National
Engineering
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Royal Academy
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Windfall

the recovery and remanufacturing of neodymium magnets from UK wind turbines

IChemE

WMG
THE UNIVERSITY OF WARWICK

IOM3
Institute of Materials,
Minerals & Mining

Wind turbines are being installed in the UK that contain large stocks of neodymium magnets. By 2038, enough will be being decommissioned to return ~1 million kg per year of this critical mineral to the manufacturing economy.

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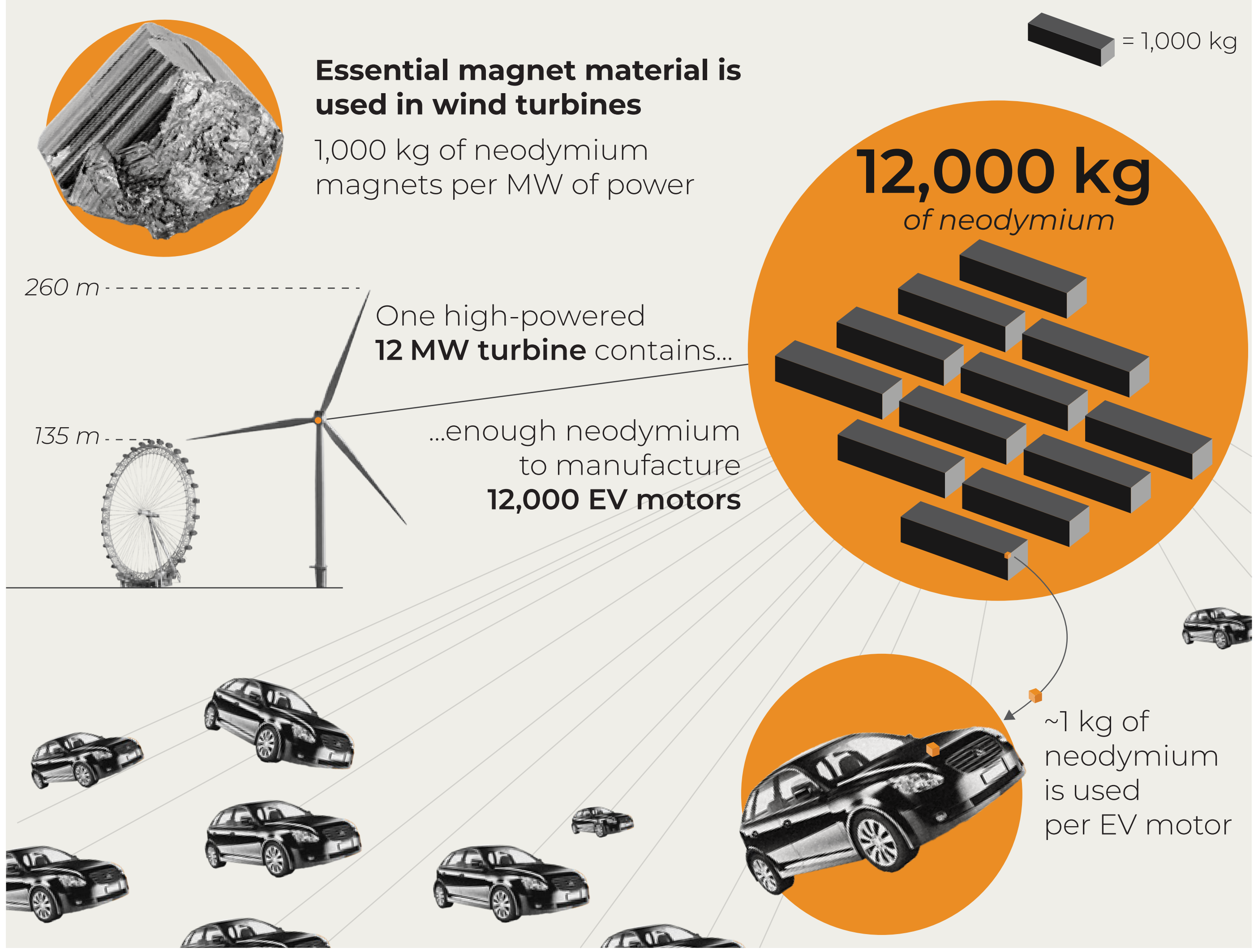
Contents



Essential magnet material is used in wind turbines

1,000 kg of neodymium magnets per MW of power

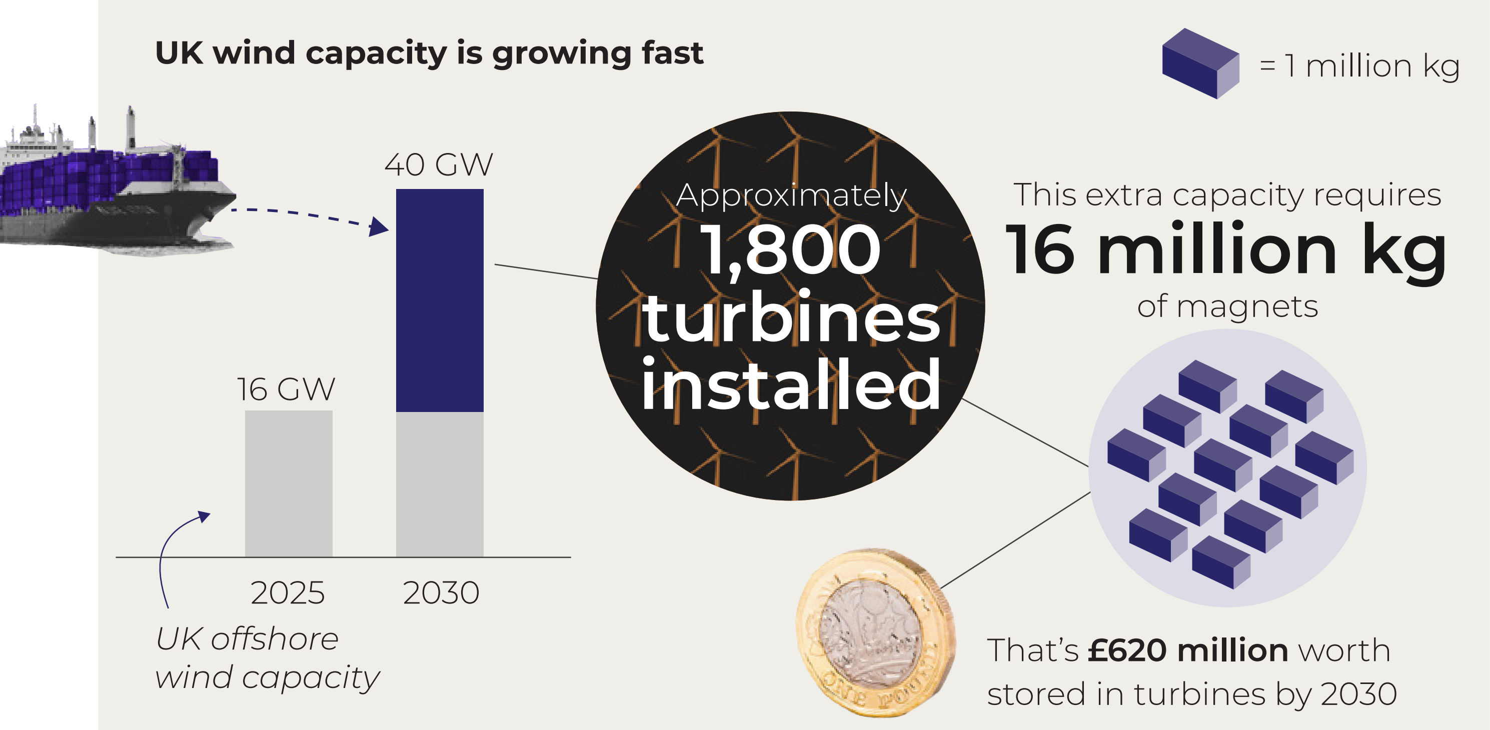
= 1,000 kg

12,000 kg
of neodymium

One high-powered **12 MW turbine** contains...

...enough neodymium to manufacture **12,000 EV motors**

~1 kg of neodymium is used per EV motor



UK wind capacity is growing fast

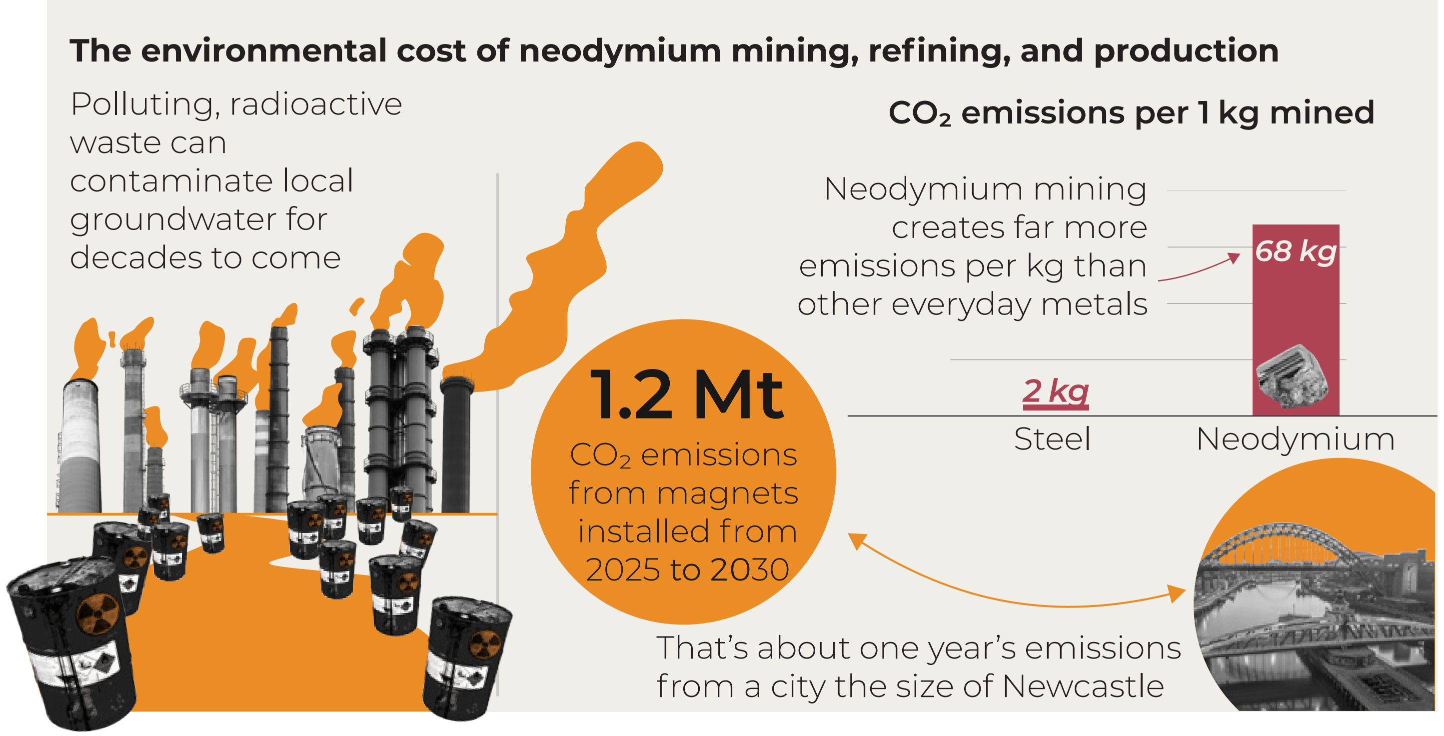
= 1 million kg

UK offshore wind capacity

Approximately **1,800 turbines installed**

This extra capacity requires **16 million kg** of magnets

That's **£620 million** worth stored in turbines by 2030



The environmental cost of neodymium mining, refining, and production

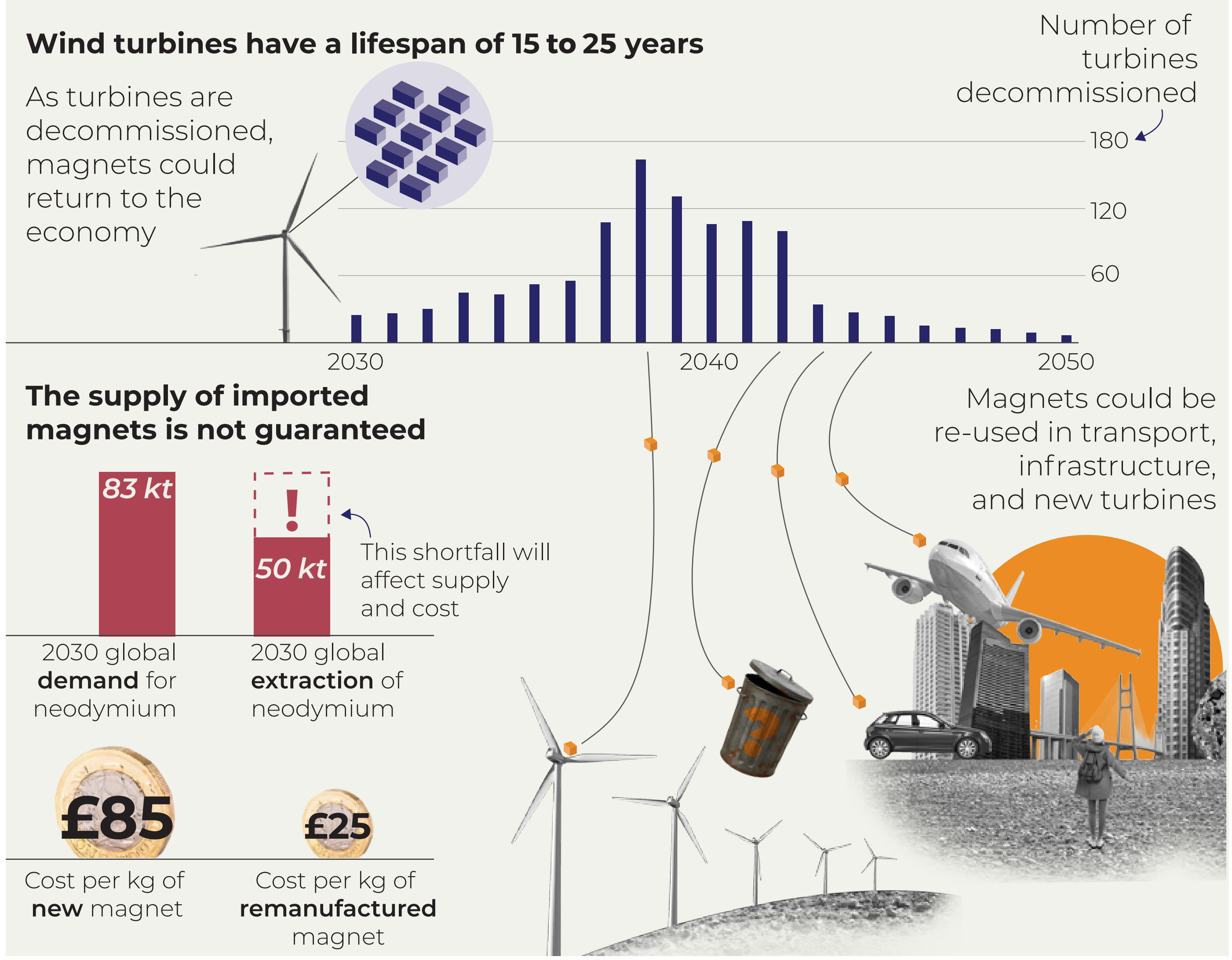
Polluting, radioactive waste can contaminate local groundwater for decades to come

1.2 Mt
CO_2 emissions from magnets installed from 2025 to 2030

That's about one year's emissions from a city the size of Newcastle

CO_2 emissions per 1 kg mined

Neodymium mining creates far more emissions per kg than other everyday metals



Wind turbines have a lifespan of 15 to 25 years

As turbines are decommissioned, magnets could return to the economy

Magnets could be re-used in transport, infrastructure, and new turbines

The supply of imported magnets is not guaranteed

This shortfall will affect supply and cost

1. Executive summary

> A single 12 MW wind turbine of the kind which will be being decommissioned in 2038 can contain more than 12,000 kg of neodymium magnets, which is enough to meet the permanent magnet demand for manufacturing around 12,000 electric vehicles (EVs) such as the third generation Nissan Leaf, made in Sunderland

This report presents research commissioned from Dr Stuart Bradley and Dr Russ Hall, of Warwick Manufacturing Group[1] with additional drafting and editing by the Royal Academy of Engineering.

Key takeaways

The UK has a significant strategic, economic and environmentally beneficial opportunity to recover large stocks of critical minerals from existing and future wind turbines as they reach end-of-life but is underprepared to do so. The UK lacks domestic capacity to produce the neodymium magnets used in large turbines and their future supply chains may be constrained, so in the event of trade disruption, recovering these materials could provide resilience to UK manufacturing, including of key decarbonisation technologies. There are many barriers to creating a circular economy for wind turbines that must be overcome, including the need to design new turbines for disassembly, data collection and sharing on materials at many levels, anticipatory investment, and creating an enabling policy and regulatory environment.

This report presents a technical assessment of future neodymium permanent magnet material stocks available from UK wind turbine decommissioning and their potential for remanufacture and use in domestic manufacturing. Based on what is found to be feasible from an engineering perspective, this report lists gaps in policy and practice that must be addressed for the UK to grasp the opportunity, and which should be assessed from economic and policy perspectives in the context of a UK industrial strategy and circular economy policy for the clean energy sector. Such assessments of future circular economy opportunities created by infrastructure deployment should be a routine practice, especially for large-scale infrastructure where valuable materials are present in large quantities with predictable availability, and for critical minerals whose recovery is of strategic and economic importance.

The UK has been an early mover in the deployment of wind power, having deployed 30 GW of combined onshore and offshore wind as of 2025 and forecast to reach around 40 GW of offshore wind by 2030 in this analysis. This also means the UK will be early among nations in which there is large scale offshore wind turbine decommissioning taking place, as the machines reach the end of their 15–25 year intended design life. While older, lower power turbines such as those typically deployed onshore do not contain very significant quantities of neodymium, a designated critical mineral, the larger turbines (4–16 MW) and especially much of the offshore fleet contain around 1,000 kg of neodymium magnets per MW generation capacity. In aggregate this is a significant quantity to the UK economy.

There will be 16 million kg of neodymium magnet material in the offshore wind turbines installed in UK and territorial waters over the next five years (2025 to 2030), representing a value of £620 million using today's cost of £85/kg. Smaller wind turbines are already being decommissioned, but recovery of neodymium magnets will start in commercially significant volumes from 2038 onwards, with an average of 1 million kg of magnet being made available per year. This is enough to make around 1 million automotive traction motors at a reduced cost. Alongside this benefit, it will also reduce the material value lost to waste streams, reduce supply chain risks for UK manufacturing, and avoid environmental harms globally from new magnet production.

A single 12 MW wind turbine of the kind that will be being decommissioned in 2038 can contain more than 12,000 kg of neodymium magnets, which is enough to meet the permanent magnet demand for manufacturing around 12,000 electric vehicles (EVs) such as the third generation Nissan Leaf, made in Sunderland. For a single offshore wind turbine magnet block of 100 mm square and 25 mm thick, weighing 1.85 kg, we could obtain 108 smaller magnets for an EV rotor set, with 0.3 kg of waste magnet material for recycling. This analysis estimates that recovered material can be remanufactured rather than recycled with lower projected costs: circa £25/kg, a discount of 70% over newly mined and made. This compares favourably with new magnet blocks, which are between £85 to £100 per kg, and reduces commercial risk and embodied carbon with a much shorter supply chain within UK territory. Recycling is also an option for magnets unsuitable for remanufacture.

Supply chain risks and environmental benefits

UK wind turbines can be a large domestic source of neodymium magnets, a material for which demand will likely soon outstrip supply. Mining and refining of neodymium is highly geographically concentrated and growth of the sector is slow, with the IEA estimating that in 2030 54% of mining and 77% of refining of rare earth elements (REEs) such as neodymium will occur in China.

Estimates suggest that by 2030 the demand for REE's for neodymium magnet production will have grown to 83 kt per year, compared to the 23 kt per year extraction there was in 2020. Extraction of REEs for neodymium magnets is projected to reach 50 kt per year by 2030, leaving a 33 kt p.a. shortfall.[2]

The reuse of neodymium magnets over the purchase of newly produced ones provides very significant environmental benefits, avoiding what would be an uplift in existing harm from the extraction of materials and magnet manufacturing. REE mining and processing leads to the production of significant quantities of radioactive waste, acidifying gas and liquids, carcinogens and other toxic pollutants that frequently pollute local groundwater systems.[3] Mining and refining of neodymium also creates far more carbon emissions per kilogram than everyday metals like iron and steel: ~68 kg CO_2e for neodymium[4] compared to ~2 kg CO_2e for steel.[5] Despite being an alloy of neodymium, iron and boron, the additional manufacturing and processing steps means that production of 1 kg of neodymium magnets creates ~75 kg CO_2e.[6]

The manufacturing of the 16 million kg of permanent magnet material, needed to install the UK's planned wind turbines for the next five years (2025–30) will produce 1.2 Mt (megatonnes) CO_2e, making it important to ensure that these costly resources are used to the greatest extent of their

> Once partially demagnetised, the magnets could be resized and remagnetised to be suitable for applications such as propulsion motors for cars, aeroplanes and ships, or for the next generation of wind turbines

potential rather than wasted and made anew. For context, the UK's carbon budget for all territorial emissions for the year 2030 is 297 Mt CO_2e.[7]

Remanufacturing process and opportunities

Magnet assemblies are used within generators to provide the stationary magnetic field that interacts with the rotating parts to create a voltage. In wind turbine applications, the magnet assemblies operate at low-frequencies and temperatures, and with minimal performance degradation over their lifetime. This paper presents a speculative process for recovering and remanufacturing these magnets by partially, temporarily demagnetising them by heating to 200°C in an oven or by induction heating.[8] Once partially demagnetised, the magnets could be resized and remagnetised to be suitable for applications such as propulsion motors for cars, aeroplanes and ships, or for the next generation of wind turbines.

Their removal does depend on the installation process used — in particular, while magnets can be bolted into place, some are fixed with epoxy glues, which make their recovery more challenging. This should be addressed within designs to ensure recoverability of these materials from turbines.

Report contents

This report describes the recovery and remanufacturing opportunities for wind turbine generator rotor magnet assemblies, which contain nationally significant amounts of critical minerals in the form of neodymium permanent magnets. Specifically, this analysis:

- Assesses onshore and offshore wind turbine deployment in UK and territorial waters up to 2025 and beyond, quantifying the mass of neodymium permanent magnets contained within them and how this has changed during that period.
- Identifies timelines for the decommissioning of these wind turbines and thus the permanent magnet material available for recovery and reuse.
- Assesses the processes for recovery and reuse of permanent magnet material, including technical and safety considerations.
- Assesses likely costs, commercial risks and scale of demand for recovered magnets from domestic markets such as aerospace, automotive, power, industrial electrification and marine sectors.
- Based on the technical assessments, identifies where current gaps in policy or practices could frustrate the recovery of neodymium magnets in the UK, and what outcomes stakeholders such as government, industry and regulatory or standards bodies should aim to achieve to ensure this opportunity is not missed due to lack of long-term anticipatory thinking.

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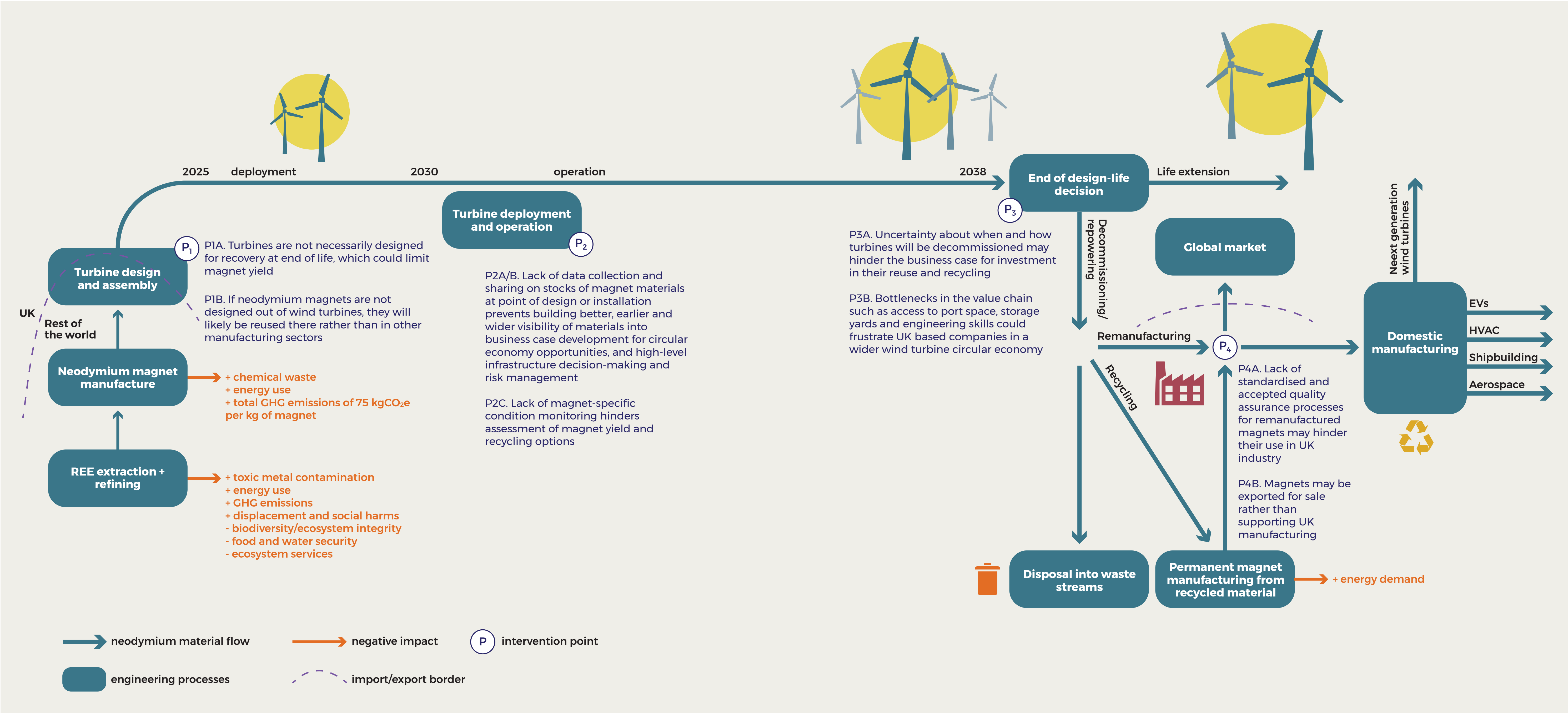

P1A. Turbines are not necessarily designed for recovery at end of life, which could limit magnet yield

P1B. If neodymium magnets are not designed out of wind turbines, they will likely be reused there rather than in other manufacturing sectors

P2A/B. Lack of data collection and sharing on stocks of magnet materials at point of design or installation prevents building better, earlier and wider visibility of materials into business case development for circular economy opportunities, and high-level infrastructure decision-making and risk management

P2C. Lack of magnet-specific condition monitoring hinders assessment of magnet yield and recycling options

P3A. Uncertainty about when and how turbines will be decommissioned may hinder the business case for investment in their reuse and recycling

P3B. Bottlenecks in the value chain such as access to port space, storage yards and engineering skills could frustrate UK based companies in a wider wind turbine circular economy

P4A. Lack of standardised and accepted quality assurance processes for remanufactured magnets may hinder their use in UK industry

P4B. Magnets may be exported for sale rather than supporting UK manufacturing

Figure 1 | **Graphical abstract**

Barriers to overcome to establish recovery and remanufacturing of neodymium magnets

The following is a list of gaps in policy or practices to overcome in the pursuit of a circular economy of wind turbines, organised around the intervention points shown in the graphical abstract, and the outcomes that government, regulators, investors and other stakeholders should seek to achieve. This report presents a technical analysis and is not an in-depth review of the policy landscape and so does not make specific recommendations for policy or regulatory solutions to the problems identified. It does, however, suggest options for policymakers to consider more fully and with further regard to strategic goals.

The outcomes considered desirable in this analysis are those that support the creation of a domestic circular economy for permanent magnets in wind turbines, within the context of a wider circular economy for wind power, and to free up those materials for use in domestic manufacturing to provide resilience and cost reduction for UK industry while reducing environmental harm.

P1 | Turbine design

Gap identified	Desired outcome	Potential policy levers to evaluate
A | Turbine design and installation choices currently hinder the rate of recovery of magnets to an unknown degree. Small choices made at the design and installation stage can determine whether magnets experience degradation, and whether they can be removed easily and safely. This is made more difficult since the relevant turbine components are not manufactured in the UK.	New wind turbines are deployed with designs that ensure magnets can be recovered safely and relatively easily upon decommissioning, with the resulting magnets not being contaminated with other materials. Magnet remanufacture or recycling is thereby maximised at least cost and wastage and replacement (at greater environmental and financial cost) minimised.	Design standards. Servitised business models. Applying Extended Producer Responsibility to neodymium magnets in wind turbines, which are currently exempted.
B | If neodymium magnets remain a key component of wind turbines in the 2040s, it is likely that recovered magnets would be reused within the wind sector. While a more positive outcome than them using new neodymium magnets, this would prevent other UK domestic manufacturing benefitting from the supply chain security and cost reductions available if secondary neodymium magnets were to be made available.	Research and development for future generations of wind turbines reduces or eliminates use of critical materials such as neodymium and instead uses sustainable, abundant materials. This would: 1. reduce the exposure of these projects to supply shortage risk as well as reducing the carbon cost and environmental impact of the materials used. 2. allow recovered neodymium magnets to support domestic manufacturing needs and thus economic resilience, rather than being primarily in demand for ongoing wind turbine deployment.	Innovation funding priorities.

P2 | Turbine planning and deployment

Gap identified	Desired outcome	Potential policy levers to evaluate
A | Lack of direct data on installed material stocks is a barrier to refining the business case for investment in recovery. While this study presents new data on magnet mass in UK wind turbines, it is less accurate and granular and takes more effort to assess than it would be if the data on material intensity were collected during the planning or installation stage.	Granular data on the stocks of magnets in UK wind turbines — their quantity, location, dimensions, owners etc. — enables both government and industry to establishing decommissioning, reuse or recycling of valuable and scarce materials into secondary markets through anticipatory investments proportionate to the quantity, nature and ownership of magnets that will be available.	Planning processes. Industry and supply chain collaboration on information needs and, where needed, trusted data sharing architectures.
B | A lack of clear data on the quantities of neodymium magnets or other high-value materials in infrastructure hinders infrastructure system-level decision-making and risk management.	Informed by material stock data, government, infrastructure bodies and industry identify and account for the supply chain vulnerabilities, circular economy opportunities, and environmental harms posed by different technological pathways and ensure that choices at the deployment stage support future prosperity, sustainability and resilience.	Planning processes.
C | There is uncertainty around the resilience of the neodymium magnets to degradation during use. This could hinder the assessment of circular economy opportunities for the magnets, especially whether they can be remanufactured versus being recycled.	Data collected by turbine operators during its lifespan is being analysed (and is sufficient to assess) the condition of the neodymium magnets through the life of the turbine. This allows for planning for secondary uses and guides investment in appropriate types of remanufacturing and recycling capacity.	Industry and supply chain collaboration on information needs and, where needed, trusted data sharing architectures.

P3 | Turbine decommissioning

Gap identified	Desired outcome	Potential policy levers to evaluate
A | End-of-life options for wind turbines include decommissioning, repowering and life extension and, while any may be appropriate, there is uncertainty over which will apply in different cases and therefore uncertainty over the decommissioning dates of wind turbines. If not resolved on a consistent basis and sufficiently in advance, this may frustrate estimates of neodymium magnet yield in different years, and the investments made based on them.	End-of-life decisions for wind turbines that appropriately weigh the sustainability and efficiency implications and that are made on a consistent basis provide sufficient clarity on future neodymium magnet yield to inform and guide timing of investments in engineering capacity for decommission and material recovery.	Decisions needed on strategic approach.
B | There is uncertainty regarding whether the engineering capacity, skills and infrastructure for decommissioning is or will be sufficient to meet the demand for decommissioning. Bottlenecks such as access to port space to bring them ashore and deconstruct them and/or store the materials could frustrate opportunities for the wider wind circular economy.	Requirements for establishing a circular economy sector around wind turbine decommissioning are evaluated based on best available data for magnet yield, and those requiring anticipatory investment are developed in time to meet a sharp increase in decommissioning demand from wind turbines alongside other offshore deployment and decommissioning of oil and gas assets.	Investment based on strategic sector approach.

P4 | Establishing a market for secondary neodymium magnets

Gap identified	Desired outcome	Potential policy levers to evaluate
A | Remanufactured magnets would be a novel product and their use in technologies where safety and reliability are paramount would require a process of quality assurance to be applied to the neodymium magnets that has not yet been developed.	Quality assurance practices are developed and implemented for remanufactured magnets to give those purchasing the magnets confidence in their performance.	Developing standards and quality control capacities for remanufactured neodymium magnets.
B | While this analysis assesses the potential benefits to UK manufacturing in terms of cost reduction and resilience to supply shortages from having a domestic source of secondary neodymium magnets, sale of remanufactured magnets would likely occur on global markets – potentially limiting the national benefit, although still providing the environmental benefits provided they find some suitable use that replaces primary demand.	If – as some nations are pursuing – it is deemed desirable for neodymium magnets in UK wind turbines to be prioritised for supporting UK manufacturing, trade policy will need to reflect this.	Export restrictions.

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Glossary of terms

	Airgap	The physical gap between rotor and stator.
	Array	A multitude of wind turbines in one geographical location, sharing a single lease as well as maintenance or decommissioning contracts, and infrastructure for connecting to the grid.
	BH magnetic energy product	A description of the magnetic strength of a magnet, typical units are MGOe, Mega Gauss Oersted (S.I. units are kJ/m^3).
	Critical minerals	Minerals that are critical are those that are economically or strategically important but are susceptible to supply chain disruption. These usually refer to specific chemical elements, but also to other kinds of material such as graphite or high-purity silicon compounds. Unless otherwise specified, 'critical minerals' in this report refers to those included on the UK's official list of critical minerals at time of publication.
	Direct drive generator	An electrical machine connected to its driven or driving device without a transmission or gearbox.
DFIG	Doubly fed induction generator	A type of electrical machine that is based on induction machine construction, with an electrical power connection to the rotor.
	Driveline	The mechanism that directs power and torque to the method of propulsion, for example from motor to wheel or propeller.
	Eddy currents	Eddy currents are electrical currents formed by induction, typically the interaction of magnetic lines of flux and a magnetic material such as an iron bar.
EDU	Electric drive unit	The propulsion motor is normally combined with a transmission and inverter, making up an EDU.
	E-machine	Electrical machine.
EV	Electric vehicle	Cars, industrial vehicles and others primarily using electric motor propulsion and battery energy sources.
EESG	Electrically excited synchronous generator	A generator that uses electro-magnets to create the rotor magnetic field that interacts with the stator to convert mechanical energy to electrical.
CO_2e	Equivalent carbon dioxide emissions	A measure of contribution to the greenhouse effect and therefore global warming, used to combine or compare the impacts of multiple greenhouse gases, such as carbon dioxide and methane, into one measurement.
	Ferrous material	A material containing iron.
Hz	Hertz	Units of frequency in cycles per second, for example running speed in revolutions per minute, divided by 60.
	HVAC	Heating, ventilation and air conditioning.
	Levelised cost of energy	A measurement of the average cost of electricity generation for a given generation asset (eg a wind turbine array) for the duration of its intended operating life, considering the full lifetime costs of building, maintaining and decommissioning the generator.
	Material modulus	A material property that describes the resistance of a material to force, load or stress.
MW	Mega watt	A million watts, where a watt is a unit of power defined as the transfer of one joule of energy per second.
	Multi-stage gear	A transmission with more than two intermeshed gear sets.
	Nominal power rating	The rated power output for continuous operation.
NdFeB	Neodymium iron boron	A mixture of elements forming a powerful permanent magnet.
	Neodymium magnets	The physical blocks of NdFeB magnets. In this report we will use 'neodymium magnet' to refer to these, however they may also be referred to as simply 'permanent magnets', or 'REE magnets' since they sometimes also contain some quantity of other REEs.
PM	Permanent magnet	This refers to magnets that are permanently energised, opposite to an electromagnet which requires the flow of current in a coil to create a magnetic field.
PEMD	Power electronics, machines and drives	The component parts that convert electrical energy into mechanical energy and vice versa. Drives are made from power electronics.
REE	Rare earth element	Lanthanide elements, which are metals, and exist as oxide ores.
	Rotor	The rotating part of a machine, transferring torque from the magnetic field to the driving or driven device.
	Stator	The stationary part of an electric machine consisting of electrical coils that make a magnetic field that interacts with the rotor.

Background and policy landscape

In the *UK Critical Minerals Strategy: Vision 2035*, published by government in 2025, government aims to ensure resilience of key sectors to the supply risks posed by dependence upon critical minerals. This reflects some of the findings of a 2024 National Engineering Policy Centre report that identified the need for more and better forecasting of the resource risks associated with vital physical infrastructure sectors. Here resource risks mean both risk to delivery and maintenance of the infrastructure due to supply chain disruptions, as well as the risks that material demands pose to the environment.

Globally, importing nations and blocs are increasingly taking action to decrease dependence on global supply chains for critical minerals. The EU's 2025 Critical Raw Materials Act mandated that 25% of rare earth supply come from recycling by 2030, and is now exploring the imposition of export restrictions that would keep more neodymium magnet material within EU borders.[9] In the US, the 2022 Inflation Reduction Act earmarked US$40 billion for strengthening supply chains including those for REE materials, and more directly the (then) Department of Defense took a stake in the only REE mine in the mainland US while committing to purchase from domestic producers[10], while Apple committed to buying nearly $500 million worth of recycled magnets from the same company.[11]

The UK is among global leaders in utilising wind energy and has high ambitions for deploying more and larger wind turbines, especially offshore. Increasingly these wind turbines contain large quantities of critical minerals in the form of permanent neodymium magnets. This large stock of a critical mineral in specific assets, instead of being thinly spread and with millions of different owners like the neodymium found in consumer electronics, creates an almost ideal opportunity to practice circular economy principles to advance the dual goals of economic resilience and sustainability.

However there are barriers to the development of this circular economy. Wind power operates as a global industry, and the UK is not currently a major site of manufacturing the wind turbine parts in which neodymium magnets are found. This means that many relevant policy levers may not sit with UK government but may need to be addressed through multinational collaboration. Furthermore, research has identified a lack of data on the materials as a key obstacle, finding that "volumes and location of [neodymium magnets] in future stocks and outflows [are] not well understood, hindering investment in investment in [circular economy] solutions" and recommending that the UK should "optimise tracking of UK-based feedstocks and end-of-use opportunities to inform private and public sector investments, thus maximising the opportunity to revalorise future REE feedstocks."[12]

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This study aims to fulfil some of that requirement with regards to the largest stock of neodymium magnets in the UK: our fleet of wind turbines. There have been previous analyses of this, however this paper brings a fresh assessment of the specific quantities of neodymium magnets in different models of wind turbines; their shape and suitability for remanufacturing; the timings and quantities of availability and the factors this depends upon; an assessment of the domestic manufacturers who require neodymium magnets and an estimate of the potential cost savings from purchasing remanufactured magnets over new ones — on top of the benefits to resilience and sustainability.

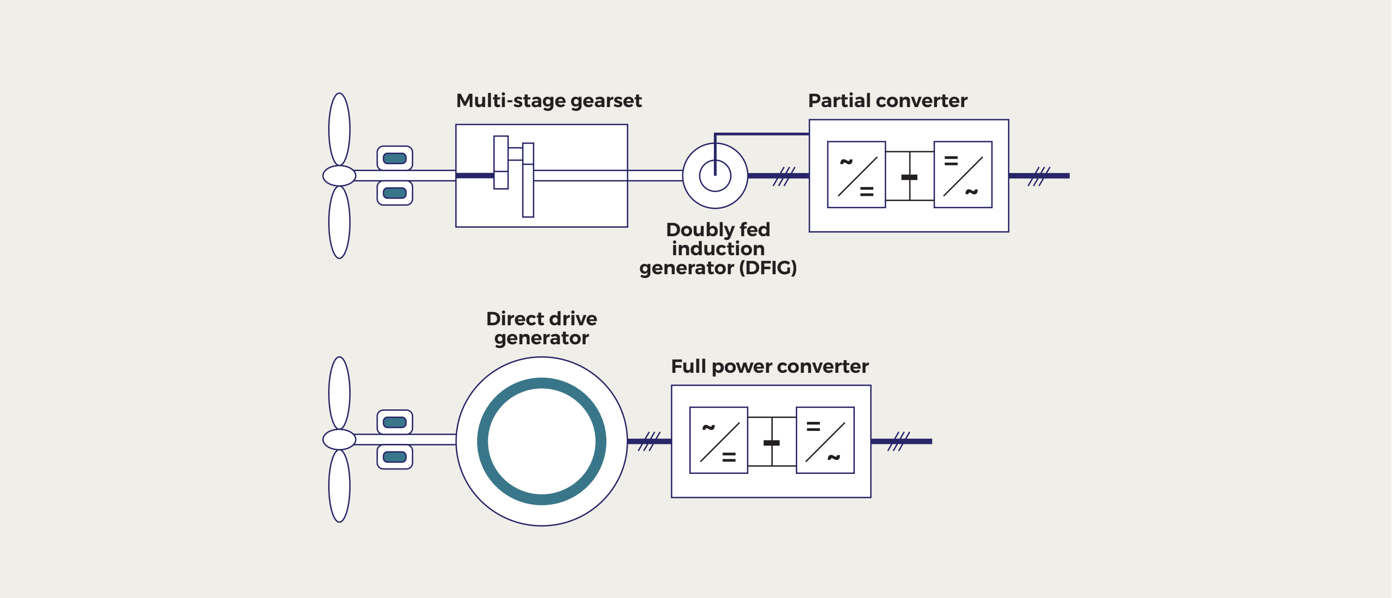
Introduction to wind turbine technology

In our analysis, we examined the UK wind turbine fleet for model and type, assessing the materials content for neodymium magnet metal grades and their amount. The relative consistency of design is important for assessing the overall opportunity for material recovery.

If we look at the structure of a wind turbine, we can see that the components have remained similar since the first kW-scale devices in the early 1980s. The tower, blades, foundations and basic control systems are similar today as to 20 years ago.

The rotor has three blades, connected to the hub via a bearing and pitch control system. The hub is connected to the driveline, turning a rotor within a generator stator to produce electricity. This electricity output is converted to electricity at a local facility for transmission to shore and the national grid.

The driveline and electrical system have to some degree changed from multi-stage gear-driven doubly fed induction generators (DFIG) for onshore and early offshore applications to gearless direct drive generators with full power conversion for high-power offshore turbines. The reasoning behind the change was to eliminate unreliable systems[13] such as gearboxes, and to improve the system compatibility aspects by using full-conversion power electronics that are more sympathetic to electrical grid conditions such as voltage and frequency fluctuations.



■ Figure 2 | **Summary of geared and non-geared drivelines**

The direct-drive generator replaces the gearbox and standard speed generator with a slow-speed, high-torque generator, and operates at a variable low speed, ranging from 8 to 15 rpm. The slow speed generator has a high number of magnet poles to be able to effectively convert the torque to electricity, with the stator producing medium voltage (typically 3.3 kV) and current.

In general, onshore wind turbines are less than 4 MW in nominal power rating, geared and with DFIG generators, with either partial or full power conversion. The first offshore arrays, from 2005 to 2010 were generally onshore turbines, installed close to shore, using known and proven technology.

Direct-drive technology

The first MW-scale wind turbines using direct drive technology in mass production were from Enercon in the early 1990s, using electrically excited synchronous generators (EESG). These large diameter generators have a rotor that carries multiple electromagnet assemblies, producing a stationery magnetic field that interacts with the stator magnetic field to produce alternating current. These simple machines are heavy and robust, efficient and controllable.

The challenge of increasing their performance and lightweighting was addressed by replacing the electromagnets and their power supplies with strong, permanent magnets using blocks of neodymium iron boron (NdFeB). These generators were at least 20% lighter than EESG of similar power rating.[14,15] The development of these generators between 2000 and 2010 gave impetus to the development of offshore wind arrays further from shore and in higher energy yield wind areas. This combination of high nominal power rating, with lower maintenance costs, high reliability and higher energy yield, with potential lower energy costs, has been popular in arrays over 50 km from shore.

All wind turbines installed in UK waters above 4 MW from Siemens Wind and GE use direct-drive, neodymium magnet generators and those from Vestas use geared neodymium magnet generators. Induction machines are more popular for lower nominal power rating turbines used for onshore applications, being robust and cheap. They do not use neodymium magnet materials but use a copper cage within the rotor construction. Offshore wind is therefore the significant source of neodymium magnet materials that can be recovered.

■ Figure 3 | **A direct-drive EESG from Enercon** | Courtesy of Enercon GMBH

■ Figure 4 | **A GE Haliade 6 MW generator on test** | Courtesy of GE Vernova/Stuart Bradley

Neodymium magnets

This report focuses on neodymium-based magnets, the dominant form of permanent magnet used in UK wind turbines, but there are a variety of permanent magnet types using different rare earth elements (REEs). There are 17 metallic REEs, including the 15 lanthanides; ranging from element number 57 (lanthanum) to 71 (lutetium), and often including yttrium and scandium due to their similar structures and chemistry.

REEs such as neodymium (Nd) and samarium (Sm) are not strictly speaking 'rare', being commonly found in the Earth's crust but not in concentrations that are commercially attractive for extraction. The most economically attractive ores are found in China, the US, Australia, Russia, Southern Africa and Greenland. The first permanent magnets using neodymium were developed by Sumitomo Industries and General Motors in the early 1980s and were used within electrical machines in the later part of that decade. The high cost of production discouraged further applications for permanent magnets until processing techniques dropped the cost to between US$20 to US$30 per kg in 2002 value. However, these first alloys used small quantities of heavy REEs like dysprosium and terbium to improve both the magnetic and mechanical properties, and these cost over $1000 per kg. Newer magnet grades and materials remove these elements, reducing the cost and environmental impact. The widespread use of neodymium in permanent magnets has made it one of the most commercially significant REEs.

The magnet blocks used in electrical machines are alloys of neodymium iron and boron (NdFeB) and are made from powdered metals in a similar way to sintered iron parts like camshaft drives. During manufacture of NdFeB blocks, the powdered metal is subjected to a magnetic field to orientate the magnetic domains, ensuring that the magnetic characteristics are uniform. Once formed and completed, the magnets can be energised with a high-power magnetic field. For wind generators, this is done by a large electro-magnet device for each magnet block, then the blocks are placed into protective structures.

■ Figure 5 | **Raw rare earth elements**

> Once formed and completed the magnets can be energised with a high-power magnetic field. For wind generators, this is done by a large electro-magnet device for each magnet block, then the blocks are placed into protective structures

Different magnet grades are available, with diverse properties and magnetic strengths including resistance to demagnetisation. Typical grades are N38HT where N is NdFeB, 38 is for the BH magnetic energy product in MGOe and HT refers to high operating temperature, (120°C or above) and corrosion resistance. The magnet blocks can be made into complex shapes within the sintered material mould and process, being cut into shape using wire erosion and similar processes.

The process of extraction and processing into industrially valuable magnets is complex and capital-intensive. The neodymium value-chain (ore mining, processing and manufacturing into magnet blocks) is geographically concentrated in China, contributing to assessments of its high risk of supply chain disruption ('criticality'). This supply chain risk and their economic value make secondary, domestic sources of permanent neodymium magnets of great significance for their potential to displace newly-made magnets and prevent the environmental and economic costs associated with the extraction and processing of REEs, which would otherwise be needed in greater quantities.

Environmental impacts of neodymium magnet production

Production of neodymium magnets is associated with significant environmental harms. REE mining, beneficiation and processing is energy intensive and produces a variety of acidifying, radioactive, or otherwise polluting metals and concentrated liquid wastes including solvents chemicals and radionuclides. These are usually stored in large 'tailing ponds' on site, leakage from which can cause groundwater contamination that can last for decades or centuries. This has reportedly caused devastation of the environment and displacement of local populations surrounding the world's largest REE mine in northern China.[16] Smaller but increasing quantities are also mined in Australia and the US.

There has been a significant increase in mining of REEs in Myanmar, which is largely unmonitored. REE mining in this area is tied into conflicts between the competing groups who control different parts of the mining regions. Reports suggest that by 2022 there were at least 300 mining sites in the 700 to 800 km^2 region that comprises the largest centre of REE mining, with many deposits in the area being exhausted. Efforts to establish new mines in this area have been

Figure 6 | **The Mountain Pass mine in California, US; a significant source of rare earth elements including neodymium**

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met with widespread civil society opposition due to environmental damage caused.[17] In Myanmar, much of the REE mining is through ‘in-situ leaching’ in which water and leaching agents such as ammonium chloride are pumped into the clay soil at the top of a hill containing a deposit and collected from pools dug at the base of the hill after they have travelled through the soil and dissolved the REE compounds. This creates direct pollution as well as increasing the risk of landslides. While there is little systematic evidence of the environmental impacts it has been alleged that collection pools leak into underlying groundwater and that toxic wastewater is intentionally released directly into rivers and streams leading to the death and/or contamination of much local wildlife including fish, which is relied upon as a food source, and local populations struggling to access safe drinking water or grow crops.[17] Some reports estimate that REE mining in Myanmar has increased five-fold since the 2021 military coup.[17]

The mining and refining of neodymium additionally creates far more carbon emissions per kg than everyday metals like iron and steel: ~68 kg CO_2e for neodymium[18] compared to ~2 kg CO_2e for steel.[19] The exact values vary based on the particulars of the mining and refining process and the energy used to power them. The emissions associated with neodymium magnet production are higher still when the additional manufacturing and processing steps and other material inputs are included, meaning that production of 1 kg of neodymium magnets creates ~75 kg CO_2e.[20]

The reuse of neodymium magnets over the purchase of newly produced ones provides very significant environmental benefits, by displacing the need to produce new magnets.

The manufacturing of the 16 million kg of neodymium magnet material in the wind turbines that will be installed in the UK over the next five years (2025–30) will produce 1.2 $MtCO_2e$, making it important to ensure that these costly resources are used to the extent of their potential rather than wasted and sourced anew. For context, the UK’s carbon budget for the year 2030 is 297 $MtCO_2e$.[21]

Turbine magnet wear and condition

Reuse of neodymium magnet materials from wind turbines depends on the magnet blocks being in good condition at the end of the turbine’s lifespan. They experience a number of stresses during this period, and design interventions can be employed to better protect the magnets for future use. Magnets unsuitable for reuse due to damage may still be recycled, through being broken down and reconstituted, but detailed examination of this is outside the scope of this report.

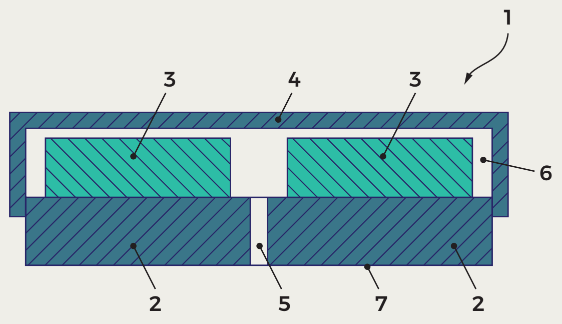
In service, turbine magnet blocks are sensitive to degradation by demagnetisation, by exposure to high magnetic fields (such as during short-circuits), high temperatures and mechanically weakened by corrosion and alternating stresses. They can be protected by structures such as ferrous magnet carriers, anti-corrosion surface coatings and covers. A typical structure is shown in Figure 7 below.

The potential for magnets to crack and chip is high due to their non-uniform grain structure made using sintered materials with the potential for high stress concentrations on vertices and edges. The magnet carriers can be arranged to capture any loose parts and hold them in place during machine operation usually this is done by using a thin metal cover and possibly a semi-cured polymer to dissipate impact energy. The magnet assemblies for wind turbines are situated in the gap between rotor and stator structures, near each other, meaning that they are continually exposed to high magnetic fields and mechanical forces from interaction with the low frequency stator magnetic field, between 0 to 20 Hz.

In direct drive generators, the magnet assemblies are bolted onto the rotor outer surface via a carrier structure. This allows the magnets to be installed to the rotor once it is assembled with the stator, allowing replacement of the magnets in case of permanent damage or for disassembly at end-of-life.

The standard speed generators are more likely to have assemblies that fulfil the same function as the low-speed direct drive machines but also contend with high centrifugal forces and induction heating. The magnet assembly may have the magnets divided into smaller blocks to prevent induction heating from eddy currents or have structural augmentation using stronger covers from non-metallic materials such as composites. These features improve the design but may make remanufacturing more costly due to added complexity.

> In direct drive generators, the magnet assemblies are bolted onto the rotor outer surface via a carrier structure. This allows the magnets to be installed to the rotor once it is assembled with the stator, allowing replacement of the magnets in case of permanent damage or for disassembly at end-of-life



1. **Magnet assembly**
2. **Magnet carrier**
3. **Magnet block**
4. **Protective cover**
5. **Thread for fixing to the rotor outer surface**
6. **Protective semi-cured polymer**
7. **Mounting face to rotor outer surface**

■ Figure 7 | **Cross-section of a typical direct-drive neodymium magnet generator magnet carrier taken from a US Patent 7,836,575 B2**

■ Figure 8 | **A direct-drive generator rotor wheel showing the magnet carrier threaded holes to suit two magnet carrier assemblies** | Courtesy of GE Vernova/Stuart Bradley

UK wind turbine deployment forecast

Clean, secure and low-cost energy has been a UK government aspiration for decades, and the intention to decarbonise the electricity system has encouraged the development of wind energy harvesting since the mid-eighties. One of the first examples of significant power delivery was the 3 MW Wind Energy Group (a joint venture between Taylor Woodrow, BAE Dynamic and GEC Energy) LS-1 demonstrator installed in Orkney in 1990. This machine had a nominal power rating higher than most other machines of the time but contained the basic components that we see in machines today — a tower with rotor and blades turning a main-shaft, a multi-stage gearbox and a generator.

If we examine the MW-scale wind turbine array installations since the early 1990s, we see that the first decade was sparsely populated with installations on land only. From the beginning of the century, the rate of installation rose from a few MW per year to 1.1 GW by 2010. During that decade the government developed plans and policy, particularly the 2002 Renewables Obligation, to install both onshore and offshore wind as part of the move to a clean, secure and cost-effective system. This was to be achieved in conjunction with small and large nuclear energy, biomass, and carbon capture and storage. Wind energy was not the main thrust of the strategy. During the 2010s the rapid cost reduction rates observed in onshore wind deployment gave confidence to offshore wind developers, and this encouraged the development of arrays sited in shallow waters, within 50 km of shore and a maintenance port. This relied on the development of larger power capacity turbines with high availability and dramatically lower levelised cost of energy. These turbines fell into two types, direct drive and geared drives, with the geared drives being a scaled-up version of the onshore turbine designs.

The UK's cumulative installed wind turbine fleet is now over 30 GW[22] and in this study we model a rise to 40 GW for offshore wind alone by 2030, based on a combination of existing forecasts. The fleet roll-out over the period 2025 to 2030 is high pace, with about 10 turbines per week expected to be installed during the installation weather window from April to October.

Our analysis shows that most wind turbines being installed in offshore locations are over 6 MW nominal rating, with most of them containing neodymium magnets. Based on our estimation of neodymium magnet material quantity per MW[23], the projected total mass of neodymium magnet material installed or being constructed and installed in the period from 2025 to 2030 is more than 16 million kg.

The 2025 to 2030 period will be one of intense activity for offshore wind turbines installation and the amount of engineering work in this area is concentrated on meeting this pace, safely and with continuous improvement at the fore. There is little radical innovation in progress, so we can be sure that the designs available now will be installed up to 2030. The pace from 2030 onwards is expected to be slower, and this may be an appropriate time for innovation in wind turbine technology — for topologies, drivelines and supply chains.

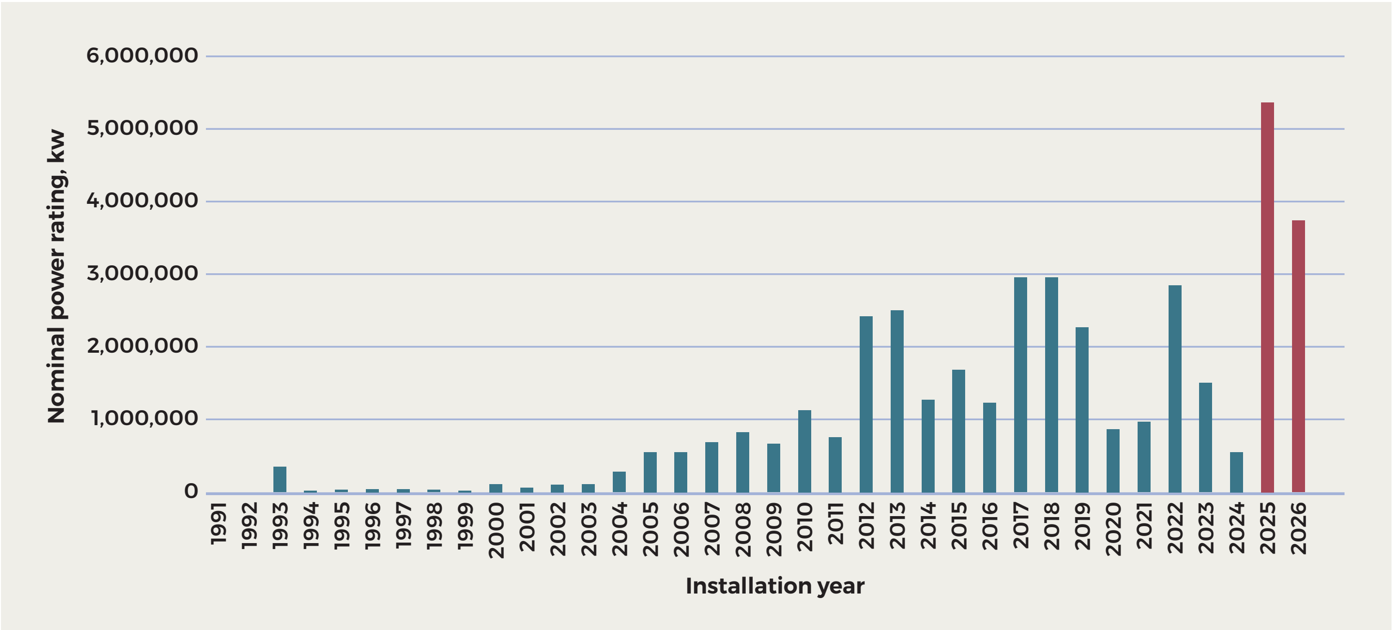


Figure 9 | **Graph of UK installation rates for wind turbines by year with 2025 and 2026 in red, as incomplete or unconfirmed**

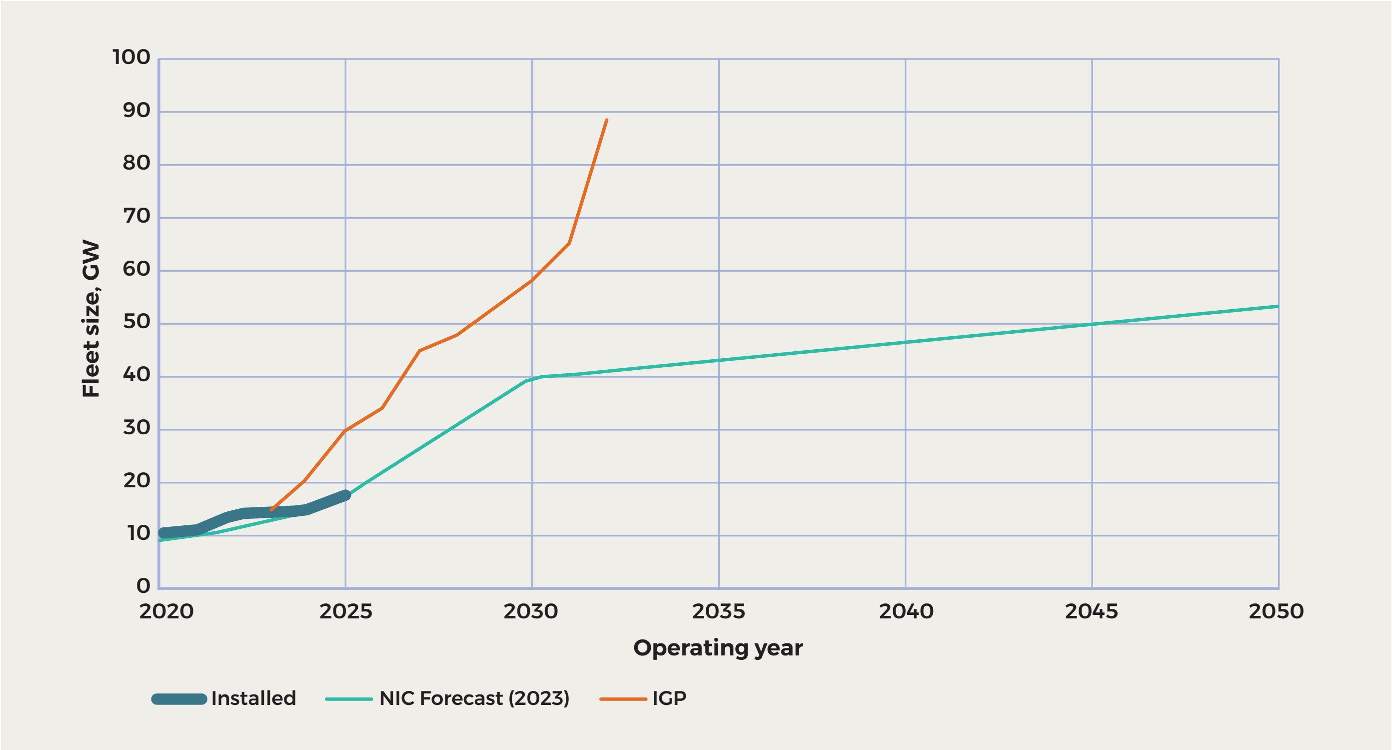


Figure 10 | **Graph of offshore wind installation projections by National Infrastructure Commission (NIC), and the Offshore Wind Industrial Growth Partnership (IGP)**

Impact of variation in deployment rates up to 2030

This study has assumed a deployment of 40 GW of offshore wind by 2030, a relatively conservative estimate in comparison to some projections or targets such as the one from the Industrial Growth Partnership in Figure 10. Any deployment above that rate would naturally increase the quantities of neodymium magnets available for recovery in a linear fashion, as well as increasing the capacity required for decommissioning.

Wind turbine decommissioning

For this report, we collated data from the decommissioning plans that exist for each existing array. We combined these with deployment projections and understanding about the design and material content of the turbine models to assess when decommissioning will likely occur and the amount of neodymium magnet material that will be available in each year.

The trends differ when examined in terms of individual wind turbines (Figure 12) vs based on the total generation power ('nominal power rating') in kW (Figure 13), because of the changing nature of the turbines being decommissioned. Onshore arrays (smaller turbines with little neodymium magnet material) are starting to be decommissioned now, with the majority due to be decommissioned between 2030 to 2038. Following that, the larger offshore turbines with larger power rating and containing more neodymium magnet material per turbine will be coming to the end of their life with a peak in the 2040s.

In general, end-of-life for wind turbines requires a decision on which of three courses to take:

1. **Decommissioning**: Disconnecting and removal of wind turbine components. This can be partial removal, leaving below-seabed foundations and some ground/seabed infrastructure in place, or full removal of everything above and below the ground/seabed.
2. **Life extension**: Continuing the operation of the turbine beyond its design life, which may involve repair or upgrading of components.
3. **Repowering**: In which the site is decommissioned but new and different wind power assets are subsequently installed in the same place.

The decision on which action to take is based on factors such as the site's lease conditions, commercial business case, energy demand, electrical grid capacity, and policy and political factors such as planning processes. These decisions have complex and different sustainability impacts, which were assessed in 2025 by Zero Waste Scotland.[24]

> Onshore arrays (smaller turbines with little neodymium magnet material) are starting to be decommissioned now, with the majority due to be decommissioned between 2030 to 2038

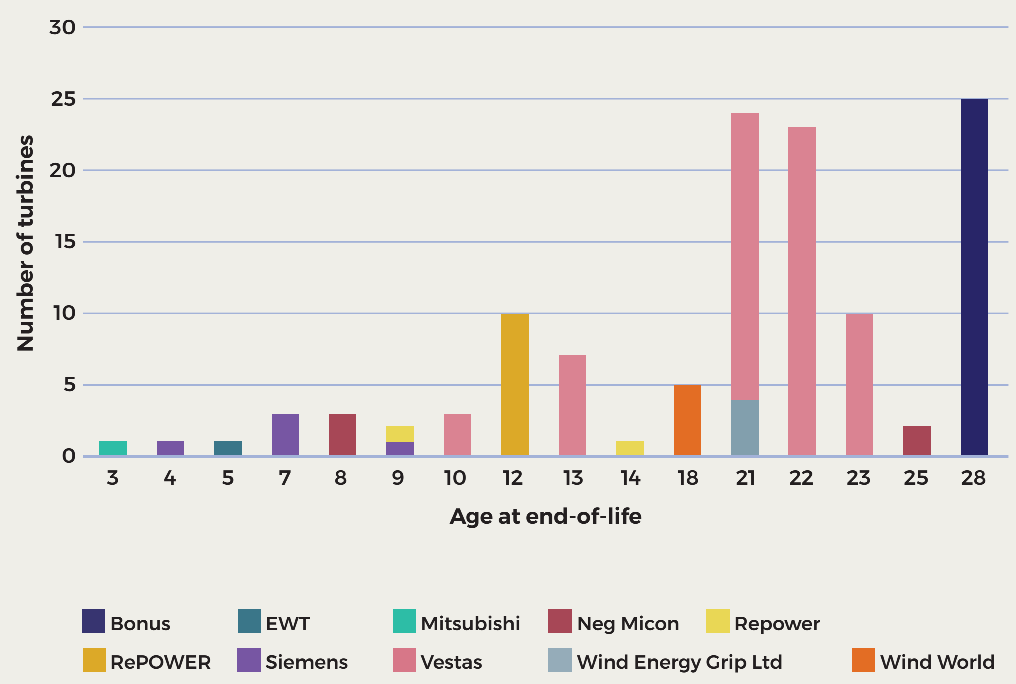


Figure 11 | **Graph of wind turbine age at decommissioning by maker**

Onshore wind turbine end-of-life

Analysis of the UK onshore wind turbine fleet shows that decommissioning has started.

As of 2025, a total of 139 turbines, in 26 arrays, have been decommissioned with a total nominal power rating of 114 MW. This data includes technology demonstrators, for example the first MW-scale onshore wind turbines. The longest life is for a 28-year-old array of Bonus B44/600 turbines, and the shortest was for a three-year old technology demonstrator from Mitsubishi. A site lease might be cut short if the turbine condition deteriorates beyond expectation and financial viability. The average life span is 14.4 years, and there are no discernible trends between makers. Ninety-eight turbines in nine locations, more than 70% of those analysed in this study, lasted longer than their expected design life or the site lease.

For the onshore fleet, most decommissioning is expected to take place from 2030 onwards.

Onshore turbine disassembly is most frequently coupled with repowering — upgrading the turbines and grid infrastructure to a higher power rating. This sometimes has a different land footprint to the original site so there is often some site restoration, but also new development. When not repowering, the intention is to minimise environmental damage as far as practical and return the site to original conditions. This might mean that the grid connection and roadway infrastructure is removed in addition to the visible turbine assets.

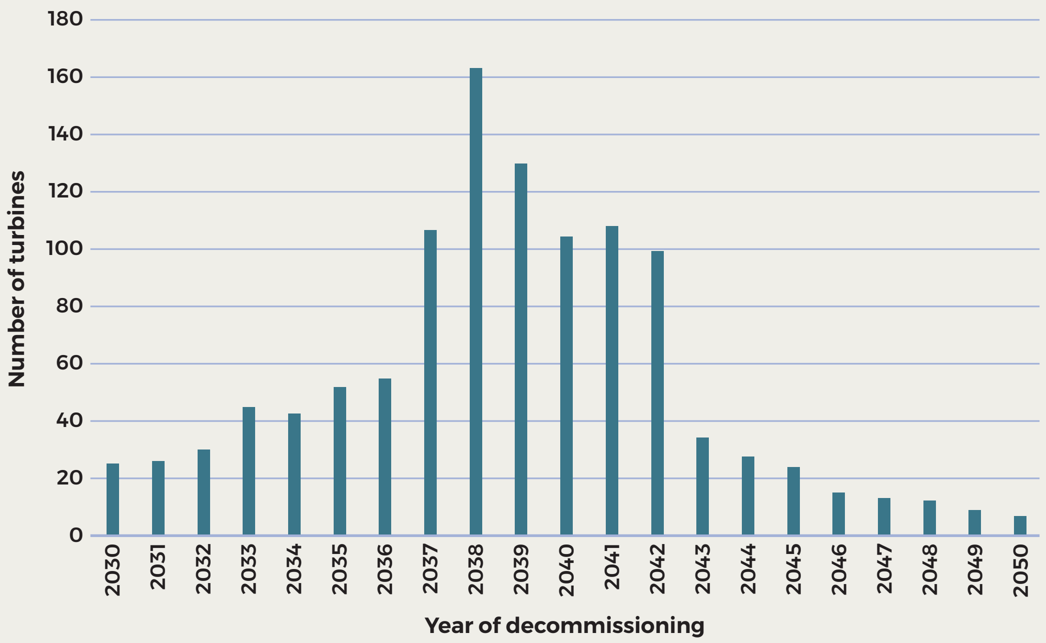


Figure 12 | **Graph showing the number of wind turbines (onshore and offshore) being decommissioned per year to 2050. This is derived from adding the expected 25-year design life onto the deployment projections for each year. However this is a source of uncertainty in this forecast, since there may be other choices made at the end of its contracted life depending on the decisions of asset owners and government**

> When not repowering, the intention is to minimise environmental damage as far as practical and return the site to original conditions. This might mean that the grid connection and roadway infrastructure is removed in addition to the visible turbine assets

Offshore wind turbine end-of-life

The process of offshore wind array decommissioning is in some ways like onshore decommissioning, though may also include substructure and cabling removal depending on the circumstances[25] and greater effort is required due to working at sea with exposure to more extreme weather conditions. In many cases the lifespan is expected to be determined by lease conditions set by The Crown Estate who typically agree a 25-year lease. Array decommissioning plans are created as a mandatory part of the consenting and lease grant process and are available to the public. The decommissioning scenarios can be full removal; partial removal; full repowering; partial repowering;[26] and life extension. The default regulatory position, and

■ Figure 13 | **Graph showing the decommissioning of turbines (onshore and offshore) by nominal power rating and year. The nominal power rating is the electrical output for continuous operation. The amount of magnet material is proportional to the nominal power rating, with a higher nominal power rating requiring more magnet material as a linear relationship – for example, a direct drive generator has between 800 and 1200 kg of magnet per MW of nominal power**

most common method to date, is full removal. This should be reviewed to ensure that sustainability and material recovery are being appropriately valued as a strategic goal (for more information, see recommendation 4).

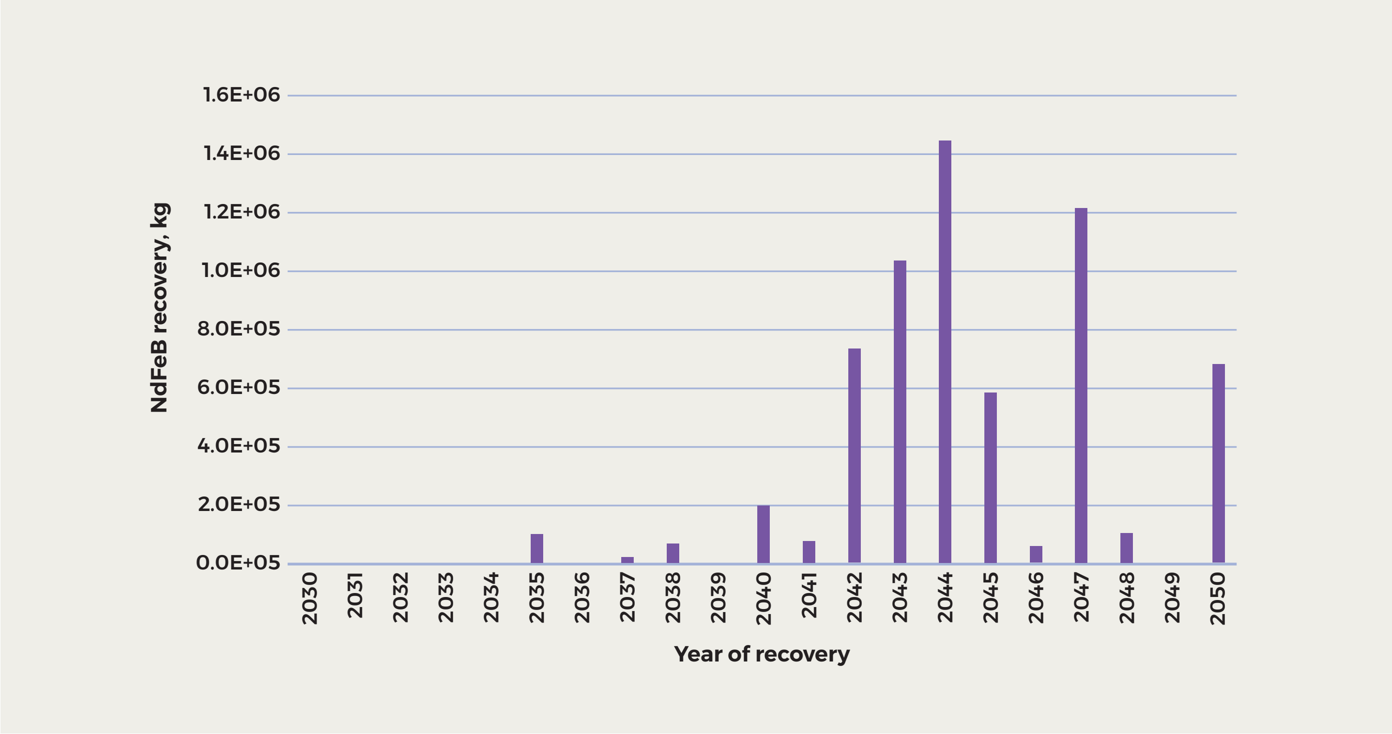
Figure 12 on page 29 shows that the number of turbines being decommissioned drops after 2042, from around 100 per year, down to 30. However, this reflects the changing size and capacity of the turbines and so the magnet material recovery correlates more closely with the total turbine nominal power rating being decommissioned each year (see Figure 13). This matches the graph of wind turbine deployment in Figure 9 by total nominal power rating but shifted 20 to 25 years in the future.

In summary, large-scale decommissioning of offshore wind turbines increases from 2038 onwards. The number of turbines being recovered from offshore increases in 2042, and peaks in 2044, however the total nominal power of the turbines being decommissioned – and thus the magnet material which can be recovered – will vary in the years 2045 to 2050 based on the years in which specific arrays are due to be decommissioned and is projected to peak in 2047.

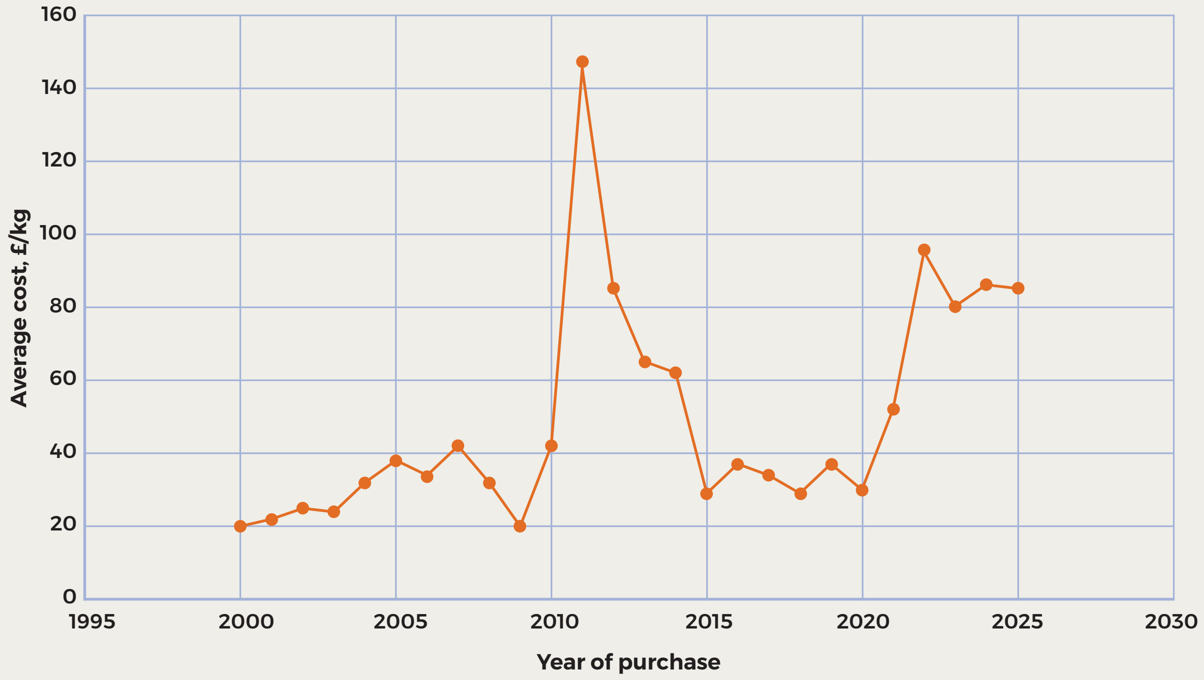
Projected yield and value of neodymium magnet material 2030 to 2050

The recovery of energised magnet assemblies is possible and realistic from an engineering standpoint and will be demonstrated during the disassembly of some onshore turbines that are being decommissioned in the next few years. These generators will yield samples and allow the practicalities of disassembly to be studied and for the mechanical and magnetic degradation under as-used conditions to be evaluated.

The graph showing the volume of magnet materials landing ashore resembles a delayed version of the installation curve, shifted into the future by the expected lifespan of the turbines. This predicts high levels of recovery in the 2042 to 2050 years. Over this time 7,300 tonnes of magnet material could be recovered, with a peak of 1,400 tonnes in 2044.



■ Figure 14 | **Graph of the amount of rare earth element mass being recovered by year for offshore wind turbines in UK and territorial waters**



■ Figure 15 | **The cost of NdFeB magnets, grade 38 HT, over the past 25 years**

The value of this material in today's costs, assuming a mean of £85/kg, is £620 million, although the scrap value is closer to £45 million. The volatility of the cost of magnet materials is described in Figure 15, which shows a variation of between £20/kg and up to £148/kg in 2011. In recent years, post-COVID-19 pandemic, there has been an increase in cost to between £80/kg and £100/kg. Price volatility and supply chain risk is considered high and is reflected in the continued development of rare-earth-free machine designs for automotive applications.

Process of magnet recovery from decommissioned offshore wind turbines

The number of offshore wind turbines being decommissioned is currently limited to those with shorter lease lengths and onshore turbine designs with 20-year design lives. Offshore specific designs such as the Siemens Wind D6 platform, the GE Haliade and Vestas V164 have a design life of 25 years, and are adapted from insights gained through the installation, operation and maintenance of earlier arrays.

With the average nominal power rating of turbines nearly doubling between 2012 to 2022 from 3.6 MW to 6 MW, and with the migration to the geared DFIG generators from onshore wind turbine drivelines, the amount of neodymium magnet material in UK wind turbine arrays has increased greatly, from a few tonnes to thousands of tonnes per array.

The first major recovery of neodymium from an offshore wind turbine is expected to be in 2038 when the lease for the Gunfleet Sands array expires, and the Siemens Wind 6.0–120 turbines can be recovered to shore, subject to any decision by the asset owners to extend the operating life of the turbine. The two demonstrators are some of the first of the new Siemens D6 platform. Each turbine is fitted with a direct-drive generator containing about 4,000 kg of recoverable magnetic material.

The rotor is arranged on the outside of the segmented stator, rather than the inside, and this allows the magnets to be unbolted in a safer and easier way due to the retaining bolts being accessible from the outside surface. Design choices such as these, which enable relatively simple recovery of the magnet materials without damaging them, are important for ensuring the economic opportunity for recovery exists.[27] Guidance on these design choices is available in the form of British Standard BS8887 (Design for manufacture, assembly, disassembly and end-of-life).

The first major recovery of neodymium from an offshore wind turbine is expected to be in 2038 when the lease for the Gunfleet Sands array expires, and the Siemens Wind 6.0–120 turbines can be recovered to shore, subject to any decision by the asset owners to extend the operating life of the turbine

Figure 16 | **A typical magnet carrier showing the fixing and extraction fastener holes with bungs, prior to salt-spray testing** | Photo from Trelleborg AVS, Leicester/Stuart Bradley

> The recovery of the energised magnet carriers needs to be in a controlled environment, with precision placement and control of the magnet carrier being critical to safety

In Figure 16, we see a magnet carrier assembly prior to salt-spray testing. The fixing bolts are closed with a bung, the carrier top cover is facing downwards into the salt-spray chamber. Each carrier has three fixing bolts that pass through the rotor, with each assembly being approximately 600 mm long and 120 mm wide. Each magnet carrier contains approximately 12 kg of NdFeB magnet blocks.

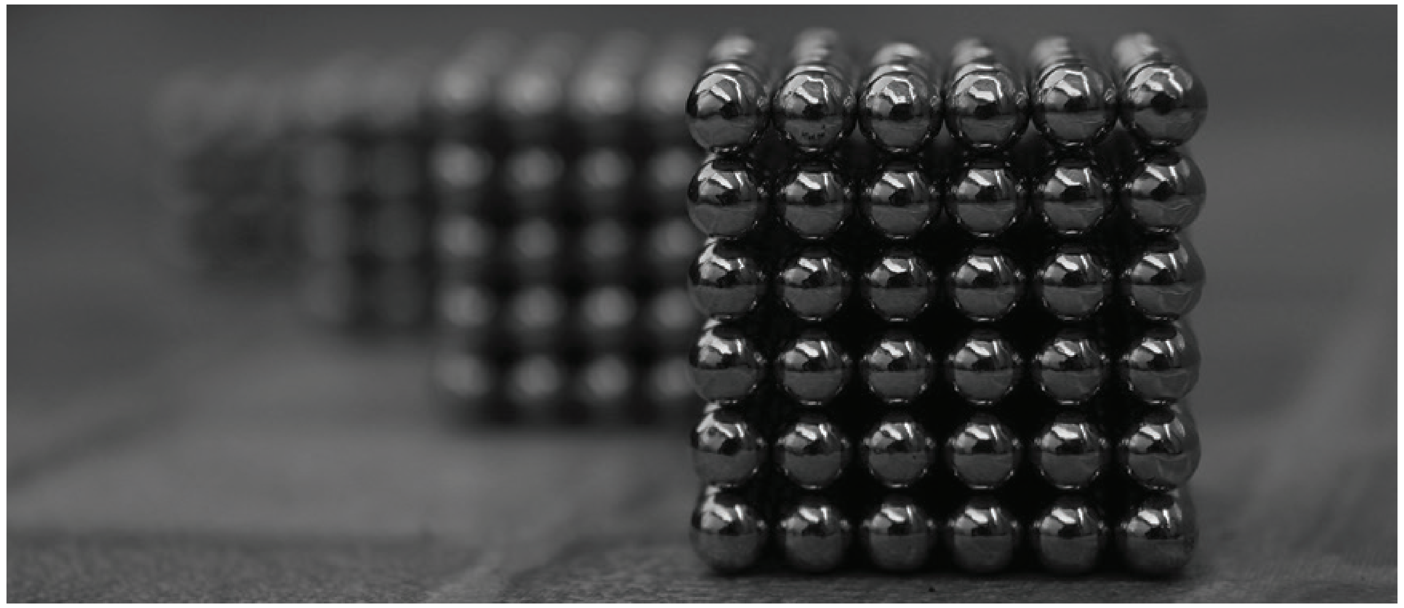
The recovery of the energised magnet carriers needs to be in a controlled environment, with precision placement and control of the magnet carrier being critical to safety. Due to the high magnetic forces in play, there are risks to those carrying out the extraction arising from magnets rapidly ‘coming together’. Extracting the magnets from the rotor to stator airgap will use an axial lead-screw extraction tool, with nylon guides to prevent uncontrolled magnet displacement toward ferrous material or other magnets.

Magnet block remanufacturing

Typical magnet carriers are 600 mm long, 120 mm side and 50 mm high, weighing about 25 kg and have a value of about £1,500 each, when new. Removing the magnet blocks is the first step towards remanufacturing, and the initial part of that process is to make the magnet carrier assemblies safe by demagnetisation. This is most easily done by placing the assemblies in an oven at a temperature close to the point at which temporary demagnetisation occurs. For the most part, this will be circa 220˚C, depending upon the magnet grade, for an extended period to ensure full demagnetisation.

Following demagnetisation, the magnet blocks can be removed from the carrier assembly. This consists of top cover removal, weakening the assembly adhesive and removal using shear forces. The magnet blocks are now ready for machining into new shapes for new applications.

Following machining, the new magnets can be measured for geometrical specification, tested for cracks and inspected for surface defects. The surface coating can be restored, either using nickel coating or a suitable anti-corrosion paint system. Tests to inform about the magnetic pole position or field orientation can be made and the magnets labelled. The magnets are then ready for redeployment to their new application to be remagnetised in-situ or dispatched already magnetised.



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Remanufactured magnet applications

In this section we assess the potential demands from UK manufacturing for remanufactured neodymium magnets of the sort that may be recovered from wind turbine decommissioning in the 2030s. These assessments are based on technology roadmaps and forecasts and the assumption that the UK's manufacturing sectors will remain largely the same – however it is unlikely that either assumption will be fully realised. Economic trends or strategies may shift what manufacturing or assembly is taking place in the UK, and technology roadmaps are inherently speculative and subject to innovation, particularly within the aerospace sector.

Automotive and aerospace

High-value manufacturing industries like automotive and aerospace require high magnetic energy materials such as NdFeB neodymium magnets for use in models with electric motors. The annual demand for neodymium magnet material from automotive manufacturing in the UK is projected to be approximately two million motors per year from 2030 to 2035, with a total annual demand of two million kg.[28]

Figure 17 | **An automotive IPM rotor showing the magnets and their encapsulation** | Photo from WMG, University of Warwick

Most automotive traction motors have the magnet materials encased within an internal permanent magnet motor (IPM), where the magnet blocks are inserted into voids within the rotor body, as shown in Figure 17. In this case, the magnets are 12 mm or 6 mm wide and 4.5 mm thick, with the axial length being made from short, individual magnet blocks. For a single offshore wind turbine magnet block of 100 mm square and 25 mm thick, weighing 1.85 kg, we could obtain 108 smaller magnets for the EV rotor set below, creating 0.3 kg of waste for recycling.

Aerospace technical requirements are like automotive, but with much more emphasis on machine power density, meaning that high power magnets are critical and, for neodymium magnets, it's likely that only higher grades are practical – certainly N38 and higher.[29] Aerospace applications are projected to need 20,000 kg of magnet material per year using a similar grade as automotive machines, based on technology roadmaps that predict a relatively high proportion of electric and hybrid aircraft, which contain motors in which neodymium magnets are likely to be found.[30]

In both application cases, the use of used or recycled materials is common, particularly for non-propulsion applications – i.e. parts of the vehicle that do not move and experience the stress created by the propulsion system. The application of remanufactured components should be subject to extensive validation and verification during the remanufacturing process in addition to extended end-of-line testing. The purpose of this scrutiny is to minimise the occurrence of defects and in-service failure, and therefore traceability of both incoming stock and outgoing finished parts will be essential to providing evidence of compliance with specifications.

Rail and marine

The application of neodymium magnet machines in both rail and marine is uncommon today. This is because of the disinterest in using expensive materials in machine types that are already highly optimised and mature. In rail, traction motors represent the largest application segment, with auxiliary machines a close second – used in the pump motors for heating, ventilation and air conditioning (HVAC) systems, as well as in braking systems and actuators. Remanufactured magnet applications are like automotive, with the magnet used within internal neodymium magnet rotors.

Marine applications of neodymium magnets are like automotive for machines with a power output less than 1 MW and closer in design to medium-speed wind turbine generators, like those used by Vestas, for those above 1 MW. The demand for magnets for marine applications is low but growing as the pace of electrification and low-carbon marine transport advances.

Power generation

For reused magnets returning to their original application in wind turbines, the classification and regulatory bodies will need to formulate policy and specify standards and processes for their recovery, restoration to original specification and return to service. Traceability during recovery processes and their subsequent reapplication will require tools and equipment with sensors. Serialisation of the incoming stock will be required from disassembly, using the machine serial number as the root number.

The demand for magnets for repowering wind turbines is likely to be higher than the stock available from recovery from UK wind turbines at any given time due to the time delay and increasing power and thus magnet requirements of new turbines. However, this assumes that design changes will not reduce or eliminate requirements for neodymium magnets, which may therefore be an important goal if there is significant demand for recovered magnets from other industries.

Other renewable power generation applications such as tidal stream and tidal range are more likely to be associated with high-speed rotors, and the deployment of the existing carrier assembly is doubtful. However, remanufacturing of the standard magnet block to meet these machines' requirements is plausible. The volumetric demand for such electric machines is expected to be in MW scale machine designs, so potentially 50 to 100 tonnes per year. Magnetic gears are used in wave energy and industrial applications where high torque is needed at low speeds.

Industrial electrification

Access to low-cost strong magnetic materials could have significant impact on improving the attractiveness of high-efficiency motors for industry and their role in the electrification of industrial processes. The difference between a standard industrial motor and an automotive one is mainly in the way that they are used, with automotive motors operating at variable speed and torque, whereas industrial motors are designed to be run at one speed for long periods of time. Using neodymium magnet motors and an inverter capable of operating at variable speeds can offer significant energy savings of between 5 to 15% compared to using a constant-speed drive.

Commercial risk

The main commercial risks associated with supply of recovered of magnet materials are the establishment of ownership and commercial risk at the recovery-to-shore and disassembly stages. The decommissioning responsibility lies with the asset owner, but the work to recover the turbines to shore for disassembly is likely to be subcontracted to a specialist engineering contractor and thereby delivered by a separate company. Tracing and establishing the transfer of material ownership during disassembly might be complex and risky.

The demand for remanufactured materials has not been assessed, and there may be reluctance to consider them for safety critical applications if provenance is not traceable. In those cases, recycling the magnet material through breaking it down and reforming the magnet may be considered a safer option though it incurs higher energy requirements.

The remanufacturing process, functional restoration and testing is likely to add between £10 and £15 per kg of remanufactured magnets, giving a potential sales cost of £20 to £30 per kg.[31] This compares favourably with new magnet blocks, which are between £85 to £100 per kg and reduces commercial risk with a much shorter supply chain, within UK territory.

Until commercially attractive technology to replace the use of neodymium magnets is developed, it can be argued that the most obvious application of this material is from where it came i.e. in offshore wind infrastructure. Unlocking this valuable material from its current application in offshore wind for use in higher value uses (UK automotive and aerospace sectors) therefore requires further development. Developing a replacement generator technology to allow these materials to be applied elsewhere, could create significant growth for UK power electronics, machines and drives (PEMD) manufacturers and benefits for wider high-value manufacturing sectors.

The replacement technologies may include electrically excited generators, superconducting generators or hybrid excitation machines, all of which are free from neodymium magnets.

Technical risk

The main risks associated with using remanufactured neodymium magnets are mechanical property degradation and unknown failure modes. Mechanical properties such as thermal performance, yield strength, impact resistance and fatigue strength are difficult to obtain from new magnet makers, and the changes from in-service conditions are yet unknown. The original design of magnet carriers was inspired by the need to protect these weak and brittle materials from mechanical damage, and to prevent any broken sections from migrating into the generator bearings and seals within the generator. Additionally, it was shown that the thermal conditions within wind turbine generators, and especially for low-speed direct drive generators, was moderate with temperatures rarely exceeding 80˚C. This ensures that the magnet materials suffer little degradation due to high temperatures.

The inspection of returning magnets can mitigate some of this risk, and if the magnets have suffered damage or unusual in-service conditions then that can be assessed and the risk judged. If the magnet blocks are suspected to be defective, then recycling them by breaking them down and reforming them (for which a variety of methods are in commercial use in the UK) can return this valuable material back into the economy. However, reuse is the optimal approach from an environmental perspective.

Summary of findings

We have examined the timing of recovery of offshore wind turbines for disassembly and remanufacturing of magnets containing neodymium. The disassembly and remanufacturing process is viable[32] from 2038 onwards, with an average of one million kg of neodymium magnet material being made available per year, enough to make one million automotive traction motors at a reduced cost while reducing the material value lost.

This domestic supply of powerful neodymium permanent magnets would drastically lower supply chain risks and improve environmental sustainability by displacing a primary material and associated mining, processing and shipping with what would otherwise be a waste product. While 2038 may seem like a far horizon, developing this supply chain would need to begin immediately to ensure that policy, regulation and supporting markets are in place.

The economic impact of this windfall would be to unlock local electric vehicle manufacturing value, potentially encouraging the manufacturing of inverters and transmissions to create a domestic electric drive unit (EDU) supply chain. This development indicates a significant contribution to high-value manufacturing, increased economic activity and high-paid jobs.

Potential social benefits might include positive impact to the wider EV roll-out, reducing environmental impact and costs.

The environmental benefits of remanufacturing are reduction in energy consumption and CO_2e emissions within industry, the reduction in waste products associated with mining the REE ores, such as slag, radioactive by-products, and water consumption and pollution.

This report has presented a technical analysis and is not an in-depth review of the policy landscape and so does not make specific recommendations for policy or regulatory solutions to the problems identified. It has, however, suggested options for policymakers to consider more fully and with further regard to strategic goals.[33] In doing so, the outcomes considered desirable are those that support the creation of a domestic circular economy for permanent magnets in wind turbines, within the context of a wider circular economy for wind power, and to free up those materials for use in domestic manufacturing to provide resilience and cost reduction for UK industry while reducing environmental harm.

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Annex A | Methodology

The purpose of this annex is to describe the calculation method, assumptions and uncertainties associated with obtaining the amount of rare earth elements used in the UK offshore wind fleet, their likely decommissioning date and value. We limit our work to 2050 because that represents a time when potential new technologies such as high-temperature superconducting machines might replace neodymium magnet rotors.

In a similar way, we will set out the calculation method for remanufacturing the recovered magnet assemblies, and their potential application to high-speed electric motors with neodymium magnet excitation rotors, often used in automotive drivelines.

This will allow calculations to be repeated, using improved data when assumptions can be validated during the disassembly of the first volumes of neodymium magnet assemblies.

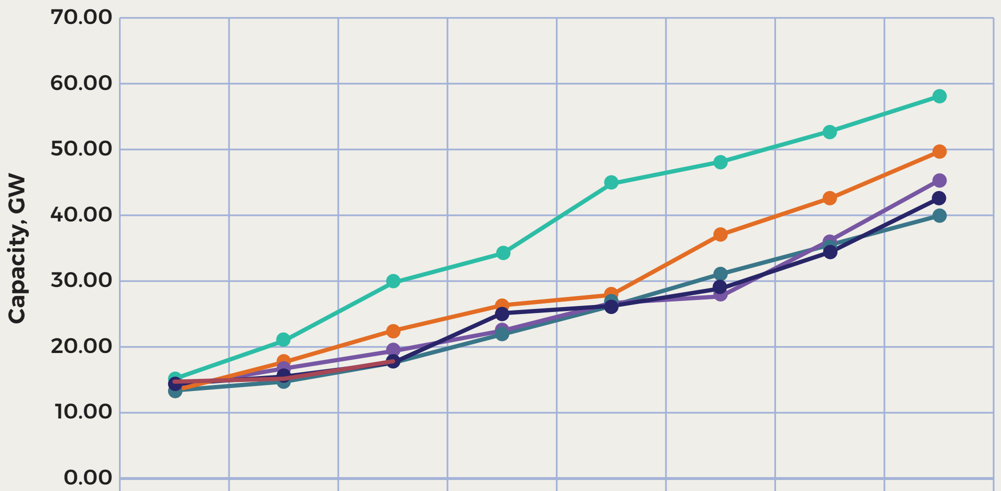
Offshore wind fleet installation

The historical installation data for the UK fleet is known and, in our case, we purchased a database from a commercial company that can state the installation date, location, wind turbine type and its driveline. This was obtained from The Windpower, 19, rue du Limousin, 31170 Tournefeuille — France, which supplied us with a database tailored for our specific needs.

This database was delivered in spring 2025, and showed existing, in construction, planned and decommissioned wind turbines for both onshore and offshore locations within the UK.

The wind turbine fleet data can be cross-checked against Renewable UK data and Crown Estate reports, plus data contained within decommissioning plans found on the array website, for example, Dudgeon Offshore Wind.[34]

For the future installation rates, we used two sources, from the former National Infrastructure Commission, now National Infrastructure and Service Transformation Authority[35], and from the Offshore Wind Industrial Growth Partnership[36]. We have updated the installation forecast to include the Future Energy Scenarios[37] from the National Energy System Operator (NESO). From this graph, we can see that the recent historical installation rates quite closely match the Future Energy Scenario forecasts for Hydrogen Evolution and Aurora.



	2023	2024	2025	2026	2027	2028	2029	2030
● Aurora / NIC 23	13.29	14.84	17.94	22.36	26.77	31.18	35.59	40.00
● OSW industry growth plan	15.15	20.95	29.93	34.39	45.03	48.25	53.05	58.39
● FES electric engagement	14.04	16.68	19.42	22.46	26.41	28.01	35.97	45.22
● FES hydrogen evolution	14.04	15.48	17.68	25.21	26.42	28.87	34.59	42.68
● Further flex and renewables	14.04	17.68	22.46	26.41	28.01	37.17	42.82	49.91
● DESNZ / OREC historical	14.67	15.20	17.80					

Figure A1 | **Graph and data table showing offshore wind scenarios** | Courtesy of Felix Martin, WMG

Decommissioning timeline for the UK offshore wind fleet

To estimate the recovery of magnet assemblies, we have looked at the design life for wind turbines from the decommissioning plans mentioned above, and the wind turbine database. The design life of most turbines and their arrays is 25 years, so taking the installation date and adding 25 gives us a likely decommissioning date.

If we sort the database to obtain array turbine models, we can use the turbine model database to find out the mass of magnet in each generator. The turbine model database also comes from The Windpower and can be cross-checked using public announcements for each array. For example, the type and model of turbine for Dudgeon Offshore Wind can be found on the array website.[38] The type of generator is given on The Windpower website, but also from the author's own research going back to 2010, which describes turbine drivelines including the gearbox, generator, drive and operational data such as nominal rating and operating speed.

The decommissioning date is given by;

$$D_{Decom} = D_{Comm} + 25$$

When D = year
Decom = end of life event, year
Comm = Commissioned event, year

For each existing array, we can take the commission date, for example, for Dudgeon, that would be 2017. If we assume a design life of 25 years, the decommissioning date would be 2042. Note that the lease length is for 50 years from financial investment decision date in 2014. Dudgeon Offshore Wind decommissioning plans[39] confirm that preparation for disassembly is 2041 to 2042.

The reason that some magnet material might be lost during decommissioning and recovery is due to mechanical damage suffered, for example while the nacelle is separated from the turbine, or the generator is removed from the nacelle

This allows us to create scenarios that describe chronological recovery of wind turbines.

Recoverable magnet mass

Each array contains a defined number of wind turbines of a known type, with generators that may, or may not contain magnet assemblies. Our purchased database identifies each array and their wind turbine model, also informing us of the generator type.

The amount of magnet available for recovery

$$M_{recovery} = (N_{array} - N_d - N_p) * (M_{ma} - M_l)$$

Where $M_{recovery}$ is the mass of recovered magnet material

N_{Array} is the number of wind turbines in the fleet or array

N_d is the number of turbines destroyed or irrecoverable

N_p is the number of turbines retained for service

M_{ma} represents the amount of magnet material originally used

M_l is an allowance for the mass of magnet material lost during recovery and scrapped

Information on magnet assemblies

The reason that some magnet material might be lost during decommissioning and recovery is due to mechanical damage suffered, for example while the nacelle is separated from the turbine, or the generator is removed from the nacelle. This should be a small amount, less than 1 event in 20.

In our calculations, we used N_d and $N_p = 0$ since we assume that the recovered turbines will be handled with care and precision, and that part repowering at end of life with turbines operating beyond their design life will be very rare. We have assumed that M_l will be equivalent to 5% scrapped or destroyed during recovery. The process of recovery is proven during generator build, being the reverse of the build process.

The amount of magnet material originally used, M_{ma} is obtained from technical literature, such as the published data from the turbine equipment makers.[40] In some cases, the amount of magnet material was obtained from the authors' knowledge and from more unusual sources such as dimensional information for spare parts.[41] For most generator models, we were able to obtain the amount of magnet material.

For example, the magnet assembly used in the Siemens Wind D3 platform has approximately 12.7 kg of permanent magnet material in each pole assembly, and there are 120 poles, so approximately 1,520 kg. This information was found from spare parts enquiries and the authors' personal knowledge.

Turbine models	kg/MW	Information
GE	**3285**	
2.75–118	0	Authors' work
Haliade 6–150	845	Authors' work
Haliade X	800	Calculated from magnet assembly drawings
Haliade X–12	840	Calculated from magnet assembly drawings
Haliade X–13	800	Calculated from magnet assembly drawings
Samsung	**85**	
7.0–171	85	Leavenmouth demonstrator – OREC
Siemens	**8170**	
3.0–101	800	Authors' work
3.0–113	800	Authors' work
3.6–107 DFIG	0	Authors' work
3.6–120	0	Authors' work
3.6–130	0	Authors' work
D10–206	900	Calculated from magnet assembly drawings
D14–222	800	Calculated from magnet assembly drawings
D6–150	800	Calculated from magnet assembly drawings
D6–154	800	Calculated from magnet assembly drawings
D7–154	800	Calculated from magnet assembly drawings
D8–154	835	Calculated from magnet assembly drawings
D8–167	835	Calculated from magnet assembly drawings
SWT–6.0–120	800	Calculated from magnet assembly drawings
Vestas	**420**	
V150/6.0MW	70	Life cycle analysis – Vestas
V164–8000	115	Life cycle analysis – Vestas
V164–8400	110	Life cycle analysis – Vestas
V236	125	Life cycle analysis – Vestas

Table A1 | **Extract from authors' database of wind turbine data showing the most popular offshore wind models and their magnet mass per MW nominal rating**

Table A1 can be used to clarify the data sources for magnet mass per MW installed in popular turbine models. Notably this suggests that DFIG turbines contain no neodymium magnets, although there is some uncertainty about whether these models include some smaller neodymium magnets in things such as ladder fixings.

If we substitute into the above, then the recoverable materials for a typical wind farm[42] is:

$$M_{recovery} = (N_{array} - N_d - N_p) * (M_{ma} - M_l)$$

$$M_{recovery} = (6 - 0 - 0) * (1520 - (1520 * 0.05)$$

Meaning that the recovered amount of magnet material is likely to be 1,444 kg for this small array, in 2037.

Remanufacturing

Once the magnet assemblies are recovered, we have assumed that they will be sent for remanufacturing. In this process, we have estimated the magnet yield and costs associated with this process. This work was made using in-house knowledge of machining and processes associated with sintered metals.

The cost of remanufacturing was calculated.

$$C_{reman} = C_{fixed} + C_{variable}$$

$$C_{fixed} = C_{labour} + C_{rent,\ rates} + C_{capital} + C_{admin} + C_{insurance}$$

$$C_{variable} = C_{energy} + C_{bill\ of\ materials} + C_{consumables} + C_{pack\ and\ ship}$$

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The fixed costs, C_{fixed} are obtained from UK Government statistics maintained by the Office for National Statistics[43] and from working with local and national manufacturers. Labour costs can be considered a variable cost for production line workers whose contracts are flexible. Design, sales and administration staff costs are fixed, sometimes with a small variable cost to represent sales commissions and bonuses. In many manufacturing companies fixed costs range between 5 to 30% of the product cost.

Variable costs are associated with the bill of materials, energy and consumables such as lubricants, disposable assembly aids, adhesives. Pack and ship costs also include transportation, including tariffs and taxes.

In our case, we have taken the bill of materials cost for a magnet assembly to be circa £6 to £10 per kg, representing the purchase cost of the recovered magnet assembly. This cost is likely to change as demand changes over time, and the opportunity for remanufacturing and recycling is realised. The cost of consumables such as lubrication and process gases is estimated from our knowledge and research.[44,45] Packing and shipping is estimated from using reusable wooden and polystyrene materials for improved safety and robustness.

Our cost estimate has taken the bill of process from this report and calculated the time for processing, the energy consumption using semi-automated tooling such as CNC machines and co-bots, the amount of capital employed and cost of finance being 10%.

Cost example

As an example, we have used a recovered magnet assembly of 6 blocks of 100 mm square and 25 mm high. The demand from a typical automotive motor is for magnets with sections of 10 mm wide and 4.5 mm high, with a length of 23 mm. The length is small because the installation into rotor sections is by using short blocks to help with eddy currents and potential rotor skewing to minimise torque ripple. This means that each magnet weighs approximately 7.8 g from the 12.7 kg assembly, and our experimental data indicates 0.76 kg of waste is created due to machining (6% of the total mass).

We estimate the amount of energy needed to machine the magnet blocks on the ferrous magnet carrier. This means that the work piece can be clamped and the magnets do not have to be disbanded from the carrier. Using an energy consumption rate of 0.08 kWh per minute for slitting[46], and estimating feed rates and number of operations, we see that the cost of energy for machining the magnet assembly is between £0.88 and £1.20 depending on the range of energy costs.[47]

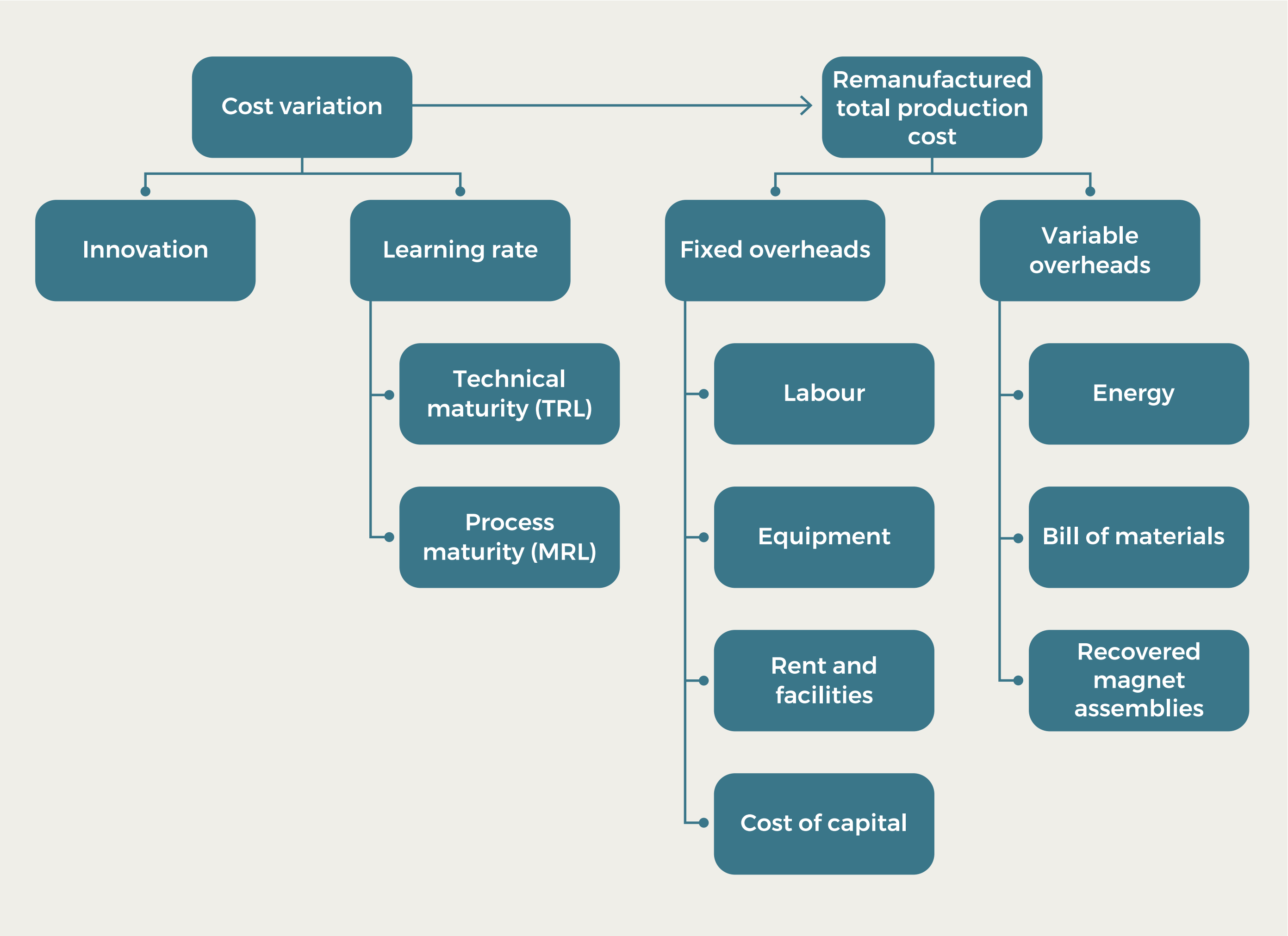

Figure A2 | **Diagram showing structure of cost model**

Manufacturing cost estimation method

The cost estimation model consists of three strands. The fixed and variable overheads are estimated using consolidated statistical information. The fixed costs might include cost of capital for small, medium and high risks, exchange rates, some labour and energy costs and facilities costs. Variable overheads are associated with the volume of product made, so raw materials and consumables, energy specific to the production process and manufacturing labour costs. The output from this agglomeration of costs is the total production cost, and is valid for a baseline production volume of goods at a production site.

The influence of manufacturing know-how can be represented by a non-linear relationship that reduces the cost in proportion to the volume of made products. If products are made in larger quantities than represented by the total production cost, it can be adjusted by the learning rate, which represents the cost reduction achieved by process improvements and practise, and is proportional to the manufacturing readiness level. Cost can also be adjusted by design improvements such as those suggested by the supply chain, by learning from application feedback and is proportional to TRL. Examples might include relaxation of some geometrical or performance tolerances, and tightening of others, by material changes and similar.

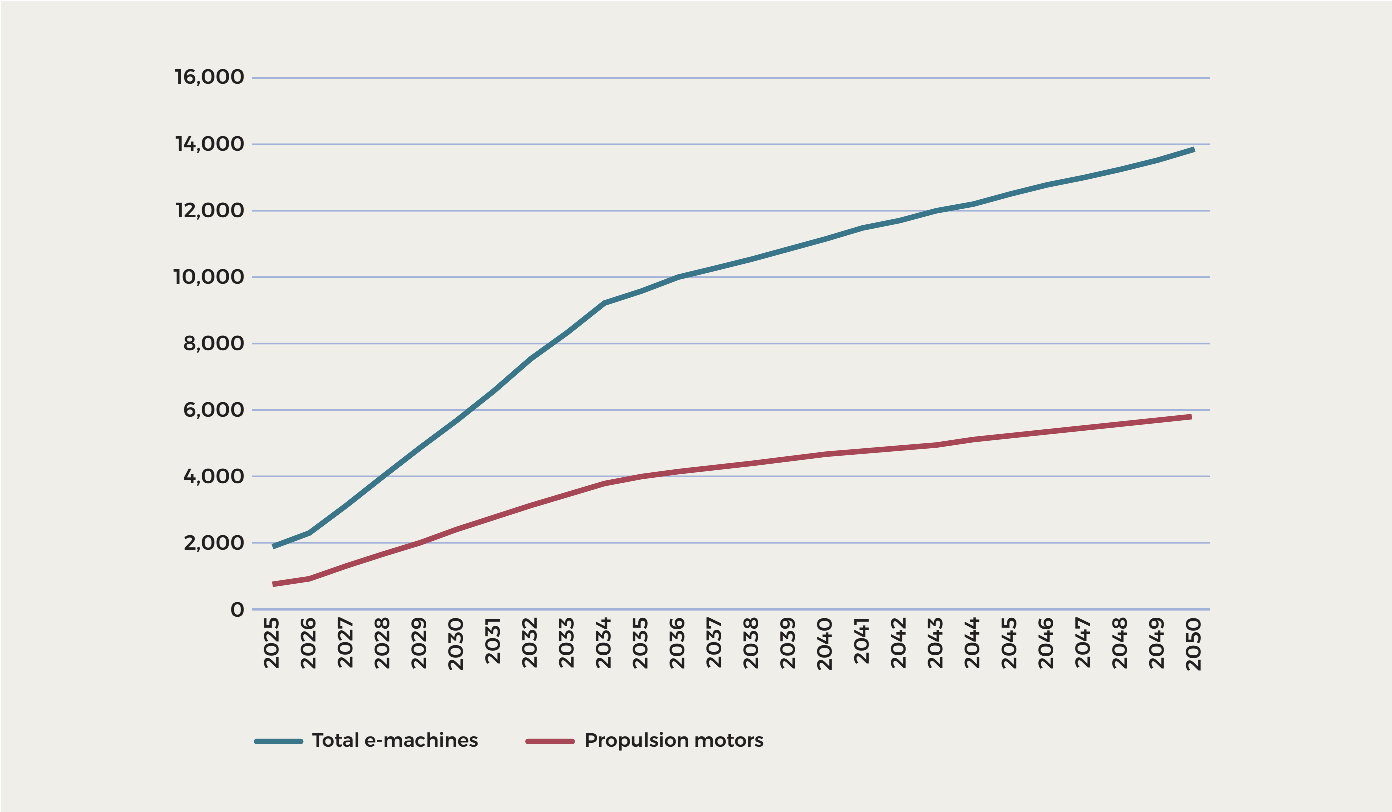

Figure A3 | **Graph showing forecast growth in UK manufacture of neodymium permanent magnet-containing aerospace components, 2025 to 2050**

Innovation is a potential cost reduction method, for example, the introduction of a new manufacturing capability. This is a one-off cost reduction method, giving a step change in cost base, and not always influenced by the TRL or MRL.

Neodymium demand from aerospace sector

The neodymium magnets material demand per annum for UK aerospace manufacturing was estimated to be 20,000 kg per year. Sources including Aerospace Technologies Institute technology roadmaps[48,49], and a Faraday Institute assessment of aircraft types and forecast service dates[50] were used to estimate magnet volume in different machines and the timeline for deployment of those machines. From this a forecast of the UK demand for neodymium-containing components (e-machines and propulsion motors) in the aerospace sector, assuming an average of six propulsion motors per electric aircraft and two motors per hybrid aircraft.

In this forecast, annual demand for neodymium permanent magnet material reaches 20,000 kg in 2034, rising by about 1,000 kg per year. This is however a high-level estimate based on uncertain assumptions about trends in aerospace technology.

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25 It is often more environmentally friendly, and encouraged by OSPAR regulations, to leave cables and substructures in place. They also may ideally retain roles in future power generation from the same site

26 Partial repowering refers to repowering only a certain number of turbines with higher power turbines, to maintain the total nominal power rating of the array. For example, 20 3MW turbines may be 'partially repowered' by turning six of the turbines into 10 MW installations

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30 See the Methodology Annex for more details

31 Based on a costing estimation method that uses estimations of labour hours, capital employed, cost of energy, resources and quality control taken from real projects. See Methodology Annex for further details

32 Viable here meaning that the recovery, remanufacturing and reapplication costs are less than the cost of new magnets, and that the risks can most likely be controlled and mitigated

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