemical agent achieves mechanochemical devulcanisation of GTR, and the resulting devulcanised rubber facilitates homogeneous silica dispersion in the re-vulcanised rubber compound. The degree of devulcanisation and the quality of the devulcanised rubber are evaluated through swelling experiments and the Horikx theory. Experimental findings indicate that the optimal devulcanisation time is 40 minutes, resulting in higher quality devulcanised rubber and improved mechanical and thermal performance of the re-vulcanised rubber. Scanning electron microscopy images support the homogeneous dispersion of silica in the rubber matrix.

Ultimately, the developed technology proves suitable for rubber reclaiming, contributing to advancements in ecological sustainability (Mondal et al., 2023).

A widely adopted and efficient approach for recovering raw rubber from waste tyres, such as truck tyres, involves devulcanisation in **scCO_2 using commercial and typical devulcanising agents**. ScCO_2 is favoured over traditional liquid-based devulcanisation media due to its perceived eco-friendliness and the resulting higher quality of devulcanised rubber. When scCO_2 is employed to recover rubber from waste tyres and blended with virgin natural rubber (NR) in various compositions, the curing and mechanical properties of the blends closely mirror those of virgin NR. The shift towards greener devulcanisation practices, primarily utilising organic and readily available devulcanising agents, is driven by the atmospheric toxicity and cost associated with commonly used devulcanisation materials such as chemical agents, oils, and solvents. Gumede et al. (2022) have reviewed environmentally friendly approaches in the chemical devulcanisation of rubber vulcanisates, particularly emphasising thermo-chemical devulcanisation of waste tyres in scCO_2 using common organic devulcanising agents.

Powdering tyres, especially using scCO_2 pulverization, shows promise, with factors like particle size, purity, and cost influencing efficacy. Devulcanisation is a focal point, yet a method has yet to reach large-scale readiness. Literature suggests potential in **extrusion with ultrasonics or scCO_2 using diphenyl disulfide**. Dissolution extraction, employing solvent extraction, yields purer products than other methods (Abbas-Abadi et al., 2022).

Mangili et al. (2014) subjected truck-tyre rubber to devulcanisation in **supercritical carbon dioxide (scCO_2) with diphenyl disulfide (DD)** as the devulcanising agent. The process maintained a temperature of 180°C and a pressure of 15 MPa, with a rubber-to-DD ratio of 10 wt%. The impact of this treatment on GTR properties was thoroughly examined, revealing an achieved degree of devulcanisation of approximately 50% with a minimal solid fraction. Results indicated that the treatment involving DD in the presence of scCO_2 effectively diminished the cross-link density of GTR, enhancing the gel fraction property and the compatibility of the material with raw rubber. The potential for reutilising devulcanised GTR in new tyre blends was explored by assessing final mechanical properties. It was observed that the unreacted DD notably influenced the re-vulcanisation process based on the FTIR analysis. This aspect emerged as the sole limiting factor for applying this devulcanisation process (Mangili et al., 2014).

Li et al. (2020) investigated the cryogenic grinding performance of devulcanised scrap tyre rubber (treated in **scCO_2** using a fluidised-bed jet mill. Various concentrations of devulcanising reagents were applied to devulcanise scrap tyre rubbers, and the ground product's particle size distribution was analysed to assess the impact of the degree of devulcanisation. Population balance modelling, incorporating selection and breakage functions, was employed to elucidate the evolution of particle sizes during the grinding process. Experimental results from the cryogenic grinding experiment indicated that devulcanisation treatment enhanced particle size reduction and shifts the grinding mechanism from abrasion to cleavage or fracture (Li et al., 2020).

Tyromer Inc. has developed since 2009 the devulcanisation technology out of the University of Waterloo in Canada. They have devulcanised rubber, mainly from tyres, but any rubber that has been cured with sulfur, using **supercritical fluid in twin screw extrusion technology**. They intend to license the technology, and that is basically the strategy of how they can get this out fast but also set up a few facilities themselves. They have developed a tyre-derived polymer, and re-blend the material with/without additives depending on the end-market target. They claim that a virgin tyre manufacturer has 2.7922 kg CO_2e/kg greenhouse gas (GHG) emission while the Tyromer Inc. technology only has 0.5832 Kg CO_2e/kg, a 21% difference. Chemical reclaimed rubber reaches 2.4561 Kg CO_2e/kg GHG emission, again a 24% difference in favour of Tyromer Inc. technology. This technology opens the possibility of close-loop recycling if the quality level reaches the requirements of tyre manufacturers. This is why Tyromer Inc. partners with manufacturers and educates them about the technology potential. However, the choice of this technology should be based on the potential end market for the output materials. If local/national rubber manufacturers can benefit from higher-value materials to create higher-value products, this technology can certainly play a crucial role (Personal communication, 2023).

Saputra et al. (2021) have reviewed the latest developments in devulcanisation using **ionic liquids and deep eutectic solvents**. Such devulcanisation techniques not only offer sustainable pathways for WTR but also generate devulcanisates with physical properties comparable to virgin products, paving the way for novel circular economic opportunities on a global scale (Saputra et al., 2021).

Saputra et al. (2019) marked the first exploration of the impact of **deep eutectic solvents (DES)** on the devulcanisation of ground tyre rubber (GTR). Three distinct DESs (chloromethylene (ChCl):urea, ChCl:$ZnCl_2$, and $ZnCl_2$:urea) were prepared, and their physicochemical properties were systematically examined. GTR was combined with various DESs, subjected to sonication, and heated at varying intervals. The treated GTR underwent analysis through energy dispersive X-ray analysis (EDX), Fourier-transform infrared spectroscopy (FTIR), field emission scanning electron microscopy (FESEM), and thermogravimetric analysis (TGA). Additionally, the degree of devulcanisation was quantified using parameters such as soluble fraction and cross-link density and was correlated using the Horikx theory. The study also investigated the relationship between the viscosities of DESs and their efficiency in devulcanisation (Saputra et al., 2019).

Irradiation-based devulcanisation

Microwave-based devulcanisation of rubber stands out as an environmentally friendly technique (de Sousa and Ornaghi Júnior, 2020). It draws considerable attention in the recycling field for its distinct advantages, including high productivity, uniform heating, and the absence of chemical involvement. A study by de Sousa and Ornaghi Júnior (2020) used microwaves at varying exposure times to devulcanise ground tyre rubber (GTR). The thermal stability of devulcanised samples and their re-vulcanisation behaviour were examined, correlating these properties with structural modifications occurring during devulcanisation. While the obtained results offer new insights, a more comprehensive understanding of the chemical structure and reactions was recommended to ensure accurate interpretations beyond the experimental range. These findings contribute to predicting and optimising kinetic properties, which is crucial for advancing microwave devulcanisation as an authentically sustainable recycling process (de Sousa and Ornaghi Júnior, 2020).

Simon and Bárány (2023) explored **microwave devulcanisation** of ground tyre rubber (GTR) at various temperatures (140−200 °C) and heating rates (2−18 °C/min). The soluble content and cross-link density of the samples were measured, and their evaluation was carried out using Horikx's analysis. Additionally, the authors determined the specific microwave energy during devulcanisation and introduced the selectivity parameter for the treatments. A novel parameter, the K·D number, was introduced, calculated as the product of the selectivity parameter (K) and the relative decrease in cross-link density (D). The results indicated that GTR devulcanisation at lower temperatures exhibited very high selectivity, and the degree of devulcanisation was satisfactory. At higher temperatures (180−200 °C), although the degree of devulcanisation reached 85%, the selectivity parameter was low, indicating severe degradation in this temperature range. Lower temperatures (140−160 °C) and decreasing heating rates led to an increase in the degree of devulcanisation. However, at higher temperatures, the heating rate had no significant effect on the degree of devulcanisation (Simon and Bárány, 2023).

Thermomechanical vulcanisation

Simon and Bárány (2021) evaluated **thermomechanical devulcanisation** process on ground tyre rubber (GTR) using a co-rotating twin-screw extruder with varying barrel temperatures and screw speeds. Soluble content and cross-link density measurements were conducted, followed by an evaluation using Horikx's analysis. Results indicated that, at lower temperatures, selective cross-link scission dominated, with no notable impact from screw speed. However, at higher temperatures and screw speeds, polymer chain degradation became increasingly severe. Optimal parameters were identified to maximize cross-link scission without causing significant degradation to the leading chains (Simon and Bárány, 2021).

Yazdani et al. (2011) explored the devulcanisation process of the tread section's waste tyres, utilizing a **twin-screw extruder**. The study revealed that the percent of devulcanisation and solid fraction were influenced by the screw speed and barrel temperature, respectively. The devulcanised samples, formulated with virgin rubber at a 15/85 wt% ratio, were successfully re-cured. Evaluation of mechanical properties, including tensile strength, elongation at break, compression set, hardness, and resilience, indicated that the compound containing devulcanisates exhibited slightly inferior performance compared to the virgin compound (Yazdani et al., 2011).

Combination of chemical, thermal, mechanical and/or irradiation approaches for devulcanisation

Ghosh et al. (2023) aimed to develop a sustainable devulcanisation process for passenger car tyre rubber using silanes. Employing a **thermomechanical–chemical devulcanisation** process, six potential devulcanisation aids (DAs) were screened, with silanes chosen for their widespread use in tyre rubber as coupling agents for silica. The efficiency of devulcanisation was assessed based on the degree of network breakdown, miscibility of the devulcanised material, and mechanical properties of the de- and re-vulcanised material. The results demonstrated a notable 55–60% network breakdown for the devulcanisation, accompanied by 50–55% tensile strength recovery compared to the parent compound. Apart from its superior devulcanisation efficiency, this devulcanisation aid offers a sustainable alternative to conventional ones, such as di-phenyl-di-sulfide, meeting safety regulations. The resulting devulcanisate can find applications in high-performance uses like tyres and seals, while 100% devulcanisate can be utilized in low-strength technical rubber products (Ghosh et al., 2023).

Alonso Pastor et al. (2021) explored the novel application of devulcanised tyre powder as an effective reinforcement in self-healing SBR compounds. The research investigated the evolution of the microstructure of rubber from EOLTs during granulation, grinding, and devulcanisation. Various morphologies were analysed through a comprehensive characterization process obtained by cryogenic and water jet grinding processes and **different devulcanisation techniques (thermo-mechanical, microwave, and thermo-chemical**). The results underscored the impact of ground tyre rubber (GTR) morphology on the resulting devulcanised products (dGTR). The study validated predictions, establishing a model of the microstructure of these materials. This model facilitated the correlation of GTR and dGTR morphology with their efficacy as reinforcement in self-healing formulations. Notably, higher specific surface area and a greater percentage of free surface polymeric chains correlated with improved mechanical performance and enhanced healing capabilities. The strategy employed demonstrated an overall healing efficiency exceeding 80% in terms of real mechanical recovery (tensile strength and elongation at break) with the addition of 30 part per hundreds of dGTR. These findings presented a significant opportunity to strike a balance between mechanical properties before and after self-repair, thereby providing substantial technological value to waste tyres (Alonso Pastor et al., 2021).

de Sousa et al. (2017) have examined chemical modifications, flow characteristics, and **thermo-oxidative degradation** behaviour based on the exposure time of GTR to **microwaves**. A key observation was that the success of the process hinged on the final temperature reached by the sample. Different sulfur bonds can be broken depending on this final temperature, highlighting the delicate balance between breakdown and forming new bonds. Careful process control was crucial to prevent the degradation of leading chains. Notably, tyres, typically composed of a mixture of synthetic and natural rubbers, may experience varying degrees of degradation under microwaves, with a potential emphasis on the degradation of natural rubber due to the prevalence of carbon black in this phase (de Sousa et al., 2017).

Biological devulcanisation

Apart from physical and chemical methods, devulcanisation can also be conducted using biological methods. For instance, in one study eleven bacterial strains were assessed for their ability to devulcanise ground tyres (GTs) biologically (Ghavipanjeh et al., 2018). Each bacterium treated the GTs in a mineral medium, and devulcanisation was quantified by increasing the sulfate in the medium and reducing the sulphur in the GTs. The study investigated the influence of incubation time (10 and 20 days) and the percentage of ground tyre in the medium (0.5 and 5 w/v %) on desulfurisation. No significant alterations were observed after ten days of incubation. However, after 20 days, the total sulfur content of all bio-treated GTs decreased by 6–21% in 0.5% GTs. In the case of 5% GTs, *Acidithiobacillus ferroxidans* (previously called *Thiobacillus ferrooxidans*) DSMZ 583 and PTCC 1647 were particularly effective, leading to up to 27% and 15% reductions, respectively (Ghavipanjeh et al., 2018). A summary of advantages and disadvantages of devulcanisation is shown in Table 24.

Table 24. A summary of advantages and disadvantages of devulcanisation for end-of-life tyres (EOLTs) and conveyor belts.

Advantages	Disadvantages
- Alignment with circular economy principles - Reduces virgin material consumption - Reduces waste generation - Adaptability of various devulcanisation technologies to different EOLT compositions - Improved properties enabling high-performance applications and re-engineering - Active research presents opportunities for technology innovation	- Process complexity and requirement for optimisation of multiple parameters posing challenges for large-scale implementation - Energy intensity (in thermal and microwave assisted devulcanisation) - Hazardous nature of some devulcanisation chemicals - Economic viability depends on factors such as input costs, market demand, and scalability

Key messages: Devulcanisation technology is a process that can reverse the vulcanisation of rubber by breaking the sulfur cross-links in the vulcanised rubber. This process restores the material's plasticity, allowing the waste rubber to be reused in the production of new rubber products, thereby supporting circularity. Various methods can be used for devulcanisation, including chemical, mechanical, thermal, irradiation, and biological. Each method has its advantages and disadvantages in terms of efficiency, cost, and environmental impact. The resulting devulcanised rubber can be blended with virgin rubber to create new products. Therefore, it has the potential to reduce the need for raw virgin rubber materials and offer higher quality products than conventional mechanical size reduction. However, in Australia markets are needed for the use of devulcanised rubber products.

Recommendations: The potential of devulcanisation technologies could be explored in Australia for providing feedstock for the manufacturing of various rubber products. This may be facilitated through: (1) Investment in research and development to improve devulcanization technologies for Australian waste rubbers (tyres and conveyor belts); (2) encourage the use of devulcanized rubber in the production of new products; (3) advocate for government policies and incentives; (4) foster collaboration among industrial stakeholders, including manufacturers, recyclers, and researchers, to share knowledge and best practices; (5) develop standardised processes and quality controls.

6.2.3 Size reduction technologies for end-of-life off-the-road tyres

End-of-life (EOL) OTR tyres are difficult to recycle primarily due to the size of the tyres, and the regional locations where the majority of EOL OTR tyres are generated. Size reduction of OTR tyres and conveyor belts prior to further processing is a critical consideration related to recycling efficiency, and when considering remote and regional EOL OTR tyre generation in Australia, mitigation of transport costs and logistics is key. An overview of EOL OTR splitting and size reduction technologies are shown in Table 25.

Table 25. Overview of some technologies for splitting OTR end-of-life tyres (EOLTs).

Technology	Description
'Punch Cutter'	The Eagle Punch Cutter splits (OTR) tyres in half along the tread's centre'. When mounted on the tyre, it rotates around the exterior, using a blade to puncture the tyre while a programmable logic controller (PLC) guides the process. This technology can cut up to 8 inches per punch (Brehmer Manufacturing, 2024).
'Eco Razor 63'	Eco Razor 63' removes high-quality rubber from large tyres, allowing for downstream processing. Its patented technology extracts rubber from all sides, producing wire-free buffing chips. It has customisable blade configurations available that allow the output size to be tailored for market demand (Eco Green Equipment, 2024).
Modular three part size reduction for OTR tyres	Gradeall has developed three machines to reduce the size of large OTR tyres. The technology can transform five OTR-sized tyres into PAS108-sized bales, reducing storage requirements and cutting transport expenses for rubber waste. The initial step in this process involves the OTR Splitter, which divides the tyre in half. Following this, the OTR Tyre Sidewall Cutter comes into play for large OTR tyre processing. The final stage is the OTR Shear, which cuts the tyre into sizes that can be then baled (Gradeall International Ltd, 2024).
Automated Hydraulic Shears	Automated Hydraulic Shears do not require bead removal pre-processing. Instead, the equipment discharges downsized rubber onto a conveyor system. It is fully automated and has the capability to cut through 30 OTR tyres per hour, featuring alloy blades manufactured to quality control standards. This allows for extended blade longevity, hence minimising downtime for blade replacements. Being automated enables a saving of labour costs and mitigates occupational health and safety (OHS) issues related to workplace safety and injury (e.g., Wolverine 18-51R, Salvadori, Italy) (Salvadori, 2024b)
Steel Debearer	Steel Debearer reclaims steel beads from OTR, removing most of the rubber (e.g., Hercules 90, Salvadori, Italy). This technology specialises in breaking the steel beads, which facilitates subsequent recycling process and extends the lifespan of shredder blades (approximately 60%). As a result, not only are cleaner rubber granules generated, but the shredding efficiency is improved by minimising machine downtime. It ensures safe handling of large tyres with its integrated safety features (Salvadori, 2024a).
High pressure water jet cutting	Abrasive water machining, which includes the generation of high-pressure water jets is a widely used technology in cutting, 3D profiling, cleaning, milling and drilling (Singh et al, 2021; Wang et al, 2017). The water jet cutting system can cut a material of thickness up to 24 inches with precision down to 0.001 inches. The jet impact creates high compression and shear on EOLTs (Wang et al., 2022), facilitating tyre size reduction. Furthermore, ultra-high pressure water jet (UHPWJ) tests have demonstrated some advantages over conventional room temperature or cryogenic grinding of EOLTs including fine particle size distribution and large surface area of crumb rubber as well as partial devulcanisation (Wang et al., 2017). The latter being one of the by-products from size reduction treatments that has a wide application range, such as construction materials or pavement (Wang et al., 2017). High-pressure water jet technologies present an option to produce crumb rubber from EOLTs.

Like EOL OTR tyres, conveyor belts require size reduction, shredding and reclamation into new products. OTR tyres have a complex structure with several materials including steel beads, nylon fabric, and different rubber compounds for tread and sidewalls (Tirebuyer, 2023). In comparison, conveyor belts are usually made from materials including fabric–rubber carcass and rubber covers. Latex is impregnated between the fabric and rubber to prevent delamination; the cover and rims are designed to protect the carcass from weathering, damage and chemicals (Barburski, 2014). However, unlike EOL tyres, conveyor belts are typically challenging to recycle and recover. Length, structure, and weight are all factors that exclude conveyor belts from the typical EOLT recycling pathways. Built for durability, conveyor belts have significantly higher amounts of steel cords and strong textile fibres that can damage EOL OTR and EOLT size reduction equipment. EOL conveyor belts often require fit for purpose equipment for size reduction and granulation and relies on good source separation to determine recoverability based on damage and contamination (Rubbergem, 2024). Once through the size reduction process, the recovered materials can follow similar pathways established for resource recovery from EOL rubber products. A summary of the advantages and disadvantages of size reduction technologies is shown in Table 26.

Table 26. A summary of advantages and disadvantages of end-of-life off-the-road (OTR) tyre size reduction technologies.

Advantages	Disadvantages
- Reduces the size of OTR tyres to be suitable for subsequent resource recovery technologies	- Represents pre-treatment rather than actual resource recovery technology - Energy consumption - Reduces value of original tyres and conveyor belts

Key messages: Size reduction of OTR tyres and conveyor belts prior to further processing is a critical step for ensuring recycling efficiency, and reduce of transport costs.

Recommendations: Size reduction technologies should be explored and utilised for reducing the size of OTR tyres and conveyor belts in Australia, to enable value recovery from these wastes, improve reverse logistics and minimise transport costs.

End-of-life tyres as an alternative carbon feedstock for steel making

Globally, the iron and steel industry consumed approximately 14% of the world's fossil coal in 2013 (Echterhof, 2021). As a result, the industry is also one of the world's highest industrial CO_2 emitters. Sustainable steel production research has focussed on trying to reduce the coal used by the industry, whilst also reducing the industrial environmental footprint as the introduction of net zero and emissions reduction policies are introduced around the world.

The two main routes for steel production are to use a blast furnace followed by a basic oxygen furnace (BOF) or to use an electric arc furnace (EAF) (Figure 25). The blast furnace traditionally uses metallurgical coke to drive the high temperature processing of primary iron ore into steel.

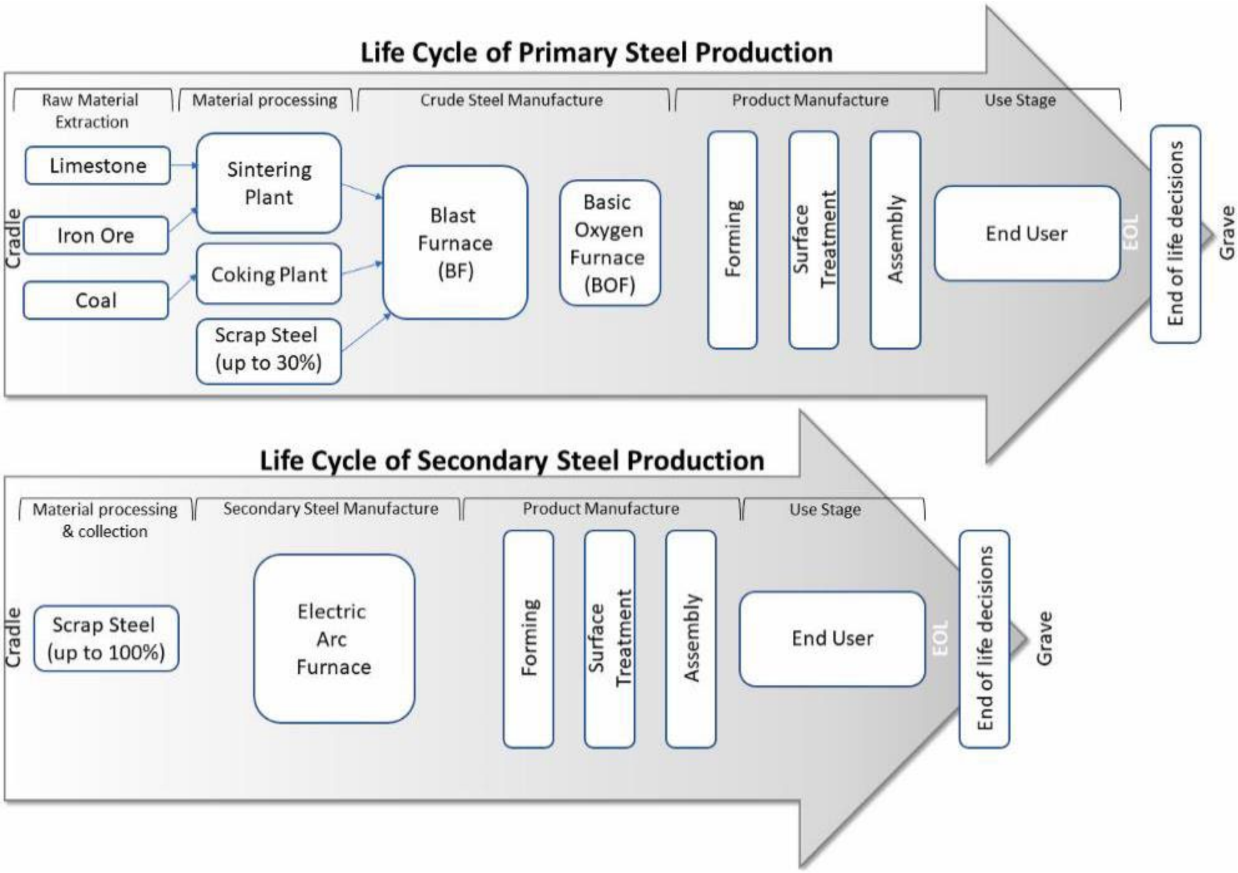

Figure 25. Typical steel making processes (Davies and Hastings, 2022)

According to Echterhof (2021), steel is produced in an EAF via charging iron sources (e.g., scrap metal, direct reduced iron, iron briquettes), alloying elements, slag formers and carbon sources. The charged mix is melted with chemical and electrical energy to produce a steel melt and a slag material. Despite a reduction in metallurgical coke requirement in EAF when compared to steel production with blast furnace followed by BOF, carbon sources are still required for carburising the melt and slag formation during steel production. Approximately 12 kg of coal have been estimated to be used per 1 t of steel produced by EAF (International Iron and Steel Institute 2000). When combined with electricity consumption generated from coal-fired power and solid carbon sources, EAF steel production still contributes on average 102 kg CO_2/t of steel (Ecofys and Fraunhofer Institute for Systems and Innovation Research and Öko-Institut, 2009) and represents 40-70% of the direct emissions for EAF steel production (Echterhof, 2021).

EOLTs and other recycled rubber products can be used an alternative or partial replacement for coke for steel making via EAF. EOLTs contain natural or synthetic rubbers, textiles and carbon black that can provide an alternative carbon substrate to metallurgical coke. In addition, EOLTs also contain steel wires, which can be concurrently recycled with scrap metal via EAF. It has been reported in the literature that rubber/coke blends are a more efficient feedstock for EAF steel making than pure metallurgical coke in laboratory and industrial trials (for examples, see review: Echterhof, 2021). Life cycle assessment completed by Clauzade et al. (2010) showed that the environmental benefits for EOLT use as an alternative carbon source in EAF is likely to be more beneficial than reuse in other industries (e.g., energy recovery, cement making or civil engineering).

In 2023, Australian steel and footwear manufacturers, the University of New South Wales (UNSW) SMaRT Centre and the Advanced Manufacturing Growth Centre, announced the commercialisation of an EAF steel production process using waste rubber from EOLTs (and other rubber products) as feedstock (Anonymous, 2023; Hart and Hill, 2023). It was reported that the large-scale technology would reduce the reliance on imported carbonaceous materials by 20% and remove up to 90,000 tyres from landfill per year. At the same time, electricity consumption and scope one carbon emissions (direct GHG emissions that occur from sources that are controlled or owned by organisations (United States Environmental Protection Agency, 2024) would also be reduced (Anonymous, 2023). A summary of advantages and disadvantages of using EOLTs as a carbon feedstock for steelmaking is shown in Table 27.

Table 27. A summary of advantages and disadvantages of using end-of-life tyres (EOLTs) as a carbon feedstock for steelmaking.

Advantages	Disadvantages
- Can reduce coal demand for steelmaking - Enables recovery of steel from tyres - Environmental benefits as compared to the use of EOLTs for energy recovery, cement making or civil engineering - Reduce need for EOLT landfilling - Reduces electricity consumption and scope one carbon emissions	- Rubber and fibre materials are not recovered for reuse

Key messages: Green steel production (from primary and secondary resources) is an emerging industry in Australia and there is an increasing potential to use EOLT and other rubber materials as an alternative for replacing metallurgical coal and to reduce impacts and emissions related to steel production.

Recommendations: The potential for implementing green steel production could be further explored in Australia as one market for recovered rubber from EOLTs and conveyor belts.

6.2.4 Pyrolysis

Rubber waste can be complex to recycle, and in many instances unfeasible for logistics, economic or technological issues. Tyres and conveyor belts, for example, are often dirty or their chemical composition makes recycling inefficient, since the end-product might have poor quality characteristics. Besides direct energy recovery (or waste-to-energy), pyrolysis also provides an alternative waste management strategy for complex waste feedstocks (Afash et al., 2023).

To enable a process of pyrolysis (also called thermal degradation, or devolatilization; Seidelt et al., 2006), the waste is burn at temperatures of 200 to 800 °C (Nisar et al., 2018; Campuzano et al., 2023) in an atmosphere free of oxygen (Miguel et al., 1998). In these conditions, tyres get typically separated in three main components: oil, char/carbon black, and gas, although a point of difference is their initial composition. On a steel-free basis the approximate outputs from tyres are 40-50% oil, 30-40% carbon and 10-12% gas. Steel wire can also be recovered from EOLTs during feed preparation or after pyrolysis and typically represents approximately 15% of the EOLT (Tyre Stewardship Australia, 2024). Conveyor belts are made of a mix of rubber and polyethylene mesh, yet they both result in similar amounts of oil and char, i.e., about 45-50% and 39% by weight, for oil and char respectively (Januszewicz et al., 2020). Additionally, steel can be recovered in the process.

Carbon black can be used effectively as a filler and pigment in new rubber products or in the production of activated carbon (Xu et al., 2020). Commercially, its use as activated carbon seems the most valid choice since it can be used as a cheap material for heavy metals removal in the agriculture sector and wastewater treatment (Trubetskaya et al., 2019). On the other hand, oils resulting from tyre pyrolysis cannot be directly used as fuel before processes such as removal of moisture, desulfurisation and vacuum distillation to improve its characteristic. Once these processes are completed though, rubber pyrolysis oils can be used as fuels and that is often the case in developing countries such as Pakistan, where the need for independent energy sources is substantial (Yaqoob et al., 2021). For example, pyrolytic oil can be mixed with commercial diesel (20% oil) and used directly in engines without modifications (Mavukwana and Sempuga, 2022). Alternatively, pyrolysis oil can be refined through distillation (Tyre Stewardship Australia, 2024).

Numerous pyrolysis plants have been established across the world, e.g. in Europe (Sweden, Germany, Poland, Hungary), Asia (Taiwan), North America (USA) and South America (Chile) (Tyre Stewardship Australia, 2024). It has been estimated that 3-5% of EOLTs generated globally are processed through pyrolysis (Tyre Stewardship Australia, 2024).

Currently, approximately 1% of EOLTs generated in Australia are processed through pyrolysis plants (Tyre Stewardship Australia, 2024). Pyrolysis may provide an alternative solution for managing complex rubber waste in Australia. The country generates a notable amount of rubbery end-of-life products, and largely from the resource sector (such as large conveyor belts used to transport minerals and OTRs). These can be challenging to recycle using traditional methods, often due to the volume and weight and their remote locations, but also because they are often dirty and contaminated. Pyrolysis presents an opportunity to recover valuable resources like steel, oil, and carbon black from these waste streams, reducing the reliance on landfilling and promoting resource recovery. Additionally, pyrolysis can help mitigate the environmental impact of rubber waste disposal by converting it into useful products, thereby reducing greenhouse gas emissions and the consumption of virgin resources as well as environmental risks connected with tyre stockpiling. Moreover, establishing pyrolysis facilities can create economic opportunities, generating revenue from the sale of recovered resources and providing employment in waste management and recycling industries. Furthermore, the pyrolysis oil produced can serve as an alternative fuel source, contributing to energy security and reducing reliance on fossil fuels. Finally, the steel recovered from the process can be sold for recycling (Zerin et al., 2023).

Companies such as Entyr are already applying pyrolysis in Australia, despite their process being declared as patented thermal processing to convert EOLTs into high-quality raw materials (Entyr, 2024). Active in Queensland, Entyr process over 2 million EOLTs per year. Other pyrolysis companies in Australia include Clean Energy Group (demonstration plant in Victoria), Waste Recovery & Energy Solutions (commissioning a plant in Queensland) and Elan Energy Matrix (plant under construction in Western Australia) (Tyre Stewardship Australia, 2024). Similarly, global companies such as Beston are promoting investments of pyrolysis plants in Australia (Beston, 2024).

Pyrolysis can be conducted in various reactor configurations, such as static or rotary batch reactors, continuous rotary reactors or continuous reactors with internal screw. Moreover, pyrolysis approaches very in term of feed pre-treatment, reactor heating method and operation, e.g. heating rate, peak temperature, catalyst use, solids and gas retention time and pressure (Tyre Stewardship Australia, 2024). Process parameters and reactor design impact pyrolysis products, with catalytic pyrolysis and hydro-treating offering higher yields of valuable products at the expense of some undesired byproducts. Demineralization and activated carbon production further enhance tyre recovery rates (Abbas-Abadi et al., 2022).

Microwave pyrolysis has emerged as a promising approach for EOLT treatment (Song et al., 2023). Song et al. (2023) introduced a novel method combining swelling modification with microwave-induced pyrolysis, capitalising on the benefits of swelling pretreatment in reducing the cross-link density of rubber molecular chains and leveraging the distinctive advantages of microwave pyrolysis. The research delved into the modification impact of swelling on EOLTs and explored how swelling pretreatment influenced the yields and compositions of three-phase products under various power levels. The findings revealed enhanced completeness in the pyrolysis of swelled EOLTs, substantially reducing solid product yields. At 900 W, the solid product yield was 22.69%, representing a notable decrease of about 14.57 percentage points compared to raw EOLTs. Moreover, a synergistic effect between coal tar and EOLTs was identified, notably increasing the yields of liquid products, reaching up to 67.18%. This study offered valuable insights for enhancing the efficiency of microwave pyrolysis for EOLTs (Song et al., 2023).

Among the valuable fractions obtained from EOLT pyrolysis, tyre pyrolysis oil (TPO) stands out, containing key chemicals such as benzene, toluene, ethylbenzene, xylene, and limonene—essential building blocks in the petrochemical industry (Campuzano et al., 2023). Campuzano et al. (2023) reviewed various pathways currently being explored in the scientific community to produce value-added products from TPO. Given its similarity to petroleum streams, coprocessing TPO with existing units in conventional refineries holds notable potential. This approach allows for fine-tuning the properties of derived products according to the requirements of the hydrocarbons and petrochemical market. Campuzano et al. (2023) discussed the advantages, recent progress, and challenges in implementing conventional refinery practices—such as distillation, fluid catalytic cracking (FCC), hydro-processing, and steam cracking—for TPO post-treatment. These processes are seen as crucial steps toward integrating TPO into the current hydrocarbon/petrochemical market (Campuzano et al., 2023).

Pyrolysis case study: Kal Tire, Chile

Circular economy has become a part of Kal Tire Chile's business model, specifically in the lifecycle of tyres. For this purpose, Kal Tire Chile has defined five stages. The first is the sale of the tyre. The second is the tyre maintenance service, which is carried out within mining operations. The third stage involves tyre repair, occurring when a tyre sustains damage that can be addressed with preventive or corrective repairs. The fourth stage involves tyre retreading. Once a tyre wears out, an evaluation is made to determine if the tyre's casing is still in good condition. If it is, the tyre goes through an automated process where rubber is added to its tread, allowing it to continue rolling for several more hours.

When a tyre can no longer be repaired or retreaded, the idea is to recycle it to create new products. To achieve this, Kal Tire employs the world's first thermal conversion plant for giant mining tyres, located in the city of Antofagasta. Through a pyrolysis process, EOLTs are broken down and transformed into three new products: steel, carbon black, and pyrolytic oil. With these three new products, Kal Tire is forming alliances with both national and international organisations and private companies to promote new markets for the utilisation of these products. The pyrolytic oil is already being used in generators, and the carbon black has been reused in the rubber compounds that Kal Tire uses to create new repairs and retreading processes.

The Chilean legislative demands on miners for the EOLTs served as the catalyst for Kal Tire to initiate the development of a mining tyre recycling solution, first of its kind in Chile. In 2020, Kal Tire inaugurated a thermal conversion recycling facility in Antofagasta, a port community within the Chilean mining industry, able to handle up to 20 t of EOLTs daily, including ultra-class products (very large and heavy-duty tires). The pyrolysis employs heat and friction in an oxygen-free environment to break down organic tyre materials to convert them back into their original constituents (Kal Tire Mining Tire Group, 2023b): fuel oil, steel wire, and carbon black. These components are then refined to ensure that every part of the tyre can be fully reused. All the material can be repurposed, with no harmful emissions being released. In this facility, a single 63-inch tyre can yield as much as 1 t of high-tensile steel, almost 2,000 litres of alternative oil and 1,600 kg of carbon black. Additionally, 350 m^3 of synthetic gas are generated (Craig Guthrie, 2022) (Figure 26). Full load tests for one of two thermal conversation reactors in the facility show the following breakdown after processing 20 t of tyres (the equivalent to five 63" Tyres): 4,000 kg of steel, 8,000 kg of carbon black, 6,500 litres of alternative fuel and enough synthetic gas to fuel the reactor itself for seven hours (Kal Tire Mining Tire Group, 2021). An overview of the products from the pyrolysis process and their uses are shown in Table 28.

The direct utilisation of alternative fuel or tyre pyrolysis oil (TPO) as a fuel may not align well with the principles of the circular economy (Campuzano et al., 2023). Rather than fuel applications, TPO has garnered significant interest for its potential as a feedstock in refinery units, where it can be transformed into high-value chemicals, such as benzene, toluene, and ethylbenzene. These chemical commodities are essential building blocks in various industries spanning solvents, adhesives, resins, plastics, pigments, pesticides, and paints, among others. Furthermore, integrating TPO as a supplementary feed in refinery operations can yield specific fuels such as naphtha, light cycle oil (LCO), and liquefied petroleum gas (LPG), which represents continued potential in the hydrocarbons market. Carbon black from pyrolysis can be incorporated into the production of new tyres, thereby providing pathways to enhance circularity outcomes (Campuzano et al., 2023).

Figure 26. Products obtained from the pyrolysis process at Kal Tire's facility in Antofagasta, Chile, for a 63-inch tyre (Adapted based on data from (Craig Guthrie, 2022) and (Lehighluke, 2016) https://commons.wikimedia.org/wiki/File:ATV_Tire_and_Wheel.jpg. CC BY-SA 4.0.

Table 28. Thermal conversion products, with their applications, from the pyrolysis process at Kal Tire's facility in Antofagasta, Chile. Based on (Kal Tire Mining Tire Group, 2023b).

Pyrolysis products	Application
Steel	High quality tensile steel found in off-the-road tyres can be recycled for a variety of purposes (e.g. foundries).
Carbon black	Refined carbon black can be used in batteries, pigments, paints, plastics and new rubber and tyre production. Carbon black is reused in the rubber compounds that Kal Tire uses to create new repairs and retreading processes.
Pyrolysis oil	Heavy fuel oil suits generators and other machinery. Additionally, it can be refined into alternative fuel for reuse in mine site equipment.
Gas	Gases are fed back to run the pyrolysis plant.

International Sustainability and Carbon Certification

Kal Tire received the International Sustainability and Carbon Certification (ISCC) PLUS certification which verifies that the facility meets the circular material standards for the process outputs synthetic gas, pyrolysis oil and carbon black (International Sustainability and Carbon Certification, 2023). The scope of the certification involves the mass balance option as a chain of custody option (International Sustainability and Carbon Certification, 2023). The chain of custody helps to trace the materials along the supply chain. The mass balance approach allows to track the amount and sustainability features of materials across the value chain and verify it against corresponding bookkeeping (International Sustainability and Carbon Certification, 2024). This certification demonstrates to Kal Tire customers that they promote a circular economy as the facility's outcomes are derived exclusively from waste materials, ensuring they are put to their highest and best use (Kal Tire Mining Tire Group, 2023a).

Challenges

Even though the thermal recycling process at Kal Tire, Antofagasta yields a significant number of useful materials, the marketing of the products has been a challenge. For instance, carbon black is not as clean as its virgin counterpart (Craig Guthrie, 2022). While Kal Tire is reusing some pyrolysis byproducts, such as alternative fuel in their generators and black carbon in retreading processes, the company is actively pursuing partnerships with private companies both nationally and overseas to foster new markets for these products. Finding new end-markets has proven to be challenging in some other cases, with Western Australia serving as a prime example. In 2003, Tox Free Solutions, a waste management and industrial services company in Western Australia, and a subsidiary of Cleanaway since 2018, conducted feasibility trials on a pyrolysis plant. These trials successfully broke down shredded tyres into constituents and achieved the correct mass balance when the process was finalised. However, several challenges arose, leading the company to refrain from entering the market. One significant obstacle was the necessity to shred tyres to a suitable size for the kiln, a daunting task given the varied sizes of tyres, especially larger OTR tyres. Another obstacle was that the carbon black produced was contaminated with heavy metals, necessitating multiple purification steps before resale to tyre manufacturers, and the oil had low flammability with limited applications. As previously highlighted, product quality also seems to be a hurdle to overcome in Kal Tire pyrolysis operations. The primary issue, however, was the lack of end markets for the resulting products (Matthews, 2005).

A number of process variations exist for pyrolysis, with terminologies including, destructive distillation, endothermic thermal desorption, thermal decomposition, thermal depolymerisation and thermal desorption (Tyre Stewardship Australia, 2024). The thermal decomposition of EOLTs takes place in four main stages: (i) decomposition of additives (<320 °C), (ii) decomposition of natural rubber (NR)(320–400 °C), (iii) decomposition of synthetic rubber (SR) (400–520 °C), and (iv) secondary pyrolysis of volatile compounds (520–700 °C). Temperatures for EOLT pyrolysis frequently range from 200 to 800 °C even though some works have reported higher temperatures up to 1000 °C (Nisar et al., 2018; Campuzano et al., 2023). Destructive distillation operates at the lower temperature end of pyrolysis (Green Distillation Technologies Corporation LTD, 2019) and produces carbon black (47%), steel (20%), oil (33%) (Green Distillation Technologies Corporation LTD, 2024). Tyre oil from destructive distillation has similar physicochemical properties to diesel fuel and is miscible with diesel in any blended ratio. This oil could replace conventional diesel fuel as 10% and 20% blends based on engine performance and emissions results (Hossain et al., 2020). Given the type of tyre oil produced, which is compatible with diesel, and based on the work on tyre pyrolysis oil distilled fractions by Campuzano et al. (2021), it is anticipated that the operational temperature of the destructive distillation falls in the lower range of pyrolysis, within the range of (176 – 240 °C) (Tyre Stewardship Australia, 2024).

The process begins by loading whole waste tyres as feedstock into a sealed chamber where air has been removed. In the chamber the rubber and non-steel parts are reduced into their molecular state. Some of the newly formed molecules recombine and are then condensed into 'manufactured' crude oil. A small fraction of this recycled oil is then used as a heat source for production. The remaining manufactured oil is collected to later be refined into oils. Other compounds left in the chamber namely the remaining carbon and the steel wire, which is unaltered, are then extracted, cooled, and separated. These materials can be used as a raw material in the tyre and rubber industries (Green Distillation Technologies Corporation LTD, 2019).

Case study: Australian destructive distillation in action

In Australia, destructive distillation has been utilised by Green Distillation Technologies Corporation LTD (GDTC). GDTC partnered with Tytec Group to jointly establish Perth-based Tytec Recycling Pty Ltd. The venture uses the destructive distillation technology to process OTR tyres with rim sizes ranging from 25 to 63 inches. Such OTR tyres are used on large mining dump trucks, road equipment and agricultural machinery (Green Distillation Technologies Corporation LTD, 2019).

A summary of advantages and disadvantages of pyrolysis is shown in Table 29.

Table 29. A summary of advantages and disadvantages of pyrolysis for end-of-life tyres (EOLTs).

Advantages	Disadvantages
Some pyrolysis processes do not require feedstock size reduction Enables the recovery of pyrolysis oil, carbon black and steel from EOLTs Distilled oil has physicochemical properties similar to diesel fuel Reduces need for EOLT landfilling (CE1)	Some pyrolysis processes require feedstock size reduction Rubber material is not recovered as rubber Reduces the value of original material Challenges with carbon black and pyrolysis oil quality No existing economically viable large-scale implementations in Australia Difficulty in finding commercial markets for products generated

Key messages: Pyrolysis is able to recover valuable resources such as steel, oil, and carbon black from complex waste such as EOLTs. However, some key challenges include proving the technology at an industrial scale, as it is not yet fully commercialised, and finding commercial markets for the products.

Recommendations: International Sustainability and Carbon Certification (ISCC) PLUS certification, akin to Kal Tire Chile approach, could enhance credibility and open markets for pyrolysis operations. Additionally, given the multiple challenges associated with pyrolysis technology, the economic viability of the technology should be evaluated for each location on a case-by-case basis. Comprehensive techno-economic analysis, and engagement with local communities and other relevant stakeholders should be conducted as a part of viability studies. Other key factors to consider are environmental impacts (e.g., Life Cycle Assessment), end-markets, and policy implications. These studies should inform strategic decisions and ensure alignment with broader sustainability objectives. Collaboration among stakeholders (e.g., recyclers, manufacturers, researchers) should be encouraged to enhance knowledge sharing of lessons learnt and best practices.

6.2.5 Energy recovery

Energy recovery, often also referred as waste-to-energy (Yi, 2018), is a term used to describe the extraction of energy from resources, typically waste and in this case tyres and conveyor belts. The literature tends to include pyrolysis as an energy recovery strategy, however the main difference between these two technologies is that energy recovery extracts energy whilst pyrolysis helps the extraction of other resources such as oils and carbon black (Williams, 2013).

Energy recovery is widely considered among the least efficient waste hierarchy operations since, besides extracting energy, it doesn't allow for further reuse of materials, therefore is misaligned with a circular economy framework and still promotes a linear use-dispose model (Pires and Martinho, 2019). Yet, especially in developed countries, energy recovery risks to be seen as an economic tool to create an income without the effective need to salvage resources' energy, leading to incinerators burning waste where they do not use the energy thus produced (Cimpan et al., 2015). Still, tyres have a substantial potential energy levelling at up to 35 MJ/kg, which surpasses the potential energy of coal, leaving behind fewer ashes (Ruwona et al., 2019). This high amount of energy, the decreased pressure on landfills, the avoided environmental pressure of buried tyres and other health risks make energy recovery a viable and attractive option when other technologies are not available. It is important to underline that tyre incineration may produce harmful emissions (Xiao et al., 2022) and other alternatives, such as rubber shredding for reuse could help reduce the emissions from end-of-life treatments of a further 50% (Bianco et al., 2021).

Incineration technologies and regulation

Energy recovery is typically done through incineration, which produces energy that can be used in other energy-intensive industrial plants such as cement kilns or power plants (Van Beukering and Janssen, 2001), which could guarantee an efficiency of about 40% when using steam cycle (Mavukwana et al., 2020). Because of the harmful emissions from tyre incineration in cement kilns, which was common practice in the early 2000's, European directives such as 2000/76/EC imposed strict emission limits for cement kilns and material separation strategies (Valentini and Pegoretti, 2022). A more recent European Directive, 2010/75/EU imposes even stricter emissions on nitrogen oxides (NO_x) and sulfuric dioxide (SO_2). Despite these stringent parameters, incineration in cement kilns requires minimal treatment of rubber, making it a more appealing procedure. However, how to safely remain below the limitations imposed by the Directive remain under-researched (Goevert, 2024). Problematically, the ashes that result from incineration can be landfilled, but they are considered unsafe for commercial use (Fajimi et al., 2024).

Global examples of energy recovery

Despite the many concerns related to tyre incineration, it could be a practical solution in developing countries which often need to divert tyres from landfills and address their often-struggling electricity grids. This is, for example, the case of South Africa, where tyre incineration is considered a promising solution (Mavukwana et al., 2020). Additionally, incineration can be seen as the best option when planning for rubber end-of-life strategies due to the complexity of other options, since, for example, rubber impurities in recovered fibres could hinder their reusability, making incineration and energy recovery a preferrable option (Battista et al., 2021). Still, many countries opt for pyrolysis as a more effective way to manage tyres and rubber waste (Campuzano et al., 2023; Son et al., 2023; Yaqoob et al., 2021). A summary of advantages and disadvantages of energy recovery from EOLTs and conveyor belts through incineration is shown in Table 30.

Table 30. A summary of advantages and disadvantages of energy recovery from end-of-life tyres (EOLTs) and conveyor belts through incineration.

Advantages	Disadvantages
- Enables energy recovery - Reduces need for EOLT landfilling	- Not aligned with circular economy - Rubber material is not recovered

Key messages: Energy recovery, including incineration, is an alternative waste management strategy for complex rubber wastes in Australia. While not as resource efficient as pyrolysis, energy recovery can effectively utilize the high energy content of rubber waste, particularly tyres and conveyor belts, to generate electricity or heat, reducing the reliance on fossil fuels and mitigating environmental impacts associated with landfilling.

Recommendations: Incorporating energy recovery into the waste management strategy for rubber waste in Australia can offer several benefits. It can help address the substantial energy content of rubber waste, especially from the resource sector, which can be challenging to recycle using traditional methods. Establishing energy recovery facilities, particularly incineration plants equipped with proper emission control technologies, can contribute to reducing greenhouse gas emissions and providing a sustainable energy source. Collaborating with experienced partners and aligning with strict emission standards, as seen in European directives, can ensure that energy recovery from rubber waste is conducted safely and efficiently in Australia. Additionally, raising awareness among stakeholders about the benefits of energy recovery and its role in a circular economy framework can encourage its adoption and contribute to a more sustainable waste management system in the region.

6.3 Comparison of technology for EOLTs and conveyor belts in Australia

Improving the value recovery of EOLTs and conveyor belts in Australia is unlikely to result from the uptake of a single technology or market pathway. Typically, technologies for resource recovery and recycling are preference based on alignment with the mandated waste hierarchy in Australia, and a comparison of the various technologies discussed in this report related to the waste hierarchy is shown in Figure 27.

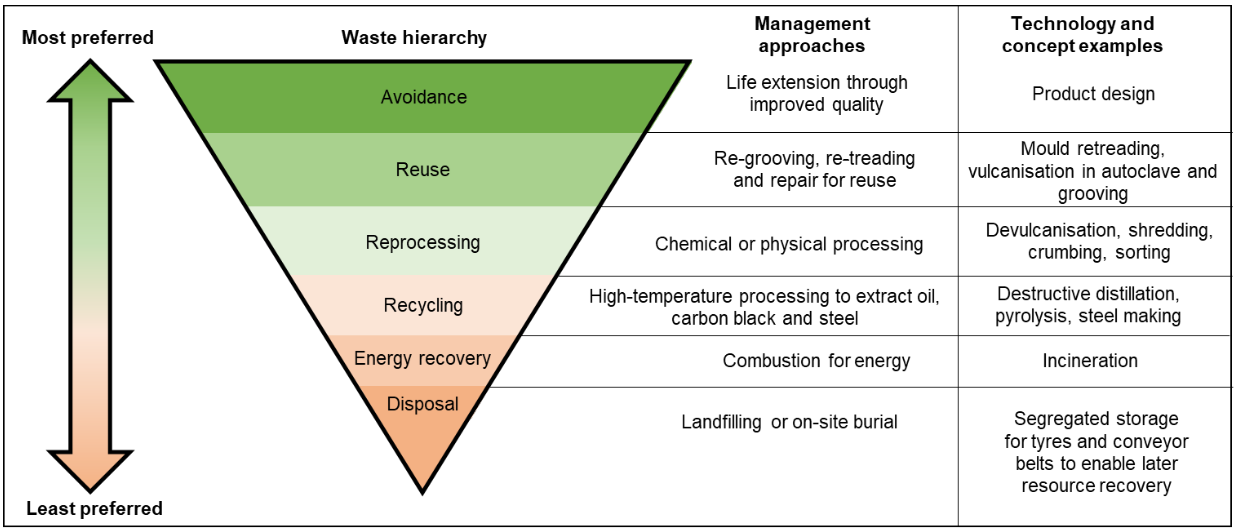

Figure 27. Tyre management approaches and technologies mapped against the waste hierarchy.

Extending the life of tyres and conveyor belts with improved quality through product design enables the avoidance of waste generation, whereas re-grooving, retreading and repair of tyres and conveyor belts facilitates their reuse and circularity. Chemical and physical reprocessing of EOLTs and conveyor belts through devulcanisation, size reduction and sorting enables the recovery of valuable materials for use in other applications. High temperature processing through pyrolysis or destructive distillation does not facilitate the recovery of rubber, but it does produce other end-products, namely oil, carbon black and steel. The least preferred resource recovery option is combustion through incineration for energy as material recovery is not possible.

Using the traditional waste hierarchy to prioritise or approve technology can be problematic, as it does not allow the value of inputs, outputs and impacts to be captured in a wholistic manner across a value chain. More recently, considering circular economy principles as a more wholistic approach to technology prioritisation is likely to be the basis of technology selection and prioritisation in the future as Australia moves towards circular economy. The circular economy principles are driven by design and are defined as (1) eliminate waste and pollution, (2) circular products and materials (at their highest value) and regenerate nature (3) (Ellen MacArthur Foundation, 2024).

Considering both the waste hierarchy and circular economy principles, some advantages and disadvantages of various technologies are shown in Table 31.

Table 31. Advantages and disadvantages of various technologies for value recovery from end-of-life tyres (EOLTs) and conveyor belts based on the waste hierarchy and circular economy (CE) principles#.

Technology	Advantages	Disadvantages
Re-grooving and retreading	- Aligned with waste hierarchy priorities for enabling tyre reuse - Extend the tyre life and improve circularity (CE2) - Reduce virgin material consumption, waste generation, energy consumption and emissions (CE1) - Potential for economic savings for good quality tyres - Creates local jobs and thus support local economy	- Poor quality tyres are not suitable for retreading
Devulcanisation	- Extend the tyre life and improve circularity (CE2) - Reduces virgin material consumption (CE1) - Reduces waste generation (CE1) - Adaptability of various devulcanisation technologies to different EOLT compositions - Improved properties enabling high-performance applications and re-engineering (CE2) - Active research presents opportunities for technology innovation	- Process complexity and requirement for optimisation of multiple parameters posing challenges for large-scale implementation - Energy intensity (in thermal and microwave assisted devulcanisation) - Hazardous nature of some devulcanisation chemicals - Economic viability depends on factors such as input costs, market demand, and scalability
OTR tyre size reduction technologies	- Reduces the size of OTR tyres to be suitable for subsequent resource recovery technologies	- Represents pre-treatment rather than actual resource recovery technology - Reduces value of original material - Energy consumption
EOLTs as carbon feedstock in steel-making	- Can reduce coal demand for steelmaking from virgin and recycled metals (CE1) - Enables recovery of steel from tyres (CE2) - Environmental benefits as compared to the use of EOLTs for energy recovery, cement making or civil engineering (CE1) - Reduce need for EOLT landfilling (CE1) - Reduces electricity consumption and scope one carbon emissions (CE1)	- Rubber and fibre materials are not recovered for reuse
Pyrolysis	- Enables the recovery of pyrolysis oil, carbon black and steel from EOLTs - Some pyrolysis processes do not require feedstock size reduction - Distilled oil has physicochemical properties similar to diesel fuel - Reduces need for EOLT landfilling (CE1)	- Some pyrolysis processes require feedstock size reduction - Rubber material is not recovered as rubber - Reduces value of original material - Challenges with carbon black and pyrolysis oil quality - No existing economically viable large-scale implementations in Australia - Difficulty in finding commercial markets for products generated
	-	-
Incineration	- Enables energy recovery - Reduces need for EOLT landfilling (CE1)	- Rubber material is not recovered - Reduces value of original materials

#Circular economy principles are based on design and are defined as (1) eliminate waste and pollution, (2) circular products and materials (at their highest value) and regenerate nature (3).

To enable circularity of rubber containing materials, Value Retention Models (VRM), Life Cycle Assessment (LCA) and Material Circular Indicators (MCI) as key metrics for material circularity with the aim of reducing consumption and production, diverting waste, valuing materials, emissions accounting and closing material loops are likely to drive investment and market development for EOLT and conveyor belt management. In all instances, enablers including product stewardship, tracking and traceability, data related to material flows and feedstock composition are all critical to the development of EOLT and conveyor belt management technology. Furthermore, technology assessments should also consider contextual elements such as location, supply chain dynamics, market conditions, policy mechanisms in place, process efficiency, as well as impacts on the local and broader community and the environment. A comprehensive assessment will enable informed, unbiased decisions.

7 Strategy for communicating with Indigenous communities

NESP2 outlines three categorical approaches for engaging Indigenous communities: (i) Indigenous-Led, (ii) Co-Design, and (iii) Communication. In the context of this project, communication is considered an integral component of the engagement strategies aimed at disseminating project findings.

As part of the NESP2 programme, the project considers the Australian Institute of Aboriginal and Torres Strait Islander Studies (AIATSIS) Code of Ethics while communicating and collaborating with the Aboriginal communities in Australia. The AIATSIS Code respects Aboriginal and Torres Strait Islander values and worldviews, acknowledging the wisdom and diversity of Indigenous knowledge systems (Australian Institute of Aboriginal and Torres Strait Islander Studies, 2020).

The AIATSIS research ethics framework is structured around four principles:

1. Indigenous self-determination
2. Indigenous leadership
3. Impact and value
4. Sustainability and accountability.

Each principle gives rise to responsibilities while considering various aspects of research collaboration, data collection and research integrity as shown in Figure 28.

Figure 28. Responsibilities attached to the consideration of the Australian Institute of Aboriginal and Torres Strait Islander Studies Code of Ethics (Australian Institute of Aboriginal and Torres Strait Islander Studies, 2020).

Since the study considers communication as means of disseminating and collaborating with the Indigenous communities, the current NESP2 governance of communication channel will consider navigate with effective communication mechanisms.

The governance structure of the NESP2 project incorporates Hub Senior representatives, including the Senior Indigenous Facilitator. Consequently, project findings will be shared with NESP and Hub Indigenous representatives to identify pertinent Indigenous communities and organizations for effective communication.

To effectively communicate key findings for potential future co-design and Indigenous-led research projects, the following actions will be undertaken:

- Engaging with the Hub Senior Representative and the representative from the Department for comprehensive dissemination.
- Establishing communication channels with Indigenous communities/representatives actively involved in NESP projects (e.g., IP5.4 project) to share research findings and solicit feedback.
- Collaborating with cross-hub programs such as Resilient Landscape to ensure broader dissemination and engagement across various initiatives.

This strategic approach aims to foster transparent and inclusive communication channels, ensuring that project outcomes are effectively communicated to all relevant stakeholders and promote meaningful engagement and collaboration with Indigenous communities.

8 Conclusions and recommendations

Product stewardship schemes

While the reviewed overseas tyre stewardship schemes were all compulsory, the Australian tyre stewardship scheme is voluntary, and as a result, not all imported tyres are captured under the Australian scheme. Moreover, tyre landfilling and/or on-site disposal bans exist in many countries, whereas in Australia, landfilling and on-site disposal of tyres e.g. at mine sites is still allowed, which reduces the tyre flows collected for value recovery. Many of the reviewed countries (including Australia) had implemented auditing of the companies that carry out EOLT collections and processing to ensure that the stewardship scheme is effectively implemented. Import levies or fees were used for tyres in Australia, Denmark, Finland and New Zealand. In most countries except for Australia, recycling fees were included to the purchase price of new tyres. However, in the Australian stewardship scheme, there is no incentive to encourage returning waste tyres for recycling. Rather, disposal fees are charged when disposing EOLTs, leading to illegal dumping or stockpiling. Incentives are implemented in some countries to support tyre recycling, e.g. in the form of lower recycling fees for retreaded tyres, subsidies provided to end-of-life collectors or incentive payments for EOLT processing and manufacturing of tyre-derived products. None of the reviewed stewardship schemes included conveyor belts into the scheme. Based on the review of the examples of overseas stewardship schemes, the following recommendations were made for Australia:

- Including rubbery conveyor belts into the stewardship scheme
- Enacting a regulated stewardship scheme to capture all tyre and conveyor belt importers, and all stakeholders that sell new tyres and conveyor belts and collect, transport, and/or process EOLTs
- Import levies to be extended to all tyre and conveyor belt imports (including tyres fitted on vehicles and equipment) to cover costs of EOLT and conveyor belt recycling
- Implementing a recycling fee as part of the price of new tyres and conveyor belts instead of charging a fee for returning EOLTs or conveyor belts for recycling. Moreover, an additional bond fee could be charged as part of the price of new tyres/conveyor belts to allow a refund to be paid upon returning the used tyres/CB for recycling, to further incentivise material recovery. These fees (import levies passed to consumers, recycling fees and bond) could be bundled into a single fee to consumers paid at the point of purchase. More complete economic modelling of fee disbursements across the value chain needs to be completed.
- Banning landfilling and on-site disposal of EOLTs and conveyor belts in all states and territories to complement the compulsory stewardship regulations
- Extending auditing to all stakeholders that carry out tyre and conveyor belt imports and all stakeholders that sell new tyres and conveyor belts and collect, transport, and/or process EOLTs
- Setting clear targets and timeframes to provide a roadmap for all stakeholders, and unifying collection and valorisation targets over a specific timeframe to enable building recycling capacity, but preventing excessive stockpiling
- Separating tyres based on categories and recognising the logistical and economic differences between categories to allow for tailored collection and valorisation strategies

- Incentivising remote, geographically isolated industries (e.g., mining companies) and allowing them flexibility to valorise EOLTs and conveyor belts themselves rather than having to deal with long-distance transport
- Implementing robust tracking systems to effectively monitor EOLTs and conveyor belts that also cover EOLTs and conveyor belts valorised independently by industries, where they have to report directly to the government and not through waste management systems (producer responsibility organisations)
- Proactively developing policies, incentive mechanisms and research and development initiatives to encourage retreading, collection and processing of EOLTs and manufacturing and use of tyre-derived products

Enablers for recycling

Currently classification systems for EOLTs vary across Australia, and waste conveyor belts are not classified as controlled waste in Australia, leading to inadequate monitoring and lack of data on arisings, transport, and fate of waste conveyor belts. Moreover, the alignment of jurisdictional hazardous waste codes remains poor, and there is a lack of regulatory consistency across borders, diminishing the capacity to develop a consistent national system for waste management. Classifying waste tyres and conveyor belts consistently is crucial for enabling their recycling. Moreover, establishing comprehensive tracking mechanisms is necessary to monitor the movement of these waste streams accurately. Standardising the units of measurement (mass or volume) across stakeholders is essential for reliable data collection and analysis. Without standardised units, meaningful insights from the data become challenging to derive. Standards should also be implemented for imported tyres, to ensure that they are of good enough quality to allow retreading. Enablers including consistent waste classifications, coordinated tracking and traceability, data related to material flows and feedstock composition, and collaboration across the value chain are all critical to the successful development of EOLT and conveyor belt management technology and development of market pathways. Moreover, the creation and support of recycling hubs or ecosystems where tyre/conveyor belt recyclers and industries that consume tyre/conveyor belt-derived products and fuels co-exist allows technology development and conversion of rubber waste to valuable products to support circularity.

Reverse logistics

Reverse logistics, including the adoption of Industry 4.0 technologies, are crucial for managing EOLTs, conveyor belts and other rubbery wastes in Australia. Reverse logistics can contribute to a more sustainable waste management system by repurposing end-of-life materials and minimising landfilling. To enhance reverse logistics for rubber waste in Australia, it is recommended to explore opportunities and challenges encountered for the reverse logistics of other materials, e.g. in terms of the application of technologies, supply chain logistics, and economic systems supporting effective waste management. Addressing the complexity of Australia's geography by drawing lessons from global examples and applying them to both urban and rural settings is essential. A regulatory framework that mandates waste separation and diversion to collection points should be established and can ensure effective waste management and resource recovery. It is also important to consider Industry 4.0 technologies to improve reverse logistics operations, but their implementation should be approached cautiously, considering their feasibility and economic viability in the rubber waste industry.

Technologies for value recovery

Products derived from EOLTs and conveyor belts have versatile applications across industries, contributing to environmental sustainability and fostering innovation. The increasing recognition of the economic and environmental benefits of recycling, coupled with technological advancements, is driving the expansion of the market for recycled rubber products. However, to foster circular economy solutions effectively, it is crucial to maximize the material value of EOLTs and prioritize waste hierarchy in product markets, thus ensuring the achievement of sustainability goals. The following are the key considerations for reusing and creating a secondary market for EOLTs:

- Retreading Benefits: Retreading worn-out tyres extends their life cycle, conserves resources, and significantly reduces environmental impact. Advanced technologies and quality control measures in the retreading industry make it a viable and environmentally responsible alternative to manufacturing new tyres.
- Upcycling Opportunities: Upcycling EOLTs involves repurposing tyre components into higher-value products, such as playground surfaces and construction materials, contributing to resource efficiency and reduced emissions.
- Recycling Initiatives: Recycling EOLTs involves breaking them down into constituent materials for reuse in various applications, including road construction and energy production. Effective recycling initiatives contribute to reducing landfill waste, conserving raw materials, and addressing environmental hazards.
- Tyre-derived fuel (TDF): Converting EOLTs into tyre-derived fuel offers an alternative energy source, contributing to waste reduction and energy production while addressing environmental concerns associated with tyre incineration.

Improving the value recovery of EOLTs and conveyor belts in Australia is unlikely to result from the uptake of a single technology or market pathway. Prioritisation and investment into technologies should be aligned to circular economy principles, enabled through wholistic value chain assessments such as Value Retention Models (VRM), cost/benefit comparison, Life Cycle Assessment (LCA) and Material Circular Indicators (MCI). Enablers including product stewardship, tracking and traceability, data related to material flows and feedstock composition are all critical to the development of EOLT and conveyor belt management technology. Technology assessments should also consider contextual elements such as location, supply chain dynamics, market conditions, policy mechanisms in place, process efficiency, as well as impacts on the local and broader community and the environment. A comprehensive assessment will enable informed, unbiased decisions and ensure that sustainable development of EOLT and conveyor belt management is implemented in Australia.

Strategy for communicating with Indigenous communities

This project considers communication as a part of the dissemination of the research findings and engagement of Indigenous communities. The governance structure of the NESP2 project includes Hub representatives, including the Senior Indigenous Facilitator, ensuring that project findings are effectively shared with Indigenous communities and organizations. To facilitate meaningful engagement, key actions will be taken, such as engaging with Hub Senior Representatives and the Department for dissemination, establishing communication channels with Indigenous communities actively involved in NESP projects, and collaborating with cross-hub programs. This strategic approach aims to promote transparent and inclusive communication, ensuring that project outcomes are effectively communicated and foster meaningful engagement and collaboration with Indigenous communities for potential future co-design and Indigenous-led research projects.

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WorldData (2024c) Italy. https://www.worlddata.info/europe/italy/economy.php

WorldData (2024d) New Zealand. https://www.worlddata.info/oceania/new-zealand/economy.php

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Appendix 1: List of engaged organisations

Organisations engaged in Stage 1 of the project with response:

Australian Flexible Pavement Association (AfPA)
Australian Tyre Recyclers Association (ATRA)
Bandag Bridgestone
Chamber of Minerals and Energy (CME)
Continental (Conveying Solutions)
Data WA
DWER (Controlled Waste tracking, secondary reuse of recovered materials)
Elan Energy Matrix Pty Ltd
Fremantle Ports Authority
Great Southern Development Commission
Better Wear Solutions
Infrastructure WA
Kimberley Development Commission
Kimberly Ports Authority
Main Roads WA
Michelin Australia Pty Ltd
4M Waste Pty Ltd
Newcrest Mining Ltd
Pearl Global
Southern Ports Authority
Tyre Stewardship Australia
Tyrecycle
Unnamed conveyor belt engineering consultancy
Unnamed framer from the Great Southern Region
Western Australian Local Government Association (WALGA)
Wheatbelt Development Commission

Organisations engaged in Stage 2 of the project with response:

Aliapur, France
Australian Tyre Recyclers Association (ATRA), Australia
British Columbia Tyre Stewardship, Canada
Canadian Association of Tyre Recycling Agencies (CATRA), Canada
Danish Tyre Trade Environmental Foundation (Dækbranchens Miljøfond), Denmark
Department of Climate Change, Energy, the Environment and Water, Australia
Ecopneus, Italy
Finnish Tyre Recycling (Suomen Rengaskierrätys), Finland
Manitoba Tyre Stewardship, Canada
Marangoni S.p.A., Italy
Ontario Tyre Stewardship, Canada
New Brunswick Tyre Stewardship, Canada
Saskatchewan Tyre Stewardship, Canada
Tyre Stewardship Australia (TSA), Australia
Tyromer Inc, Canada
Quebec Tyre Stewardship, Canada
Graphene Engineering Innovation Centre, UK

Ministerio del Medio Ambiente (Environment Minister), Chile
Kal Tyre, Canada
Kal Tyre, Australia

Organisations engaged in Stage 1 of the project with no response:

Austroads
CD Dodd Scrap Metal Recyclers
Department of Transport
Development WA
Gascoyne Development Commission
Goldfields Esperance Development Commission
Forrestfield Recyclers
Landgate
Lomwest Enterprises Pty Ltd
Mid West Development Commission
Mid West Ports Authority
One Rail Australia
Peel Development Commission
Pilbara Development Commission
Pilbara Ports Authority
Primary Industries and Regional Development
PROK Conveyors
Public Transport Authority
Rural Business Development Corporation
South West Development Commission
Tytec Recycling Australia
WA Belting
WA Farmers
Western Australian Farmers Federation (WAFarmers)
Western Australian Planning Commission

Organisations engaged in Stage 2 of the project with no response:

Alberta Tyre Stewardship, Canada
Conica, UK
Kal Tyre, Chile
Liberty Tyre, Canada and USA
Michelin, France
Newfoundland Tyre Stewardship, Canada
Nova Scotia Tyre Stewardship, Canada
Provulco, France
Pyrum, Germany
Stepchange, Canada
Tyrewise, New Zealand

Appendix 2: Background information on countries with product stewardship schemes for end-of-life tyres (EOLTs) and conveyor belts

Table A1. Background information on countries with product stewardship schemes for end-of-life tyres (EOLTs) and conveyor belts.

Country	Annual EOLT generation (t)	Population	Country land area (km^2)	Gross domestic product (GDP) of country	Mining (% of GDP)	Agriculture, includes forestry and fishing (% of GDP)
Australia	545,000	27,313,964 (2023)	7,688,287	AU$2.4 trillion (2023)	13.6 (2023)	2.7 (2022)#
Canada	446,647 (2020)	38,929,902 (2022)	[i]8,965,590	US$2.16 trillion (2022)	5.78 (2021)	1.8 (2020)
Chile	140.000	19,603,733 (2022)	2.006.096 (including territories in the American continent, Oceania and Antarctica) 743,532 (in the American continent)	0.30 trillion (2022)	Direct impact: 14.6 Including indirect impacts: 20 (2021)	3.5 (2022)
Denmark	46,000	5,903,000 (2024)	42,920	US$0.40 trillion (2022)	1.25 (2022, includes quarrying)	1.2 (2022)
Finland	64,600	5,611934 (2024)	338,450	US$0.283 trillion (2022)	Not available	2.3 (2022)
France	422.579 (2019)	67,971,311 (2022)	635,933	US$2.78 trillion (2022)	1.73 (2020)	1.9 (2022)
Italy	350,000	58,940,000 (2022)	301,340	US$2.05 trillion (2022)	0.3 (2019)	1.8 (2022)
New Zealand	55,000	5,124,000 (2022)	267,710	US$0.248 trillion (2022)	0.8 (2023)	5.7 (2020)

Data Sources:

Australia: Australian Bureau of Statistics, 2024a; Australian Bureau of Statistics, 2024b; Department of Agriculture, Fisheries and Forestry, 2024; Geoscience Australia, 2024; International Trade Association, 2024a; Tyre Stewardship Australia, 2023; World Bank Group, 2024a

Canada: Agriculture and Agrifood Canada, 2024; Canadian Association of Tire Recycling Agencies, 2021; The Mining Association of Canada, 2024; United Nationals Trade & Development, 2024; World Bank Group, 2024b

Chile: Biblioteca del Congreso Nacional de Chile, 2024; Ministerio del Medio Ambiente, 2021; World Bank Group, 2024c; World Bank Group, 2024b

Denmark: Danish Tyre Trade Environmental Foundation, 2023c; Statista, 2024; World Bank Group, 2024a; WorldData, 2024a

Finland: Lloyds Bank, 2024; Tuominen, 2024; Statistics Finland, 2024; WorldData, 2024b

France: European Tyre & Rubber Manufacturers' Association, 2020; Institut national de la statistique et des études économiques, 2024; United Nationals Trade & Development, 2024; World Bank Group, 2024e

Italy: Ecopneus, 2024j; Trimmer, 2019; World Bank Group, 2024a; WorldData, 2024c

New Zealand: Infometrics, 2024; WorldData, 2024d

Appendix 3: Waste codes and material classified as Controlled Waste by the National Environment Protection Council (NEPC)

Table A2. Waste codes and material classified as Controlled Waste by the National Environment Protection Council (NEPC)

Waste Code	Waste materials
B100	Acidic solutions or acids in solid form
K100	Animal effluent and residues (abattoir effluent, poultry and fish processing waste)
D170	Antimony, antimony compounds
D130	Arsenic, arsenic compounds
N220	Asbestos
D290	Barium compounds other than barium sulphate
C100	Basic solutions or bases in solid form
D160	Beryllium, beryllium compounds
D310	Boron compounds
D150	Cadmium, cadmium compounds
N230	Ceramic-based fibres with physico-chemical characteristics similar to those of asbestos
D350	Chlorates
D140	Chromium compounds that are hexavalent or trivalent
R100	Clinical and related wastes
D200	Cobalt compounds
N100	Containers that are contaminated with residues of a listed waste
D190	Copper compounds
A130	Cyanides (inorganic)
M210	Cyanides (organic)
N160	Encapsulated, chemically fixed, solidified or polymerised wastes
G100	Ethers
N190	Filter cake
N190	Fire debris and fire wash waters
N140	Fly ash
N150	Grease trap waste
G150	Halogenated organic solvents
M260	Highly odorous organic chemicals (including mercaptans and acrylates)
D110	Inorganic fluorine compounds excluding calcium fluoride
D330	Inorganic sulphides
M220	Isocyanate compounds
D220	Lead; lead compounds
D120	Mercury; mercury compounds
D100	Metal carbonyls
D210	Nickel compounds
D300	Non-toxic salts
H110	Organic phosphorus compounds
G110	Organic solvents excluding halogenated solvents

Waste Code	Waste materials
M160	Organohalogen compounds - other than substances referred to in this list
D340	Oxidising agents
M150	Perchlorates
D360	Phenols, phenol compounds including chlorophenols
T120	Phosphorus compounds excluding mineral phosphates
M170	Polychlorinated dibenzo-furan (any congener)
M180	Polychlorinated dibenzo-p-dioxin (any congener)
T210	Reactive chemicals
T220	Reducing agents
T190	Residues from industrial waste treatment/disposal operations.
D240	Selenium; selenium compounds
N120	Soils contaminated with a controlled waste
M250	Surface active agents (surfactants), containing principally organic constituents and which may contain metals and inorganic materials
K140	Tannery wastes (including leather dust, ash, sludges and flours)
D250	Tellurium, tellurium compounds
D180	Thallium; thallium compounds
M230	Triethylamine catalysts for setting foundry sands
T140	Tyres
D270	Vanadium compounds
T100	Waste chemical substances arising from research and development or teaching activities including those which are not identified and/or are new and whose effects on human health and/or the environment are not known
E100	Waste containing peroxides other than hydrogen peroxide
A120	Waste from heat treatment and tempering operations containing cyanides
H170	Waste from the manufacture, formulation and use of wood-preserving chemicals
R140	Waste from the production and preparation of pharmaceutical products
R120	Waste from the production, formulation and use of biocides and phytopharmaceuticals
F100	Waste from the production, formulation and use of inks, dyes, pigments, paints lacquers and varnish
G160	Waste from the production, formulation and use of organic solvents
T120	Waste from the production, formulation and use of photographic chemicals and processing materials
F110	Waste from the production, formulation and use of resins, latex, plasticisers, glues and adhesives
J100	Waste mineral oils unfit for their original intended use
E120	Waste of an explosive nature not subject to other legislation
J120	Waste oil/water, hydrocarbons/water mixtures or emulsions
R120	Waste pharmaceuticals, drugs and medicines
A100	Waste resulting from surface treatment of metals and plastics
J160	Waste tarry residues arising from refining, distillation, and any pyrolytic treatment
M100	Waste, substances and articles containing or contaminated with polychlorinated biphenyls (PCBs), polychlorinated naphthalenes (PCNs), polychlorinated terphenyls (PCTs) and/or polybrominated biphenyls (PBBs)
K190	Wool scouring waste
D230	Zinc compounds

Table A3. Controlled waste categories in Western Australia.

Category Group	Waste Code	Description of Waste Type
A – Plating and heat treatment	A100	Waste resulting from the surface treatment of metals and plastics
	A110	Waste from heat treatment and tempering processes which use cyanide
	A130	Inorganic cyanide
B – Acids	B100	Acidic solutions or acids in solid form
C – Bases	C100	Basic (alkaline) solutions or bases (alkalis) in solid form
D – Inorganic chemicals	D100	Metal carbonyls
	D110	Inorganic fluorine compounds (excluding calcium fluoride)
	D120	Mercury and mercury compounds
	D130	Arsenic and arsenic compounds
	D140	Chromium compounds
	D141	Tannery waste containing chromium
	D150	Cadmium and cadmium compounds
	D151	Used nickel cadmium batteries
	D160	Beryllium and beryllium compounds
	D170	Antimony and antimony compounds
	D180	Thallium and thallium compounds
	D190	Copper compounds
	D200	Cobalt compounds
	D210	Nickel compounds
	D211	Used nickel metal hydride batteries
	D220	Lead and lead compounds
	D221	Used lead acid batteries
	D230	Zinc compounds
	D240	Selenium and selenium compounds
	D250	Tellurium and tellurium compounds
	D270	Vanadium compounds
	D290	Barium and barium compounds
	D300	Non-toxic salts
	D310	Boron compounds
	D330	Inorganic sulfides
	D340	Perchlorates
	D350	Chlorates
	D360	Phosphorus compounds excluding mineral phosphates
E – Reactive chemicals	E100	Waste containing peroxides excluding hydrogen peroxide
	E120	Waste of an explosive nature not subject to other legislation
	E130	Highly reactive chemicals not otherwise specified
F - Paints, resins, inks and organic sludges	F100	Aqueous-based wastes from the production, formulation and use of inks, dyes, pigments, paints, lacquers and varnish
	F110	Aqueous-based wastes from the production, formulation and use of resins, latex, plasticisers, glues and adhesives
	F120	Solvent based-wastes from the production, formulation and use of inks, dyes, pigments, paints, lacquers and varnish
	F130	Solvent based wastes from the production, formulation and use of resins, latex, plasticisers, glues and adhesives
G – Organic solvents	G100	Ethers & highly flammable hydrocarbons
	G110	Non-halogenated organic solvents
	G130	Dry-cleaning wastes containing perchloroethylene
	G150	Halogenated organic solvents Not otherwise specified

Category Group	Waste Code	Description of Waste Type
	G160	Waste from production, use and formulation of organic solvents not otherwise specified
	H100	Waste from the production, formulation or use of biocides and phytopharmaceuticals
	H110	Organic phosphorous compounds
	H130	Organochlorine pesticides
	H170	Waste wood-preserving chemicals
J – Oils	J100	Waste mineral oils unfit for their intended purpose
	J120	Waste oil and water mixtures or emulsions, and hydrocarbon and water mixtures or emulsions
	J130	Oil interceptor wastes
	J160	Waste tarry residues arising from refining, distillation or pyrolytic treatment
	J170	Used oil filters
	J180	Oil sludge
K – Putrescible and organic wastes	K100	Animal effluent and residues
	K110	Waste from grease traps
	K130	Sewage waste from the reticulated sewerage system
	K140	Tannery wastes not containing chromium
	K190	Wool scouring wastes
	K200	Food and beverage processing wastes
	K210	Septage wastes
L – Industrial wash water	L100	Car and truck wash waters
	L150	Industrial wash waters contaminated with a controlled waste
M – Organic chemicals	M100	Waste substances and articles containing polychlorinated biphenyls (PCBs)
	M105	Waste substances and articles containing polybrominated biphenyls (PBB), polychlorinated naphthalenes (PCN), and/or polychlorinated terphenyls (PCT)
	M130	Non-halogenated organic chemicals
	M150	Phenols, phenol compounds including halogenated phenols
	M160	Organohalogen compounds not elsewhere listed
	M170	Polychlorinated dibenzo-furan (any congener)
	M180	Polychlorinated dibenzo p-dioxin (any congener)
	M210	Cyanides (organic)/ nitriles
	M220	Isocyanate compounds
	M230	Triethylamine catalysts
	M250	Surfactants and detergents
	M260	Highly odorous organic chemicals including mercaptans and acrylates
	M270	Per- and poly-fluoroalkyl substances (PFAS) contaminated materials, including waste PFAS containing products and contaminated containers
N -Soils and Sludge	N100	Containers or drums contaminated with residues of a controlled waste
	N120	Soils contaminated with a controlled waste
	N140	Fire debris or fire wash waters
	N150	Fly ash excluding fly ash generated from Australian coal fired power stations
	N160	Encapsulated, chemically fixed, solidified or polymerised controlled wastes
	N190	Filter cake containing a controlled waste

Category Group	Waste Code	Description of Waste Type
	N205	Industrial waste treatment plant residues
	N220	Asbestos
	N230	Ceramic based fibres with physico-chemical characteristics similar to asbestos
R – Clinical and pharmaceutical	R100	Clinical and related wastes
	R120	Waste pharmaceuticals, drugs and medicines
	R130	Cytotoxic waste
	R140	Waste from production or preparation of pharmaceutical products
T – Miscellaneous	T100	Waste chemical substances arising from research and development or teaching activities
	T120	Waste from production or formulation of photographic chemicals or processing materials.
	T140	Used Tyres

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