Forecasting the end-of-life wind turbine material flow in Australia under various energy transformation scenarios

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Abstract

A circular world requires sustainability of all products and services even those often perceived as clean technologies. The unprecedented growth of wind turbine (WT) deployment in Australia as a green energy system is promising with over eight gigawatts (GW) by 2021. However, sustainable management of wind turbines is important to avoid the potential environmental burden of significant waste at end-of-life and to identify opportunities for resource recovery. As the first step toward this aim, this paper provides a holistic outlook of the current and future WT installation and the projected future waste flow under five scenarios for the national energy system transformation. The projected cumulative WT installation capacity will be between 13 and 38 GW by 2041. Also, the volume of the cumulative WT waste stream is projected to vary between 6.69 and 19.76 million tonnes for the "slow change" scenario (creating the lowest volume of waste) and "step change" scenario (creating the highest volume of waste), respectively. The first volume of wind turbine waste has arrived in 2013, however, it will reach more than 1 million tonnes around 2030. The projected waste stream in 2061 includes a wide range of materials, predominantly concrete at 10.20 million tonnes, followed by 2.20 million tonnes of steel. Also, there will be some other valuable materials including iron (520 kilo tonnes), copper (260 kilo tonnes), Aluminium (40 kilo tonnes) and rare-earth elements (1280 tonnes) in 2061. This significant amount of waste flow implies the requirement of a circular economy approach for wind energy system management by connecting all the supply chains from production to end of life recycling and material recovery.

Keywords: Circular economy; End-of-life recycling; wind turbines; waste management; material flow analysis.

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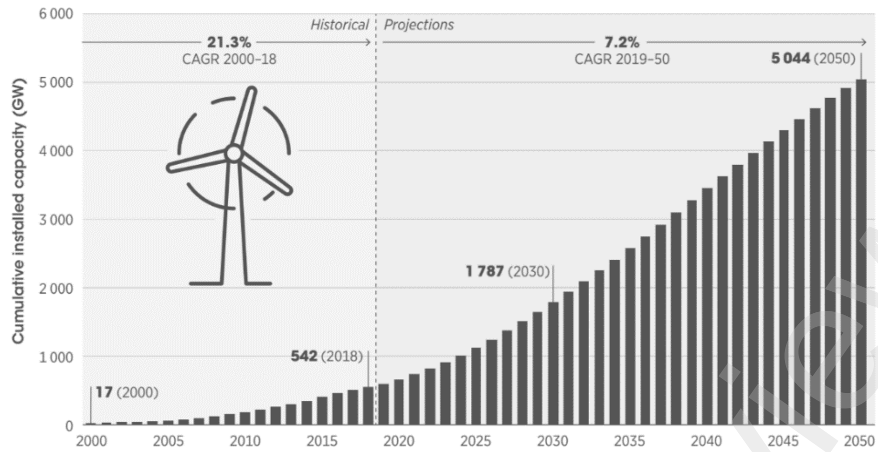
1. Introduction

In recent decades, a combination of reasons including high oil prices, reduced costs of some renewable energy technologies (due to the emergence of large-scale manufacturing), and climate and energy policy innovation resulted in increasing growth of different types of renewable energy technologies, especially photovoltaic panels and wind turbines [1]. There are currently more than 21,866 wind farms with a capacity of 953.8 GW (as of Sep 2021) across the world [2]. IRENA has anticipated (Figure 1A) that the onshore wind turbine installations will reach 1787 GW and 5044 GW by 2030, and 2050, respectively.



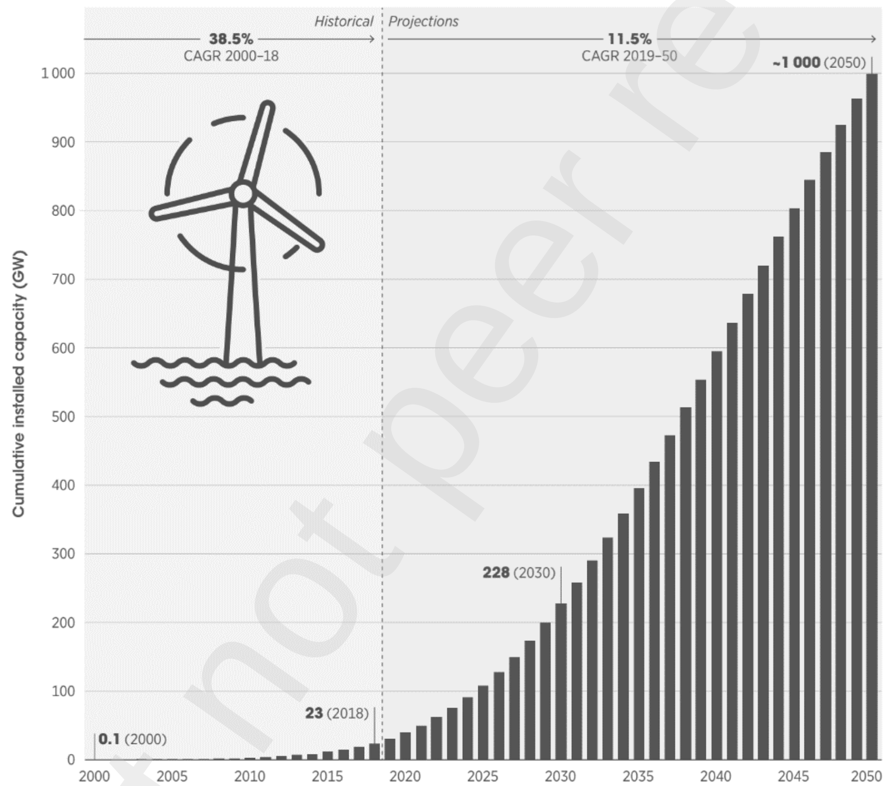


Figure 1: Projection of the global A) onshore and B) offshore wind power capacity until 2050 in Gigawatt (Image: courtesy of IRENA [3])

Compared to the current installations, this implies a growth rate of threefold by 2030 and 10-fold by 2050 [3]. The anticipated growth rate for offshore wind development (Figure 1B) is even more dramatic, with growth around 50-fold from 23 GW in 2018 to 1000 GW in 2050 [3]. Although the generation of energy from wind supports a clean energy transition with a relatively low carbon emission footprint [4], there are further opportunities to improve the environmental impact considering the entire technology lifecycle, specifically the management of wind turbine waste [5]. Therefore, there is an emerging challenge regarding the management of the end-of-life of wind turbines.

Generally, there are two main wind turbine technologies which is usually used in the world: gearbox (GB) and direct drive (DD). These two types have different designs and generators. It means each one has its own advantages and disadvantages. However, the direct-drive technology is newer.

Table **1** categorizes different wind turbine technologies and defines abbreviations that will be used later.

Table 1: Wind turbine technologies [6]

Type of generator	Type of turbine
Direct drive (DD)	High-Temperature Superconductors (HTS)
	Electrically Excited Synchronous Generator (EESG)
	Permanent Magnet Synchronous Generator (PMSG)
Gearbox (GB)	Electrically Excited Synchronous Generator (EESG)
	Permanent Magnet Synchronous Generator (PMSG)
	Double-Fed Induction Generator (DFIG)
	Single Fed Induction Generator-With Full converter (SFIG)
	Squirrel Cage Induction Generator (SCIG) – Without full converter
	Squirrel Cage Induction Generator (SCIG) – With full converter
	Wound Rotor Induction Generator (WRIG)

The materials embedded in the wind turbines include concrete, steel, polymers, glass/carbon composites, aluminium, boron, copper, iron, manganese, nickel, zinc, and rare-earth elements. The amounts of t/GW of these materials used in different wind turbines depend on the type of generator, blade diameter and hub height. On the other hand, although the wind turbines with larger hub height and diameter can produce more energy, the material consumption will increase.

With quick growth of the wind energy development in the world, it appears that identification and projection of wind turbine waste streams is very beneficial for predicting their environmental ([7], [8]) and economic impacts ([9], [10]) and developing a global surveillance and management system ([11] [12]).

Early work by Andersen [13] and [14] estimating wind turbine waste in Sweden was one of the first case studies to highlight the magnitude of the waste challenge. They developed a forecasting and material flow analysis (MFA) model by assuming a constant lifetime of 20 years and estimated waste volumes out to 2034. Also, Andersen [13] provided a detailed basis for estimating the materials present in the wind turbine waste stream. Recently, Tazi et al [15] used MFA to estimate the materials embedded in decommissioned wind turbines in Champagne-Ardenne (CA) region in France during 2002-2020. Their study highlighted the importance of maintenance as an efficient way to increase the useful lifetime of wind turbines and reduce the overall waste flow. In the most recent research, Chen et al [4] estimated that the total waste of wind turbines in Guangdong (a province in China) could range from 490 -1,200 kilo tonnes by 2050 under different scenarios. This detailed study considered different assumptions of the foundation type for offshore wind turbines depending on water depth.

Europe is a pioneer in deploying wind power for generating green energy. Lichtenegger [16] analysed the situation of Europe in 2050 in terms of cumulative wind turbine waste. In addition to considering onshore and offshore wind turbines separately, they concentrated on waste forecasting based on the regional growth rate, which leads to more accurate and reliable data estimation for different countries. Also, in the UK, as a leader in using wind energy in Europe, Tota-Maharaj and McMahon [17] anticipated and quantified the wind turbine waste flow and containing materials between 2000 and 2039.

Another case study published by Cooperman et al [18] focuses on estimating wind turbine waste until 2050 in the USA. Almost 2.2 million tonnes of cumulative waste are estimated by 2050. Regarding their calculation with 20 years of wind turbine lifetime, the cost of landfilling for wind turbine waste relative to the life cycle cost of energy as well as the required capacity for landfilling are not important factors for promoting alternative waste treatments such as recycling instead of landfilling. They considered two treatment scenarios for the wind turbine blade including 1) cutting them into large segments, and 2) shredding them into small segments and transporting them on average 25 km to landfill. The overall cost of EoL treatment was reported as \$19 and \$39 USD/kW. Therefore, the low cost of landfall does not provide an incentive to recycle materials.

Delaney et al. [19] attempted to gather comprehensive information about the wind power industry in Ireland until 2040. They utilised an integrated Geographical Information Science (GIS) framework for identifying the blade model and type of wind turbines and estimating the overall amount of fibre reinforced polymers from decommissioned wind turbines in Ireland. Such a study can help diverse stakeholders including researchers, investors, policymakers, and local governments in better insight into the future of wind farms in the given region.

One of the important and challenging components of wind turbines is blades which are manufactured from carbon fibres. This material, due to difficulties in recycling, has resulted in some problems for the end of life of wind turbines and researchers attempt to find new ways to manage this composite waste ([20], [21]). Therefore, some scholars have explored the volume of this issue in their countries and also worldwide. As an example, Arias and Bank [22] estimated the total amount of composite waste from installed wind turbines (after 20 years of useful lifetime) until 2015 and predicted the yearly magnitude of composite waste generation from the wind energy sector until 2055 in the United States. The authors used wind turbine design specifications from commercial wind turbine manufacturers reports to accurately estimate the waste volumes and material composition.

One of the comprehensive and inclusive works done by Liu and Barlow [11] discovered the overall amount of composite (blade) waste produced in the whole life cycle of wind turbine lifetime worldwide. As a dominant material in wind turbines, carbon fibre reinforced plastic has an increasing consumption trend globally. As the recycling stage for used wind turbine blades is currently challenging and is not yet an inclusive and commercial process, it is necessary to view the future usage of carbon fibres. This issue has been illustrated in [12] to predict carbon fibre waste until 2050 worldwide. The classification of geographical areas is as follows: Europe, Asia, North America, Latin America, Oceania, Africa, and the Middle East. Results show that most of the cumulative amount of composite fibre waste belongs to Europe by 190 kilo tonnes, followed by Asia with roughly 149 kilo tonnes in 2050.

Wind turbines with direct drive generators are lighter than WT with gearbox generators as they are using permanent magnets instead of heavy gearboxes. Rare earth materials such as Neodymium praseodymium (NdPr) have increasing usage as the most significant material for manufacturing modern permanent magnet wind turbines [23]. Based on the forecasting scenarios and using dynamic material flow analysis by [24], during 2019-2040, the amounts of NdPr needed for the wind energy sector will enhance from 228 to 788 kilo tonnes. It shows that recycling NdPr as an alternative way to supply the required amount of this rare material should be considered in the future.

Although the amounts of current existence obsolete wind turbine waste are not too much, which could capitalize on the economies of scale, the wind turbine waste volumes in the future will be significant. Hence, currently as a motivative factor, effective policy and regulations are required to support and cast light on the recycling systems development for EoL wind turbines, because the value of material in the waste stream currently is not a sufficient driver to encourage the emergence of recycling industries. In order to ensure that the proposed treatment techniques recover and recycle the wind turbine waste materials effectively, official data and comprehensive datasets for forecasting the waste stream of wind turbines are nationally essential.

As mentioned before, wind power market has expanded significantly during the last decades and now is considered as the cheapest renewable energy source when it comes to the large-scale [25]. As the useful lifetime of a wind turbine is about 20-30 years ([26], [27], [28], [29]), a substantial wind turbine waste flow is anticipated in the coming years. A proactive plan is needed to ensure the sustainable management of the EoL wind turbines to avoid adverse environmental impacts that could undermine the technology's green credentials and exploit resource recovery opportunities [14]. Hence scholars have started to estimate the wind turbine waste volumes in different countries such as the USA [22], Sweden [14], The UK [17], Europe [16] and China [4] as an initial step for management of end of life of wind power industry. Among the countries tend to develop wind power industry, Australia possesses a special importance.

In 2020, Australia's wind farms produced 35.4 percent of the overall clean energy in the country and provided 9.9% of Australia's overall electricity by around 7376 MW [25]. Also, by the end of 2020, 21 wind farms constituted a capacity of 4 GW were either under construction or financially committed nationally [25]. Furthermore, Australia has had nearly one percent of global wind energy capacity until 2021. Hence Australia is the eleventh country in the world in terms of generating electricity via wind turbines. The data indicates that the wind power market in Australia is growing rapidly. As discussed above, if not properly managed this could result in a huge amount of waste with adverse environmental and ecological impacts [14]. Therefore, paying serious attention to wind turbine waste management will be an essential context in Australia's economy, industry, and environment for a promising horizon in the upcoming years. On the other hand, there are reports about some E-waste managements in Australia such as televisions and computers [30], [31], batteries [32] and solar panels [33], [34]. However, there is not any research for presenting the management of wind turbine's waste in Australia. Therefore, this paper provides: 1) a comprehensive database of operational wind farms, including location, technology type and lifetime, 2) an MFA to estimate future waste volume up to 2061, and 3) a detailed breakdown by material to estimate resource recovery opportunities. The findings are relevant to government and industry to inform the timely development of new recycling industries

2. Materials and method

In this research, the EoL stage of wind turbines is considered for estimating of waste volume as can be seen in Figure 2. However, there are some waste in the production process and maintenance that they are not very significant because of the small amount of generated waste in comparison with the EoL waste [4]. Data from [35], [2], [36] and [3] combined to obtain the cumulative installed capacity until 2041 and create a comprehensive database for all installed operational wind farms in Australia until 2021.

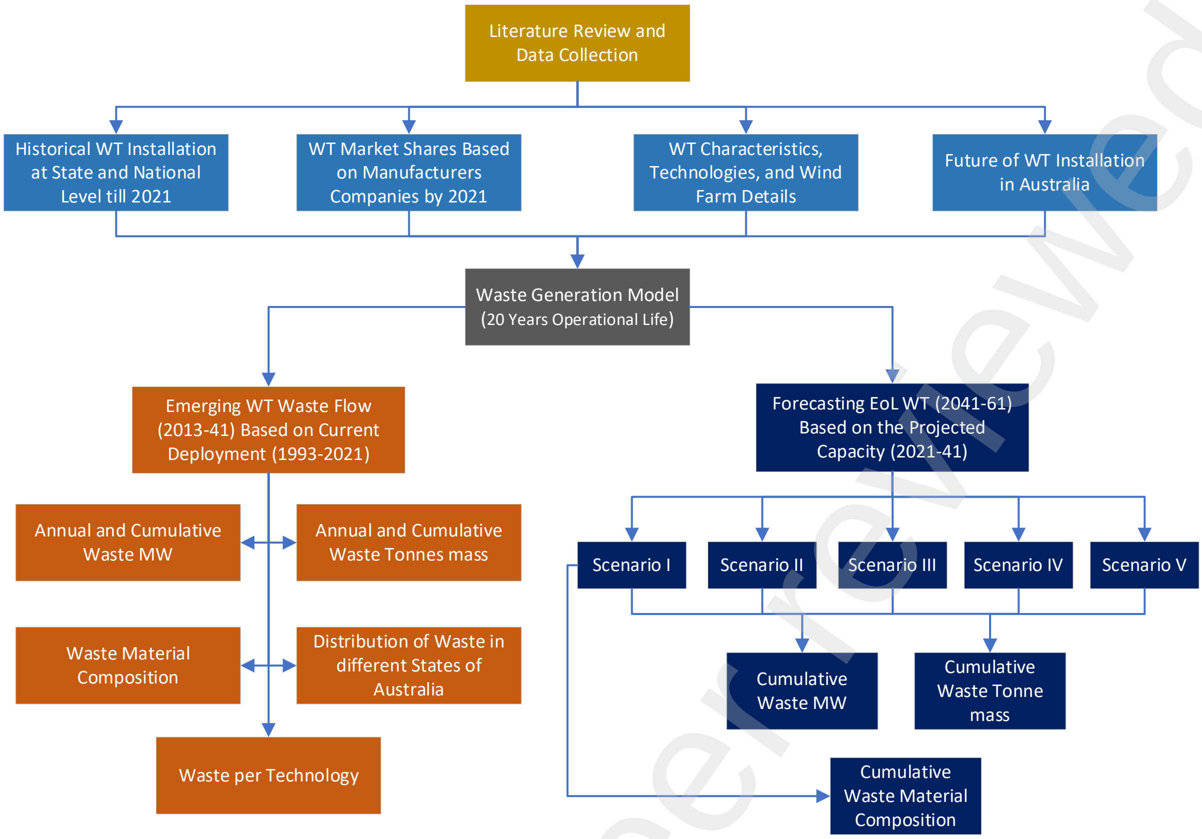


Figure 2: Flowchart of the research framework of this study (WT: wind turbine)

The information of all Australian operational wind farms (2021), including 125 onshore wind projects, has been provided in this database. Table 2 presents a part of this database, illustrating the contained information.

Table 2: The first ten rows of the Australian wind farms database (data extracted from [2])

Name	Area	Power (MW)	Number of turbines	Hub height (m)	Turbine manufacturer	Commissioning year	Wind turbine model	wind turbine power (kW)	wind turbine diameter (m)	Wind turbine technology
Ten Mile Lagoon	Western Australia	2.025	9	-	Vestas	1993	Vestas V27/225	225	27	GB-WRIG
Denham	Western Australia	0.46	2	-	Enercon	1997	Enercon	230	-	DD-EESG
Thursday Island	Queensland	0.45	2	-		1997		225	-	
Denham	Western Australia	0.23	1	-	Enercon	1998	Enercon	230	-	DD-EESG
Huxley Hill	Tasmania	0.75	3	-	Nordex	1998	Nordex N29/250	250	29	GB-SCIG
Crookwell	New South Wales	4.8	8	45	Vestas	1998	Vestas V44/600	600	44	GB-WRIG
Windy Hill	Queensland	12	20	46	Enercon	2000	Enercon E44/600	600	44	DD-EESG
Portland Wind Farm	Victoria	18.2	14	50	Bonus	2001	Bonus B62/1300	1300	62	GB-SCIG
Albany	Western Australia	21.6	12	65	Enercon	2001	Enercon E66/1800	1800	66	DD-EESG

The material recovered from discarded wind turbines is estimated by examining the installed wind turbines so far (2021) and considering their useful lifetime of 20 years as well as different wind turbines reports from Vestas Company and a technical report regarding wind turbine technologies published in European Union [6]. Moreover, a prognosis of future decommissioned wind turbines is carried out by applying the AEMO forecasting scenarios for wind energy penetration in Australia until 2041.

[36] has anticipated the future of wind energy development by introducing five scenarios considering the extent of energy network decentralisation and decarbonisation. These are defined based on three key factors including 1) the extent of distributed energy resources (DER) uptake, 2) the growth rate of energy demand, and 3) the extent of variable renewable energy (VRE) uptake. Figure 3 illustrates the differences between these five AEMO forecasting scenarios ranging from "Slow Change" as the most conservative to "Step Change" as the most optimistic scenario. In terms of the three factors, the "Slow Change" scenario assumes the slowest rate of change in terms of DER, demand change, and VRE towards decarbonisation and decentralisation while the "Step Change" assumes the highest rate of change. The other three scenarios fall somewhere between these two extreme scenarios. The "Central Scenario" consider middle speed values for the three factors based on the limitations and policies undertaken by government and federal regulations regarding the transition from coal-fired generation to renewable energy resources. Hence, for each of these five scenarios, AEMO has projected the wind technology uptake which will be used in this study for our material flow analysis.

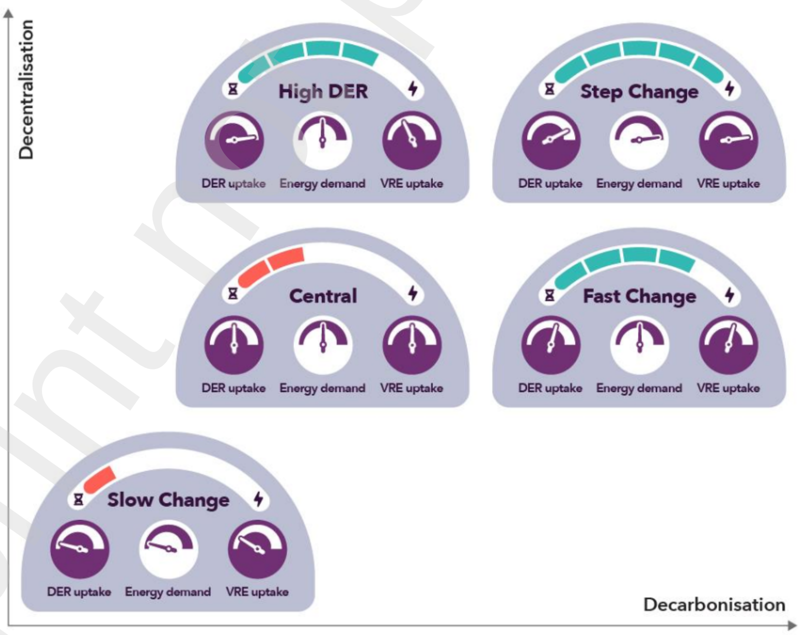


Figure 3: Decarbonisation and decentralisation over five transition scenarios prepared by (AEMO, 2020). DER: distributed energy resources, VRE: variable renewable energy

Material flow analysis (MFA) is usually utilised as an important quantifying model for flows and stocks of materials [15] in a specific time duration. For example, [17] and [4] published their reports about the generating waste from discarded wind turbines over a period of time using MFA in the UK and Guangdong in China, respectively. Equation 1 demonstrates the balanced relationship among stock (f_s), output (f_o), and input (f_i) flows [15].

$$\sum f_i = \sum f_o + \sum f_s \qquad (1)$$

In this study, we employ the MFA method for measuring the amount of waste generated from Australian wind turbines by the end of their life in two separate periods of, 2003-2041 and 2041-2061. The first period is based on the already installed wind turbines while the second period also accounts for the projected installations by AEMO. Regarding Figure 2, first, the capacity (kW) of decommissioned wind turbines is calculated in each period of time, and then this capacity is converted to an overall mass of waste (tonnes). Finally, the detailed mass of WT material composition will be calculated using the technology type and producer of the wind turbine.

3. Results and findings

3.1. WT Deployment Outlook in Australia

WT deployment varies in Australia. Presently, Victoria has the highest penetration with 31% of total national capacity in 2021. South Australia and New South Wales have 25% and 21%, respectively. While Western Australia and Queensland were pioneers with some of the first installations in Australia, WT turbine deployment has lagged over the past two decades compared to other jurisdictions. Presently there is no WT capacity in Northern Territory (Figure 4).

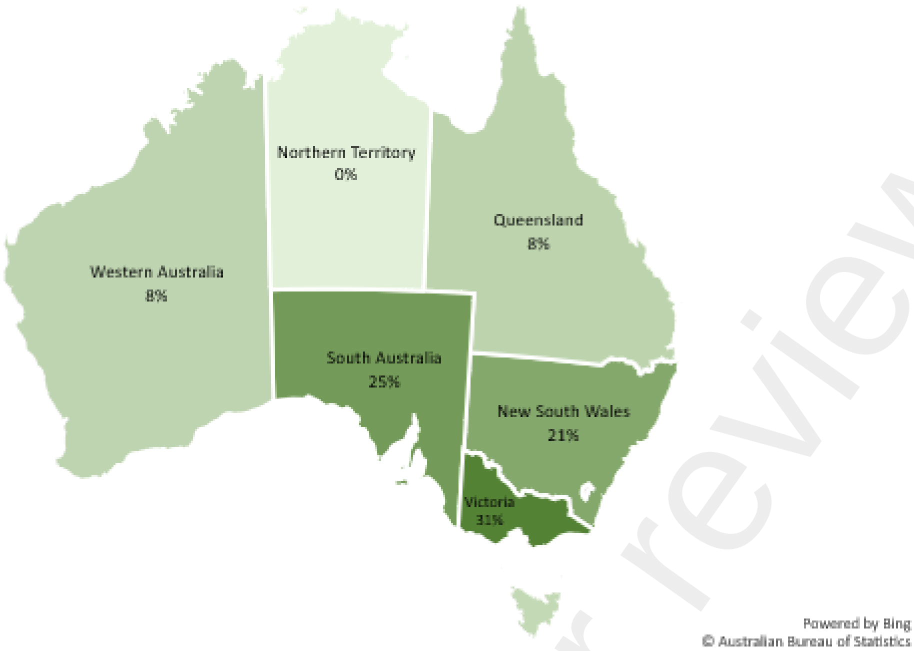


Figure 4: Nationwide distribution of WT deployment in the states and territories of Australia as of 2021

Figure 5 indicates the overall capacity of WT in Victoria is just over 2620 MW, followed by South Australia by nearly 2053 MW. The WT deployment in New South Wales (ACT included) is 1738 MW. On the other hand, the utilization of the WT system for power generation is very close in Queensland, Western Australia, and Tasmania by almost 685 MW, 657 MW, and 571 MW systematically. No WT capacity in Northern Territory is reported. These results are valid until 2021.

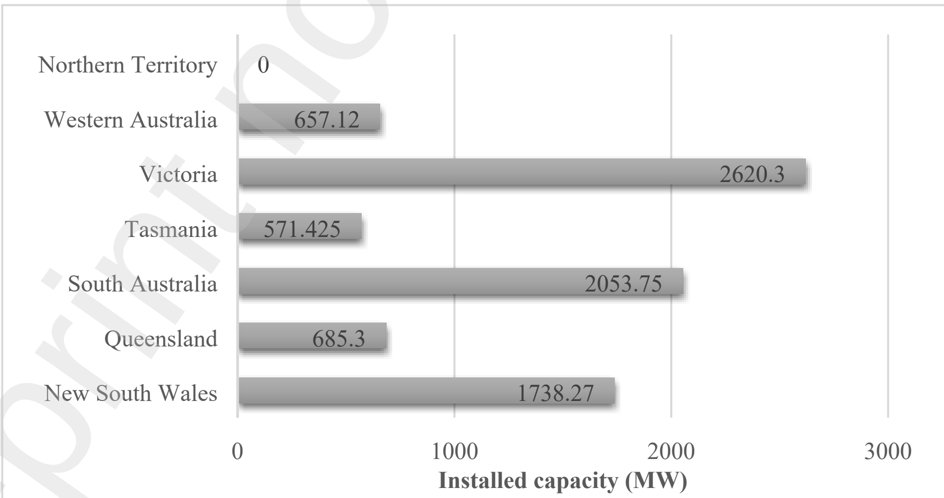


Figure 5: Australia's State-wide WT capacity in MW as of 2021 (data extracted from [2])

Figure 6 shows the cumulative wind turbine installation (number), as well as the capacity (MW) between 1993 and 2021 for the various manufacturers. As can be seen, the installation in numbers, as well as MW, is dominated by Vestas Wind Turbines with 3299 MW (1182 turbines) followed by

General Electric with 1377 MW (438 turbines). Also, the cumulative installation of wind turbines by other manufacturers is proportionally much less share in the Australian market, with approximately 764 MW (364 turbines) the highest and 0.75 MW (three turbines) the lowest among eleven different companies by 2021. It is worth noting that the overall installation of the Wind turbines in Australia has exceeded from 3257 WTs tills 2021 equals to 8327 MW, respectively.

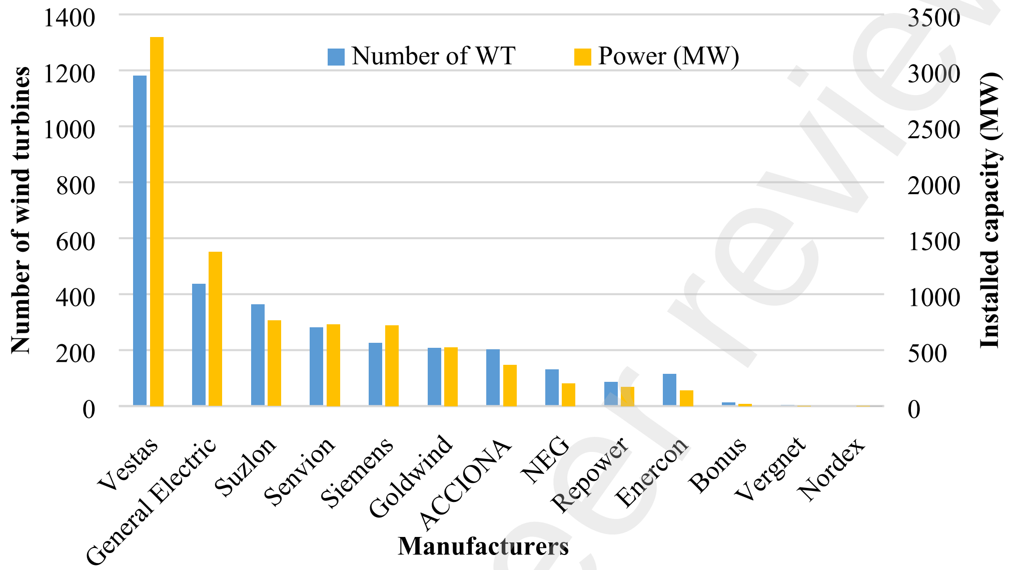


Figure 6: Quantity and capacity of wind turbine installed in Australia based on the historical deployment between 1993 and 2021 by various manufacturers

Figure 7 indicates the share by producers in the overall wind turbine power generation in Australia by 2041 based on the wind turbine deployed between 1993 and September 2021. Accordingly, Vestas has the highest share with 40%, followed by General Electric with 17% compared to other major players like Suzlon, Senvion, and Siemens with 9% each. The other players have smaller shares between 1% and 6%.

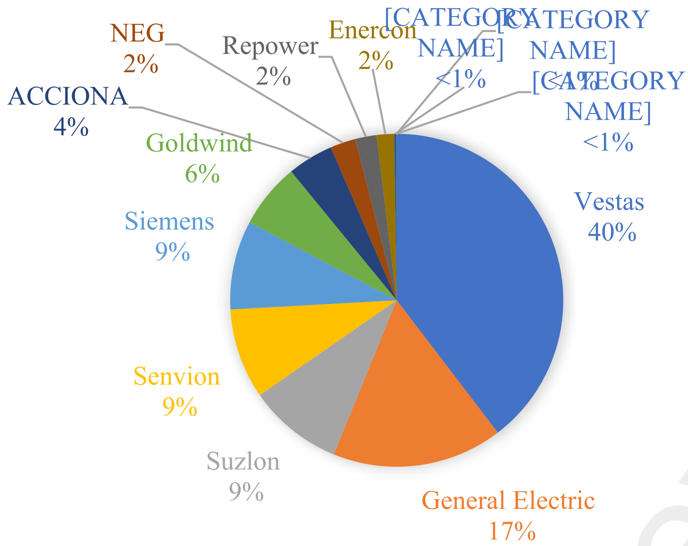


Figure 7: Power distribution percentage of various Wind Turbine installed between 1993 and 2021 in Australia based on the manufacturers' brand

By analysing the technical specifications of the installed wind turbines in wind farms of Australia, the distribution of the wind turbine power, wind turbine hub height, and wind turbine diameter are plotted in Figure 8-Figure **10**, respectively. The overall trend of wind farm development is increasing from 1993 to 2021 (Figure 8). The growth of wind farms was accompanied by the power of installed WT installed in each wind farm. Over time, the number of wind farms with higher WT powers had a substantial increase in contract with the first decade of developing early wind farms in Australia. The Results disclosed that nowadays, there are a number of wind farms with WT power capacity of over 3000 kW. Also, the hub height and blade diameter of the installed WT in these wind farms had a rising trend with just 45 and 27 meters respectively in 1993 all the way up to 137 m and 150 m in 2021 (Figure 9 and Figure 10).

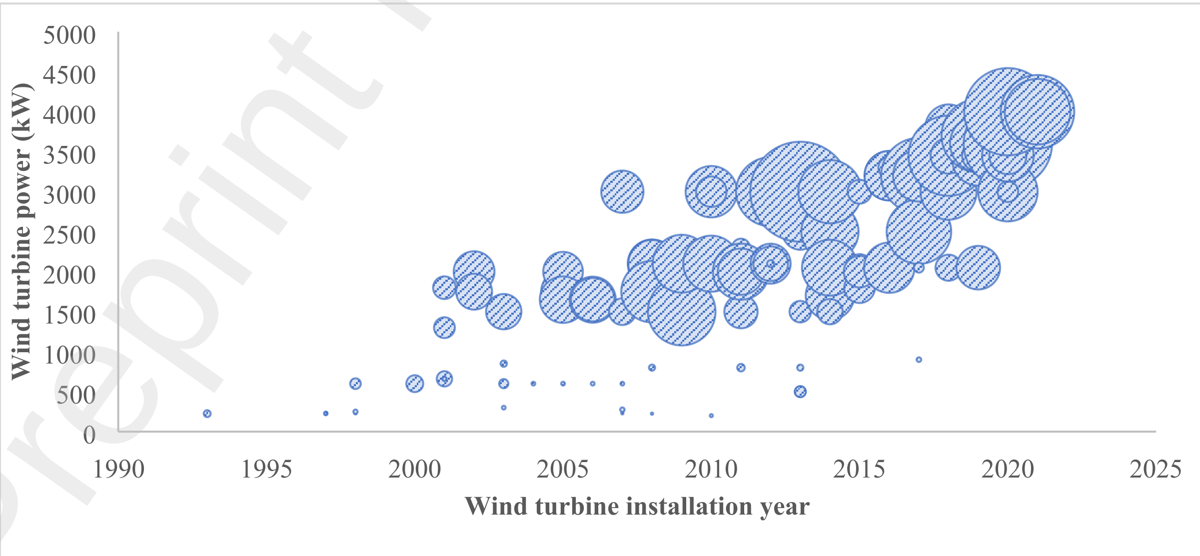


Figure 8: Power Distribution of wind turbines over time in kW

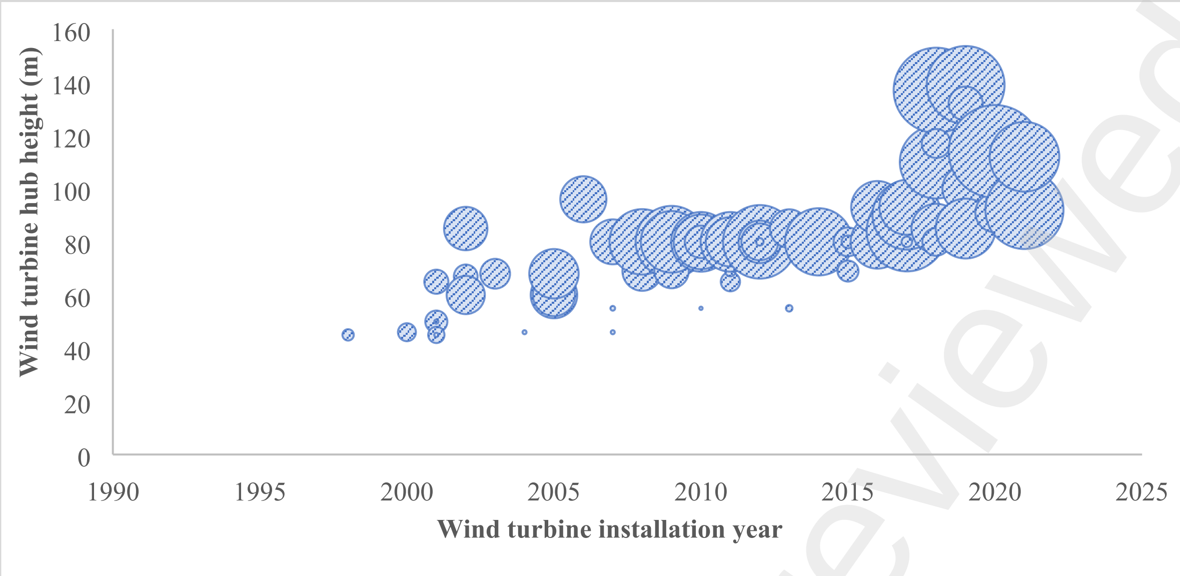


Figure 9: Hub height values of wind turbines over time in meter (m)

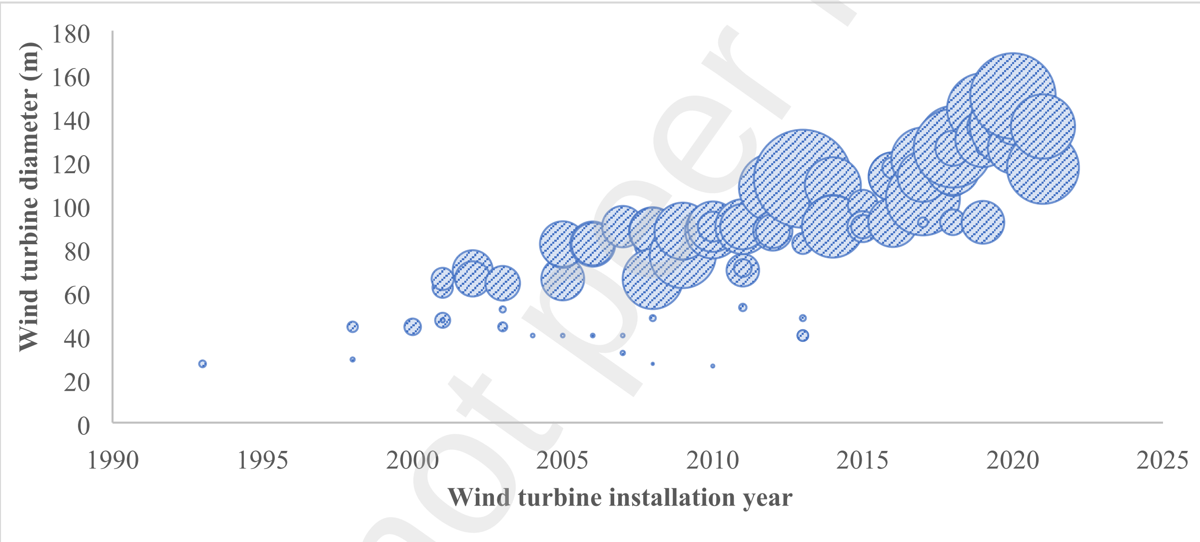


Figure 10: Blade diameter of wind turbines over time

In the following, the type of technology for a wide range of installed wind turbines is shown in Figure 11 based on the year of wind turbine installation. Furthermore, the market share of each type of wind turbine technology is depicted in Figure 12 . These data are used to compute the material inventory. As can be seen, GB-DFIG, which is a kind of gearbox wind turbine has 40% share of the total installed wind turbines; however, in the recent years, using the GB-SFIG which is another high-tech gearbox wind turbine has been increased. Also, DD-PMSG as a direct drive technology wind turbine is employed more after 2012. Although, in the Direct drive-PMSG generators, rare-earth elements are used more than the other types, they are less weight than the gearbox generator wind turbines which results in overall wind turbine weight reduction [6].

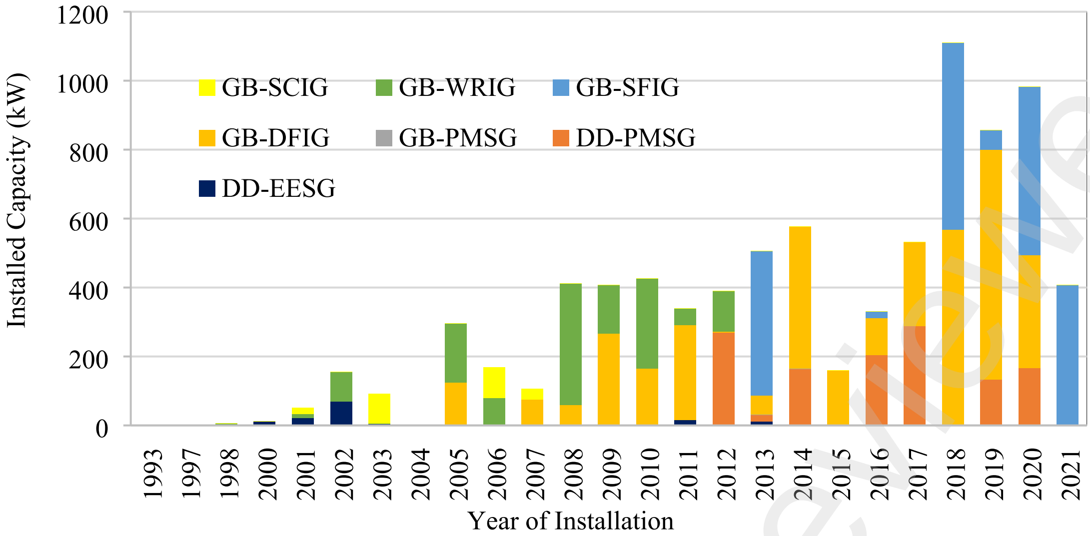


Figure 11: Technology-wise distribution of installed wind turbines in Australia in kW (for the abbreviations refer to Table 1)

The result of this study shows that there is a wide range of WT used in the Australian market, and each has a certain market penetration based on the quality, specification, services, and other factors. Figure 12 provides a breakdown by technologies. GB-DFIG has achieved the highest market share by 42% among other available technologies. It is followed by GB-SFIG by 23%. At the next level, 15% market share is the same for GB-WRIG and DD-PMSG technologies. Also, there are two other technologies of GB-SCIG and DD-EESG which have a very low share in the Australian Market so far by 3% and 2%, respectively because they have been outdated in the recent years.

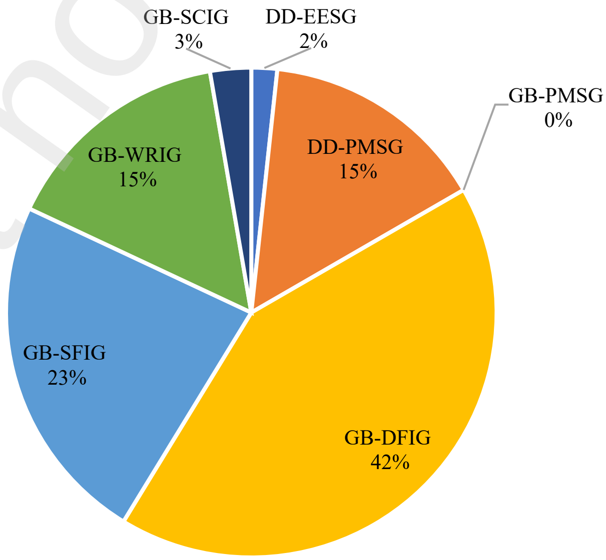


Figure 12: Market share of deployed WT in Australia based on their utilized technologies

Figure 13 clearly demonstrates the annual and cumulative WT development trend in terms of installation and capacity in Australia over the course of 28 years (from 1993 to 2021). Although the annual installation capacity has fluctuated over the years, it had a considerable growing trend, reaching about 983 MW in 2020. The cumulative result is very promising and shows continued growth in the WT installation deployment from just over 2MW in 1993 to over 8000 MW in 2021.

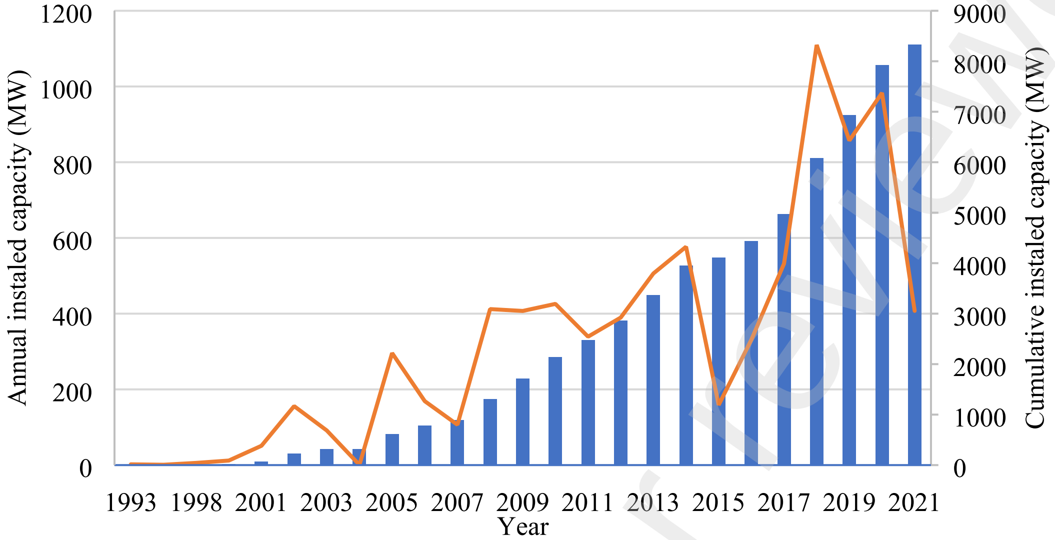


Figure 13: Annual and cumulative WT deployment in Australia by 2021

Figure 14 indicates the overall outlook of the current and projected cumulative WT installation rate based on five AEMO forecasting scenarios. According to the Slow Change scenario, the installation growth rate between 2022 and 2041 would be 4513 MW. The most promising growth in the WT deployment during the same time period will be 29595 MW based on Step Change Scenario.

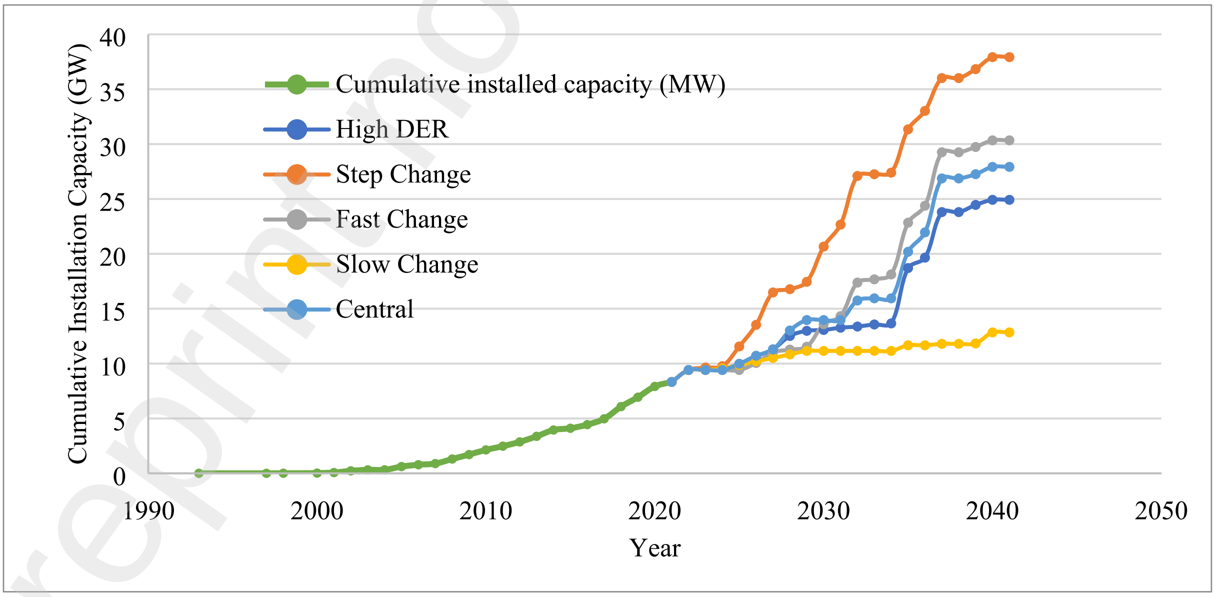


Figure 14: Historical and projected cumulative WT capacity in Australia based on forecasting scenarios

3.2. WT waste projection from 2013 to 2061

A critical forecast of the WT waste generation is presented in this section. To achieve this, the historical WT installation (discussed in section 3.1) was considered to calculate the waste generation outlook based on the fixed lifetime scenarios. Over an in-depth review of the literature, the various fixed lifetime was considered by the scholars in different wind turbines case studies. Figure 15 demonstrates the overall trend of wind turbine waste generation based on the three main fixed lifetimes reported for wind turbines in various scientific research publications, including 15, 20 and 25 years ([15], [14], [12]). As can be seen, the waste generation just started to rise mostly between 2016 to 2026 based on the various fixed lifetime scenarios of the wind turbine. It is projected to be scaled up very rapidly (exponentially) over the next decade exceeding 4 million tonnes of waste between 2036 to 2046. In this case study, the fixed lifetime of 20 years is considered as reported in the majority of the scientific papers reviewed ([14], [22], [17], [18]). The selected lifetime is used to estimate the possible wind turbine waste generation stream in Australia over the next 20 years based on the historical and projected deployment of wind turbine nationwide.

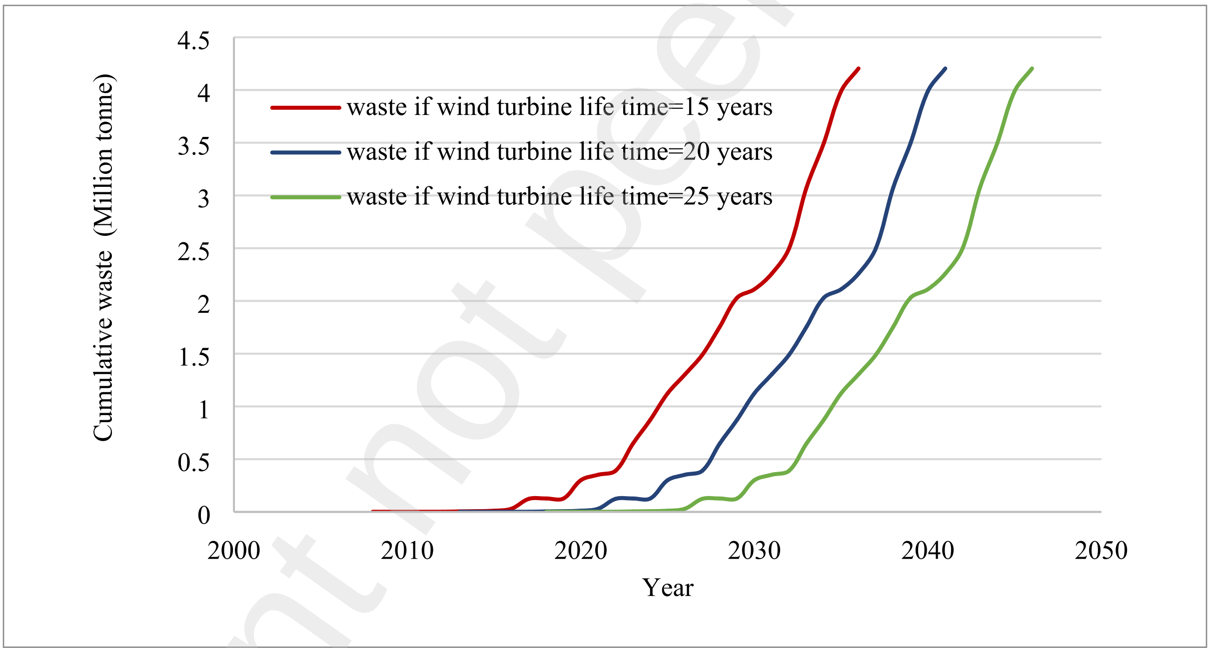


Figure 15: Cumulative waste generation flow based on the three fixed lifetime scenarios

Figure 16 shows the cumulative decommissioned WT in million tonnes for the various WT technologies between 2013 and 2041. The results vary based on the utilized technologies for example, we see that GB-DFIG has the highest share compared to other technologies reaching about 1.8 Mt of waste by 2041. GB-SFIG, at about 1.0 Mt, contributes to the second major waste flow. The lowest waste volume is estimated for GB-WRIG and GB-PMSG at 0.8 and 0.5 Mt as of 2041, respectively. Also, the GB-EESG technology is placed last in terms of volume of waste by under 0.1 Mt in 2041.

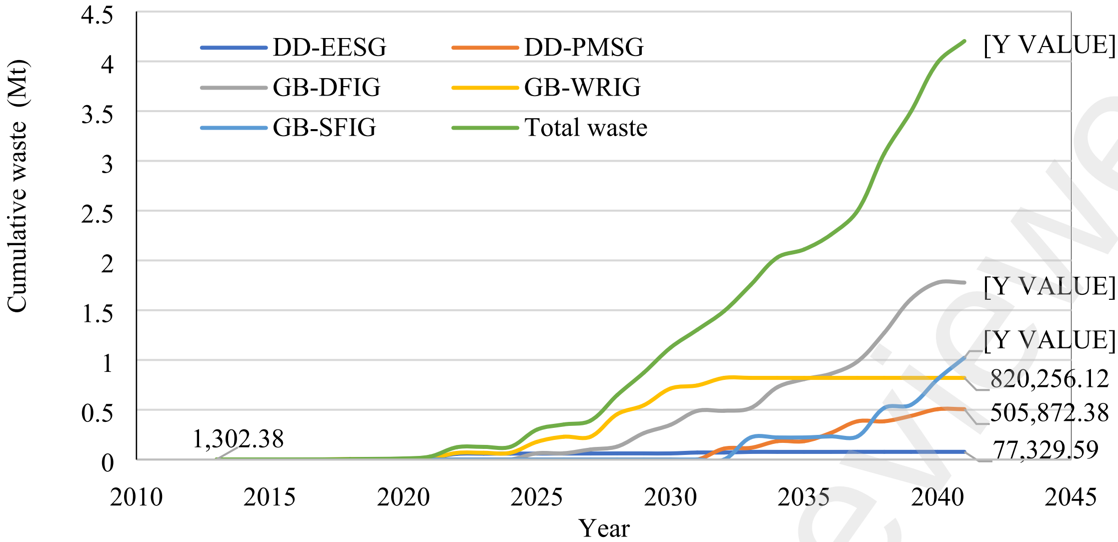


Figure 16: WT waste generation based on various WT technologies between 2013 and 2041

Currently, the comprehensive forecast of WT waste stream in Australia is presented from 2041 to 2061 based on the potential WT deployment capacity estimated in section 3.1. The importance of this projection is as it provides critical insight for the decision-makers on implementing proper legislation addressing effective, sustainable management of the primary WT as a power generation system in Australia. Also, the results will be very helpful for all types of businesses aiming to invest in the recycling of wind turbine waste in terms of resource management, cost-benefit analysis, economic feasibility assessment and other important business-related matters.

The results presented in Figure 17 discloses the variety of waste generation trend based on policy, economic conditions, and other important factors that can impact the growing trend of WT deployment in Australia between 2041 and 2061. Hence, the results are quite diverse and statistically different in terms of the overall volume of the waste. While all these five scenarios present an increasing trend over the course of twenty years, the volume of the waste in million tonnes varies from 6.69 Mt by slow change scenario as the lowest amount, followed by 12.99, 14.55, 15.81 Mt for the scenarios of High DER, Central, and Fast Change respectively. Additionally, Step Change showed the highest volume of waste generation by 19.76 Mt.

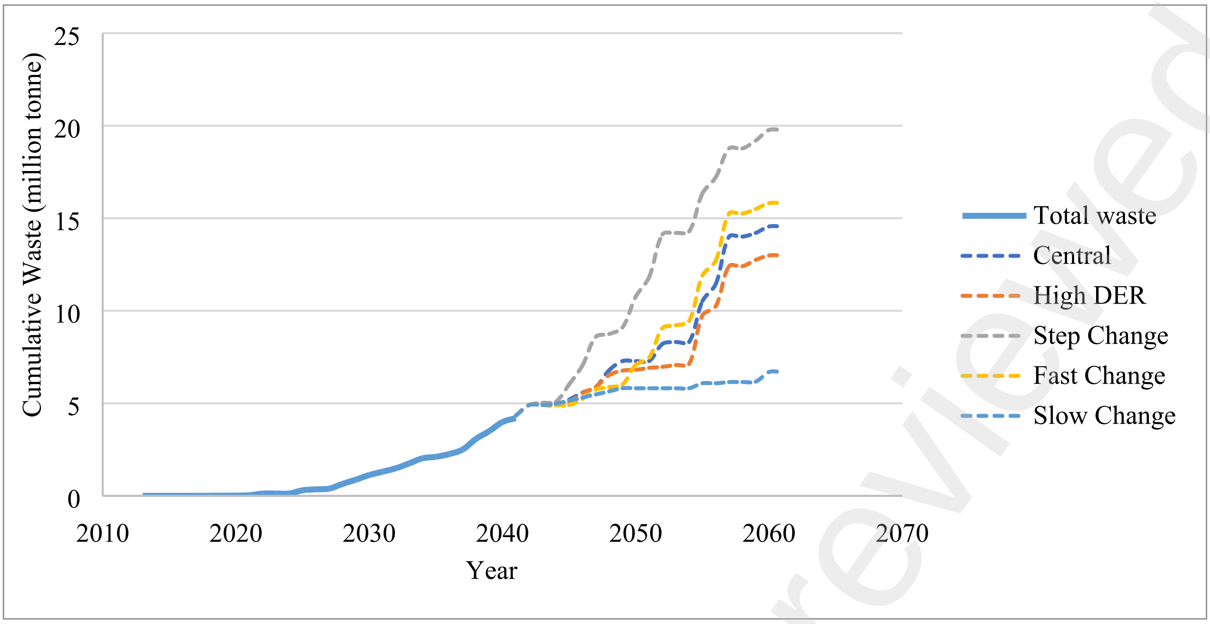


Figure 17: Total waste based on the installed wind turbines until 2041 and projection of future WT waste flow in million tonnes from 2041-61 based on AEMO forecasting scenarios

The waste generation projection is used to estimate the inventory of the waste materials over the period of time. The major composition of waste materials in WT waste stream are shown in Figure 18-Figure **21**. Concrete contributes the largest share by mass with a cumulative 10.20 Mt by 2061, followed by steel at 3.21 Mt also with a much lower growth rate from about 2020.

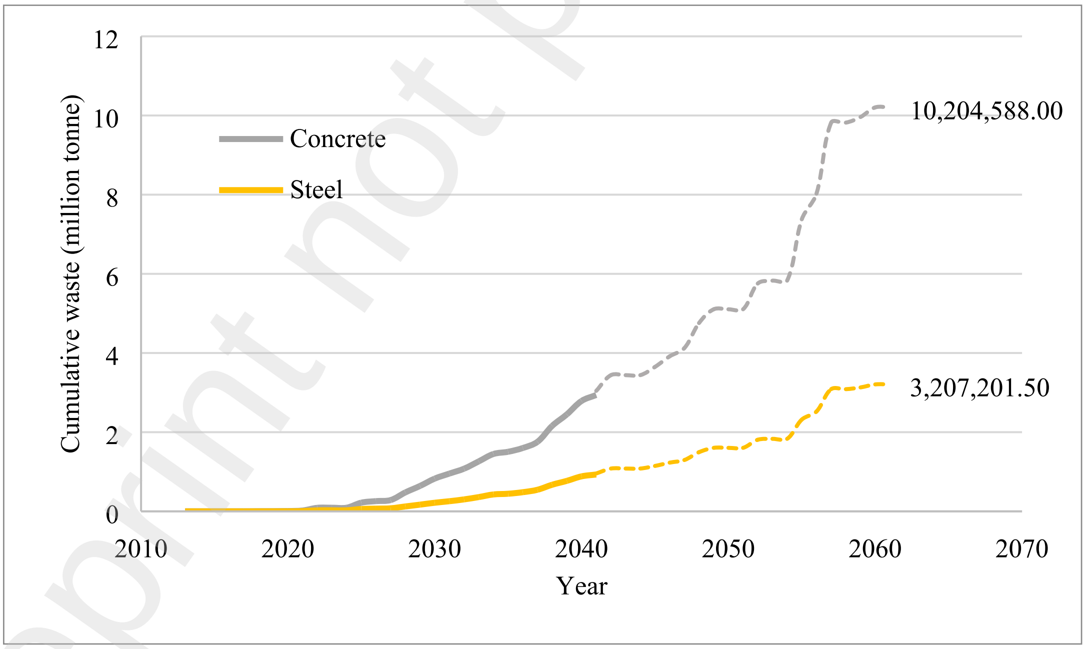


Figure 18: The Steel and Concrete waste generation out of EoL WT in Australia between 2013 and 2041 with solid line and waste projection until 2061 with dashed line

Considering the other materials, the cumulative volume by 2061 includes 38.11 kt of Aluminium, 35.41 kt of Copper, 518.78 kt Iron, 262.93 kt of glass/carbon composites, 117.33 kt Polymers, 97.52 kt of

Zinc, 13.88 kt Manganese, 6.71 kt of Nickel, 1279.96 tonnes of rare earth elements (including Dysprosium (Dy), Neodymium (Nd), Praseodymium (Pr), Terbium (Tb)) and 27.04 tonnes of Boron. Although after Boron, the volume of rare earth elements has the lowest share rather than the other materials, it has the most expensive price. For example, from dailymetalprice.com, one kilogram of iron, steel, aluminium, zinc, nickel and Neodymium (Nd as a rare earth metal) are $0.1357, $0.64, $2.514, $3.5815, $25.581 and $179.12 in June 2022, respectively.

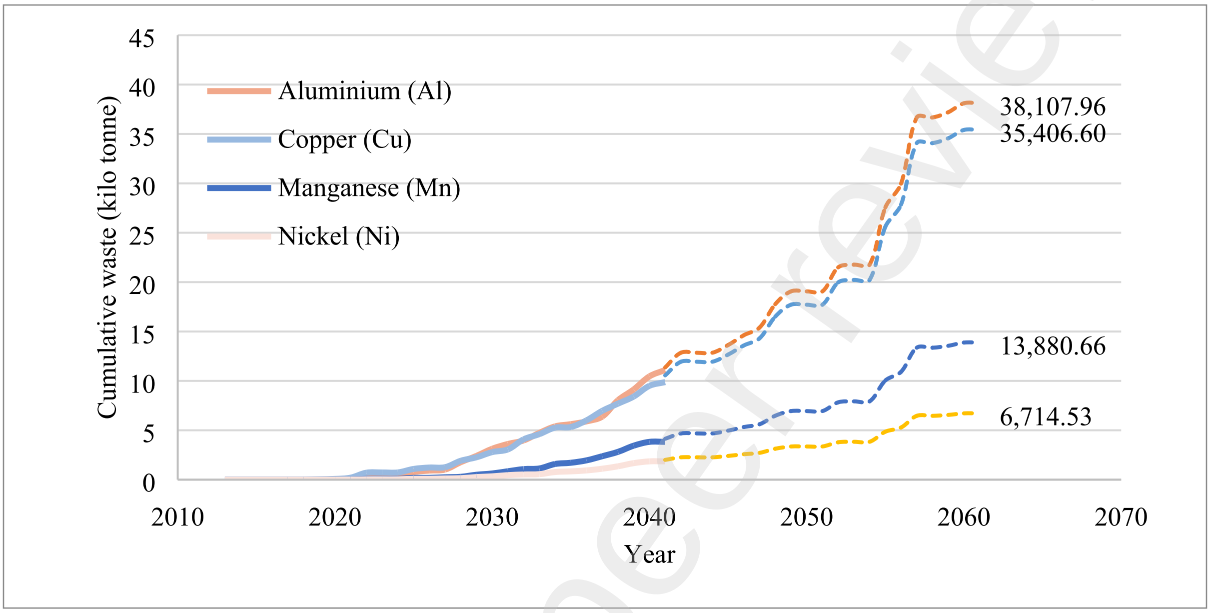


Figure 19: The Manganese, Nickel, Aluminium and Copper waste generation out of EoL WT in Australia between 2013 and 2041 with solid line and waste projection until 2061 with dashed line

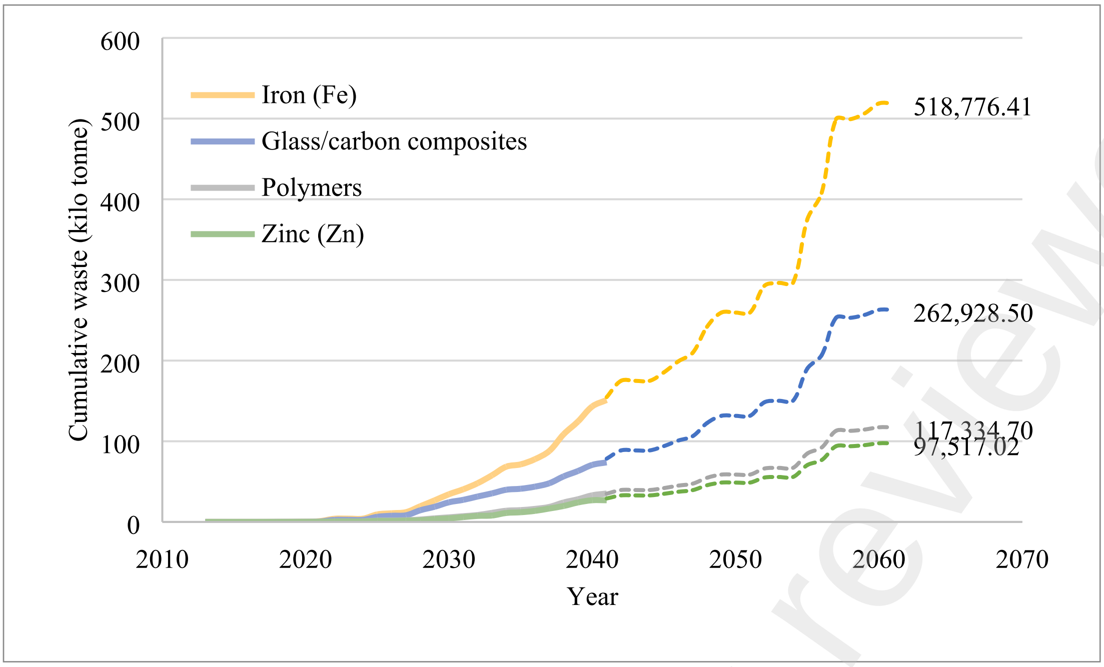


Figure 20: The Glass/carbon compositions, and polymers waste flow along with Fe and Zn waste flow out EoL WT in Australia between 2013 and 2041 with solid line and waste projection until 2061 with dashed line

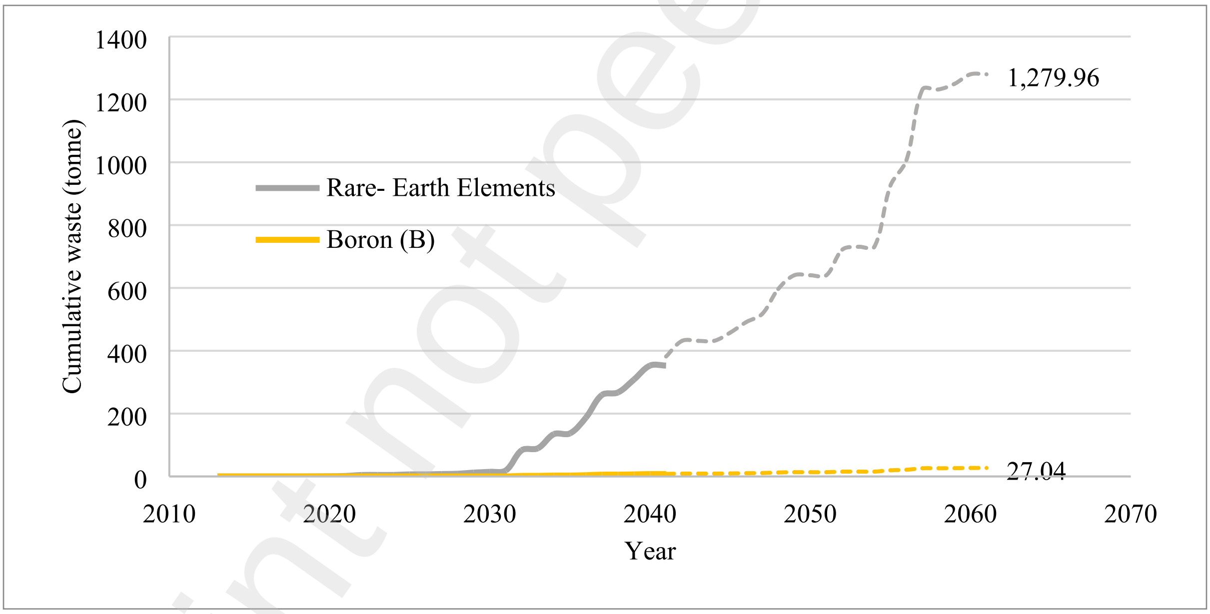


Figure 21: The Rare-Earth and Boron (B) waste generation out of EoL WT in Australia between 2013 and 2041 with solid line and waste projection until 2061 with dashed line

4. Discussion

Australia will face a considerable growth of EoL wind turbines in the coming decade. It is important to put in place an approach to ensure the sustainable management of this waste stream, to avoid adverse impacts and exploit a potential resource recovery opportunity. This study is a critical step toward this aim by providing in-depth evaluation of the current and future waste stream of wind turbines in Australia over the next four decades.

Figure 22 shows the cumulative material inventory estimated for EOL wind turbines by 2061. This is calculated considering all systems installed by 2041and comprises 10205 kt Concrete, 3928 kt Metals, 263 kt Composite, 117 kt Plastic, and 1 kt rare earth materials. Concrete is the major type of EoL WT waste that needs to be addressed. The management of concrete waste is different. For example, Japan is a leading country by recycling 100% of discarded concrete and using recycled concrete in construction applications again, however, in Australia, only about half of the concrete scrap is recycled [37]. Metal is also a major and precious type of WT waste stream that requires a proper treatment strategy for sustainable management. In Australia, about 90 percent of metal waste is recycled and then used together with origin metal in the related industries [38]. Plastic in the EoL wind turbine has a minor portion in the waste stream, but still, because of major environmental impacts need to be properly taken into consideration. Recently, very interesting sustainable solution for plastic waste was introduced by scholars which can be utilized in this case. Some of these applications are packaging, construction and automotive industries [39]. The current solution and application of the plastic waste recycling in the other sectors would be a potential solution for the effective treatment of plastic waste treatment in the wind turbine waste stream. However, there is a lack of in-depth research in this case and the proper treatment of plastic waste in the wind turbine waste stream requires further research and investigation.

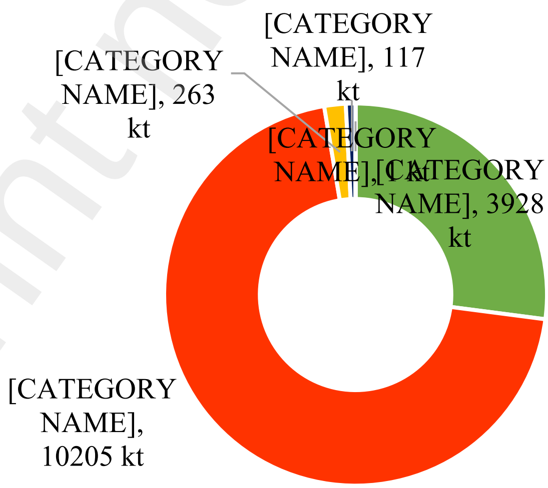


Figure 22: Classification of the mass share of materials contained in the waste until 2061

As of the great importance of sustainable treatment of EoL WT waste metal, Figure 23 provides a critical detail of this waste stream in Australia. The metal waste at EoL stage were divided into nine types which were extracted from the literature review. The core components of WT, such as hub, nacelle, tower, and generator are made from metals like Aluminium, copper and steel which there are mature technologies out there for proper recycling of these kinds of materials. The current recycling rate of waste metals in Australia is 90% [38]; however, some types of toxic, precious and rare metals are still being landfilled which although they are low in terms of volume, their environmental impacts and economic lost are high. The good news is that the majority of the metals used in wind turbine are similar to the type of materials which are being recycled and economically proven. So, the same approach can be utilized for the EoL metal-based waste of wind turbine. The results indicated that steel has the highest share among all metal waste in EoL WT stream by over 81%, followed by Iron by just over 13% (Figure 23). More than 80 percent of this amount of steel scrap belongs to wind turbine tower and foundation that is easy to recycle compared the steel embedded in nacelle and rotor [40]. At the moment, Australia's annual imports of Iron & Steel are averagely about 300 million AUD [41]. Recycling would positively support the economy both economically and environmentally. The composition of the other waste metals embedded in WT waste stream is not significant (up to 5% of the total metal waste flow) but critical to be well treated. The overall composition of these waste metals includes Copper (around 0.9%), Boron (around 0.001%), Chromium (around 0.2%), Aluminium (around 0.9%), Manganese (around 0.3%), Nickel (around 0.2%), Molybdenum (around 0.05%), Zinc (around 2.5%) under the current data extraction and estimation in literature and this research.

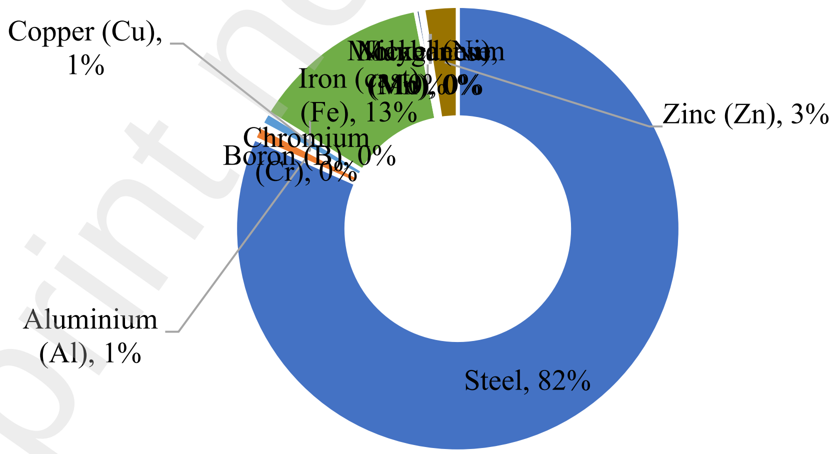


Figure 23: Mass share of the metals in the waste until 2061

One of the key steps in sustainable management of WT waste is to address the proper reverse supply chain issues, which are often neglected in contrast with remanufacturing and recycling. When it comes to reverse logistics network design (RLND), the information on the locations of the waste flow becomes very important. Therefore, the proper estimation of the waste amount, along with the geographical location and distribution of the waste flow and the treatment capacity and infrastructure, will be critically important for green RLND.

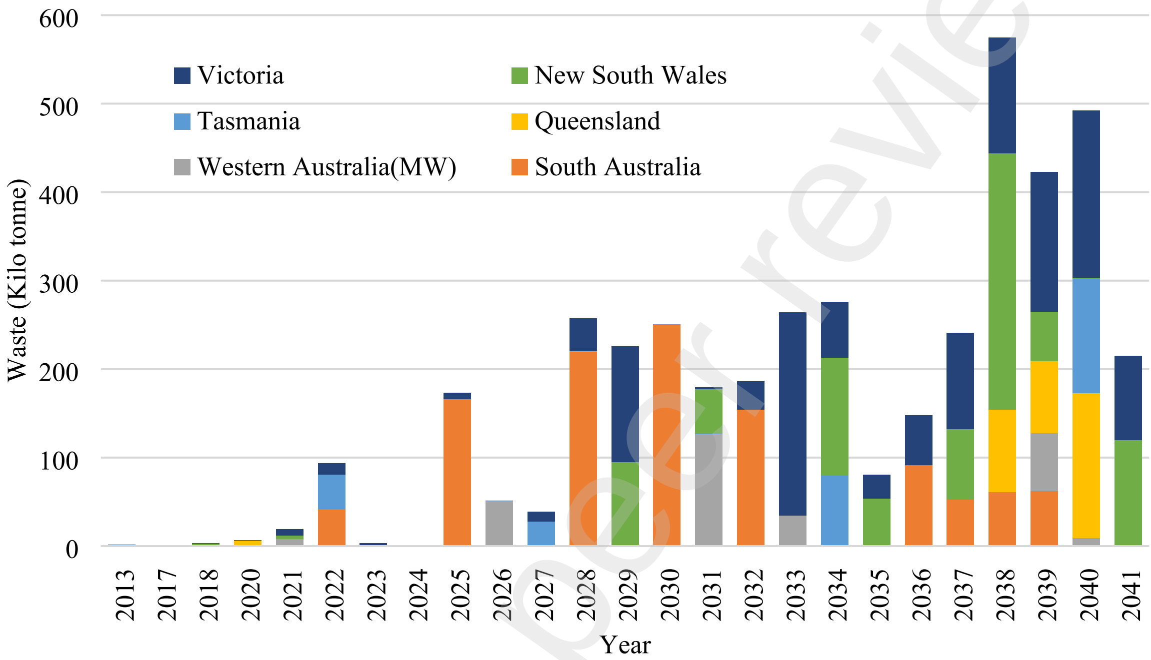


Figure 24: The breakdown of annual waste generation until 2041 Nation wide

WT waste flow is shown in Figure 24 based on the amount, location, and year of generation. As can be seen, there is a high risk of a fast increase in waste material from discarded WT. A gradual increase in annual WT waste material growth is seen from 2028 and onwards which is because of the accelerated deployment of WT in Australia over the last decade. The good news is that these waste materials are not immediately hazardous which therefore outlines the possibility of short-term sorting without major issue until the capacity and the volume of waste meets the requirement of sustainable and economically wise profitable treatment. However, it will shortly become a crucial problem that challenges the industry and authorities to meet the requirements of the circular economy in handling this product at the EoL stage in a sustainable way.

Currently, most of the materials embedded in the nacelle and tower of wind turbines are recyclable. Table 3 presents the potential end of life solutions for various materials of the wind turbine V90-2MW from Vestas company which possesses the most installed wind turbines in Australia. [17] also presents a table of treatment for decommissioned turbine components that has the similar data.

Table 3: EoL treatment of the WT component [42]

Material	Treatment
Steel	90% Recycled + 10% Landfilled
Aluminium	90% Recycled + 10% Landfilled
Copper	90% Recycled + 10% Landfilled
Polymers	50% Incinerated + 50% Landfilled
Lubricants	100% incinerated
All other materials (including concrete)	100% Landfilled

Metals such as Steel, Aluminium and copper can be infinitely recycled without any degradation, leads to more sustainability [17]. According to [43], about 97 percent of structural steel waste and 83 percent of other steel scraps are recycled in Australia. In contrast, more than 95 percent of Aluminium scrap is exported to overseas for recycling [44]. Moreover, about 70 percent of all discarded Copper and 40 percent of zinc scrap are currently recycled in Australia [45]. Therefore, the most concerning issue resulting in decommissioned wind turbines belongs to discarded composites and concretes. They are usually landfilled, and there are some challenges in finding new sustainable solutions for the end of life of these two materials [18]. Although some scholars published their findings to reuse, repurpose and recycle them, these methods are not used commercially yet.

According to the waste hierarchy [46], reusing and repurposing wind turbines are the best ways for decommissioned wind turbines in contrast with other treatment pathways such as recycling and recovery. In the reusing and repurposing processes, the waste with the original shape and specifications is utilized for the same or a new application. Since 2010, several efforts have been performed to introduce innovative methods for utilizing discarded wind turbine blades that are generally made of composites in new applications to make movement towards circular economy. For example, Goodman [47] suggested some potential applications in buildings and solar collectors by reusing decommissioned wind turbine blades. These could avoid extra costs for producing structural members for these applications. Also, Rahnama [48] pinpointed the utilization of discarded blades as artificial sea reefs. Furthermore, some scholars outlined the application of EoL WT blades in civil projects such as making a roof for the houses ([49],[50]), and the application of EoL WT in some manufacturing purposes such as electrical transmission towers [51], and finally reusing the elements of wind turbine blades in a new bridge design [52]. We note that all of these proposed reuse pathways are quite niche and not well established.

It is evident that the civil and manufacturing industry would be a promising solution for repurposing end of life wind turbine blades by preventing landfilling and incineration in this industry.

Simultaneously, as glass fibre and carbon fibre composites have been promoted to many applications specially wind energy industry because of their physical and mechanical characteristics, other studies have concentrated on the recycling and recovery of wind turbine composite blade waste. Recycling of end-of-life wind turbine blades via a hammer-mill process for producing new composites [53] and also using recycled blade waste in concrete [54] [55], are some of the new secondary markets for recycled wind turbine blades.

It should be noted that, as it is clear from Figure 10, early wind turbines had small diameters, however, today, diameters of wind turbines even exceed 150 meters. Therefore, these huge parts of wind turbines require more attention to achieve sustainable treatment solutions. On the other hand, it is obtained from Figure 8 that Australia has been eager to employ wind turbines with higher powers in recent years. Based on the results of this study, the increasing power of wind turbines leads to an increase t/GW for each wind turbine which will result in more amount of waste from decommissioned wind turbines.

Although the magnitude of metal-based material in the WT waste flow is reasonably considerable, the industry in this segment is mature and well developed so that it can gradually adapt to the requirement of sustainable recycling. Hence, perhaps the sustainable management of end-of-life waste metal would not be the most problematic one but essential economic-wise. Electronic waste and composite waste seem to be the most challenging components of the WT waste flow, which need to be focused on achieving a smooth transition towards sustainable management in this industry.

5. Conclusion

This study has evaluated and projected the amount of wind turbine waste flow that will be generated from 2012 to 2061, utilizing the available data from various reliable resources on the historical and projected deployment of wind turbine in Australia. This study considered the end-of-life of wind turbine only as the major source to estimate the overall waste flow of wind turbine. The results revealed that the cumulative end-of-life waste stream by 2061 varies between 12 million tonnes and 37 million tonnes based on different WT deployments scenarios with the probable average waste level of 24.5 Mt. This is a huge waste inventory for Australia which urges proper holistic strategy to deal with it in a sustainable way. The findings of this study illuminate the potential and the threat behind this significant waste flow and warn the authorities to advance actions. By 2061, the breakdown of the cumulative waste flow raised from deployed WT in Australia comprises 10205 kt Concrete, 3928 kt Metals, 263 kt

Composite, 117 kt Plastic, and 1 kt rare earth materials. Steel is the major metal waste in WT waste stream by over 81%, followed by Iron by just over 13%.

WT waste generation is focused on the locations with greater wind power installation and capacity: Victoria and South Australia alone account for 56% of the total waste flow. There are a variety of waste materials that can be utilized in different industries. At a very high level it would support the country in various aspects such great contribution in lowering the overall environmental impacts of the country, creating new job opportunities, supporting the economy as well as reducing the demand in importing of embedded WT materials. It is essential to review the current waste treatment legislation in Australia and extend the producer responsibility and all parties to make sure the sustainable recycling of Wind turbine is properly taken into account in Australia in the future. Policymakers and scholars will find this study as an insightful piece of work in the planning of sustainable WT waste management, mostly in terms of resource management, and in the next level in assessing the environmental impacts and developing reverse logistics network design.

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