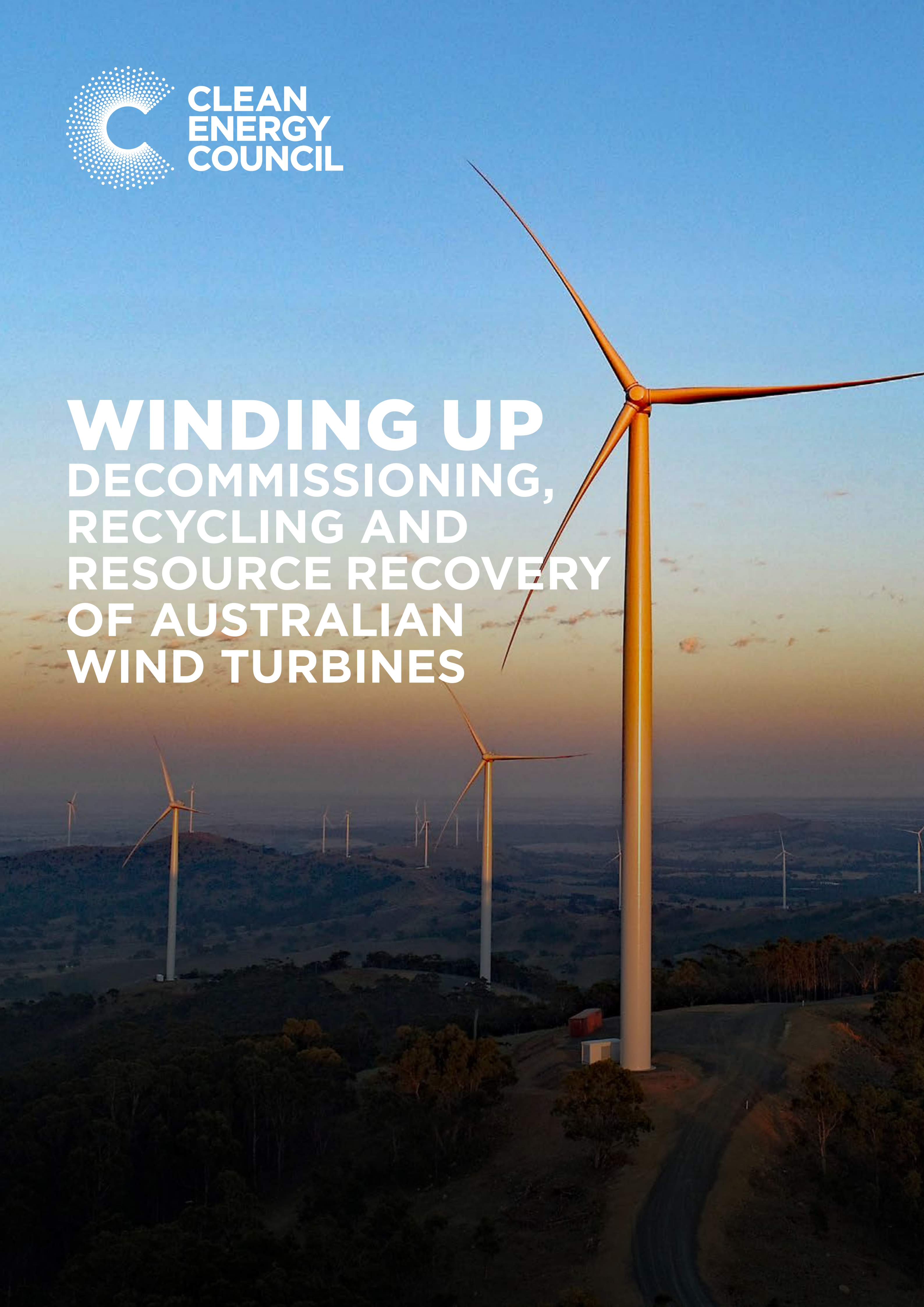
CLEAN ENERGY COUNCIL

WINDING UP

DECOMMISSIONING, RECYCLING AND RESOURCE RECOVERY OF AUSTRALIAN WIND TURBINES



Contents

We respectfully acknowledge Aboriginal and Torres Strait Islander people as the Traditional Custodians of the lands and waters on which we work and live. We commit to collaborate with First Nations communities, to promote sustainable practice, protect ancient sites and culture with equitable access to the benefits of clean energy. Sovereignty has never been ceded.

We acknowledge Elders, past and present, and their continuing culture and connection to Country.

FOREWORD

Kane Thornton
Chief Executive Officer
CLEAN ENERGY COUNCIL

The wind industry, essential to the decarbonisation of the Australian economy, has been providing clean energy to Australia's energy system since the mid-1990s. Its decades' long contribution to Australia's clean energy transition, and the large pipeline of future wind farms, means we need to consider what to do at the end of a wind farm's life.

The Clean Energy Council advocates for responsible decommissioning and waste management at the end of a renewable energy project's life. This commitment is included in our Best Practice Charter for Renewable Energy Projects, to which there are over 50 leading renewable energy companies as signatories.

But what does responsible decommissioning and recycling look like for a wind farm? Working with our members, the Clean Energy Council has been researching and learning about end-of-life options and pathways for wind farms. This report is a summary of the information and insights on this important issue.

While there are clear and established pathways for most parts of a wind turbine, it is clear that the wind industry still has work to do, alongside governments and other industries, to ensure that wind turbines can have a circular economy. I am optimistic that collaboration, and the innovations and solutions being developed at this very moment, will mean that Australian wind farms will have clear, sustainable pathways at the end of their lives.

I encourage you to read this report to learn what happens at the end of a wind turbine's life, the gaps in our current capabilities and how we can work together to address them.

Maja Barnett
Chair, Clean Energy Council Wind Recycling Working Group
TILT RENEWABLES

I am delighted to present this report on the decommissioning, recycling, and waste management of wind turbines in Australia. As we transition to a low-carbon economy, wind energy will continue to play a critical role in Australia's energy mix. However, with an increasing number of turbines reaching the end of their life, it's important that we consider the environmental, social, and economic impact of their disposal.

This report provides an overview of best practice end of life pathways for wind turbines and the status of wind turbine recycling and waste management practices within Australia. Drawing from national and international experience, it identifies pathways currently available, as well as some of the key barriers to achieving a circular economy for wind energy.

This report has been a collaboration with key stakeholders that are as passionate as I am about ensuring our industry provides guidance and establishes clear pathways for the decommissioning of wind turbines in a socially responsible way. While we still have some work to do, I am confident that through further industry collaboration, research and development, and government support, the wind industry will achieve zero-waste turbines.

ACKNOWLEDGEMENTS

This report has been written and developed by the Clean Energy Council's Wind Recycling Working Group. The Clean Energy Council is the peak body for the clean energy industry in Australia. We represent and work with more than 1000 of the leading businesses operating in renewable energy and energy storage. We are committed to accelerating Australia's clean energy transformation.

The Wind Recycling Working Group is made up of a wide range of stakeholders across the Clean Energy Council's membership, representing those who are interested in establishing an end-of-life pathway for wind turbines. Thank you to the Working Group for their contributions to this guide, particularly the Chair of the Working Group, Maja Barnett, and the former Chair, Katrina Swalwell.

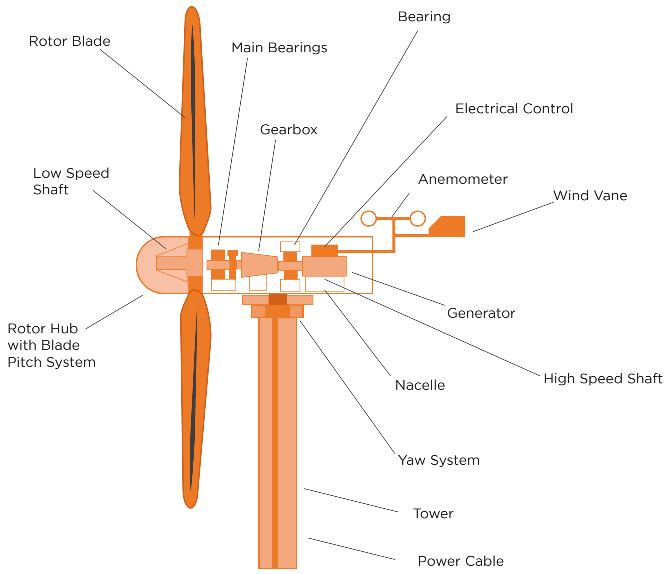
As of publication, the following organisations were members of the Wind Recycling Working Group:

ACCIONA	**MURPHY PIPE AND CIVIL**
ALLENS	**OCTOPUS INVESTMENTS AUS**
ALLTHREAD INDUSTRIES	**PACIFIC HYDRO**
AURECON	**RES AUSTRALIA**
GE RENEWABLE ENERGY	**SQUADRON ENERGY**
GHD	**SYNERGY**
GOLDWIND AUSTRALIA	**TILT RENEWABLES**
IBERDROLA	**VESTAS**
JACOBS GROUP	**WESTWIND**
KPMG	**WOOLNORTH RENEWABLES**

We would like to thank the many people who presented to the Working Group and spoke to us during the drafting of the report, including Suzanne Toumbourou, CEO of the Australian Council of Recycling, UNSW and UTS, ResourceCo, Peter Majewski at the University of Adelaide, Veolia, Blair Fox and Austrak.

GLOSSARY

Partial repowering	Overhauling, optimising or upgrading components, specifically the nacelle, rotor and blades.
Full repowering	Building an entirely new facility, requiring the decommissioning of the old wind farm.
Decommissioning	Wind turbines, site office and any other ancillary infrastructure is removed from the site. Roads and foundation pads are covered and revegetated, allowing land to be returned to its former use.



Wind turbine components. Source: D Ancona and J McVeigh, Wind Turbine – Materials and Manufacturing Fact Sheet, August 29 2001, perihq.com/documents/WindTurbine-MaterialsandManufacturing_FactSheet.pdf

EXECUTIVE SUMMARY

Renewable energy generation is critical to Australia's clean energy transition and achieving the Climate Change Act 2022 (Cth) target of a 43 per cent reduction in greenhouse gas emissions by 2030. Wind energy generation is key to decarbonising Australia's electricity system and is currently the second largest contributor to the clean energy transition (after rooftop and large-scale solar combined) in the country. The Australian Energy Market Operator estimates that twice the current amount of wind capacity will be required by 2030 to meet electricity demand.

While there has been a focus on building new wind farms to accelerate Australia's clean energy transition, retiring and removing old wind farms, or 'decommissioning', has become more topical recently as some of Australia's earliest wind farms approach their end of life.

There are several options when a wind farm reaches the end of its design life, including extending the lifetime of the asset, partial or full repowering, and decommissioning. Decommissioning involves several different processes, including dismantling the wind turbine, removing it from site and rehabilitating the land, or in some cases building a new wind farm on the same site. The decommissioning of the site is the responsibility of the owner of the wind farm.

Once a wind turbine is no longer needed, a key question is what happens to the old wind turbine parts.

A wind turbine is predominantly made of recyclable metals:

- **steel**
- **aluminium**
- **copper**
- **cast iron**

The non-metal components include epoxies, oils and composite materials.

Approximately 85–94 per cent of a wind turbine (by mass) is recyclable[1] and can be recycled in Australia. This recovery rate is well above the national average for commercial and industrial streams in 2018–2019 (57 per cent)[2] and exceeds the National Waste Policy Action Plan target of 80 per cent average resource recovery rate from all waste streams by 2030.[3]

The wind industry is currently seeking to go further and avoid any disposal of waste. The biggest opportunity to further reduce waste in the industry is establishing an end-of-life pathway for turbine blades, which are mainly made of fibreglass and carbon fibre (composite materials).[4] There are currently very limited commercial or feasible end-of-life options for composite materials, which are materials used by many industries.

It is estimated that by 2034, a total of 15,000 tonnes of blade composite waste will have been created in Australia due to decommissioned wind farms, and up to 4000 tonnes in any given year. Without a clear pathway for the management of composite waste, there is a risk that these blades will be disposed of into landfill. There are, however, several innovative solutions emerging globally to sustainably manage blades at their end of life.

This report outlines environmentally and socially responsible approaches and practices for the decommissioning of wind farms. It seeks to promote responsible recycling and waste management by identifying existing pathways for decommissioned wind turbines as well as gaps in recycling capabilities that can be addressed. This report has been developed as part of the industry's commitment to environmentally responsible practices.

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1 Vestas, Zero-Waste, vestas.com/en/sustainability/environment/zero-waste

2 Department of Agriculture, Water and the Environment, National Waste Report 2020, 4 November 2020, dcceew.gov.au/sites/default/files/env/pages/5a160ae2-d3a9-480e-9344-4eac42ef9001/files/national-waste-report-2020.pdf

3 Department of Climate Change, Environment, Energy and Water, National Waste Policy Action Plan 2019, dcceew.gov.au/sites/default/files/documents/national-waste-policy-action-plan-2019.pdf

4 Ibid.

INTRODUCTION

Renewable energy is essential to decarbonise Australia's electricity system and achieve the federal target of a 43 per cent reduction in greenhouse gas emissions by 2030. However, while the current focus is building the necessary, new renewable energy infrastructure for Australia's clean energy transition, what happens at the end of life for a renewable energy project is also an important consideration, whether it be a solar farm, wind farm or big battery.

The wind industry, along with many other industries across the globe, is increasingly focusing on the importance of a circular economy. This is not only from a corporate social responsibility lens, but also to mitigate supply chain issues and acknowledge that certain materials required to build wind turbines may be hard to secure as economies all over the globe seek to transition to clean energy.

This report provides an overview of the wind industry in Australia; the different options for ageing wind farms, decommissioning, waste streams and material volumes; and recommendations on how the wind industry can work together with other sectors and governments to work towards achieving a circular economy.

WIND INDUSTRY IN AUSTRALIA

Wind farms are currently the second largest contributor to Australia's clean energy transition (after rooftop and large-scale solar combined), accounting for 35.6 per cent of renewable power generation in 2022.[5]

There are currently 115[6] wind farms operating across all states in Australia. Australia's oldest wind farm, Ten Mile Lagoon in Western Australia, began operating in 1993. The country's wind industry accelerated in the early 2000s, with the construction of wind farms steadily increasing through the following two decades. A new record of 10 wind farms being commissioned in one year was achieved in 2020, followed by a record-breaking 1746 MW of new wind capacity commissioned in 2021.

These numbers are only set to continue as Australia transitions to clean energy, with the Australian Energy Market Operator estimating that twice the current amount of wind capacity will be required by 2030 to meet electricity demand.[7]

A wind farm typically has a nominal design life of 20–30 years. However, site conditions being less severe than the design conditions and enhancements in technology and maintenance practices mean that many turbines can exceed this design life. Some wind farms are now designed for an operating life of a minimum of 30 years.

There are currently 31 Australian wind farms over 15 years old, equating to a total of 599 wind turbines[8] approaching the end of their design life. While these wind farms are located across the continent, a majority of the older turbines are located in Western Australia, South Australia and Victoria.

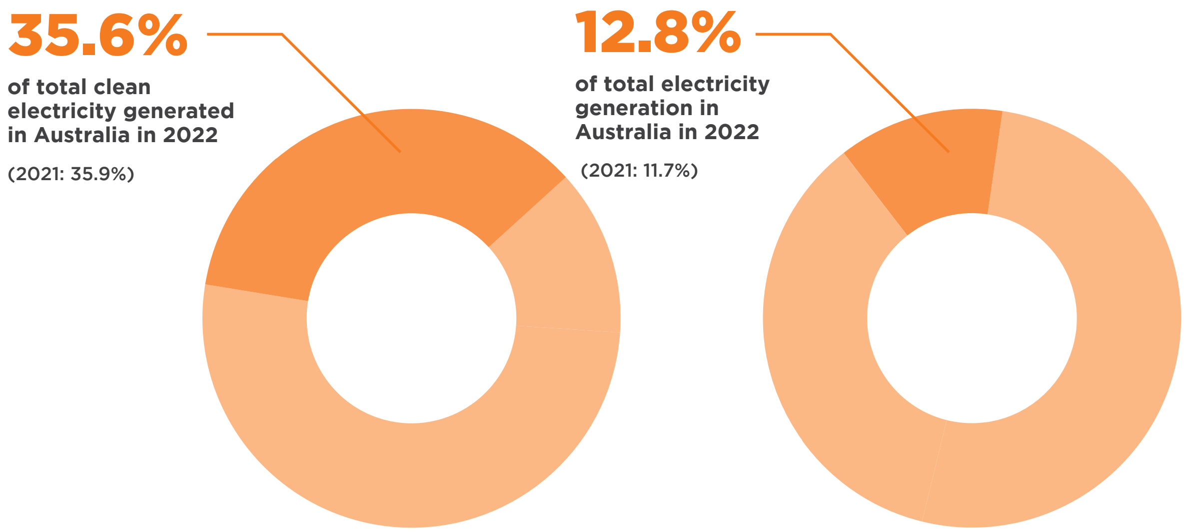

Figure 1: The wind industry's contribution to Australia's electricity supply in 2022.

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5 Clean Energy Council, Clean Energy Australia Report 2022, 1 April 2022, cleanenergycouncil.org.au/resources/resources-hub/clean-energy-australia-report. Wind is the second largest contributor to the energy transition when rooftop and utility scale solar are combined.

6 Rystad Energy, database, July 2022, rystadenergy.com

7 Australian Energy Market Operator, 2022 Integrated System Plan, 30 June 2022, https://aemo.com.au/en/energy-systems/major-publications/integrated-system-plan-isp.

8 Excludes wind farms with refurbished wind turbines and Coral Bay Wind Farm in WA. Includes two single turbine installations (Bremer Bay and Rottnest Island). Data is from November 2022.

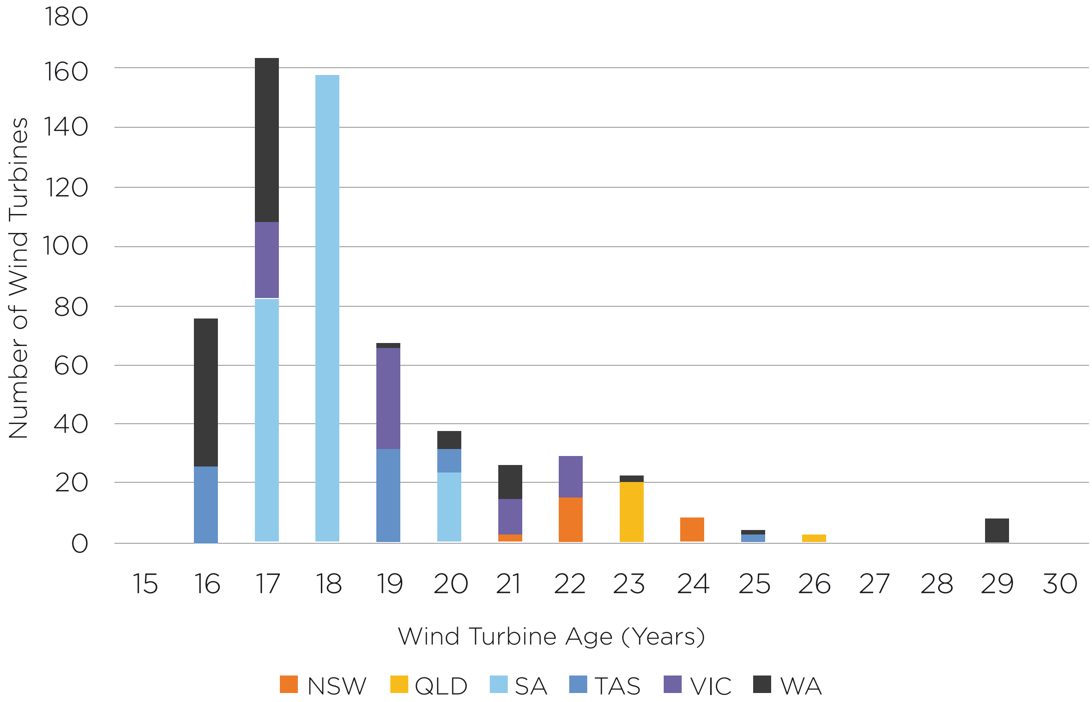
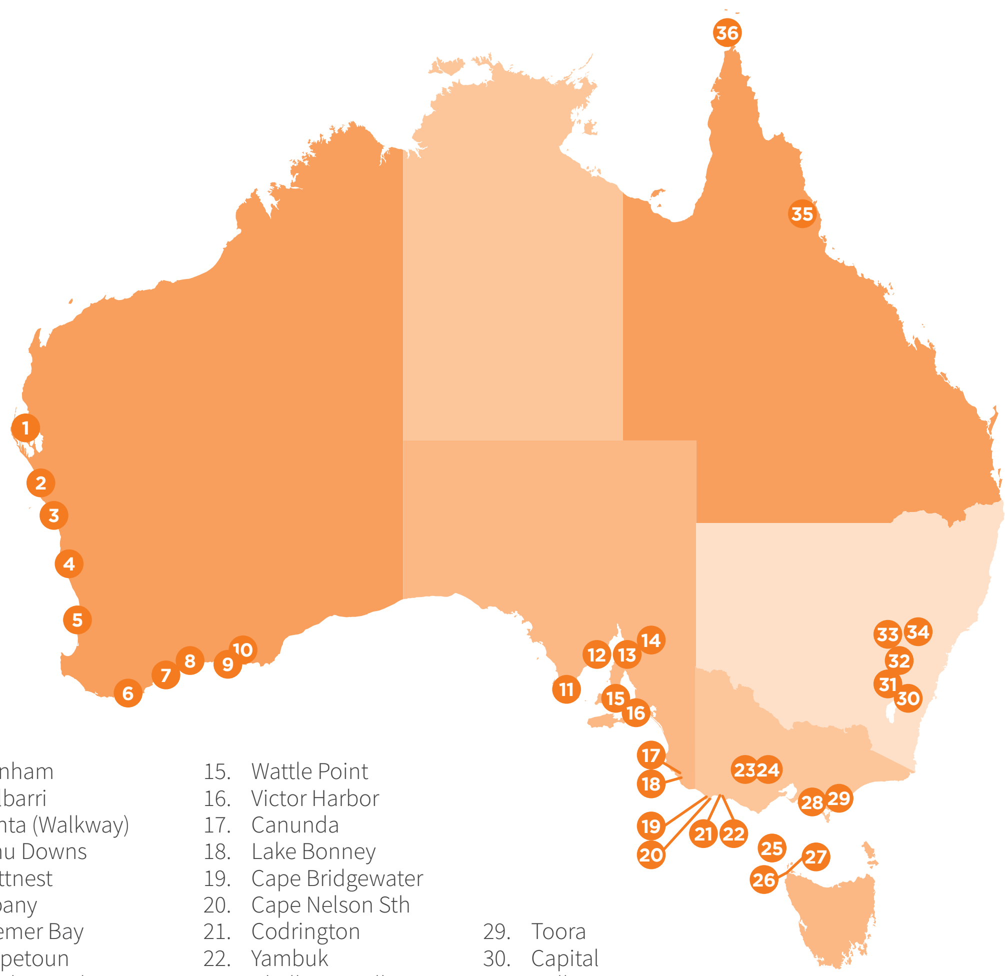


Figure 2: Age and distribution of wind turbines over 15 years old in Australia.



1. Denham
2. Kalbarri
3. Alinta (Walkway)
4. Emu Downs
5. Rottnest
6. Albany
7. Bremer Bay
8. Hopetoun
9. 9 Mile Beach
10. 10 Mile Lagoon
11. Cathedral Rocks
12. Mt Millar
13. Snowtown
14. Hallet Stage 1
15. Wattle Point
16. Victor Harbor
17. Canunda
18. Lake Bonney
19. Cape Bridgewater
20. Cape Nelson Sth
21. Codrington
22. Yambuk
23. Challicum Hills
24. Waubra
25. King Island 1&2
26. Woolnorth 1&2
27. Woolnorth 3
28. Wonthaggi
29. Toora
30. Capital
31. Cullerin
32. Crookwell
33. Blayney
34. Hampton
35. Windy Hill
36. Thursday Island

Figure 3 shows the age of wind farms in Australia and their distribution across Australia.

WIND TURBINE COMPONENTS AND WASTE VOLUMES

While turbine designs vary between manufacturers – especially in early wind turbine designs – the components remain largely the same. The key components are the rotor with blades attached to the hub, a nacelle that contains the gearbox and other machinery including the generator, the tower and foundations.

Despite the differing designs, it is possible to estimate the weights of the primary turbine components. Table 1 provides the average proportion of weight of each wind turbine component based on a sample of 28 (earlier) turbine models.[9]

Table 1: Average weight of wind turbine components as a percentage of the turbine's total weight. [10]

Component	% of Machine Weight
Rotor	10–14
Nacelle and Machinery, less	25–40
Gearbox and Drivetrain	5–15
Generator Systems	2–6
Weight on Top of Tower	35–50
Tower	30–65

Figure 4 uses wind turbine manufacturer Vestas' V82 model as an example of the materials used for each of the components of a wind turbine. Looking at the V82,[11] most of the wind turbine is made from metals. Most of the non-metallic components are contained in the blades, which are predominantly made from epoxy resin and fibreglass but also contain other components such as birch and balsa wood. It should be noted that the blades also contain steel components that have been included in the metallic components for this analysis. While some modern wind turbines use carbon fibre in their blades, Figure 4 is representative of older wind turbines which mostly use fibreglass.

9 D Ancona and J McVeigh, Wind Turbine – Materials and Manufacturing Fact Sheet, August 29 2001, perihq.com/documents/WindTurbine-MaterialsandManufacturing_FactSheet.pdf

10 D Ancona and J McVeigh, Wind Turbine – Materials and Manufacturing Fact Sheet, August 29 2001, perihq.com/documents/WindTurbine-MaterialsandManufacturing_FactSheet.pdf

11 Vestas, Life cycle assessment of electricity produced from onshore sited wind power plants based on Vestas V82-1.65 MW turbines, 29 December 2006, vestas.com/content/dam/vestas-com/global/en/sustainability/reports-and-ratings/lcas/LCA%20V82165%20MW%20onshore2007.pdf.coredownload.inline.pdf

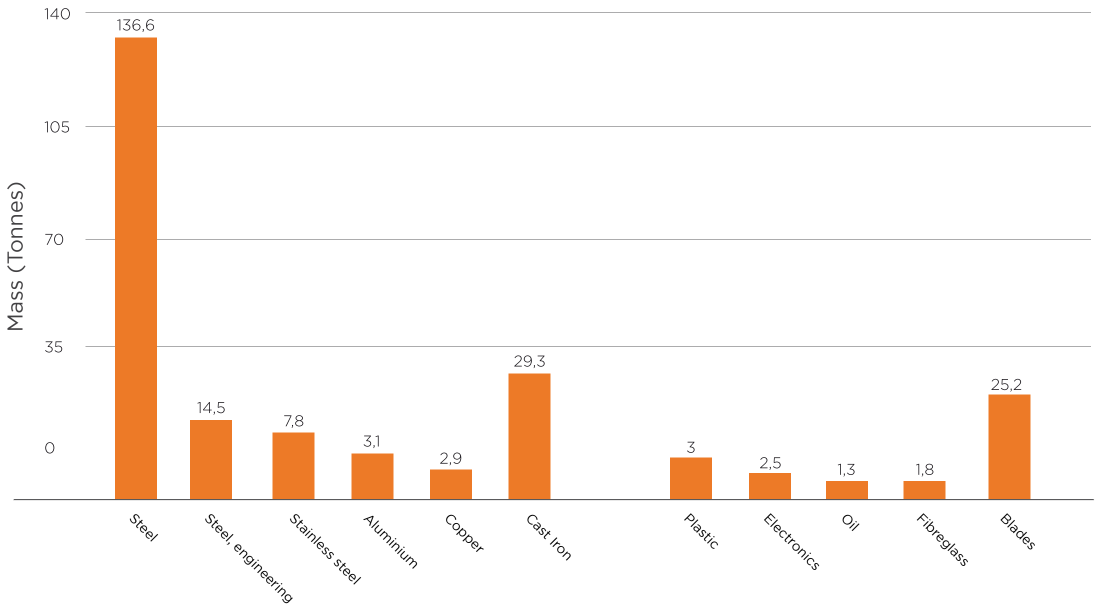


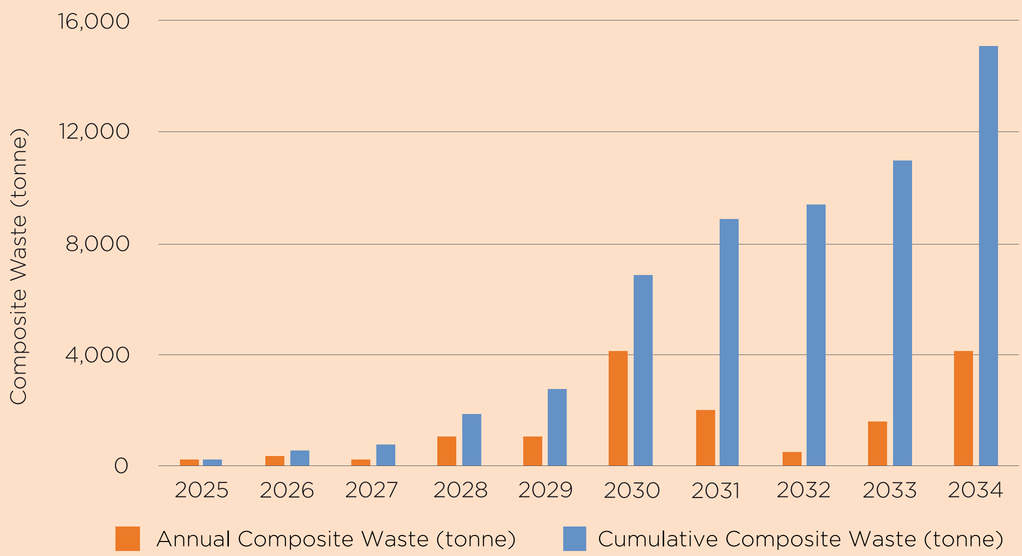
Figure 4: Typical composition of the Vestas V82 1.65 MW wind turbine.

Future blade volumes in Australia

It is estimated that by 2034, a total of 15,000 tonnes of blade composite waste will have been created in Australia due to decommissioned wind farms, and up to 4000 tonnes in any given year.

This is based on information about the turbine models installed at each of the older wind farms in Australia, their associated blade weight,assumptions that the first decommissioning will occur in 2025 and wind farms will be decommissioned on average 25 years after installation.

Composite material volume estimates such as these can be used to guide investment in recycling facilities and research needs.



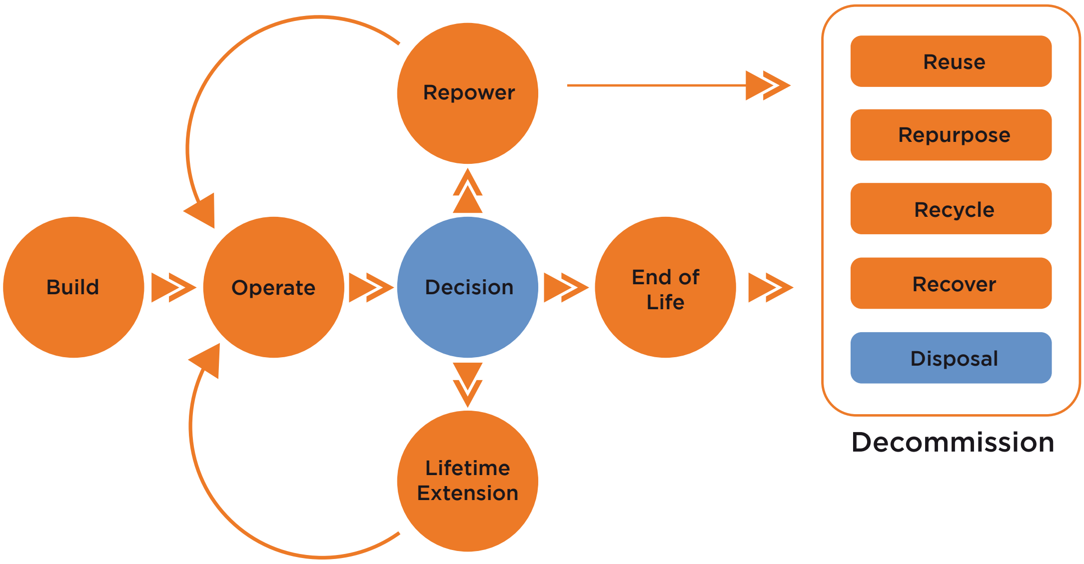
WIND FARM END-OF-LIFE OPTIONS

When a wind turbine approaches the end of its standard design life, the asset owner needs to decide what to do with the wind farm. This decision depends on several factors, including the safety of the asset, the condition of the asset and the cost of energy of the wind farm. End-of-life options include:

- extend the life of the wind turbine for longer than the design life
- partially repower the existing wind farm by overhauling, optimising or upgrading components, specifically the nacelle, rotor and blades
- fully repower the wind farm, which effectively means decommissioning the old wind farm and building an entirely new facility
- decommission the wind farm.

The decision that the asset owner makes is dependent on a number of factors, including regulatory conditions and landowner agreements. Whichever option the asset owner chooses, the wind farm will eventually need to be decommissioned and consideration will need to be given to each of the different waste streams of the wind turbine components.

This section discusses these end-of-life decisions in more detail and what should be considered as part of each process.



Lifetime extension

Many turbines approaching the end of their standard design life are in excellent condition and can be operated beyond their design life with minimal investment. Two key assessments must be made when considering whether wind turbines can be operated beyond their design life:

- theoretical load assessment
- turbine inspection.

If turbines are serviced and maintained according to performance standards and any identified issues are resolved, the design life of many wind farms can be extended.

The desktop theoretical load assessment uses historical site-specific climate data to determine the wind turbine loads and forecasts these beyond the design life of the wind farm. These forecast conditions are compared against the design conditions of the turbine model to calculate the expected remaining design life of a turbine. This desktop assessment is undertaken for the five major components of the wind turbine: blades, blade bearings, hub, nacelle and tower.

Physical turbine inspections focus on the structural components and consider the safe operation of the turbine. These include inspections of the foundations, tower, yaw system, bed plate, main shaft, hub, blades and pitch system. The inspections identify any wear and tear, cracks, corrosion, leakages, torque and sealing. Any identified issues are then rectified to ensure the safe operation of the wind turbine.

It is important to note that while many turbines can operate beyond their standard design life, this assessment is site-specific. Turbines that operate in harsher environments, such as coastal areas, may require significant investment if they are to be extended beyond their standard design life.

Partial and full repower

Partial repowering typically involves an upgrade of the nacelle, rotor and blades while retaining the existing tower. This is designed to generate more energy from the wind farm, improve its availability and extend the operational life. There are several critical considerations when determining whether a wind farm is a strong candidate for partial repowering:

- **Wind turbine foundations:** The integrity and capacity of existing foundations needs to be assessed, including strength, serviceability and fatigue analyses.
- **Electrical balance-of-plant (BOP):** Reusing the electrical BOP components requires a risk assessment to gauge the suitability of the existing electrical BOP for the repowered wind turbines and the impact of additional years of operating life on the equipment.
- **Wind turbine towers:** Reusing existing towers requires an external and internal assessment of the condition of the towers to ensure that they are in good condition and properly maintained.
- **Wind resource assessment:** Repowering typically involves replacing existing blades with longer blades that are able to capture more energy from the wind. These may also result in increased wake losses and wake-induced turbulence, causing additional wear on downwind turbines.
- **Wind turbine technology and site suitability review:** Wind farm owners must assess the potential implications of combining existing components with new ones. This includes the consideration of loads, wear and fatigue on existing components.
- **Commercial and permitting review:** Wind farm owners must review commercial agreements and permitting requirements to determine whether the wind farm will remain compliant after partial repowering.
- **Operations and maintenance (O&M) cost assessment:** Wind farm owners should assess the projected O&M costs following partial repowering through to the end of the project's life.

Full repowering enables owners to retrofit power plants on existing sites with new and/or refurbished technology. This can include erecting taller, more efficient wind turbines to increase productivity while utilising existing grid connection infrastructure. A full repowering is similar to building an entirely new wind farm, but with the added complexity of decommissioning the old wind farm.

The decision to fully repower a wind farm should address the following considerations:

- **Turbine layout:** A new turbine layout will need to be designed for the larger, more efficient turbines.
- **Landowner agreements:** New agreements may be necessary to accommodate the new wind farm, including leases and noise agreements.
- **Monitoring:** The installation of masts and other monitoring equipment may be required to monitor at the new hub height.
- **Specialist studies:** Studies may need to be conducted to assess the effect of the new wind farm design on aspects such as biodiversity, visual impact, traffic, noise and cultural heritage.
- **Planning and environment approvals:** A fully repowered wind farm will need to go through the relevant planning process, including stakeholder consultation and submissions to state and federal governments.
- **Detailed design:** While infrastructure such as electrical connections may be reused, other components such as tracks, cabling and foundations will need to be rebuilt.
- **Grid connection:** Wind farm owners may need to consider grid capacity due to the change in size and capacity of the wind farm.
- **Decommissioning**: The decommissioning of the old wind farm will need to be coordinated with the construction of the new project.

Decommissioning

Decommissioning generally means that the wind turbines, site office and any other ancillary infrastructure is removed from the site. Roads and foundation pads must also be covered and revegetated, allowing land to be returned to its former use. The removal of foundations may be required, depending on landholder agreements and regulatory requirements.

Sometimes, parts of the wind farm that continue to serve a functional purpose may be left in place, such as the substation or access tracks. What remains will be negotiated and agreed with the landowners.

The decommissioning of the site is the responsibility of the owner of the wind farm. Generally, development approvals and landowner contracts contain clauses explicitly setting out the amount of time between the wind farm's operational end of life and the decommissioning and the expectations around rehabilitating the site.

To ensure a well-planned decommissioning, wind farm operators should start the planning process early and undertake the following:

- determine the likely timing of decommissioning and whether the site will be repowered
- consult with landowners to understand which (if any) infrastructure should remain on the land after termination of the lease
- prepare a decommissioning plan that complies with any agreements and conditions of approval
- estimate the decommissioning costs, including the cost of transporting materials offsite and any salvage or resale value of the wind farm components
- during the operational lease, set aside funds solely for decommissioning activities.

The physical decommissioning of a wind farm should follow best practice process and include the following practices:

- site preparation
- health and safety
- preparation for laydown
- laying down of components
- disassembling and cutting
- materials management
- site rehabilitation.

WASTE MANAGEMENT

When a wind farm is decommissioned, the components of a wind turbine must be managed. This section will explore the many options for wind turbine waste management, following the well-established waste hierarchy: [12]

- **avoidance** – waste minimisation and reduction
- **resource recovery** – re-use (maintains the original product function), recycle (requires energy and resources to convert product into a different functional use) and energy recovery (treatment processes used to generate a usable form of energy from waste materials, for example heat or fuel)[13]
- **disposal** – management of all disposal options in the most environmentally responsible manner.

The recycling system is comprised of three essential elements:

- collection / aggregation of materials;
- processing (i.e. infrastructure across a recycling value chain to transform recovered material into a resource); and
- markets for recycled content. Markets cannot be assumed and must be proactively supported.

This section explores the options currently available for wind turbines in line with the waste hierarchy. Currently, 85–94 per cent of a wind turbine (by mass) can avoid landfill.[15] This rate of recovery is higher than the national recycling average (in 2019, over half of all waste was sent for recycling, while 27 per cent was sent to landfill for disposal).[16] It also exceeds the National Waste Policy Action Plan target of an 80 per cent average resource recovery rate from all waste streams by 2030.[17]

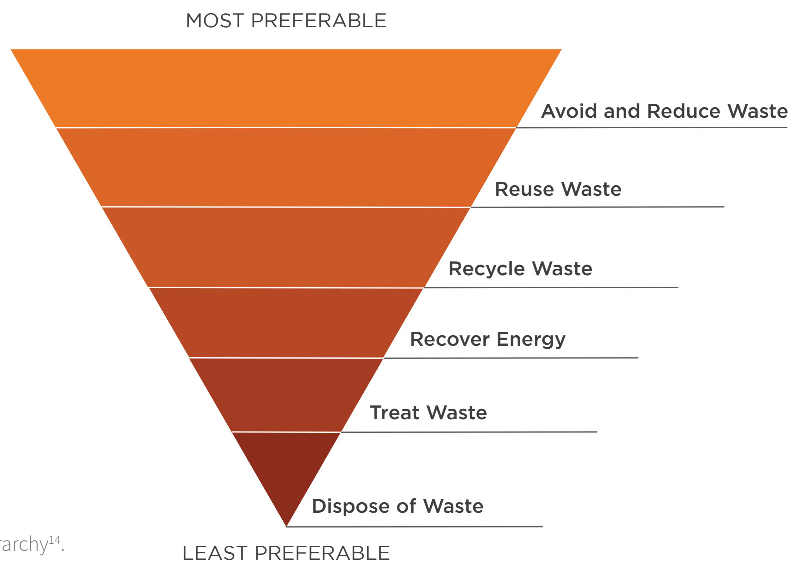


Figure 8: The waste hierarchy[14].

[12] NSW Environment Protection Agency, The waste hierarchy, 20 October 2022, epa.nsw.gov.au/your-environment/recycling-and-reuse/warr-strategy/the-waste-hierarchy

[13] Environment Protection Authority Victoria, Energy from waste, September 2013, epa.vic.gov.au/-/media/epa/files/publications/1549.pdf

[14] NSW Environment Protection Agency, The waste hierarchy, 20 October 2022, epa.nsw.gov.au/your-environment/recycling-and-reuse/warr-strategy/the-waste-hierarchy

[15] Vestas, Zero-Waste, vestas.com/en/sustainability/environment/zero-waste

[16] Australian Bureau of Statistics, Waste account, Australia, experimental estimates, 6 November 2020, abs.gov.au/statistics/environment/environmental-management/waste-account-australia-experimental-estimates/latest-release

[17] Department of Climate Change, Environment, Energy and Water, National Waste Policy Action Plan 2019, dcceew.gov.au/sites/default/files/documents/national-waste-policy-action-plan-2019.pdf

Recycling wind turbine blades

The biggest barrier to zero-waste turbines are the wind turbine blades. These are made of epoxy and composite materials such as fibreglass or carbon fibre. Composite materials are currently difficult to recycle as the polymers used are 'cross-linked' in an irreversible process to obtain the desired material durability and strength while retaining a low weight.[18] The exact material composition varies between wind turbine designs, however the general composition can be seen in Figure 9.

- Spar Caps/Girders: Unidirectional (UD) Glass/Carbonfibre, supported by Epoxy, Polyester, Polyutherane or Vinylester matrix
- Shear Webs and Shell Panels: Multiaxial GFRP Sandwich laminates using Balsa/PVC/PET as core material and Epoxy, Polyester, Polyutherane or Vinylester as matrix systems
- Leading/Trailing Edge and Webs Bonding: Epoy/Polyutherane based structural adhesive
- Lightning Protection Cable: Aluminium or Copper
- Surface Coating: Polyutherane based lacquer
- LEP (Leading Edge Protection): Polyutherane based lacquer/tape[19]

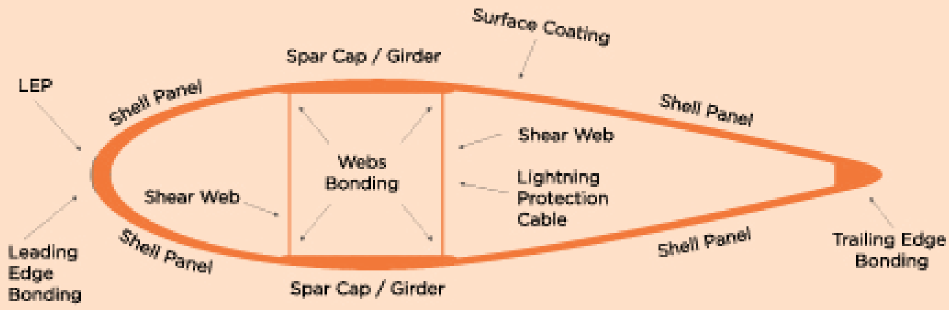


Figure 9: generic cross-section of a generic rotor blade and material breakdown
(by Wind Europe in their report Accelerating Wind Turbine Blade Circularity)

This section also explores solutions to address the remaining 6–25 per cent of turbines that cannot currently be commercially recycled, which is primarily the wind turbine blades. Some solutions, explored in more detail below, include refurbishment, coprocessing with cement and innovative new products.

Composite recycling is a challenge affecting several industries. For example, the building and construction, transportation, marine and electrical sectors are all expected to produce more composite waste than the wind industry in Europe (see Figure 10). The relatively low volume of composite wind blade waste to date has made it difficult to develop a recycling business built purely off wind blade waste streams.[20] As a result, all sectors using composite materials must work together to find cost-effective solutions and value chains for the combined volume of composite waste.[21]

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18 Ibid.

19 Wind Europe, Accelerating Wind Turbine Blade Circularity, May 2020, windeurope.org/wp-content/uploads/files/about-wind/reports/WindEurope-Accelerating-wind-turbine-blade-circularity.pdf

20 Wind Europe, Accelerating Wind Turbine Blade Circularity, May 2020, windeurope.org/wp-content/uploads/files/about-wind/reports/WindEurope-Accelerating-wind-turbine-blade-circularity.pdf

21 Ibid.

The diagram and the material breakdowns all come from: Wind Europe WindEurope-Accelerating-wind-turbineblade-circularity.pdf

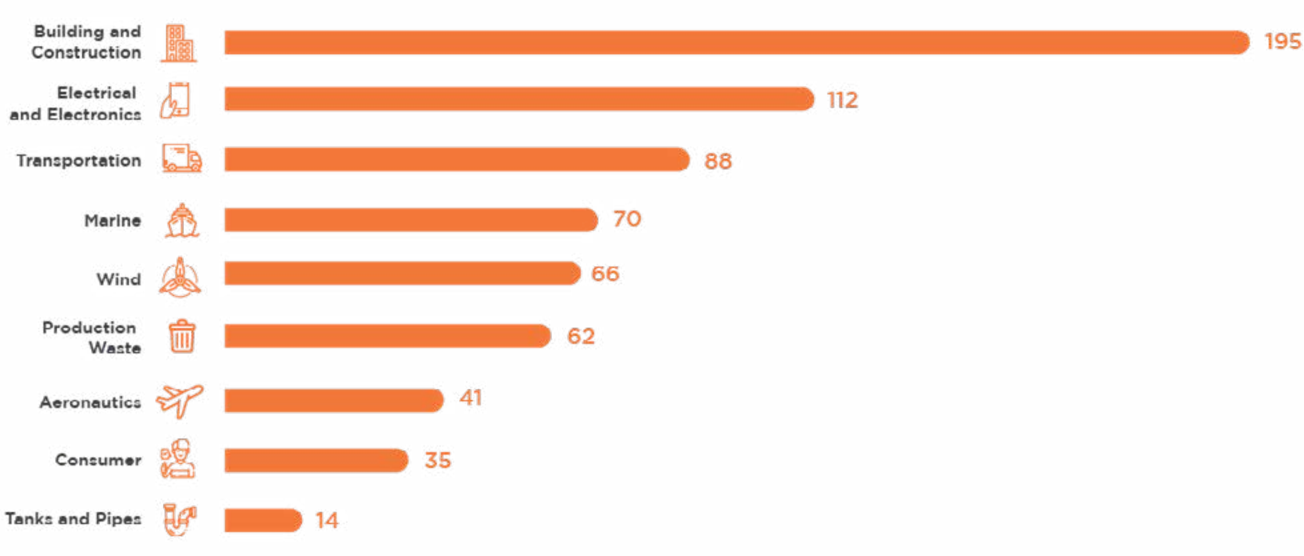

Figure 10: Estimated volume of composite waste in the European Union in 2025.[22]

Reduce

The good news is that the recyclability of new composite material blades is being addressed, with wind turbine manufacturers developing new blades that can be recycled as part of their commitment to zero-waste turbines by 2040.

Siemens Gamesa has developed the RecyclableBlade, the world's first recyclable offshore wind turbine blades ready for commercial use, and already has agreements to provide them to three major customers from 2022.[23] GE is also developing a recyclable blade through a project program called ZEBRA (Zero wastE Blade ReseArch).[24]

These recyclable blades use new types of resin that can be separated from the other components of the blade (fibreglass, plastic, wood and metals) through a chemical process, allowing the materials to be reused for new applications.

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[22] European Technology & Innovation Platform on Wind Energy, How wind is going circular: blade recycling, https://etipwind.eu/files/reports/ETIPWind-How-wind-is-going-circular-blade-recycling.pdf

[23] SiemensGamesa, Siemens Gamesa pioneers wind circularity: launch of world's first recyclable wind turbine blade for commercial use offshore, 7 September 2021, siemensgamesa.com/en-int/newsroom/2021/09/launch-world-first-recyclable-wind-turbine-blade

[24] GE, ZEBRA project achieves key milestone with production of the first prototype of its recyclable wind turbine blade, 17 March 2022, ge.com/news/press-releases/zebra-project-achieves-key-milestone-with-production-of-first-prototype-of-recyclable-wind-turbine-blade

Reuse

Reusing turbines or turbine parts, considered to be the option with the highest value for decommissioned wind turbines, is an effective and feasible way of obtaining a second life cycle.

The pre-owned demand can take several forms, as shown in Table 2.

International examples have seen pre-owned turbines and parts providing lower-cost systems for smaller projects and developing markets. Companies offering dismantling and resale services have been set up to support this pre-owned market, including in Australia (see Box 2) and several e-businesses exist to advertise and buy used wind turbine components.[25]

So far, Vestas has used pre-owned rotor upgrades on projects in 22 countries. One potential market for pre-owned wind turbines in Australia is the mining sector, which is turning to renewable energy behind-the-meter and for off-grid applications in order to decarbonise its operations.

While it may be possible to reuse turbine parts for repowers or component refurbishments (seen in Table 2) at other wind farms in Australia, this opportunity is limited by the number of compatible turbine models in operation. Table 3 shows that many of the turbines currently in use in Australia only have a small number of equivalent turbines from which replacement parts could be obtained or on which replacement parts could be used.

This lack of domestic opportunity means the reuse of components would likely have to involve international trade with other wind farms. It is important to note that if supplying pre-owned turbines to other countries, there should be an established waste pathway in that country for wind turbines so that the components do not simply end up in landfill in another country.

Table 2: Reuse cases for wind turbine components.[26]

Approach	Description	Suitability	Lifetime extension
New installation	Installation of pre-owned turbines on newly developed sites	All ages	20+ years
Partial repower	Installing new nacelle and rotor, reusing existing towers and foundations	Assets aged 12–15 years	20 years
Drivetrain repower	Replacing rotor and select drivetrain components (including electrical system), reusing all remaining structures	Assets aged 9–10 years	20 years
Component refurbishment	Replacing components like-for-like and/or installing upgrades	12 years or older	

[25] One example is wind-turbine.com

[26] McMillan, Craig (2022, March) End of Life or New Life: Vestas approach to Ageing Fleet [Conference presentation]. Australian Wind Industry Summit, online.

Table 3: Variability of turbines currently deployed at Australian wind farms.

Manufacturer	Model	Rating (MW)	Number of turbines	Number of wind farms
Acciona Nordex	N29	0.25	3	1
Enercon	E30	0.23	3	1
	E31	0.33	1	1
	E40	0.6	30	5
	E66	1.8	12	1
	E70	2.0	35	1
Senvion	MM82	2.0	6	1
Siemens Gamesa	AN Bonus 1.3	1.3	14	1
Suzlon	S88	2.1	47	1
Vestas	V27	0.225	11	2
	V44	0.6	8	1
	V47	0.6	17	2
	V52	0.85	2	1
	NM64	1.5	58	2
	V66	1.75	95	3
	NM72C	1.5	20	1
	V80	2.0	55	2
	V82	1.65	157	3
	V90	3.0	25	1

Repurpose

Repurposing involves using the original engineered structure and properties of an object for a new, different purpose and involves less processing than recycling.[27] Wind turbine blades can be repurposed for several, alternative functions. For example, in Europe, blades have been transformed into bus stops, playground equipment and public seats.

The Re-Wind Network, a research partnership comprised of Irish and American universities, has developed a catalogue that presents designs and details of different structures and products made from repurposed wind turbine blades, including bridges, poles, sound barriers, roofs and farming equipment. made from repurposed wind turbine blades.[28]

While this repurposing avoids the need for using new materials to build those structures, the current alternative uses for blades are not easily scaled to commercial production production and is not very sustainable.[29] The main barriers to repurposing include:

- perceived lower quality of used materials
- unknown residual structural properties
- lack of end markets for the materials
- unfamiliarity with sourcing and using recycled products
- unpredictable material availability
- uncertainty as to whether repurposing is truly better environmentally.[30]

[27] S M Woo and J Whale, Waste Management & Research, A mini-review of end-of-life management of wind turbines: Current practices and closing the circular economy gap, December 2022, journals.sagepub.com/doi/epub/10.1177/0734242X221105434

[28] Re-Wind Network, Re-Wind Design Catalog Fall 2021, static1.squarespace.com/static/5b324c409772ae52fecb6698/t/61e95d5f4ef3ad0d5eddd595/1642683746379/Re-Wind+Design+Catalog+Fall+2021+Nov+12+2021+%28low+res%29.pdf

[29] S M Woo and J Whale, Waste Management & Research, A mini-review of end-of-life management of wind turbines: Current practices and closing the circular economy gap, journals.sagepub.com/doi/epub/10.1177/0734242X221105434

[30] A J Nagle, G Mullally, P G Leahy and N P Dunphy, Journal of Environmental Management , Life cycle assessment of the use of decommissioned wind blades in second life applications, 15 January 2022, sciencedirect.com/science/article/pii/S0301479721020569?via%3Dihub https://www.sciencedirect.com/science/article/pii/S0301479721020569?via=ihub

Re-installing pre-owned wind farms in Australia

Blair Fox is a family-run, Western Australian company whose business model involves building, owning and operating wind farms in Western Australia using decommissioned wind turbines. In the past decade, Blair Fox has successfully dismantled, transported and re-installed over 50 turbines. This includes transporting ENERCON E40 500 kW turbines from Europe to Western Australia where they were then refurbished and re-installed at new sites throughout the state.

More recently, Blair Fox was responsible for the dismantling of Synergy's Esperance Wind Farm, which used ENERCON 600 kW turbines. The Esperance Wind Farm site was complex due to it being an environmentally sensitive area with limited hardstand space, and the dismantling process took six weeks. A purchaser for the wind farm was found, and the decommissioned turbines were taken straight to site, where the refurbishment occurs in order to minimise transportation. Generally, the refurbishment of the turbines applies mainly to the blades. They are inspected on the ground and refurbished to near new condition.

The electricity generated by Blair Fox's wind farms is supplied to local horticulturalists and farmers, with any excess electricity supplied to Blair Fox's retail customers through Western Australia's main electricity grid, the South-West Interconnected System.

Blair Fox is now commissioning its fourth site and has seen an increase in interest since the Western Australian Government announced the closure of state-owned coal-fired power plants. The reuse of Australian wind farm turbines is particularly attractive in the current economy where the cost of shipping has increased significantly. Some potential challenges for Blair Fox and other second-hand businesses include the impacts of decommissioning larger turbines on cranes and transport and changing grid connection regulations prohibiting older turbine technology from connecting to the grid

Recycling

TURBINE TOWER

Scrap metal recycling has been an important industry in Australia for more than 100 years. Recycled metals are extremely valuable. When traded, recovered metal scraps have a high market value compared with other recyclable materials. Steel scraps represent the majority of metal waste exports, but copper and aluminium are more valuable and therefore provide higher revenues.

There are several major scrap metal recycling companies in Australia that can process metal and aggregates from turbines. Each major city is home to large-scale recycling facilities equipped with industrial-scale shredders, emission scrubbers and dust particle collectors. In addition to these large processing companies, there are also thousands of second- and third-tier operators and scrap metal merchants that service remote areas. These operators can process the material onsite for transport to larger recycling centres.

According to the 2020 National Waste Report[31], Australia recovered around 5 million tonnes or 90 per cent of metal wastes for recycling in 2018–2019. It is estimated that up to 47,000 tonnes of scrap metal may be added to the waste stream in any given year from decommissioned wind turbines, accounting for less than 1 per cent of the annual total scrap metal recycling in Australia.

BLADES

Wind turbine blade recycling is not yet commercialised or competitive. There are several current options at varying degrees of maturity, and new innovations being discovered as the industry seeks to find solutions.

Currently, the most common technology to recycle blades is mechanical grinding, which is the use of a grinding machine to process the composite materials into short fibres and ground matrix (powder). While this method is effective, low-cost and less energy-intensive than other technologies, the recycled products are considered less valuable than the original composite material. The shredded material can be used as fillers or reinforcement in construction or manufacturing, such as panels for decking and construction, light poles, and possibly cement. For this process to be considered a sustainable recycling option, there must be clear, secure and robust end markets. While this is not the case yet, there are some innovative options being explored. For example, one manufacturer in Australia has been using recycled turbine blades in their new rail track product (see Box 3).

31 Department of Agriculture, Water and the Environment, National Waste Report 2020, 4 November 2020, dcceew.gov.au/sites/default/files/env/pages/5a160ae2-d3a9-480e-9344-4eac42ef9001/files/national-waste-report-2020.pdf

Austrak

Austrak, Australia's largest pre-stressed concrete sleeper manufacturer, has developed an innovative rail sleeper using recycled fibreglass as part of its commitment to sustainability through its parent company, Vossloh. Rail sleepers provide several functions, including supporting the railroad tracks, holding rail fastenings in place, and stabilising the track. Traditionally, sleepers have been made of timber, which provide the right properties but are vulnerable to environmental degradation, have a life span of 5–20 years and are becoming increasingly difficult to source.

Austrak has designed a composite product that meets the functional requirements of a sleeper, but is also fire, UV, moisture, and insect resistant; has good thermal stability; and is drillable with standard installation equipment. Furthermore, the shape and structural performance of the product can be customised for different loading applications (i.e. higher tonne-axle loads, open-deck bridges, low profile etc.).

Recycled fibreglass has been identified as a preferred core material and Austrak has indicated projected annual use for recycled fibreglass. To date, Austrak has been sourcing recycled fibreglass panels from international suppliers, including one that recycles wind turbine blades.

A critical gap in this supply chain is a domestic supplier that can crush the blade source material and manufacture it into a panel product for use in Austrak's composite sleeper. This capability does not currently exist in Australia.

Another method, revealed by Vestas in early 2023, is a newly discovered chemical technology that can be applied to blades that are currently in use. The new process can chemically break down epoxy resin into virgin-grade materials. Vestas will now focus on scaling up the novel chemical disassembly process into a commercial solution. Once mature, the solution will signal the beginning of a circular economy for all existing, and future epoxy-based turbine blades, possibly providing the opportunity to produce new turbine blades made from reused materials.[32]

Other possible recycling methods include:

- **Thermal processes:**
  - Pyrolysis is currently the optimal composite recycling technology and is considered suitable for industrial-scale implementation.[33] The process involves recovering the fibres from the resultant char product, which can then be resold at a competitive price compared to the original product. The by-products of the process, syngas and charcoal, are also potentially useable in combustion engines and fertilizer respectively.
  - Fluidised bed combustion or gasification recovers the reinforcing fibres, although reportedly at a much lower quality than the original fibre.
- **Thermo-chemical (solvolysis)** uses solvents to break down resins in the composites, recovering both fibres (glass and carbon). Its efficacy is dependent on the type of resin used in the blades.
- **Electro-mechanical (high-voltage pulse fragmentation)** is a pilot-scale process that uses electricity to separate fibres from the composite matrices. Recovered fibres are short but cleaner and longer than those from the mechanical process.[34]

Several promising studies are being undertaken by Australian universities to find a solution to composite recycling. The Porous Materials Research Group at the School of Materials Science and Engineering at UNSW-Sydney has

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32 Vestas, Vestas unveils circularity solution to end landfill for turbine blades, 8 February 2023.

33 S M Woo and J Whale, Waste Management & Research, A mini-review of end-of-life management of wind turbines: Current practices and closing the circular economy gap, journals.sagepub.com/doi/epub/10.1177/0734242X221105434.

34 Wind Europe, Accelerating Wind Turbine Blade Circularity, May 2020, windeurope.org/wp-content/uploads/files/about-wind/reports/WindEurope-Accelerating-wind-turbine-blade-circularity.pdf

Cement kiln processing

In Germany, waste with a total organic content higher than 5 per cent has been banned from entering landfill since 2009. Blades fall under this regulatory restriction due to the resin in the blades being considered organic.

To address this issue, a cement co-processing plant was established in northern Germany that uses around 15,000 tonnes of composite waste annually, 10,000 tonnes of which comes from wind turbine blades. The plant has a total current capacity of 30,000 tonnes per year. Companies such as neocomp in Germany specialise in treating fibreglass, including mechanical processing, cement co-processing, and transportation to the processing site.[37]

In Australia, Resource Recovery Facilities (RRFs) in NSW and SA use residual timber, paper, plastic and carboard waste produced from dry construction and demolition waste, and commercial and industrial waste materials to produce Process Engineered Fuel (PEF). ResourceCo services well-established markets for 'high energy users' in both Australia and South-East Asia where PEF is consumed for energy production in cement kilns without generating residues.

been exploring the conversion of fibreglass plastic into biodegradable porous carriers for use in agriculture. At the University of Sydney, researchers have developed improved recycling processes for carbon fibres using pyrolysis and oxidisation, with the trial process retaining 90 per cent of the material's original strength.[35]

Recover

Currently, the main technology for recycling wind turbine blades and other composite waste is cement co-processing. This process is categorised as energy recovery as the polymer matrix is burned as fuel. Using fibreglass blades as energy recovery reduces the carbon footprint of cement production by up to 16 per cent.[36] This process is currently being used by wind farms in Germany (see Box 4). While only available for fibreglass (not carbon fibre), this option is scalable, simple and cost-effective.

However, there are several issues with this process, first and foremost that recovery is low in the waste hierarchy. Other issues include the energy intensity required and the original structure of the blades is lost.

Landfill

Landfill is the final option on the waste hierarchy. While there have been instances of blades being disposed via landfill in Australia, to date these have been minimal and mainly due to the replacement of faulty or damaged blades from operating wind farms. It is estimated that by 2034, a total of 15,000 tonnes of blade composite waste will have been created in Australia due to decommissioned wind farms which is why it is important to establish suitable recycling and recovery pathways for composite materials

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35 The University of Sydney, Researchers develop improved recycling process for carbon fibres, 8 March 2021, sydney.edu.au/news-opinion/news/2021/03/08/researchers-develop-improved-recycling-process-for-carbon-fibres.html

36 Wind Europe, Accelerating Wind Turbine Blade Circularity, May 2020, windeurope.org/wp-content/uploads/files/about-wind/reports/WindEurope-Accelerating-wind-turbine-blade-circularity.pdf

37 Neocomp website, Services, neocomp.eu/de/Leistungen

RECOMMENDATIONS

There is a large and steady volume of wind turbines that will need to be decommissioned in the next decade. This report shows that existing waste management options enable reuse or recycling of most turbine components.

However, there is no clear pathway for wind turbine blades. While this report only focuses on the volumes of composite waste produced by wind farms, this waste stream is a widespread issue shared by the construction, maritime and aviation industries. There are potential solutions, such as using recycled composite material for construction or manufacturing, but greater focus and action is required by both the public and private sectors.

There are four key recommendations for the wind industry, government and other composite-using industries:

- support research and development
- establish pathways and set targets
- support recycling supply chains
- share knowledge.

	Wind industry	Government	Other industries
Support research and development	Create partnerships with research facilities (as well as other composite-using industries) to invest in R&D in composite waste, particularly in the recycling and reuse of fibreglass and carbon fibre. This should include university research into the scalability and commercialisation of recycling processes. Provide research facilities with access to decommissioned wind turbine blades to support further research.	Federal and state governments should develop partnerships with composite-using industries to invest in R&D in composite waste, particularly in the recycling and reuse of fibreglass and carbon fibre. This should include university research into the scalability and commercialisation of recycling processes and pilot programs.	Other composite-using industries should partner with the wind industry and invest in R&D in composite waste, particularly in the recycling and reuse of fibreglass and carbon fibre. This should include university research into the scalability and commercialisation of recycling processes.
Establish pathways and set targets	Engage with state environmental protection authorities and agencies to work towards recycling pathways for composite materials. Investigate aggregating composite material with other composite-using industries.	State environmental protection authorities should consider composite waste management, including setting goals and pathways for the next decade. The state agencies should engage with key industries, such as the wind industry, to understand the issue and develop solutions to avoid composite waste being disposed into landfill.	Investigate aggregating composite material with other composite-using industries including the wind industry.

	Wind industry	Government	Other industries
Support supply chains	Investigate and support end-markets for recycled composite materials.	There is a gap in the market for mechanical grinding/ crushing recycling services, which is critical to allow the establishment of a supply chain for new products that use recycled composite materials. The necessary equipment is available internationally but is currently not commercially viable in Australia and requires government support.	Investigate and support end-markets for recycled composite materials.
Knowledge sharing	Collaboration is recommended within the wind industry, with other industries that use composite materials and with those industries that could recycle and manufacture composite materials. Suggested areas of collaboration and knowledge sharing include: ***Wind industry:*** Volume forecast out to 2050 Transportation of wind turbines to recycling facilities Storage of old blades if necessary Best practice for decommissioning Initiatives that demand recycled composite materials ***Recycling facilities:*** Assisting with technical changes required to accommodate wind turbines at recycling facilities ***Other composite-using industries:*** Breakthroughs/scaling up in composite recycling processes Demand for recycled composite materials	The government should support knowledge sharing between composite-using industries, including forums, working groups and online platform	Composite-using industries, including the maritime and construction industries, should share knowledge with the recycling industry of developments and capabilities for fibreglass and carbon fibre recycling, as well as predicted supply volume estimates.

CONCLUSION

The decommissioning of wind turbines has become increasingly topical as some of Australia's ageing wind farms approach their end of life. Decommissioning wind turbines involves several different processes, but ultimately the turbine is dismantled and removed from the site. As wind turbines are predominantly metal, a majority of the wind turbine can be recycled using existing metal recycling facilities within Australia.

While the Australian wind industry is capable of exceeding national recycling averages due to the high metal content of wind turbines, it is seeking to go further and avoid any disposal of waste. The biggest barrier to zero-waste turbines is the wind turbine blades. Wind turbine blades from older wind farms are predominantly made from composite materials such as epoxy and fibreglass of which there are limited options available to avoid blades from entering landfill. The volume of composite waste produced in Australia is not unique to the wind industry, and there are several innovative solutions emerging to recover and recycle composite material.

This report has outlined environmentally and socially responsible approaches and practices for the decommissioning of wind farms and has identified the recycling and waste management pathways currently available. It includes key recommendations to further advance composite material waste streams, including research and development into composite recycling, the establishment of recycling pathways, the support of supply chains, and industry collaboration and knowledge sharing.

Through industry collaboration, research and development, and government support, the wind industry can tackle the cross-industry issue of managing composite materials and achieve close to a 100 per cent circular economy.

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