TyreStewardship AUSTRALIA

Hydrogen from tyres

Exploring Hydrogen Opportunities from End-of-Life Tyre Pyrolysis

Australian Government Accredited Product Stewardship Scheme

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Contents

Glossary

CCUS	Carbon capture utilisation or storage
kt	kilo tonnes (1,000 tonnes)
Mt	million tonnes (1,000,000 tonnes)
SMR	Steam methane reforming
TPC	Tyre pyrolysis carbon
TPG	Tyre pyrolysis gas
Tph	tonnes per hour
TPO	Tyre pyrolysis oil
TSA	Tyre Stewardship Australia
WGS	Water-gas shift

Executive summary

Australia generates significant volumes of end-of-life tyres (approximately 537,000 tonnes annually), with recovery outcomes constrained by limited end-markets for tyre-derived materials. Pyrolysis of end-of-life tyres remains a frequently discussed technology option, involving the thermal degradation of tyres into more fundamental materials for further use. The opportunities and challenges for pyrolysis technology in Australia have been discussed previously and informed the direction of this work.

Recent interest from the tyre industry has justified this analysis, which considers both the technical pathways for hydrogen production from tyre pyrolysis intermediates and the broader context of hydrogen market development in Australia. This is particularly relevant in the context of Australia's 2024 National Hydrogen Strategy, which focuses on accelerating the development of a competitive hydrogen industry and supporting large-scale deployment.

Globally, hydrogen production is approximately 100 Mt per year, with the majority currently derived from fossil fuels such as natural gas and coal. Hydrogen produced via these pathways is typically classified as black, brown, or blue, depending on whether carbon capture and storage is applied to mitigate associated carbon emissions.

In 2022, Australian hydrogen production was around 500 kt, almost entirely derived from natural gas, with the hydrogen used primarily as a feedstock for ammonia production (80%) and in crude oil refineries (20%). Several proposed hydrogen projects are in development, the majority of which rely on renewable energy sources such as wind and solar to power electrolysers. If successfully established, these projects have the potential to position Australia as a globally significant producer of renewable hydrogen.

Beyond technical feasibility, there are several key barriers that must be addressed to enable hydrogen production at scale. These include the high cost of hydrogen, particularly renewable hydrogen, as well as challenges associated with storage, handling, and safe transport. In addition, broader adoption of hydrogen technologies, such as fuel cells, remains necessary to support demand.

To extract hydrogen from end-of-life tyres, the chemical structure of the tyres will need to be broken down to more fundamental molecules, one option being controlled thermal degradation or 'pyrolysis'.

Modelling presented in this report estimates that for every tonne of end-of-life tyres input into pyrolysis and steam reforming could generate 0.188 tonnes of hydrogen, and 2.26 tonnes of carbon dioxide. This process is most technically similar to hydrogen generation from natural gas, which is labelled as grey hydrogen if there is no carbon capture.

Hydrogen represents an additional potential product from end-of-life tyres, aligning with Australia's National Hydrogen Strategy and decarbonisation of the economy **provided there is at least 90% capture of carbon**, similar to the requirements for blue hydrogen generated from natural gas.

Pyrolysis outputs like hydrogen can be considered in the waste hierarchy as either "recycling" or "energy recovery", depending on end market use. If hydrogen is used to generate ammonia and is further used as a chemical feedstock it could be considered recycling, whereas if it is used as a fuel, it would be considered energy recovery.

This report discusses the theoretical opportunity to generate hydrogen from end-of-life tyres. It provides an outline of what is technically possible if enabling conditions such as sufficient scale, favourable economics, supportive policy settings and reliable hydrogen offtake were in place. Realising these opportunities would still require robust pyrolysis systems to produce the necessary input materials. While the potential pathways are technically feasible, significant barriers remain to the deployment of tyre pyrolysis at scale in Australia, as discussed in detail in the previous tyre pyrolysis report.

Every year, Australia generates more end-of-life tyres than the current markets can utilise, highlighting the need for additional end-use opportunities. As tyre pyrolysis and hydrogen technologies continue to evolve, the potential role of these technologies in tyre-derived material management remains a topic of ongoing consideration for Tyre Stewardship Australia.

Introduction

An estimated 537,000 tonnes of end-of-life tyres were generated in Australia in 2023-24[1]. 66% of these tyres were recovered, of which 26% contributed to circular outcomes like reuse or recycling, and the remaining 40% of recovered tyres were utilised in energy recovery. This leaves 34% of tyres not recovered, with outcomes capped by limited demand for tyre-derived materials.

Tyre Stewardship Australia (TSA) is the organisation responsible for administering the Tyre Product Stewardship Scheme, and the key objectives include; to increase resource recovery, minimise negative impacts from end-of-life tyres generated in Australia and develop Australia's tyre recycling industry and markets for tyre-derived products.

As part of these objectives, in 2024 TSA published a report titled ***Pyrolysis of end-of-life tyres: Review of pyrolysis technologies and product opportunities for Australia***[2]. This report provided a technical review of current pyrolysis technologies in Australia and worldwide, the outputs from pyrolysis processes and possible uses and upgrade pathways for products.

Since publishing this report there has been significant engagement and feedback from the tyre pyrolysis industry, both locally and internationally. One of the areas proposed for further review is the feasibility of producing Hydrogen (H_2) through the thermal processing of tyres. The following report provides a technical review of hydrogen generation from tyres, specifically as an output from tyre pyrolysis gas and oil, via steam methane reforming and water-gas shift reactions.

1.1 Global hydrogen industry

The transition to hydrogen is a key strategy in the global shift away from carbon-intensive fossil fuels towards a low-carbon economy.

Global hydrogen production in 2024 was almost 100 Mt with the industry dominated by fossil fuels and highly carbon dioxide emissions intensive[3]. Almost 66% of global hydrogen production is derived from natural gas and 20% from coal, almost all without carbon capture and utilisation or storage (CCUS)[4].

CCUS involves the capture of carbon dioxide preventing emissions to atmosphere, however it is currently not a widely used and developed technology. The captured carbon dioxide can be utilised to create chemicals, building products or to enhance plant growth in greenhouses or algae farms. Alternatively, the carbon dioxide can be stored in geological formations, such as saline aquifers or depleted oil and gas reservoirs for permanent sequestration. Most of the remaining hydrogen production (about 15%) is a by-product from petrochemical refineries and the oil industry.

Low emissions hydrogen makes up less than 1% of global production, mostly from fossil fuels with CCUS, with most future supply expected from electrolysis. Although low emissions hydrogen production could reach 37 Mtpa by 2030, this has declined due to project delays and cancellations.

About 30% of global hydrogen production occurs in China using coal, while the Middle East and North America each contribute about 15% using natural gas; China is also the largest user (over 29 Mt), followed by North America and the Middle East.

1.2 Australian hydrogen industry

The Australian Government's strategic direction for hydrogen is formalised in the National Hydrogen Strategy 2019[5], further updated in the National Hydrogen Strategy 2024[6]. The updated strategy outlines a national roadmap for development of a domestic hydrogen economy, supported by complementary state-level strategies and action plans.

Australia's hydrogen production in 2022 was around 500 ktpa, almost entirely derived from natural gas[7] with hydrogen used primarily as a local feedstock for ammonia production (80%) and in crude oil refineries (20%). Current hydrogen production costs in Australia are around AU$3.9/kg from steam methane reforming (SMR) and AU$4.5/kg for steam methane reforming (SMR) *with* CCUS, and renewable hydrogen in the range AU$5-10/kg[6]. In the future, renewable hydrogen production costs are expected to fall to under AU$4/kg with reductions in electrolyser capital costs and renewable energy costs[6].

The Australian Government is providing financial incentives for early-mover hydrogen projects through the Hydrogen Production Tax Incentive[8] and the expanded Hydrogen Headstart Program[9]. The Hydrogen Production Tax Incentive program supports the production of hydrogen produced from renewable resources in Australia and provides a tax credit of $2/kg per eligible renewable hydrogen produced. Hydrogen Headstart Program is a $4 Billion program that provides production-based grants to support large-scale renewable hydrogen projects. The program has announced a shortlist of projects for round 2 in 2026[10].

Whilst there is no commercial production of hydrogen from end-of-life tyres globally, there have been a number of research studies and pilot examples of technologies embarking on possible options. Production of hydrogen from end-of-life tyres could provide another opportunity for energy recovery in Australia, particularly once infrastructure for hydrogen use is established in critical industries such as shipping, mining and agricultural.

Properties, challenges and production in Australia

2.1 Properties of hydrogen

Hydrogen is the lightest and most abundant element in the universe. Hydrogen gas is colourless, odourless and tasteless, with a density of 1/14th that of air at ambient temperature and pressure.[11]

However, hydrogen has three major issues to overcome for practical use as a renewable energy source, which are explained in more detail below. These are:

1. low density at ambient temperature and pressure,
2. additional safety hazards compared to current fuels, and
3. carbon emissions from hydrogen production using fossil fuels.

2.1.1 Energy density

Hydrogen has a high mass energy density of 120 MJ/kg compared to 46 MJ/kg for petrol, meaning there is more energy stored per unit of mass. However, when considering volume, the energy density of hydrogen is very low. At ambient temperature and pressure hydrogen has an energy density of 0.01 MJ/L (compared to 34 MJ/L for petrol for example). This means gaseous hydrogen requires much larger volumes for storage for the same energy output compared to petrol.

To improve this, hydrogen can be stored as a highly pressurised gas (700 bar) increasing energy density to ~5.6 MJ/L or liquefied at extremely cold temperatures (-253 °C) increasing energy density to 8 MJ/L. Both formats require specialised technology to carry out effectively and have a considerable increase in safety hazards.

For bulk transport and storage hydrogen can be converted into a hydrogen-rich chemical such as ammonia and converted back to hydrogen for energy generation.

2.1.2 Storage and handling

Safe storage, transport and use of hydrogen require extra care compared to liquid or solid fuels. Hydrogen forms combustible mixtures in air at concentrations from 4% to 75% by volume and explosive mixtures in the range 18.3 to 59%. Small hydrogen leaks can easily result in fires and explosions.

2.1.3 Carbon emissions

As a fuel, the combustion product of hydrogen is water, meaning engines running on hydrogen have no direct carbon emissions. However, 99% of current hydrogen production is largely from fossil fuel sources (natural gas, carbon or naphtha) with unabated carbon emissions. The volume of hydrogen from low emissions electrolysis or hydrogen produced from fossil fuels with carbon capture in place is steadily increasing, however, currently account for less than 1% of global hydrogen.

2.2 Production methods

Hydrogen is commercially produced through four main routes:

- Steam methane reforming of natural gas
- Coal gasification
- By-product of the petrochemicals industry
- Electrolysis

As outlined above, steam methane reforming of natural gas produces two-thirds of all hydrogen volume globally. Coal gasification produced an estimated 20% and by-products of the petrochemicals industry produced approximately 15%. Electrolysis and methods utilising CCUS with capture rates of up to 90% or more, account for the 1%, but the sector continues to show growth with a notable increase from 2024 to 2025[3].

2.2.1 Steam methane reforming (SMR)

Step 1: Steam methane reforming

High temperature steam reacts with the methane in natural gas using a catalyst to produce hydrogen and carbon monoxide:

$CH_4 + H_2O \rightleftharpoons CO + 3H_2$ *(syngas)*

SMR plants typically operate at 800°C to 900°C and pressures of 20 to 30 bar.

The reaction requires an input of energy, often supplied by external combustion of gases that may include the tail gas (containing methane, carbon monoxide and hydrogen) from the down-stream hydrogen separation stage.

Step 2: Water-gas shift

The carbon monoxide produced during steam methane reforming is further reacted with steam over a catalyst to increase the hydrogen yield:

$CO + H_2O \rightleftharpoons CO_2 + H_2$

Step 3: Pressure swing adsorption

A series of high- and low-pressure chambers combined with different adsorbent materials are used to separate a high-purity hydrogen stream and a residual tail gas stream containing carbon monoxide, hydrogen, methane and carbon dioxide, typically used as a fuel for heating the SMR reactor[12].

2.2.2 Coal gasification

Coal gasification is a complex process with drying, pyrolysis, combustion and gasification reactions occurring under controlled conditions[13]. The main gasification reactions lead to the reaction of the carbon in coal with a mixture of oxygen and steam to produce a carbon monoxide and hydrogen-rich syngas:

$3C + O_2 + H_2O \rightarrow H_2 + 3CO$

It is important that the amount of oxygen supplied is insufficient to fully react with the coal so that carbon monoxide and hydrogen is produced instead of carbon dioxide and water.

Carbon monoxide can be reacted with steam to create additional hydrogen via the water gas shift (step 2 in 2.2.1). Hydrogen can be separated using pressure swing adsorption (step 3 in 2.2.1).

2.2.3 By-product of petrochemicals industry

Steam cracking of hydrocarbons produces a tail gas that contains hydrogen, which can be recovered for pressure swing adsorption (step 3 in 2.2.1) and used as a source of hydrogen[14].

2.2.4 Electrolysis

Electrolysis is an electrochemical process that uses electricity to split water into hydrogen and oxygen:

$2H_2O + \textit{electricity} \rightarrow 2H_2 + O_2$

When using electricity from renewable sources such as wind or solar, the resulting hydrogen is classified as green hydrogen. **Figure 1** summarises the three main types of electrolysis cells[15].

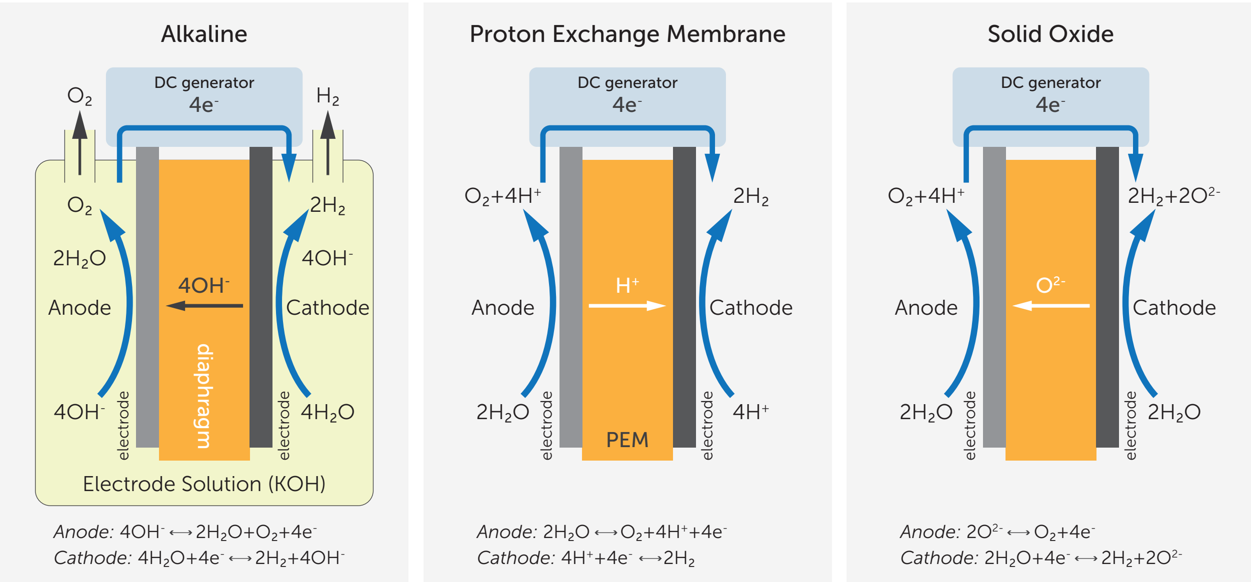

Figure 1: Basic principle of the three water electrolyser technologies.

2.3 Colours of hydrogen

The colours of hydrogen are a common way for industry to indicate the production or extraction method, and correspond to the greenhouse gas emission profile of the process used. The brighter colours (e.g. green, blue, pink) have lower emissions, while the darker colours (grey, brown and black) have higher emissions. **Table 1** summarises the colours of hydrogen based on production methods and greenhouse gas emissions.

Table 1: Colours of hydrogen[16]

Colour	Description	CO_2 Emissions
Black / Brown / Grey	Gasification of black / brown coal or steam reforming of natural gas without CCUS	High
Blue	Steam reforming of natural gas with CCUS	Low
Turquoise	Pyrolysis of natural gas (with carbon as the by-product)	Low
White	Natural occurring hydrogen	None*
Pink / Red / Purple	Electrolysis of water using electricity from nuclear	None
Green	Electrolysis of water using electricity from renewable energy Conversion of biomass	None

**Barring emissions resulting from harvesting (mining/exploration)*

2.4 Uses of hydrogen

Australia's 2024 National Hydrogen Strategy identifies that hydrogen could support the decarbonisation of 'hard-to-abate' sectors where electrification is technically or economically impractical. These sectors include:

2.4.1 Transport

Hydrogen could be used as a fuel in long-haul and heavy-duty transport, which is challenging to electrify. Applications include use of hydrogen in Fuel Cell Electric Vehicles[17] or internal combustion hydrogen engines for road vehicles[18], and direct combustion in aviation gas turbines[19].

2.4.2 Power generation

Hydrogen could be used to generate electricity using dedicated hydrogen gas turbines[20]. The hydrogen could be produced via water electrolysis using excess renewable energy (solar, wind), stored and then converted back to electricity to meet demand when renewable power generation is low. Hydrogen can also be blended with natural gas.

2.4.3 Green metals

Hydrogen could be used as a reductant and heat source for producing green iron and steel and for calcining alumina, replacing high-emission fuels like coal, natural gas, or oil.

2.4.4 Chemical production

Hydrogen is currently used in the manufacture of chemical feedstocks such as ammonia and urea. Ammonia is an important fertiliser and can also serve as a high-density transportable hydrogen carrier. The use of ammonia as a fuel in gas turbines or combustion plants is being investigated[21].

2.5 Hydrogen projects in Australia

According to Australia's 2024 National Hydrogen Strategy[6], as part of the transition to a low carbon future, Australia will target the production of at least 15 Mtpa of green hydrogen by 2050, with a milestone of 0.5 Mtpa by 2030. The strategy proposes that this will be achieved mainly from water electrolysis using renewable electricity with the remainder produced from natural gas/fossil fuels using CCUS with capture rates of up to 90% or more.
The availability of solar and wind resources for electrolysis has the potential to make Australia a major exporter of hydrogen.

CSIRO collates information on hydrogen via its Hydrogen Knowledge Centre[22]. The CSIRO HyResource webpage is a collaborative knowledge sharing resource that includes a database of active and archived hydrogen projects. As of December 2025, there are 76 Australian projects listed in the active database[23].

Table 2 below highlights some notable large-scale Australian hydrogen projects. There have been several recent cancellations of low-emissions hydrogen projects in Australia due to a combination of high production costs, market uncertainties, and weak demand that could impact on Australia achieving its hydrogen targets.

Table 2: Australian hydrogen projects, their outputs and status (limited selection)

Project	State	Output	Estimated production	Status
Murchison Hydrogen Renewables Project[24]	WA	Green hydrogen and ammonia	1.5 GW (3 GW total)	Under development
Australian Renewable Energy Hub (AREH)[25]	WA	Green hydrogen	26 GW total	Under development
Gingerah Energy Hub[26]	WA	Ammonia and green hydrogen	~180,000 tpa H_2	Under development
Western Green Energy Hub[27]	WA	Green hydrogen	Phase 1: 330,000 tpa H_2 (3.5 million total)	Under development
H_2-Hub Gladstone[28]	QLD	Ammonia from green hydrogen	5,000 tpd ammonia	Under development
Hunter Valley Hydrogen Hub[29]	NSW	Ammonia via renewables-based hydrogen	50 MW electrolyser producing 4,700 tpa H_2	Under development
Central Queensland Hydrogen Project[30]	QLD	Ammonia via green hydrogen	~200 tpd H_2	Cancelled
Gladstone PEM50[31]	QLD	Green hydrogen	8,000 tpa H_2	Cancelled
Whyalla Hydrogen Facility[32]	SA	Green hydrogen	250 MWe electrolyser	Cancelled
Port Pirie Green Hydrogen Project[33]	SA	Green hydrogen	Phase 1: 20 tpd H_2 (100 tpd total)	Cancelled

Tyre pyrolysis outputs

TSA's *Pyrolysis of end-of-life tyres* report reviewed pyrolysis technologies and their different outputs. A short summary of each output is discussed below, to provide relevant context in relation to extracting hydrogen.

Pyrolysis is a process that has been applied to tyres globally and in Australia. The process involves heating end of life tyres to sufficiently high temperatures (400°C to 600°C) in the absence or near absence of oxygen to thermally decompose the material. The pyrolysis outputs are a mixture of condensable hydrocarbons, light gases, and a carbon-rich char. Higher pyrolysis temperatures promotes thermal cracking of larger molecular weight compounds into lighter molecules.

3.1 **Tyre pyrolysis oil** (TPO)

On cooling, the condensable hydrocarbons are recovered as TPO, a tar or crude oil material. This may be used as bunker fuel oil or further refined, such as via distillation, to use in other fuel markets or as a chemical feedstock.

TPO contains a moderately high sulfur content (0.6 to 1.6% wt), significantly exceeding the limits for clean transport fuels. Sulfur levels in Australian diesel fuel are mandated to be a maximum of 10 mg/kg since 2009. Desulfurisation or hydrotreating of the TPO is typically required to ensure the product meets relevant fuel standards.

3.2 **Tyre pyrolysis carbon** (TPC)

The solid carbon fraction that remains after pyrolysis, made up of charred carbon black along with inorganic components (zinc, silica, and calcium) used in tyre manufacturing. The carbon fraction can be upgraded to a recovered carbon black by cleaning and grinding to a fine powder for use in rubber products, including new tyres, replacing some grades of virgin carbon black derived from fossil fuels.

3.3 **Tyre pyrolysis gas** (TPG)

The gas fraction from pyrolysis (rich in hydrogen, methane and light hydrocarbons) is typically used for heating the pyrolysis reactors although in some systems, the syngas is supplied to gas engines for electricity generation. The gaseous stream will contain contaminants particularly hydrogen sulfide.

3.4 **Steel wire**

The steel is usually separated from the tyres prior to pyrolysis, or afterwards if whole tyres are processed, and sold as scrap metal.

Hydrogen production from pyrolysis of tyres

Tyres are complex material, made up of crosslinked rubber chains, which all contain a hydrocarbon backbone. To extract hydrogen, the tyres will need to be broken down to more fundamental molecules, which is generally done via controlled thermal degradation or 'pyrolysis'[34,35].

Figure 2 provides a simple schematic for proposed hydrogen production from the pyrolysis of end-of-life tyres. The TPO and TPG hydrocarbon fractions can be combined and steam reformed over a catalyst (similar to step 2 in section 2.2.1) to convert hydrocarbons to carbon monoxide and hydrogen. The water-gas shift reaction (step 3 in 2.2.1) is then used to convert carbon monoxide into more hydrogen and an acid gas removal reactor to remove hydrogen sulfide gas.

Pressure swing adsorption (step 3 in 2.2.1) can then be used to separate a high-purity hydrogen product together with a reject tail gas stream containing residual impurities like carbon monoxide, nitrogen, carbon dioxide and methanes. It is crucial to remove hydrogen sulfide prior to pressure swing adsorption to protect the metal surfaces and sorbents within the pressure swing absorption unit.

If combined with CCUS to achieve high carbon dioxide capture rates, producing hydrogen from pyrolysis provides a potential utilisation pathway for end-of-life tyres, which is also aligned with Australia's National Hydrogen Strategy.

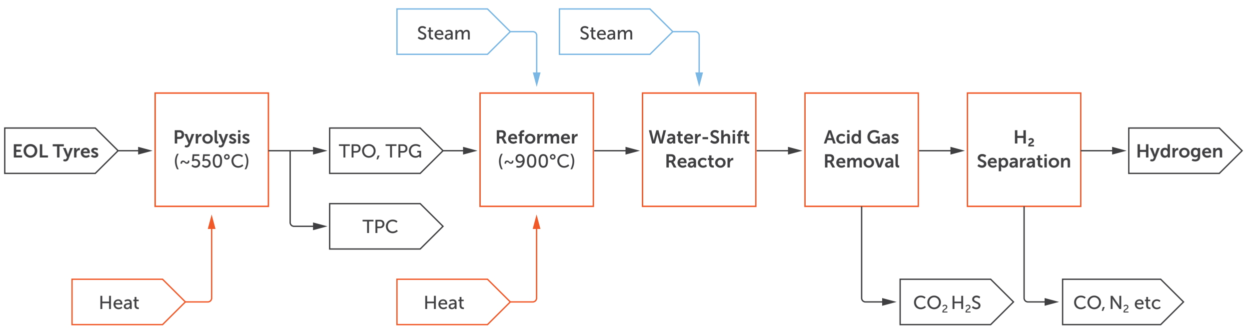

Figure 2: **Simplified schematic for the two-stage pyrolysis/steam reforming of end-of-life tyres for hydrogen production.**

An alternate approach is to apply a similar technique to coal gasification, using end-of-life tyres as a solid fuel source to produce syngas. This process is discussed in Appendix 1, along with additional modelling. Despite a number of research investigations into used tyre gasification, there appears to be no commercial tyre gasification operations and only limited reported large-scale trials.

4.1 Modelling of tyre pyrolysis to hydrogen production

To support the feasibility of hydrogen production from end-of-life tyres, modelling of the process was carried out in partnership with Anderson Energy Solutions[36]. The modelling used the energy and product inputs and outputs from the plant schematics in Figure 2 for processing 5 tonnes of tyre material per hour. Key inputs and outputs are highlighted in Table 3. The summary modelling discussed here is an overview, and further detail on model inputs/outputs, conditions and other factors, can be provided on request.

The carbon inputs include end-of-life tyres and natural gas used for heating the steam reformer and supporting the combustion of the tail gas in the waste gas boiler for steam generation. The de-wired tyres include about 36% biogenic carbon from natural rubbers used in tyre manufacture which needs to be considered as part of the carbon balances.

The carbon outputs include the TPC, the carbon dioxide captured by the acid gas removal plant, and carbon dioxide in the flue gas from the steam reformer (combustion of natural gas) and from the waste gas boiler (combustion of tail gas and natural gas).

The modelling showed that for **every tonne of end-of-life tyres** consumed, **188 kg hydrogen** is produced along with 2.26 tonnes of carbon dioxide. This process is best aligned in colour to hydrogen generation from natural gas, which is labelled as **grey hydrogen**. To produce blue hydrogen at acceptably low levels of carbon emissions, capture rates of 90% or more will likely be required.

Table 3: modelling results of pyrolysis/steam reforming of end-of-life tyres.

Parameter	Mass flow (tph)	tonne/tonne tyres (t/t)	Comment
Used tyre feed (input)	5.0	1.0	50:50 mix of passenger car and truck tyres (steel/wire free)
Natural Gas (input)	1.1	0.22	Approx. 51 GJ/hr for heating of steam reformer and supporting combustion in the tail gas boiler.
Hydrogen production rate (output)	0.94	0.188	High purity hydrogen, delivered at 200 bar
Pyrolysis char (output)	2.0	0.4	
CO_2 captured (output)	6.93	1.39	For utilisation or storage, CO_2 pressurised to 120 bar
CO_2 in flue gas	4.37	0.87	Emitted to atmosphere from reformer and tail gas boiler

Circular economy and waste hierarchy frameworks

TSA has published a comprehensive ***Material Circularity: Management Options for Tyres & Conveyor Belts*** report evaluating various management strategies for end-of-life tyres, focusing on their alignment with circular economy principles and the waste hierarchy.[37]

The circular economy describes a system where materials are recirculated for as long as possible to minimise the extraction of new materials. The waste hierarchy defines a set of priorities for the best use of resources and assesses the outcomes for waste from most to least desirable.

This report highlights that there are many material recovery options for end-of-life tyres that contribute to a circular economy for tyres. When tyres are used as fuel, the material is consumed to produce energy, so it has no material circularity. However, it is preferrable to disposal pathways such as landfilling, incineration, dumping or burial.

The options assessment tool (Figure 3) highlights that pyrolysis outputs, can sit in either the "recycling" section or the "energy recovery" section, depending on whether the output is being recirculated as a material, or whether it is being consumed as an energy source.

If the hydrogen that is generated from end-of-life tyres is used as any form of fuel/energy application, it will be categorised as similar to 'pyrolysis or gasification gas: used as a fuel/natural gas replacement', after additional the processing steps discussed above.

If hydrogen is used to generate ammonia and further used as a chemical feedstock (not a fuel), it would be categorised as similar to 'pyrolysis oil: chemicals production'.

Under this framework, the pyrolysis 'process' itself isn't classified as a recycling or energy recovery technology, rather it is a resource recovery technology, and the end-markets define the circularity and waste hierarchy position.

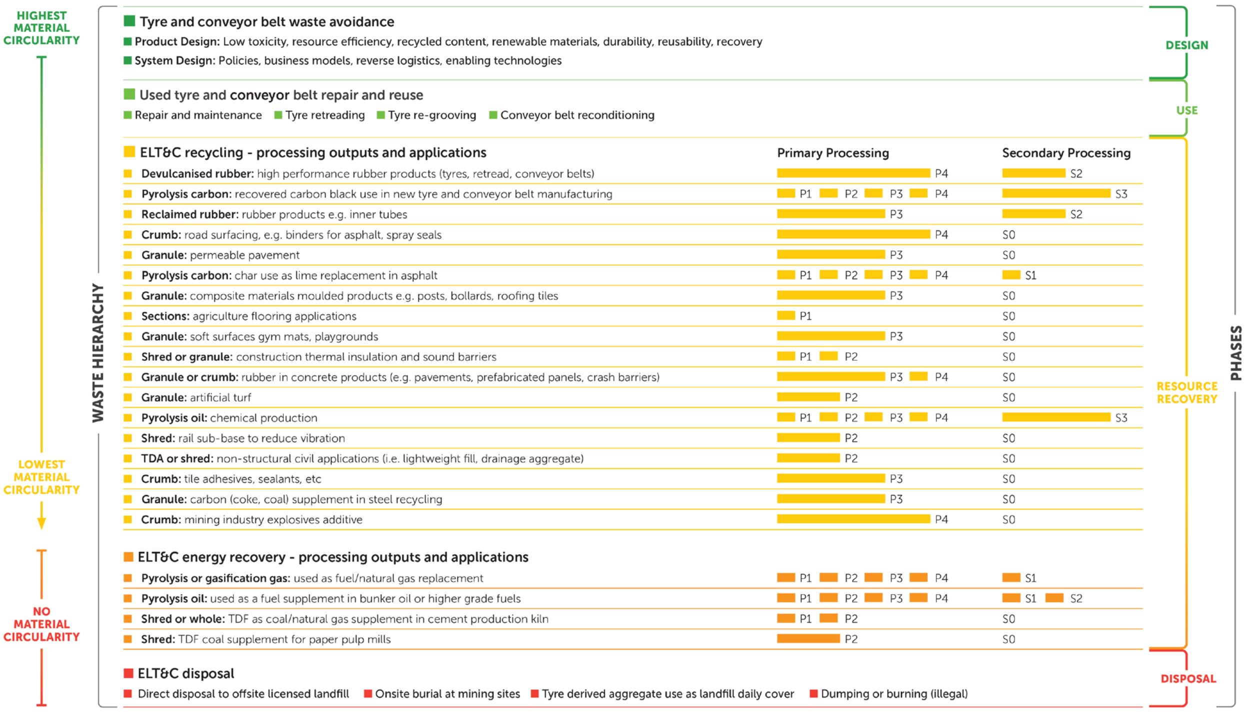

Figure 3: Options assessment tool highlighting the material circularity of different fates.
For a larger view go to page 23 of this report.

Conclusion

This report expands on the previously reviewed tyre pyrolysis topic, investigating the possible further processing of outputs into hydrogen. Hydrogen is a strategically significant commodity; however, the true widespread impact is still uncertain due to various barriers such as economics, storage, handling, and safe transport.

Globally, hydrogen production is approximately 100 Mt per year, however the majority is derived from fossil fuels such as natural gas and coal. In Australia in 2022 hydrogen production was around 500 ktpa, almost entirely derived from natural gas with hydrogen used primarily as a local feedstock for ammonia production (80%) and in crude oil refineries (20%).

The approach discussed in detail is to use steam reforming of tyre pyrolysis oil and tyre pyrolysis gas into carbon monoxide and hydrogen, followed by further purification to remove impurities. This process, along with pyrolysis, is still in its commercial infancy particularly in Australia. However, enough research and development work has taken place to be able to develop modelling estimates of hydrogen yields.

Modelling in the report estimates that for every tonne of end-of-life tyres input into pyrolysis and steam reforming generates 0.188 tonnes of hydrogen, and 2.26 tonnes of carbon dioxide. This process is closest aligned in colour to hydrogen generation from natural gas, which is labelled as grey hydrogen. With CCUS, the colour would be closest to the current blue hydrogen category.

Hydrogen production provides an additional product from end-of-life tyres, aligning with Australia's National Hydrogen Strategy and decarbonisation of the economy provided there is at least 90% capture of carbon.

Under the options assessment framework, pyrolysis outputs can be classified as either recycling or energy recovery, depending on end-market use. If the hydrogen that is generated from end-of-life tyres is used as any form of fuel/energy application, it can be categorised similar to 'pyrolysis or gasification gas: used as a fuel/natural gas replacement'. If hydrogen is used to generate ammonia and further used as a chemical feedstock (not a fuel), it can be categorised similarly to 'pyrolysis oil: chemicals production'.

The tyre processing technologies discussed in this report for pyrolysis and hydrogen are yet to be realised at scale in Australia, however this report presents an overview of what is technically possible if the appropriate settings were in place. Australia generates more end-of-life tyres than current markets can utilise, making potential new pathways such as hydrogen production from tyre-derived materials a topic of ongoing consideration for TSA.

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Hydrogen production from gasification of tyres

Gasification of end-of-life tyres is an active area of research, primarily at the laboratory- or pilot-scale, or from techno-economic modelling studies to produce electricity, liquid fuels, synthetic natural gas and hydrogen[38–40].

The process of gasification starts with shredded end-of-life tyres placed into a gasifier and reacted with oxygen and steam to produce syngas (carbon monoxide and hydrogen). Co-processing with other waste materials such as plastics or biomass would also be possible. The syngas will contain the same impurities as those resulting from pyrolysis and steam methane reforming. This will require similar gas cleaning/treatment. The water-gas shift reaction is then used to react the carbon monoxide with steam to produce additional hydrogen and carbon dioxide.

It is important to note that there are no commercial-scale plants producing hydrogen from the gasification of tyres although there have been recent laboratory-scale research papers, modelling studies and reviews. A simplified schematic for the gasification of end-of-life tyres for the production of hydrogen is presented in Figure 4.

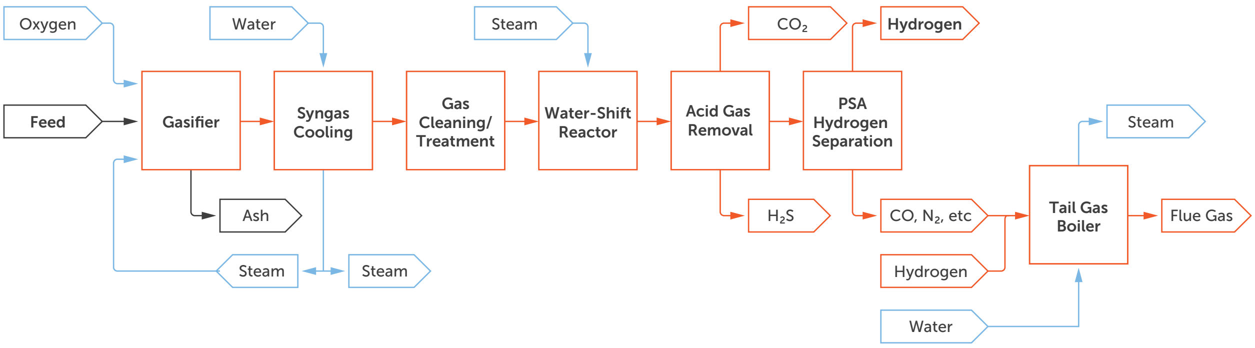

Figure 4: Simplified gasification plant scheme.

Modelling of hydrogen from gasification of tyres

Similar modelling of a hypothetical tyre gasification plant was carried out, the key inputs and outputs at each step are highlighted in Table 4.

Table 4: Modelling inputs and outputs from tyre gasification modelling

Parameter	Mass flow (tph)	tonne/tonne end-of-life tyres (t/t)	Comment
Used tyre feed (input)	5.0	1.0	50:50 mix of de-wired passenger car and truck tyres (steel/wire free)
Hydrogen production rate (input)	0.75	0.15	High purity hydrogen, delivered at 200 bar pressure
CO_2 captured (output)	10.1	2.02	For utilisation or storage, CO_2 pressurised to 120 bar
CO_2 in flue gas (output)	4.41	0.88	Emitted to atmosphere from tail gas boiler and H_2S incinerator

Process model

In conjunction with Anderson Energy Solutions[36] process models for producing hydrogen from the pyrolysis (and gasification) of end-of-life tyres were developed using the Thermoflex software modelling system[41]. These process models indicate the yield of hydrogen that may be expected, the greenhouse gas footprint and the electricity consumption.

The models include most of the required operations, however variations and optimisations are possible. As such, the models should be considered as indicative of the type of performance that may be expected rather than a definitive design.

The end-of-life tyres used in the process model were assumed to be a 50:50 mix of passenger car and truck tyres, with the tyre composition previously reported in ***Pyrolysis of end-of-life tyres: Review of pyrolysis technologies and product opportunities for Australia***.[2]

A simplified flowsheet of the pyrolysis-reforming process model for hydrogen production is presented in Figure 5. The model is based on the processing 5 tph of shredded and de-wired end-of-life tyres as a 50:50 mix of passenger car and truck tyres. Not all process blocks used in the model are represented.

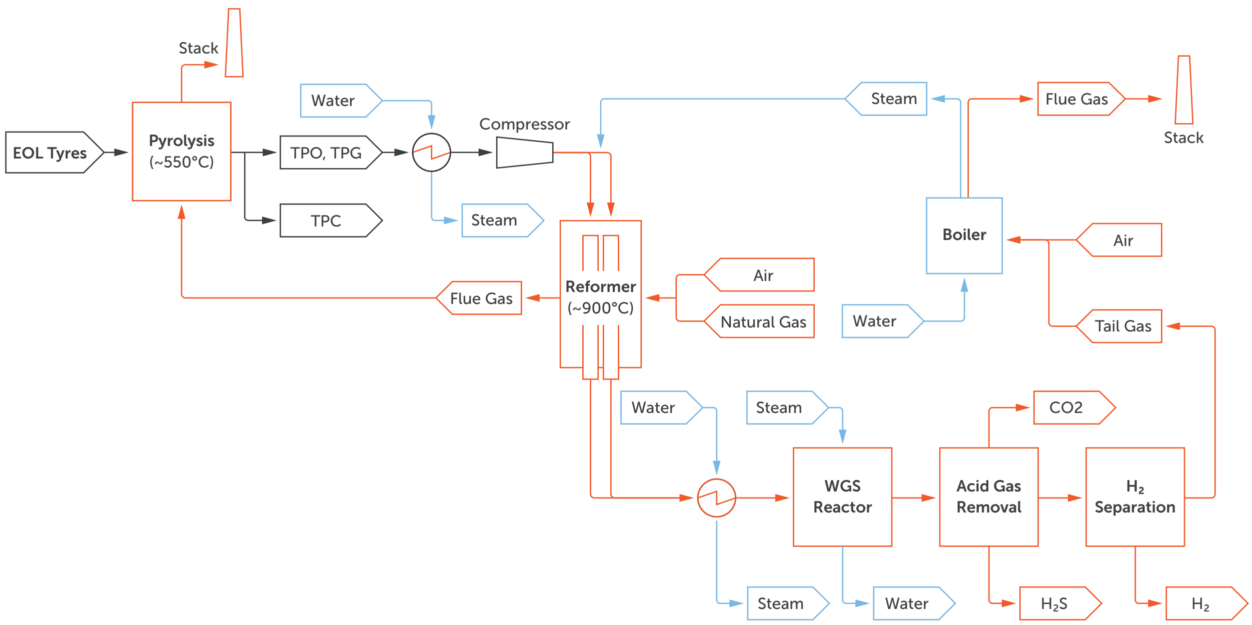

Figure 5: Simplified process flowsheet for pyrolysis-reforming of steel-free end-of-life tyres for production of hydrogen.

The Options Assessment Tool

The Options Assessment Tool presents material circularity for management options from the highest material circularity to no material circularity. This scale aligns with the waste hierarchy.

HIGHEST MATERIAL CIRCULARITY

WASTE HIERARCHY

PHASES

Tyre and conveyor belt waste avoidance

DESIGN

- **Product Design:** Low toxicity, resource efficiency, recycled content, renewable materials, durability, reusability, recovery
- **System Design:** Policies, business models, reverse logistics, enabling technologies

Used tyre and conveyor belt repair and reuse

USE

- Repair and maintenance
- Tyre retreading
- Tyre re-grooving
- Conveyor belt reconditioning

ELT&C recycling - processing outputs and applications

RESOURCE RECOVERY

ELT&C recycling - processing outputs and applications	Primary Processing	Secondary Processing
Devulcanised rubber: high performance rubber products (tyres, retread, conveyor belts)	P4	S2
Pyrolysis carbon: recovered carbon black use in new tyre and conveyor belt manufacturing	P1 P2 P3 P4	S3
Reclaimed rubber: rubber products e.g. inner tubes	P3	S2
Crumb: road surfacing, e.g. binders for asphalt, spray seals	P4	S0
Granule: permeable pavement	P3	S0
Pyrolysis carbon: char use as lime replacement in asphalt	P1 P2 P3 P4	S1
Granule: composite materials moulded products e.g. posts, bollards, roofing tiles	P3	S0
Sections: agriculture flooring applications	P1	S0
Granule: soft surfaces gym mats, playgrounds	P3	S0
Shred or granule: construction thermal insulation and sound barriers	P1 P2	S0
Granule or crumb: rubber in concrete products (e.g. pavements, prefabricated panels, crash barriers)	P3 P4	S0
Granule: artificial turf	P2	S0
Pyrolysis oil: chemical production	P1 P2 P3 P4	S3
Shred: rail sub-base to reduce vibration	P2	S0
TDA or shred: non-structural civil applications (i.e. lightweight fill, drainage aggregate)	P2	S0
Crumb: tile adhesives, sealants, etc	P3	S0
Granule: carbon (coke, coal) supplement in steel recycling	P3	S0
Crumb: mining industry explosives additive	P4	S0

LOWEST MATERIAL CIRCULARITY

ELT&C energy recovery - processing outputs and applications

ELT&C energy recovery - processing outputs and applications	Primary Processing	Secondary Processing
Pyrolysis or gasification gas: used as fuel/natural gas replacement	P1 P2 P3 P4	S1
Pyrolysis oil: used as a fuel supplement in bunker oil or higher grade fuels	P1 P2 P3 P4	S1 S2
Shred or whole: TDF as coal/natural gas supplement in cement production kiln	P1 P2	S0
Shred: TDF coal supplement for paper pulp mills	P2	S0

NO MATERIAL CIRCULARITY

ELT&C disposal

DISPOSAL

- Direct disposal to offsite licensed landfill
- Onsite burial at mining sites
- Tyre derived aggregate use as landfill daily cover
- Dumping or burning (illegal)

Legend: **Primary processing:** P1: Sectioning into pieces P2: Shredding P3: Granulation P4: Crumbing **Secondary processing:** S0: No secondary processing S1: Low level additional refinement of secondary processing outputs S2: Moderate level additional refinement of secondary processing outputs S3: High level additional refinement of secondary processing outputs **ELT&C:** End of life tyres and conveyor belts **TDF:** Tyre derived fuels **TDA:** Tyre derived aggregate

TyreStewardship AUSTRALIA

Australian Government Accredited Product Stewardship Scheme

TSA0508/07.2026