Wind energy circularity challenges

According to EC decarbonisation scenarios, wind energy will become a core component of the European energy sector with up to 1 300 GW of wind capacity installed by 2050 [EC 2020]. This increase in capacity will also increase the demand in materials and, crucially, rare earth elements. Table 1 outlines the main materials, the components in which they are present and their estimated intensity according to Carrara et al. 2020. The material intensity depends on multiple parameters including the turbine type, the location and the age of the installation.

Table 1 – Material intensity estimates in kg/MW for wind turbines in general ranges. For a comprehensive list of the materials and assumptions, refer to [Carrara et al. 2020]

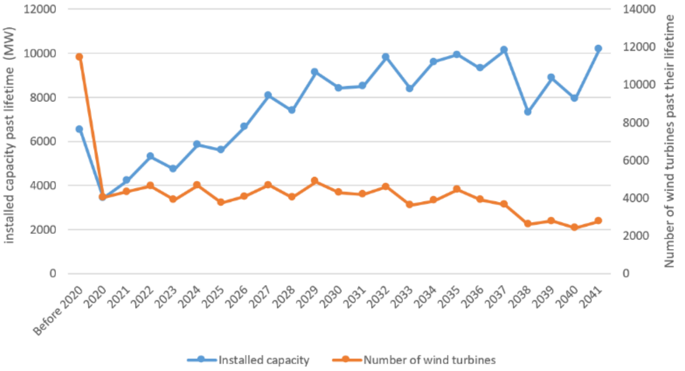
Material	Wind turbine component	Range (kg/MW)
Concrete	Tower, Foundations	243 500 – 413 000
Steel	Generator, Gearbox, Bearings, Blades, Tower, Shaft, Hub, Cables, Foundation	107 000 – 132 000
Polymers	Blades, Nacelle, Cables	4 600
Glass/carbon composites	Blades, Nacelle, Spinner	7 700 – 8 400
Balsa wood	Blades	270
Aluminium (Al)	Nacelle, Blades, Cables	500 – 1 600
Boron (B)	Generator (direct drive)	0 - 6
Chromium (Cr)	Rotor, Blades	470 - 580
Copper (Cu)	Generator, cables, blades and control systems	950 – 5 000
Dysprosium (Dy)	Generator (direct drive)	2 - 17
Iron (cast) (Fe)	Tower, Nacelle, Rotor, Gearbox	18 000 – 20 800
Manganese (Mn)	Used in steel production for many parts	780 - 800
Molybdenum (Mo)	In stainless steel composition for many components	99 - 119
Neodymium (Nd)	Generator (direct drive)	12 - 180
Nickel (Ni)	In alloys and stainless steel for many components	240 - 440
Praseodymium (Pr)	Generator (direct drive)	0 - 35
Terbium (Tb)	Generator (direct drive)	0 - 7

Source: Carrara et al. 2020

As of 2022, the average age of wind turbines in the EU is 13.7 years and the estimated operational lifetime of a wind turbine is 20 to 25 years. As presented in Figure 1, turbines amounting to approximately 14.2 GW, representing 8% of the total installed capacity in the EU and accounting for 20% of the total number of wind turbines, have already exceeded the 20-year threshold and are expected to be decommissioned or repowered in the coming years [JRC 2022a]. Moreover, it is estimated that 38 GW of onshore wind capacity is reaching the end of its average operational life of 20 years between 2021 and 2025 [EC 2022]. However, it should be noted that the operational life of a wind turbine depends on multiple parameters, including maintenance schedule and local conditions, which can lead in increased or decreased lifetime. By using distributions of lifetime of wind turbines, more accurate calculations could be produced.

According to Graulich et al., (2021), in 2020, a total waste volume of about 2.5 million tonnes are expected, increasing to 3.3 million tonnes in 2025 and 4.7 million tonnes in 2030. The expected mass of relevant materials in the wind turbine waste stream are summarised in Table 2. Not all metals listed are critical raw materials, but are important for the wind energy sector.

Figure 1: *Number of wind turbines and installed capacity reaching their end-of-life per year in EU, assuming a 20-year life span. All wind turbines presented in the graph are still operational.*



Source: JRC 2022 based on Wood Mackenzie

Table 2 – Expected mass (in tonnes) of relevant metals in waste wind turbine stream.

	2020	2025	2030
Total (t)	**2 459 913**	**3 357 422**	**4 754 347**
Zinc	25 592	35 002	50 122
Copper	11 388	15 574	22 287
Aluminium	5 560	7 570	10 577
Manganese	3 669	5 018	7 189
Chrome	2 404	3 291	4 728
Nickel	1 843	2 511	3 528
Molybdenum	500	685	983
Rare Earth Elements total	215	307	537

Source: Graulich et al. 2021

Given the ageing wind fleet and the substantial share of wind turbines reaching their end of life, decommissioning (requested in national legislations of some member states), recycling and transitioning to a more circular economy will become key.

RARE EARTH PERMANENT MAGNET CIRCULARITY

Direct drive generators are the component with the largest rare earth element intensity due to the use of permanent magnets. Since 2005, permanent magnet generators have gained popularity, especially in offshore turbines, as they combine high power density with small size and high efficiency at all speeds, offering a high annual production of energy with low lifetime cost. Most direct drive turbines are equipped with permanent magnet generators, which typically contain neodymium and smaller quantities of dysprosium. Smaller quantities of these rare earth elements are also present in some gearboxes and in the tower structure.

In 2020, generators containing permanent magnets with rare earth elements were used in nearly all offshore wind turbines in the EU, and in approximately 72% of offshore wind turbines worldwide. However, generators with rare-earth permanent magnets represented about 30% of onshore turbines at EU and global level, as here the need for powerful generators with reduced size and weight is not as strict as for the offshore turbines [Telsnig et al. 2022].

Permanent magnets used for direct drive generators account for more than 9% of the global production. The current EU production of Neodymium permanent magnets (NdFeB) is by far insufficient to meet wind energy demand, with the biggest manufacturer having a production of around 1 000 tonnes/yr and several smaller manufacturers with a capacity in the order of dozens of tonnes/yr [Alves Dias et al. 2020]. Neodymium (Nd) is one of the main rare earth elements used in the production of NdFeB permanent magnets (around 29%). To meet the REPowerEU targets set for 2030, wind turbines in the EU alone will require around 3 600 tonnes/yr of Neodymium by 2030. China is the main supplier of Neodymium, accounting for 93% of the worldwide production (approximately 35.000 tonnes in 2019) [JRC 2022b].

Since direct drive generators became popular after 2005, the end-of-life of direct drive wind turbines has not yet been reached. For this reason, the volumes of recoverable NdFeB magnets are currently small, and do not trigger yet a dedicated recycling stream and infrastructure [AMEC 2014, Patil et al. 2022]. However in the future, appropriate collection, preparation and recycling processes will be necessary to capture the rare earth elements incorporated in this component. The recycling potential of NdFeB permanent magnets from wind turbines is particularly relevant: the average weight of permanent magnets in wind turbines is 600 kg, whereas it is around 1-2 kg for electric vehicles [JRC, 2022c]. With shorter lifetimes and expected availability in dozen of millions and not in dozen of thousands, the flow of permanent magnets from electric drive motors from end-of-life vehicles is expected to be more important [JRC 2017]. However, the gigantism of wind turbine permanent magnets increase the opportunity for their collection, separate dismantling, and appropriate recycling. Still, the unavailability of dedicated recycling processes and insufficient separated collection and sorting of permanent magnets still jeopardize their circularity.

BLADES CIRCULARITY

Although 80-95% of the total mass of a wind turbine (e.g. concrete, base metals) can be recycled, some components, such as blades, pose several challenges. They contain complex composite materials – a combination of reinforced fibres (usually glass or carbon fibres) and a polymer matrix. A main material is also balsa wood, sourced mainly from Ecuador (75-90% of the world's balsa wood demand). The latest uptake in global wind energy markets resulted in a proven supply bottleneck for balsa wood, over-logging and soaring prices. Countries and manufacturers look for alternatives by planting balsa domestically (China), replacing balsa wood with recycled polyethylene terephthalate (rPET) or using hybrid designs.

The use of composites boosts the performance of wind turbines, since they allow for lighter and longer blades with optimised aerodynamics. However, their configuration poses challenges both for manufacturing and for recycling.

WindEurope (2020) estimates that by 2023, composite waste from decommissioned wind blades will amount to 60 000 tonnes, reaching about 400 000 by 2040 [WindEurope 2020]. The wind industry called for a Europe-wide landfill ban on decommissioned wind turbine blades by 2025. Within the wind energy industry, several companies and original equipment manufacturers have announced targets and new approaches with respect to recycling and circularity [WindEurope 2021]. EU recycling capacity of wind turbine blades is still limited. Wind turbine blade wastes are currently diverted to cement kilns, for energy recovery. Higher levels of circularity could be further enhanced by both design for recycling for blades, as well as further development of emerging technologies for composite wastes recycling (e.g. solvolysis or high voltage fragmentation). The composite recycling challenge also concerns other value chains such as automotive and aeronautic.

CHALLENGES AND OPPORTUNITIES FOR ENHANCED WIND TURBINES CIRCULARITY

– Binding and voluntary instruments can contribute to higher circularity and reducing supply risks for materials contained in in wind turbines. Several opportunities are possible:

– Public procurement auctions can in principle introduce non-price criteria for wind farm projects. Such criteria can be set to support eco-design and waste management efforts while strengthening the EU wind energy value chain. Non-price criteria setting should be based on a life cycle approach and help contributing to the urban mining. For instance, the ongoing Normandy offshore wind farm auction (1000-1050 MW) in France is introducing non-price criteria on the recycling and reuse rate of wind turbine blades. The EC has the opportunity to develop guidelines on specific non-price criteria for wind farm projects in order to enhance further circularity. The use of alternative wind turbine technologies where rare earth elements or other critical raw materials (e.g. silicon metal and vanadium in alloys) are reduced or phased-out is also a potential non-price criteria to be further investigated. Other criteria such as the encouragement of business models allowing local community engagement and the strengthening of SMEs across the EU wind value chain could be developed.

– Additional more binding legislative requirements to improve circularity of wind turbine materials could potentially cover both design parameters (e.g. design for dismantling, design for repair, recycled content) and waste management performances (e.g. traceability of wastes, collection rate of wind turbines, recycling efficiency of wind turbines, material recovery levels of selected materials). However, the long lifetime of wind turbines is a challenge for such Extended Producer Responsibility (EPR) initiatives.

– The complexity of collection of wind turbine from remote locations (including off-shore farms) is a logistic challenge that also need to be considered. The ageing wind farm can either benefit from a lifetime extension, retrofit, partial or full repowering and a decommissioning. These different end-of-life strategies render the waste management from wind farms more complicated.

– Whatever the binding and/or voluntary instruments and the aspects (e.g. collection, recycling, re-use, recycled content, etc.) the EC will choose to improve circularity of the wind infrastructure, it will be important to have a specific in-depth study in order to address the high heterogeneity of wind farms (including also different subsystems than the wind turbines, e.g. foundations, cables or high voltage stations) and to involve manufacturers and operators.

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