https://doi.org/10.5194/wes-2026-201
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Environmental assessment of end-of-life pathways for permanent magnets in Dutch offshore wind turbines

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Abstract. This study evaluates circular end-of-life pathways for neodymium–iron–boron permanent magnets used in Dutch offshore wind turbines by combining an asset-level projection of the offshore fleet with a life cycle assessment of a representative 2 GW wind farm. Turbines installed between 1992 and 2046 are estimated to contain 8.2–26.3 kt of permanent magnets, with end-of-life availability extending from 2036 to 2086, indicating substantial future potential for domestic recovery of rare earth materials. The principal finding is that short-loop magnet-to-magnet recycling provides the greatest climate benefit: it reduces the global warming impact of finished magnet production by 72.5% relative to virgin production, compared with 26.5% for long-loop recycling. At turbine level, however, the effect is diluted by other life cycle stages, and total impacts differ by less than 4% across the assessed pathways. Short-loop recycling should therefore be prioritised where magnet grade and scrap homogeneity permit direct reprocessing, while long-loop recycling remains necessary for mixed, degraded or compositionally complex material. Realising these benefits requires coordinated collection and dismantling, material traceability, design for disassembly and expanded European recycling and magnet-manufacturing capacity.

1 Introduction

Achieving climate neutrality by 2050 requires a rapid shift from fossil-based energy systems to renewable sources (European Climate Law, 2026). Wind energy is expected to play a central role in this transition because of its large deployment potential and improving economic performance. As global and European wind capacity expands, demand for wind turbine components and materials will increase accordingly (Costanzo, Brindley, & Tardieu, 2025). Many modern turbines, especially offshore, use permanent magnets in both medium-speed geared asynchronous generator concepts (MSPMGs) and synchronous direct-drive permanent magnet generators (PMSGs) containing neodymium-iron-boron (NdFeB) permanent magnets (PMs) (Popa & Szab, 2025). These magnets provide high efficiency, reliable operation under variable wind speeds, lower maintenance needs, and compact generator designs. Their growing use is therefore expected to substantially increase demand for rare earth elements (REEs), particularly neodymium (Nd), praseodymium (Pr), and dysprosium (Dy), which are key constituents of NdFeB magnets.

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Although PMs improve wind turbine performance and reliability, their production entails significant environmental impacts and supply chain risks. REE extraction, refining, and processing are energy-intensive and concentrated in a small number of regions, notably China (Ghorbani, Ilankoon, Dushyantha, & Nwaila, 2025), raising concerns about resource security, geopolitical dependence, and future availability. At the same time, growing wind turbine deployment will generate increasing volumes of end-of-life (EoL) PMs in the coming decades (Kim, Dhir, Dasgupta, & Scanziani, 2025). In response, the European Union has classified REEs as critical raw materials and introduced measures through the Critical Raw Materials Act (European Parliament and Council of the European Union, 2024) to reduce import dependency and strengthen strategic value chains (Li, et al., 2020). In addition to diversifying mining and refining, circular economy strategies are needed to reduce primary resource demand. These include material efficiency, lifetime extension, reuse, remanufacturing, repurposing and recycling of PMs. Such EoL pathways can recover valuable REEs and replace virgin material production, reducing environmental impacts while improving supply security. However, uncertainties remain around future decommissioning volumes, generator technology trends, collection rates, the feasibility of large-scale magnet recovery, and the effectiveness of different circular strategies (European Parliament and Council of the European Union, 2024). These uncertainties hinder the development of realistic targets and policies for circular PM supply chains in the wind sector. Meanwhile, circularity and supply chain resilience are already emerging as important non-price criteria in offshore wind procurement, increasing the need for robust quantitative assessments.

This study assesses the environmental implications of alternative EoL pathways for PMs used in wind turbines. A life cycle assessment (LCA) is conducted across the full wind turbine life cycle, including manufacturing, installation, operation and maintenance, and EoL, to ensure a consistent system boundary. The analysis focuses on PM production and EoL treatment, with scenarios ranging from conventional virgin material production to reuse, remanufacturing, repurposing and recycling. By quantifying the environmental benefits and trade-offs of these circular pathways, the study identifies promising strategies to reduce the environmental footprint of wind energy while strengthening the resilience of REE-based supply chains.

2 Materials and methods

2.1 Goal and scope

This study assesses the environmental impacts of electricity generation from offshore wind turbines equipped with PM type generators and to evaluate the potential of circular EoL strategies for NdFeB PMs to reduce these impacts. Emphasis is placed on the contribution of reuse, remanufacturing, repurposing and recycling pathways to lowering the demand for primary REEs and reducing life cycle environmental burdens. Although the investigated circular strategies focus on PMs, the assessment is performed at the wind turbine system level to ensures that the environmental benefits of circular magnet supply chains are evaluated within the context of the complete electricity-generation system. The functional unit is defined as 1 kWh of electricity delivered to the grid from an offshore wind farm located in the Dutch North Sea. A representative 2 GW offshore wind farm is used as the reference system. All the details for this wind farm are detailed below in Table 1 and Table 2.

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Table 1: Key operational parameters of the reference offshore wind farm

Parameter	Value
Capacity factor	52–60%
Lifetime	30 years
Electrical losses	6%
Availability	97%
Wake losses	8%
Degradation	0.1–0.2% per year

Table 2: Lifetime electricity generation by installed capacity for the reference offshore wind farm

Installed capacity	Lifetime electricity generation (30 years)
per MW	140–160 GWh
1 GW	140–160 TWh
2 GW	280–320 TWh
21 GW (Dutch 2032 target)	3,000–3,400 TWh

All environmental impacts are related to this functional unit, enabling a comparison of alternative PM EoL scenarios based on their contribution to electricity generation.

A cradle-to-cradle system boundary is applied. The assessment includes the complete life cycle of the wind turbine system, covering raw material extraction and refining, turbine manufacturing and assembly, installation, operation and maintenance, decommissioning, and EoL (Figure 1). Although the functional unit is based on electricity generation, the investigated scenarios differ only in the manufacturing and treatment of PMs at EoL. Consequently, while all life cycle stages are included, the analytical focus is placed on the production and EoL phases of the PM supply chain. The production of PMs is therefore separately assessed (Figure 2). Virgin magnet production comprises REEs mining, refining, material processing, and magnet manufacturing. At EoL, PMs are collected and routed to alternative circular pathways, including direct reuse, remanufacturing, repurposing and recycling. The EoL system includes operational activities (e.g., lifting, dismantling, and component separation), logistics (offshore and onshore transportation), and recovery processes such as demagnetization, shredding, grinding, hydrogen decrepitation, sandblasting, and metallurgical treatment. Recovered materials are subsequently reintroduced into PM manufacturing applications. Since repeated recycling can lead to reduced magnetic performance due to corrosion/oxidation and material loss, new REEs are required to supplement during production. Other alternative scenarios are investigated by varying the percentage of post-consumer recycled content (Binnemans, et al., 2013) (Table 3). The life cycle assessment follows the avoided-burden approach, whereby recovered materials are credited for displacing equivalent virgin material production. Because turbine installation, operation, and decommissioning processes are largely identical across

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scenarios, differences in environmental performance are primarily attributed to variations in permanent magnet production and EoL pathways.

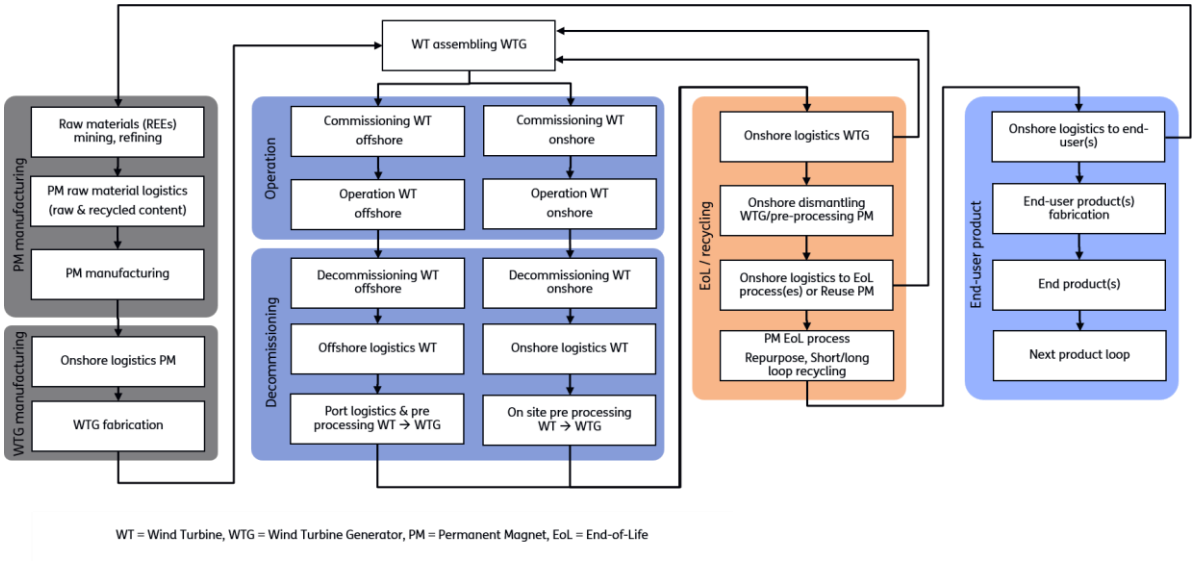


Figure 1: Full offshore wind turbine life cycle, showing where the PM system is embedded within the turbine system.

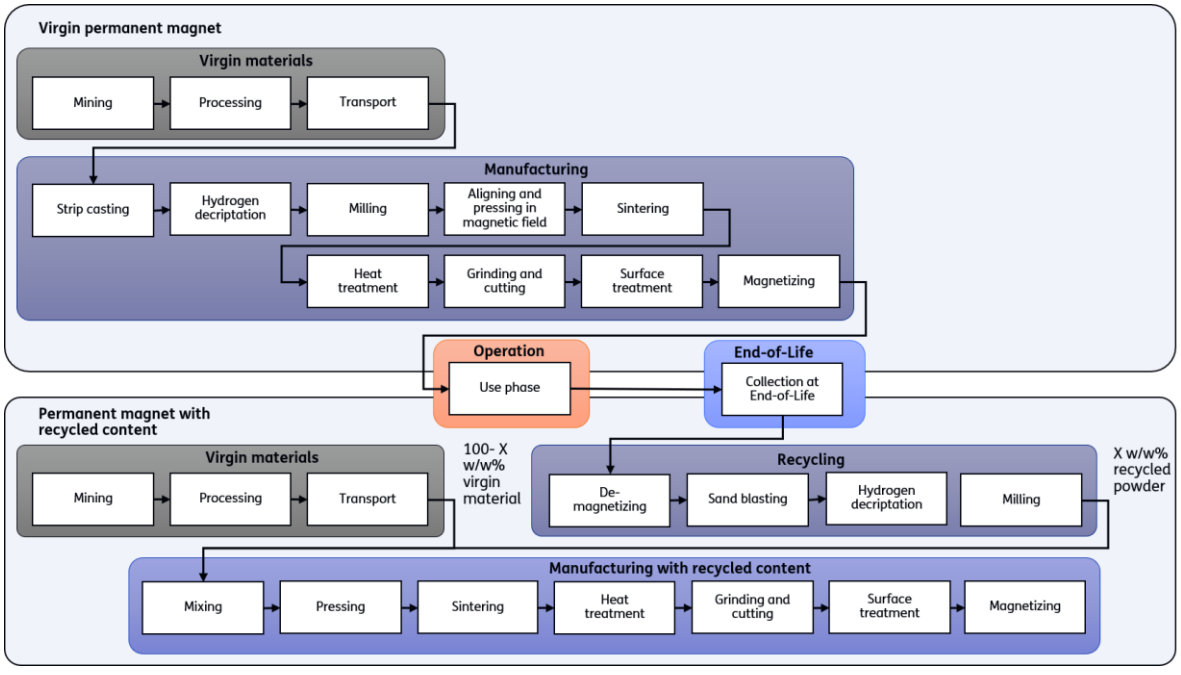


Figure 2: PM cradle-to-cradle system, including virgin production, recycling, and recycled-content loops (X w/w% recycled content), figure based on (A. Accardo, Costantino, & Spessa, 2024).

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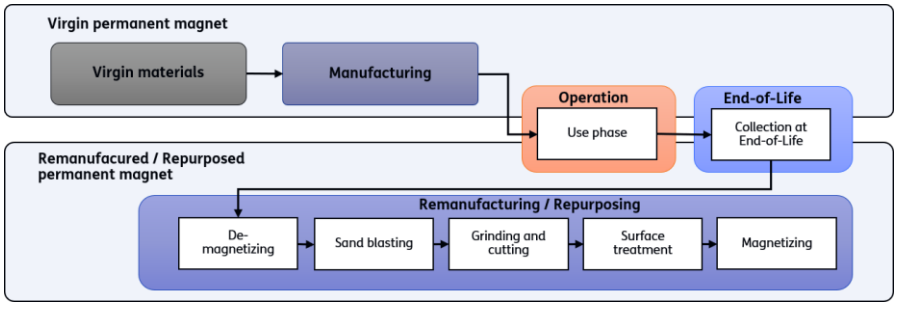


Figure 3: PM cradle-to-cradle system, including virgin production and remanufacturing or repurposing

2.2 PM volumes in the Dutch offshore fleet

To ground this scope in a realistic order of magnitude, the study first quantifies the expected volume of NdFeB magnet material entering and leaving service in the Dutch offshore wind fleet. This establishes the scale of REE material flow that the subsequent life cycle inventory and scenario analysis are intended to address. This study quantifies only the PM volume in the generator; PMs used elsewhere in the wind turbine, such as in electric motors for pitch and yaw systems or for mounting components to the tower (e.g. ladders and platforms), are excluded. The estimate underlying Figure 1 was developed from an asset-level dataset of installed, under-construction, consented, and planned Dutch offshore wind farms in the North Sea and IJsselmeer for the period 1992–2046. For each wind farm, the dataset combines commissioning year, expected turbine lifetime, installed capacity, turbine model, number of turbines, rated turbine capacity, and generator type. Historical and project-specific turbine data were derived from the 4C Offshore database (4COffshore, 2026) and supplemented with publicly available technical data sheet for Vestas (Allekotte & Garrett, 2024). For future projects where the final turbine model is not yet fixed, turbine capacity was estimated from the Dutch offshore wind roadmap and expected market development towards larger turbines, with rated capacity assumed to increase up to 22 MW.

Where turbine-specific data on PM volume in the generator was unavailable, PM mass was estimated from the rated turbine capacity using generator-type-specific PM mass factors. The applied factors were 650 kg/MW for direct-drive (PMSG), 160 kg/MW for medium-speed geared generators (MSPMGs), and 80 kg/MW for high-speed geared PM generators (HSPMG) (Viebahn, Arnold, Ritthoff, & Teubler, 2014). Turbines equipped with doubly fed induction generators (DFIG) or other electrically excited generator concepts were assumed to contain no NdFeB permanent magnets. For future wind farms, three generator-mix assumptions were evaluated: all PMSGs, all MSPMGs, and a mixed case with 50% PMSGs and 50% MSPMGs. The NdFeB magnet volume was then converted into REE content for Nd and Dy using the assumed magnet composition applied consistently in the life cycle inventory. EoL timing was estimated by adding the assumed operational lifetime to the commissioning year. The operational lifetime was assumed to increase for future offshore turbines, reaching 40 years for turbines installed in 2046, which results in an estimated EoL year of 2086 for the latest installations included in the dataset.

The estimate represents a technical material potential rather than a forecast of actual recycled material supply. It assumes that all PMs present in turbines reaching EoL become available for recovery, but it does not model collection efficiencies,

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dismantling losses, export for reuse, premature repowering, lifetime extension beyond the assumed design life, or project-specific changes in final turbine selection. The results should therefore be interpreted as indicative cumulative material volumes under defined deployment, lifetime, and generator-mix assumptions rather than as precise annual recovery volumes.

2.3 Life cycle inventory analysis

2.3.1 Extraction and production

The life cycle inventory developed in this study covers the PM material chain only from raw ore to a finished, coated, sintered NdFeB magnet. The remaining wind turbine components (structural steel, copper windings, tower, blades, bedplate) and the operation & maintenance phase are taken from an existing external turbine LCA model (Gaertner, Rinker, Sethuraman, & e.o., 2020). Three PM production routes were modeled in this study:

M0: Virgin magnet production. The full primary chain includes mining and beneficiation of REE ore, followed by acid roasting, leaching and solvent extraction to separate Pr-Nd and Dy fractions, electrolytic/calciothermic reduction to metal, and finally alloying and sintering into a finished magnet. The application of a protective surface treatment against oxidation and corrosion is modeled as a separate coating stage (see 2.3.5 and Supporting Information, SI).

M1: Short-loop (magnet-to-magnet) recycling. Collected EoL NdFeB magnets are directly reprocessed into new sintered magnets, replacing nearly all virgin material inputs while retaining the same sintering/coating steps as M0 (see 2.3.5 and SI).

M2: Long-loop recycling. EoL magnet scrap is ground, chemically dissolved, and separated back into individual REEs, which re-enter the same reduction and sintering steps as M0 recovering elemental feedstock rather than magnet powder (see 2.3.5 and SI).

These three routes are blended at varying post-consumer content shares (2%, 25%, 100%) to construct the scenarios set used later in this study (Section 2.4), directly linking the production-stage inventory to the EoL pathways.

2.3.2 Assembling, commissioning and installation

Generator assembly involves mounting the PMs in the stator, corrosion protection, and cooling system integration, followed by magnetization and electrical, mechanical and safety testing prior to commissioning. This stage is not modeled in detail in this study; its contribution is taken as an aggregated GWP value from the external turbine LCA model (Gaertner, Rinker, Sethuraman, & e.o., 2020) into which the magnet inventory of this study is embedded.

2.3.3 Operation & maintenance (O&M) and replacement

O&M covers routine inspection and servicing of the generator, including vibration analysis, electrical testing, and checks for demagnetization, corrosion, and coating damage over the turbine's operational lifetime. This stage is taken as an aggregated GWP contribution from the external turbine LCA model rather than modeled at the flow level in this study (Gaertner, Rinker, Sethuraman, & e.o., 2020). For modern 15 MW offshore turbines, O&M impacts are largely comparable across scenarios, with

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the main differences driven by generator and drivetrain configuration. Direct-drive PMSG concepts consistently show marginally lower O&M costs and higher availability than medium-speed geared PMSG concepts, although the cost gap is substantially smaller than previously reported for earlier turbine generations. Direct-drive turbines achieved 1.6-5.8% lower O&M costs and 0.5-1.7% higher availability than medium-speed geared turbines, with the largest benefit observed at sites with reduced accessibility (Donnelly, Anderson, & Carroll, 2024). For the life-extension scenario, it is assumed that extending the service life of the PMs in a wind turbine generator by 30 years increases generator-related O&M requirements by approximately 10–20%. This assumed increase is attributed mainly to ageing of bearings, insulation and auxiliary systems, while the PMs themselves are assumed to exhibit only a very minor degree of degradation under normal operating conditions. Maintenance includes the replacement of defective components during turbine operation. Replacement magnets are assumed to be produced from virgin materials (M0), except in the reuse (Scenario C) and remanufacturing (Scenario D) scenarios, where reused and remanufactured magnets are used, respectively.

2.3.4 Decommissioning

Decommissioning covers lifting, on-site disassembly, preprocessing, and transport/logistics at end of turbine life, during which the drive train is disassembled and the magnets become available for reuse or recycling. This stage's contribution is likewise taken as an aggregated GWP value from the external turbine LCA model. The subsequent PM-specific reuse and recycling routes (short-loop/long-loop) are modeled in detail in this study and are addressed in Section 2.3.5.

2.3.5 EoL

At EoL, wind turbine generators and their PMs may follow several circular pathways: reuse, in which the magnet is retained intact for use in the same or another wind turbine; remanufacturing, in which the magnet is demagnetized, machined, recoated and demagnetized for use in a wind turbine generator; repurposing, in which the same treatment enables use in a different application; and recycling through either a short-loop or long-loop route. Table 3 summarizes the EoL pathways considered in this study. Short-loop (‘direct’) recycling recovers the NdFeB alloy through physical or metallurgical processing, such as hydrogen decrepitation or smelting, preserving its alloy composition and magnetic properties and enabling direct refabrication with minimal chemical treatment. Long-loop (‘chemical’) recycling uses hydro- or pyrometallurgical processes to dissolve the magnet and recover individual rare earth elements as oxides or chlorides for re-entry into the primary supply chain. Although long-loop recycling yields higher-purity rare earth products, it is more energy- and chemical-intensive and generates more waste.

2.3.5.1 Short-loop recycling (M1)

Powder and smelting routes are used for short-loop recycling. In the powder route, scrap magnets are exposed to hydrogen gas (hydrogen decrepitation), which embrittles the alloy along grain boundaries and disintegrates it into a coarse powder, screened to remove coating debris (Yang, et al., 2017). This powder is jet-milled, magnetically aligned, pressed, and sintered (1050-1100 °C) into new magnets. In the smelting route, scrap is melted in an induction furnace, separating REEs (molten metal

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phase) from impurities (slag), and the resulting alloy is cast and reprocessed via powder metallurgy (onfeldt, Rossa, Opelt, afer, & afer, 2025). Recyclability also depends on magnet grade: high-grade magnets (e.g. from state-of-the-art wind turbines) currently have limited short-loop recyclability due to complex alloy compositions, while lower-grade PMs can be fully recycled (Mishra, et al., 2023).

2.3.5.2 Long-loop recycling (M2)

In the long-loop recycling, magnet scrap is size-reduced through shredding, crushing and grinding, and then leached with strong acids to dissolve the REEs. REEs are then separated and purified via solvent extraction, precipitation, or ion exchange, yielding high-purity REE oxides or metals, with remaining waste streams treated before discharge (Papagianni, Moschovi, Sakkas, Chalaris, & Yakoumis, 2022). Recycled magnet material alone cannot meet projected REE demand at scale so long-loop recycling is expected to remain paired with primary production for the foreseeable future (Böhm, 2023).

Landfilling and incineration are the least favourable EoL options for PMs. Landfilling results in permanent loss of REE content and is increasingly discouraged under EU waste policy (e.g. the Landfill Directive (EU, 1999) and WEEE Directive (EU, 2012), though not banned outright for magnets specifically. Incineration does not destroy the REE content itself, but where magnets are incinerated as part of mixed waste streams, REEs become diluted and dispersed within the resulting ash or slag, making them difficult and costly to recover, while incineration of any organic coatings or binders can release additional emissions.

2.4 Scenarios development

This study developed multiple scenarios to discuss multiple EoL routes as described in the previous sections. An overview of developed scenarios can be found in Table 3.

2.4.1 Baseline (Scenario A)

Baseline scenario A is the reference case: 15 MW direct-drive (PMSG) turbine (Gaertner, Rinker, Sethuraman, & e.o., 2020) using NdFeB magnets produced entirely from virgin material (M0), mined, processed and manufactured in China, with no post-consumer content.

2.4.2 Reduction (Scenario B)

Identical magnet assumptions to the baseline (M0, 0% recycled content), but with a MSPMG turbine design in place of PMSG isolating the effect of turbine architecture rather than magnet sourcing. This scenario represents Reduction (R2 on the R-ladder) through a reduction in PM volume compared with the PMSG baseline.

2.4.3 Reuse (Scenario C)

The magnet (M0) is reused (R3) intact across two operational lifetimes (modular design), rather than being reprocessed. This avoids one full production cycle's worth of virgin material and EoL burden, but does not involve short-loop or long-loop

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recycling. Scenario C is modelled across two consecutive wind turbine life cycles. The first life cycle is identical to Scenario A, except for the end-of-life treatment of the magnets, which are recovered for reuse in the second life cycle. The second life cycle therefore uses the reused magnets, avoiding the production of a new set of virgin magnets.

2.5 Remanufacturing (Scenario D)

The magnet (M0) is recovered and refurbished through recoating and remagnetization. It is then either reused in a new wind turbine generator through remanufacturing (R6) or repurposed (R7) for a different application. For this study, the remanufactured PM is assumed to remain in service in a new wind turbine for a second operational period of equal duration. Scenario Dis modelled across two consecutive wind turbine life cycles. The first life cycle is identical to Scenario A, except for the end-of-life treatment of the magnets, which are recovered for remanufacturing in the second life cycle. The second life cycle therefore uses the remanufactured magnets, avoiding the production of a new set of virgin magnets.

2.5.1 Recycling (Scenario E&F)

Recycling is evaluated via the two routes introduced in Section 2.2.5, each modeled in this study at three post-consumer content levels (2%, 25%, 100%). Short-loop (E1-E3) recycling uses the M1 dataset: the alloy structure and magnetic properties of collected magnets are retained through physical/metallurgical reprocessing (hydrogen decrepitation or smelting; Section 2.2.5.2). Long-loop recycling (F1-F3) uses the M2 dataset: collected magnets are fully broken down into elemental REEs before new magnets are produced, following pre-treatment (cleaning, de-coating, demagnetizing), leaching (acid/alkali dissolution), separation and purification (precipitation, solvent extraction, ion exchange, or double-salt precipitation), reduction, and manufacturing into new NdFeB alloy. This route recovers high-purity metals suitable even for mixed or degraded scrap, but requires more chemicals, energy, and processing steps than short-loop, resulting in higher environmental impact and waste generation.

Table 3: Overview of EoL scenarios.

Scenario	Name	Description	PM used	Recycled content
A	Baseline scenario (virgin PM)	15 MW PMSG turbine NdFeB magnets | No post consumer content Magnet mining, processing, manufacturing 100% in China	M0	0%
B	Reduction	15 MW MSPMG turbine NdFeB magnets | No post consumer content	M0	0%
C	Reuse	Reuse modular NdFeB magnets (2x operational life) 15 MW PMSG	M0 (2× lifetime)	-
D	Remanufacture	Remanufacture refurbished modular NdFeB magnets (2x operational life) | 15 MW PMSG	M0 (2× lifetime)	-
E1	Post consumer content low (2%), short-loop	NdFeB magnets with 2% post consumer content 15 MW PMSG | Short-loop	M0 + M1 blend	2%

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E2	Post consumer content high (25%), short-loop	NdFeB magnets with 25% post consumer content 15 MW PMSG | Short-loop	M0 + M1 blend	25%
E3	Post consumer content full (100%), short-loop	NdFeB magnets with 100% post consumer content 15 MW PMSG | Short-loop	M1	100%
F1	Post consumer content, Long-loop (2%)	NdFeB magnets with 2% post consumer content 15 MW PMSG | Long-loop	M0 + M2 blend	2%
F2	Post consumer content, Long-loop (25%)	NdFeB magnets with 25% post consumer content 15 MW PMSG | Long-loop	M0 + M2 blend	25%
F3	Post consumer content, Long-loop (100%)	NdFeB magnets with 100% post consumer content 15 MW PMSG | Long-loop	M2	100%

2.6 Impact assessment

Environmental impact was assessed using a single-issue indicator global warming potential (GWP) over a 100-year horizon (Masson-Delmotte, et al., 2021). The impacts are calculated with the IPCC 2021 method (v1.03) (Guidance on IPCC Methods, sd) and expressed in kg CO_2-eq. Life cycle inventory data were modeled in Activity Browser application version 2.11.2. using the ecoinvent 3.9.1 database (allocation, cut-off by classification, unit-process level) (Wernet, et al., 2016). Infrastructure processes and long-term emissions were excluded from the calculation.

3 Results

3.1 The volumes of PMs in wind turbines

Figure 4 shows that the cumulative volume of NdFeB magnet material in generators in Dutch offshore wind farms installed between 1992 and 2046 is estimated to range from 8.2 to 26.3 kt, corresponding to a REE content of 2.3–9.2 kt for Nd and Dy. The variation between the scenarios is driven primarily by the assumed future generator mix, with PMSGs resulting in the highest material demand and MSPMGs resulting in the lowest. The mixed-generator scenario, in which 50% of new turbines are assumed to use PMSGs and 50% MSPMGs, results in an estimated total NdFeB magnet volume of 17 kt and a REE content of 5.8 kt for Nd and Dy. Based on the assumed operational lifetimes, the estimated EoL years for these magnets extend from 2036 to 2086. These volumes indicate that Dutch offshore wind farms could become a substantial future source of secondary NdFeB magnet material and associated REEs. However, the values should be interpreted as indicative technical material potentials rather than deterministic forecasts of recoverable supply, as actual availability will depend on decommissioning timing, reuse, collection efficiency, dismantling losses, and the development of recycling infrastructure.

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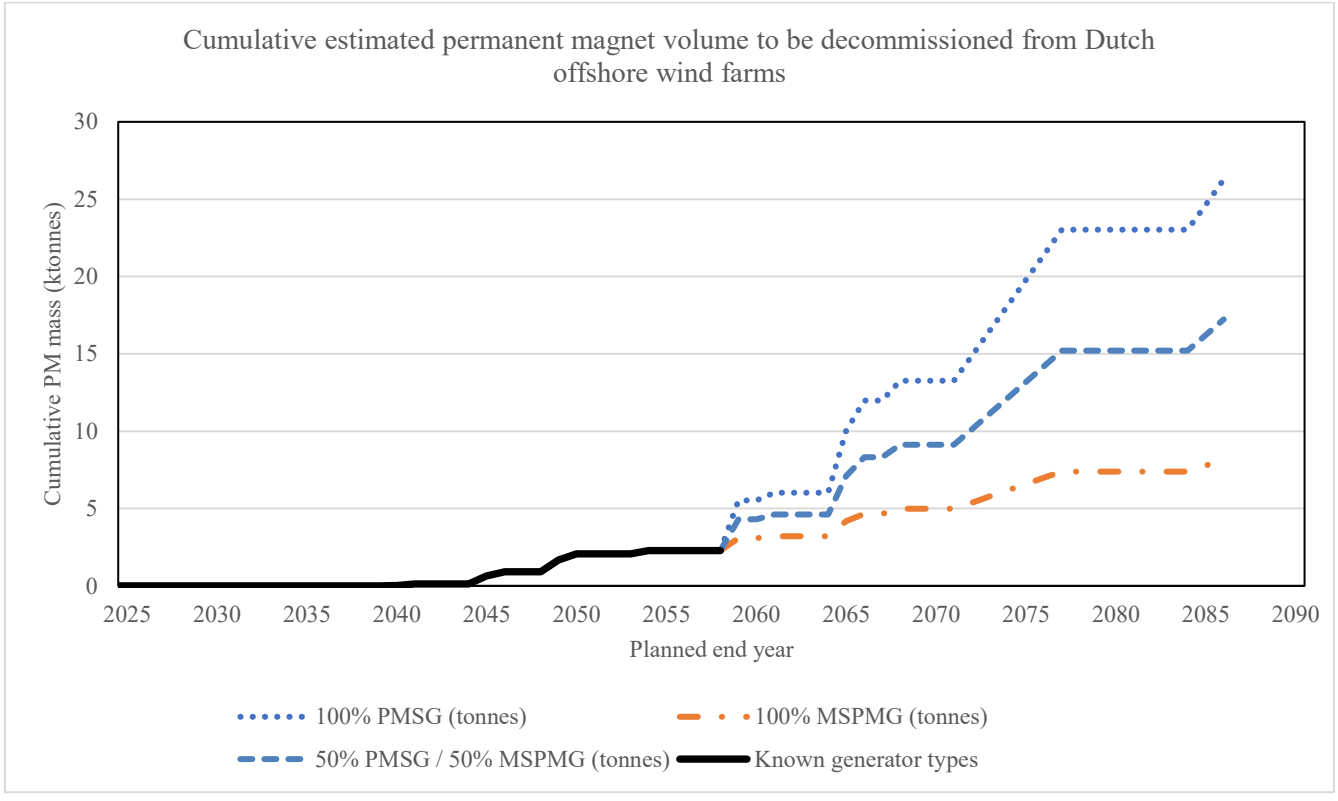


Figure 3: Estimated cumulative PM volume to be decommissioned from Dutch wind farms installed offshore and in the IJsselmeer between 1992 and 2046, with estimated EoL years in the period 2036–2086.

3.2 Environmental impacts of electricity generation from wind turbines

Across all scenarios, extraction and production remains the dominant contributor to total GWP, accounting for 72-76% of total turbine life cycle impact (5.18-5.46 g CO_2-eq/kWh), while installation and decommissioning are minor and comparable across scenarios (0.23-0.24 and 0.15 g CO_2-eq/kWh, respectively). Scenario B (MSPMGs) shows a 5.0% lower impact from extraction/production than the direct-drive baseline. The impact offset by a 19% higher O&M and replacement contribution (2.12 vs. 1.78 g CO_2-eq/kWh) from the greater maintenance demand of geared MSPMG over direct-drive PMSG types (7.25 g CO_2-eq/kWh) (Figure 4).

Introducing recycled PM content reduces the extraction/production-related burden: short-loop recycling (E3, 100% post-consumer content) lowers extraction/production impact by 3.54% relative to the virgin-magnet baseline (5.46 g CO_2-eq/kWh), whereas long-loop recycling (F3, 100%) achieves only a 1.3% reduction (5.39 g CO_2-eq/kWh) despite the same recycled-content share (Section 2.3.5). Short-loop recycling is a more climate-effective route at equal recycled-content share. All scenarios show a net negative (credit-generating) EoL contribution (-0.46 to -0. 54 g CO_2-eq/kWh) from avoided virgin-material production. Overall, total life cycle impact varies by less than 4% across all evaluated scenarios (6.94-7.22 g CO_2-

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eq/kWh) (Figure 4). The results show that recycled content and drivetrain choice modulate do not fundamentally alter the extraction/production-dominated impact profile of NdFeB-based wind turbine generators.

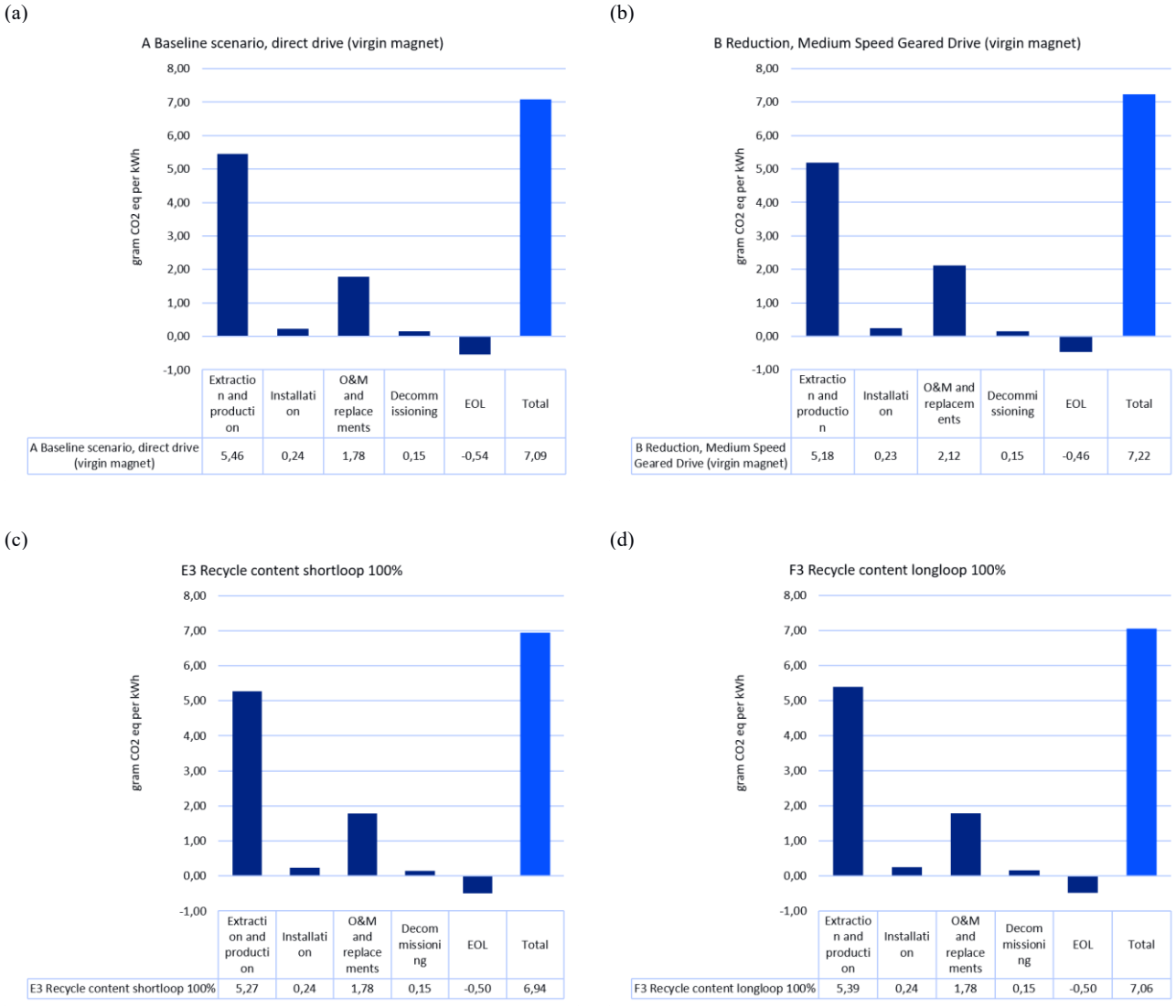


Figure 4: Life cycle GWP contribution (g CO_2-eq per kWh) by life cycle stage, for (a) baseline virgin-magnet, direct-drive scenario (A); (b) reduction scenario with medium-speed geared drive (B); (c) 100% short-loop recycled magnet content (E3); and (d) 100% long-loop recycled magnet content (F3). Extraction and production dominate total impact in all scenarios, while EoL provides a net credit (negative contribution) through avoided virgin-material production.

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3.3 Environmental impacts of PMs

At the magnet level, expressed per kilogram of finished NdFeB magnet, the choice of production route has a substantially larger effect than is visible when impacts are normalized per kWh of energy delivered (Table 4). Virgin magnet production (M0) carries a GWP of 66.01 kg CO_2-eq/kg, reflecting the cumulative burden of ore mining, REE separation, and metal reduction (Section 2.3.1). Long-loop recycling (M2) reduces this to 48.49 kg CO_2-eq/kg, a 26.5% reduction relative to virgin production. Short-loop recycling (M1) achieves a considerably larger reduction, to 18.18 kg CO_2-eq/kg, a 72.5% decrease relative to virgin production and more than double the reduction achieved by the long-loop route, by preserving the existing alloy structure and avoiding re-separation of individual REEs. This value is also consistent with, and marginally below, an independent external reference for 1 kg of magnet (18.82 kg CO_2-eq/kg (Dighe, Bansal, Jansen, Mijle Meijer, & Breuer, 2025)). These PM-level results indicate that short-loop recycling is the most climate-effective route for reducing the material footprint of NdFeB magnets, and that its benefit is considerably underrepresented when assessed only at the turbine or per-kWh level, where non-PM life cycle stages dilute the visible effect of PM-level interventions.

For the Dutch offshore wind case, applying scenarios short-loop recycling (M1) and long-loop recycling (M2) instead of the virgin-magnet baseline (M0) would reduce cumulative GWP by 824 and 302 kt CO_2-eq, respectively, for the assumed 50%/50% generator mix over the period 2040–2086 (Figure 5). If only PMSG-type generators are used for new turbines, the corresponding emission reductions would increase to 1257 and 460 kt CO_2-eq, respectively.

Table 4: Environmental impacts of per kg of finished magnet production.

Dataset	GWP (kg CO_2-eq / kg magnet)	vs. virgin (M0)
M0: Virgin magnet production	66.01	baseline
M1: Short-loop (magnet-to-magnet) recycling	18.18	-72,5%
M2: Long-loop recycling	48.49	-26,5%
Reference: 1 kg magnet (Dighe, Bansal, Jansen, Mijle Meijer, & Breuer, 2025)	18.82	(benchmark, close to M1)

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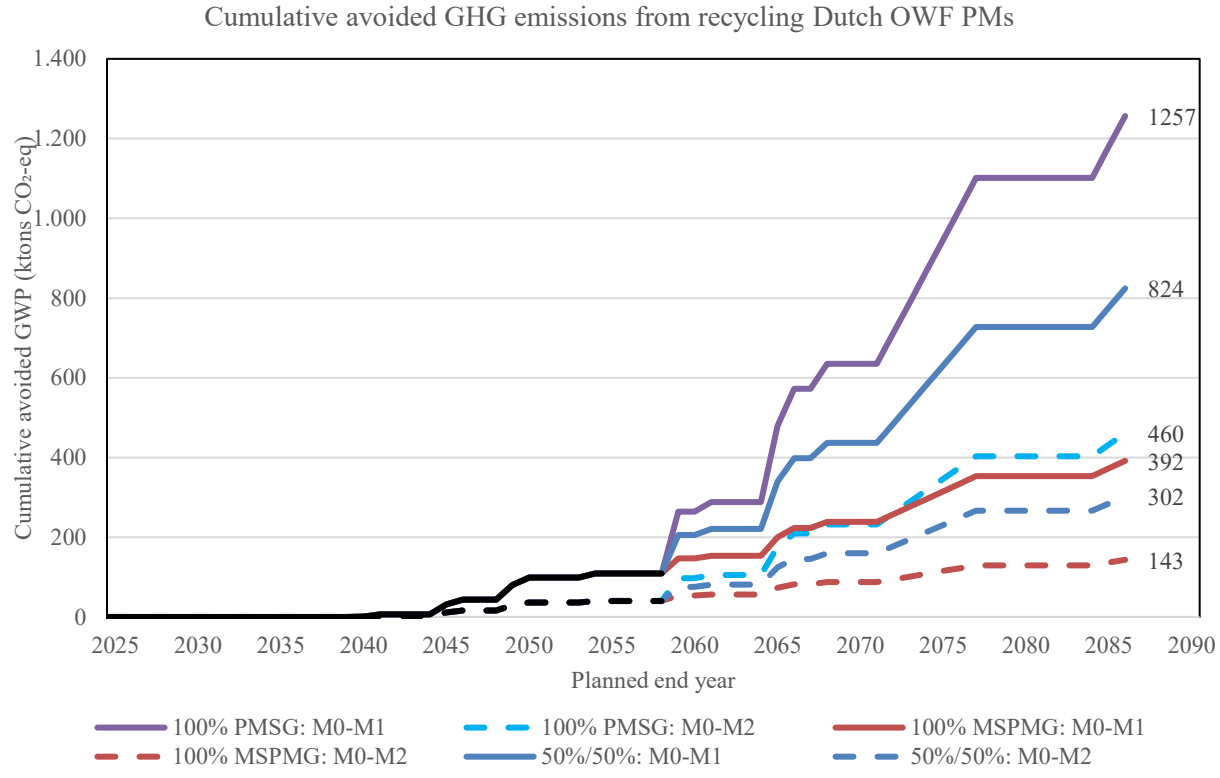
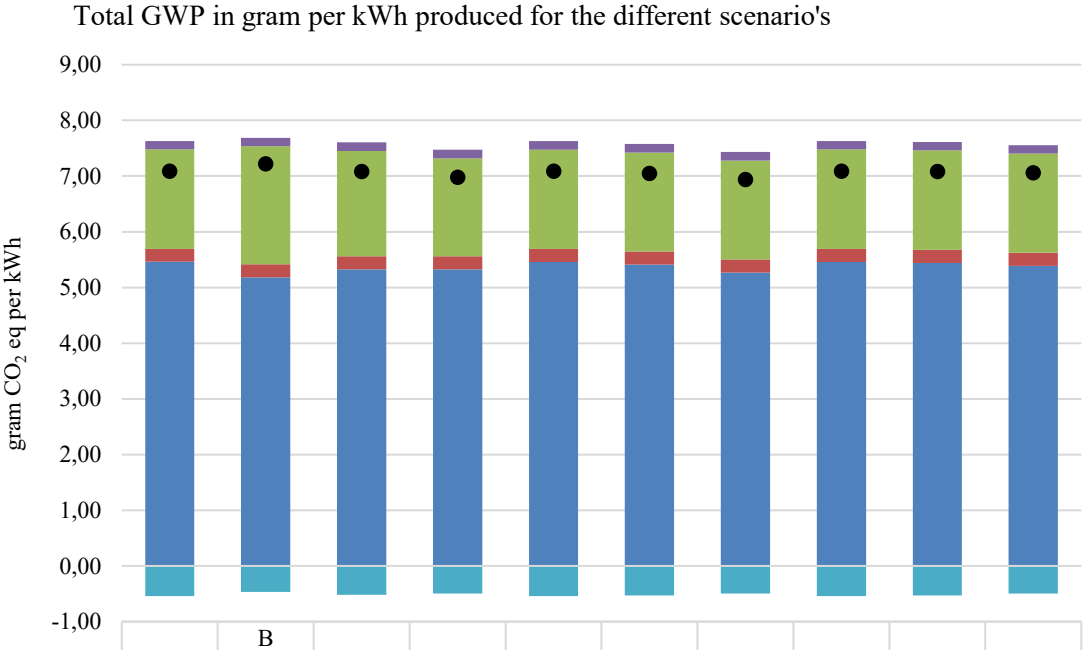


Figure 5: Cumulative avoided GWP from applying short-loop recycling (M1) and long-loop recycling (M2) instead of virgin magnet production (M0) to permanent magnet material reaching end-of-life in Dutch offshore wind farms. The three generator-mix trajectories follow the assumptions used in Figure 4, while the avoided GWP factors are based on the magnet-level GWP differences from Table 4: M0–M1 for short-loop recycling and M0–M2 for long-loop recycling.

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	A Baseline scenario, direct drive (virgin magnet)	B Reduction, Medium Speed Geared Drive (virgin magnet)	C Reuse of magnet EOL	D Remanufacture of magnet EOL	E1 Recycle content shortloop 2%	E2 Recycle content shortloop 25%	E3 Recycle content shortloop 100%	F1 Recycle content longloop 2%	F2 Recycle content longloop 25%	F3 Recycle content longloop 100%
EOL	-0,54	-0,46	-0,52	-0,50	-0,54	-0,53	-0,50	-0,54	-0,53	-0,50
Decommissioning	0,15	0,15	0,15	0,15	0,15	0,15	0,15	0,15	0,15	0,15
O&M and replacements	1,78	2,12	1,89	1,76	1,78	1,78	1,78	1,78	1,78	1,78
Installation	0,24	0,23	0,24	0,24	0,24	0,24	0,24	0,24	0,24	0,24
Extraction and production	5,46	5,18	5,33	5,33	5,46	5,41	5,27	5,46	5,44	5,39
Total	7,09	7,22	7,09	6,98	7,09	7,05	6,94	7,09	7,08	7,06

Figure 6: Environmental impacts of per kWh of electricity produced by the wind turbines under multiple scenarios.

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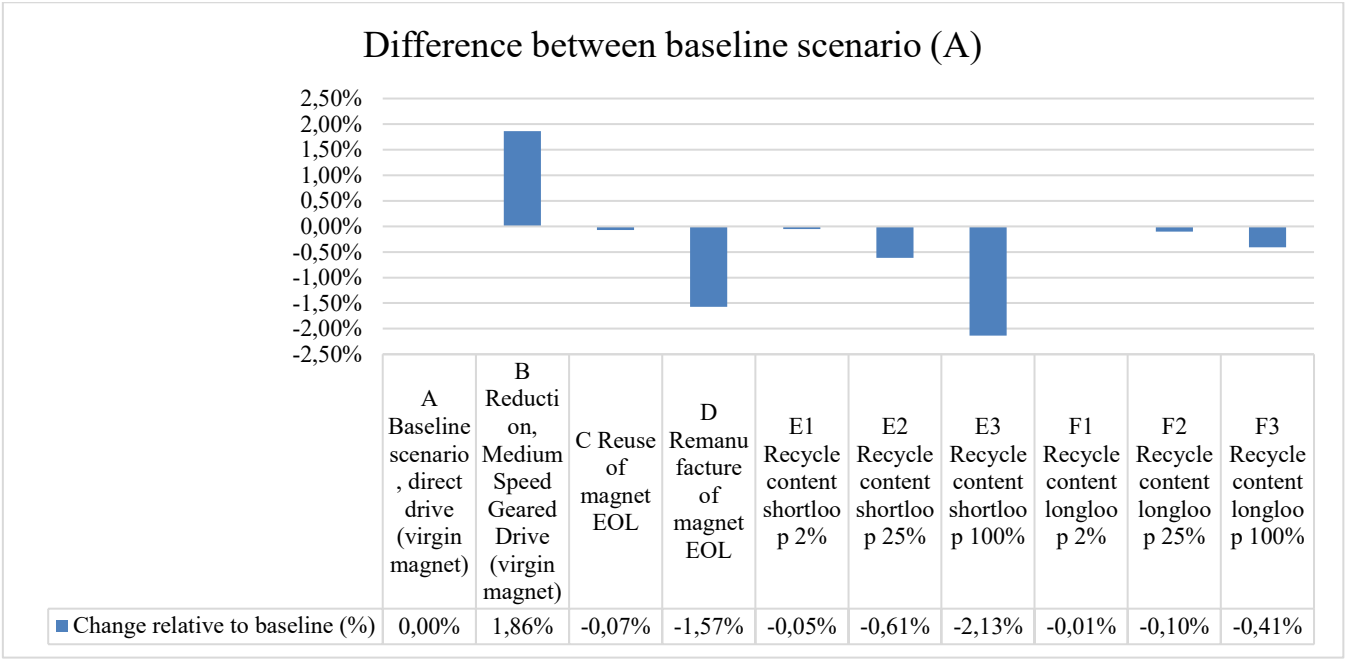


Figure 7: Scenario differences in life cycle GWP relative to baseline Scenario A. Negative values indicate lower climate impacts than the baseline, whereas positive values indicate higher impacts.

3.4 Comparison of life cycle climate impacts across scenarios

The total environmental impacts across all evaluated scenarios range from 6.94 to 7.22 g CO_2-eq/kWh (Figure 6). Relative to Scenario A, the scenarios vary by up to +1.9% for Reduction Scenario B and −2.1% for short-loop Scenario E3 (Figure 7). Extraction and production is the dominant contributor in every scenario, accounting for 72-77% of total impact (5.18-5.48 g CO_2-eq/kWh), consistent with the manufacturing-stage dominance reported, where raw material production typically contributes 75-98% of cumulative life cycle impacts (Li, Mogollón, Tukker, & Steubing, 2022). O&M and replacements form the second-largest contributor (23-29% of total), followed by installation (3.2-3.4%) and decommissioning (2.1-2.2%), while EoL provides a net credit of -7.7 to -9.0% of total impact through avoided virgin material production.

Averaged over two consecutive life cycles, reuse (Scenario C) results in a total GWP of 7.12 g CO_2-eq/kWh, approximately 0.07% below the virgin-magnet baseline (Scenario A; 7.12 g CO_2-eq/kWh). Remanufacturing (Scenario D) achieves 7.01 g CO_2-eq/kWh, corresponding to a reduction of 1.57%. In Scenario C, the savings from avoiding virgin magnet production in the second life cycle are almost entirely offset by higher O&M and replacement impacts and a smaller EoL credit. Scenario D achieves a greater net reduction, primarily because its modelled O&M and replacement burden is lower than that of reuse.

Recycled PM content scenarios E (short-loop) and F (long-loop) each show total impact declining with increasing post-consumer content. Scenario E at its highest recycled-content level achieves the lowest overall impact (E3, ~6.94 g CO_2-eq/kWh, ~2% below baseline A). short-loop recycled content is the only one that reduces total impact meaningfully below the virgin-PM baseline, while generator type choice and simple reuse do not. Within the short-loop cluster (E1-E3), total impact

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declines from ~7.09g CO_2-eq/kWh at 2% recycled content to ~7.05 at 25% and ~6.94 at 100%, a cumulative reduction of ~2% over the full content range (Figure 6). This reduction is driven almost entirely by declining extraction/production impact (from ~5.46 to ~5.41 to ~5.27 g CO_2-eq/kWh), as recycled material progressively displaces virgin feedstock, while O&M, installation, decommissioning, and EoL contributions remain approximately constant across E1-E3. A similar but considerably smaller trend is observed within the long-loop cluster (F1-F3): total impact declines from ~7.09 to ~7.08 to ~7.069 g CO_2-eq/kWh, a cumulative reduction of <1%, with extraction/production impact declining from ~5.46 to ~5.44 to ~5.39 g CO_2-eq/kWh over the same content range.

At equal recycled content, the short-loop route consistently outperforms the long-loop route (Figure 5). E1 and F1 (2% content) are essentially identical (~7.09g CO_2-eq/kWh for both), while the routes diverge as recycled content increases. This divergence is consistent with the greater processing intensity of REE-level re-separation required by the long-loop route relative to the alloy-preserving short-loop route (Section 2.3.1) and indicates that the climate benefit of recycled magnet content depends not only on the recycled share achieved but, more strongly, on which recycling route supplies that content. Potential environmental impact benefits of R strategies

Reuse (Scenario C) and remanufacturing (Scenario D) reduce virgin magnet demand by retaining magnets for a second operational life. Averaged over both life cycles, their reductions in total turbine GWP are 0.07% and 1.57%, respectively, relative to Scenario A. The greater benefit of remanufacturing primarily reflects its lower modelled O&M and replacement burden compared with reuse. These results illustrate that the climate benefits of strategies higher on the R-ladder depend on both avoided production and the maintenance, replacement and EoL impacts over successive life cycles. Short-loop recycling with 100% recycled content (E3) achieves the largest reduction among the evaluated scenarios, at approximately 2%. This result appears to contradict the conventional R-ladder, which prioritizes higher-value strategies such as reduction (R2), reuse (R3) and remanufacture (R6) over recycling (R8) and recovery (R9) (Potting, Hekkert, M., & Hanemaaijer, 2017). However, the R-ladder reflects the general preservation of product and material value rather than environmental performance under all specific system conditions. In the reuse scenario assessed here, avoided production impacts are largely offset by the greater O&M burden associated with a second operational lifetime. By contrast, recycled content reduces production impacts without a comparable increase in O&M.

The benefit of recycling becomes more pronounced at the PM material level. Short-loop recycling (M1) reduces GWP by approximately 73% relative to virgin PM production, compared with approximately 27% for long-loop recycling (M2). The turbine-level results therefore substantially understate the PM-level benefit because the effect is diluted by other turbine life-cycle stages. Reuse was not evaluated separately at the material level, and its turbine-level result is based on one reuse configuration with limited O&M data. Consequently, the findings should not be interpreted as a general rejection of the R-ladder. Rather, they show that short-loop recycling provides the most robust environmental benefit under the assumptions and system boundaries applied in this study, while the benefit of reuse remains more uncertain.

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4 Discussion

4.1 The uncertainty of volumes of PMs in wind turbines

The estimated volumes of PMs in Dutch offshore wind turbines are subject to several important uncertainties. First, the timing of EoL may deviate from the assumed operational lifetimes. Wind turbines and generators may reach premature EoL, for example due to technical failure, major component degradation, lightning strike damage, or economic repowering decisions, which would bring PM availability forward in time. Conversely, lifetime extension through improved condition monitoring, refurbishment, or continued operation beyond the design lifetime would not necessarily change the total installed amount of PM material, but would shift the moment at which this material becomes available for reuse or recycling to later years. These timing uncertainties are particularly relevant for assessing annual recovery volumes, recycling infrastructure needs, and the timing of secondary REE supply.

Second, the amount of PM material used per MW may differ from the assumptions applied in this study. Future developments in more efficient generator designs, alternative drivetrain concepts, externally excited generator systems, or REE-lean magnet technologies could reduce or partly replace the use of NdFeB PM material. This may include hybrid excitation concepts combining PMs with electromagnetic excitation, superconducting generators that could strongly reduce or eliminate PM demand, and flux-concentrating topologies that use magnetic circuit design to improve effective magnet utilization. At the same time, further upscaling of turbine capacity may increase the absolute PM volume per turbine, particularly if structural constraints lead to larger air gaps or if bearing limitations, mechanical stiffness requirements, and rotor-stator spacing must be compensated by higher magnet loading. The assumed balance between direct-drive and medium-speed geared PM generator concepts therefore has a strong influence on total PM demand and on the future availability of recoverable magnet material.

Finally, the deployment pathway itself is uncertain. This study assumes that the Dutch offshore wind ambition of approximately 70 GW by 2050 is realized, consistent with national climate-neutrality objectives and future energy-system scenarios that require large-scale electrification and green hydrogen production to meet long-term energy demand. Any deviation from this assumed deployment trajectory, either through delays, lower installed capacity, accelerated build-out, or changes in the final project pipeline, will directly affect the estimated demand for new PM material and the future EoL volumes available for circular pathways. The results should therefore be interpreted as scenario-based estimates rather than deterministic forecasts of actual magnet recovery volumes.

4.2 PM industry and recycling solutions

Our results show that short-loop recycling offers greater environmental benefits than long-loop recycling. However, no single recycling route offers a complete solution for the diverse material flow of EoL NdFeB magnets. Short-loop recycling directly reuses the NdFeB alloy, in powder or melt form, substantially reducing the energy required relative to primary production (Jin, Afiuny, Dove, Kumar, & Sutherland, 2018). It retains the original alloy composition and microstructure; however, it introduces variability in output quality when applied to a heterogeneous EoL PM stream (Kozak, Pickering, Awais, & Mahendran, 2025),

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and is therefore best suited to simpler PM grades where precise composition control is less critical, or to homogeneous EoL batches such as production scrap and rejects. Long-loop recycling is a more established process, already used alongside primary REE production, and reduces the magnet to its constituent elements, enabling use in high-grade PMs without disrupting standard manufacturing. Even though these hydrometallurgical processes are robust and safe, their chemical use has an environmental impact (Binnemans, et al., 2013). Emerging electrified leaching and separation technologies aim to reduce this chemical burden, but remain at low technology readiness level (Venkatesan, Sietsma, & Yang, 2025), (Zhijie, 2022).

Given that current recycling capacity cannot meet projected REE demand (Section 3.1), primary and secondary production will need to be combined for the foreseeable future. A hybrid approach, blending virgin alloy with a controlled share of recycled content, is generally considered the most viable path for bulk NdFeB PM manufacturing, as it can offset the compositional variability of recycled input while meeting the magnetic performance requirements of demanding applications such as wind energy and automotive drivetrains (CEPS, 2023). This is consistent with the intermediate recycled-content scenarios evaluated in this study (E1/E2, F1/F2), where partial substitution reduces impact without requiring a fully recycled feedstock. As hybrid recycling routes mature and approach cost parity with imported virgin rare-earth feedstocks, they are expected to offer a more viable pathway towards a sustainable domestic magnet manufacturing industry in Europe than fully recycled production alone, which is presently constrained by the limited availability of EoL material and cannot yet satisfy industrial-scale demand.

Realizing these environmental benefits at scale depends on a set of technical, economic, regulatory, and strategic challenges. Technically, demagnetization during disassembly, material purity, and magnet grade compatibility remain limiting factors: despite its larger environmental benefit, short-loop recycling is currently restricted to simpler grades or homogeneous scrap batches, while the complex, high-grade magnets typical of modern wind turbines are presently better suited to long-loop recycling or remain unrecycled (Yang, et al., 2017). Economically, high investment costs for recycling infrastructure, competitive pricing from virgin scrap, and market dominance by China in REE processing constrain the near-term scalability of both routes (Rizos, Righetti, & Kassab, 2024), reinforcing the case for the hybrid approach above rather than reliance on fully recycled feedstock. Regulatory barriers further complicate the transition: EU permitting requirements, the absence of standardized material passports to track the PM grade, chemical composition and postconsumer content through the value chain, and still-evolving critical raw material legislation add friction to establishing consistent EoL pathways (European Parliament and Council, 2024). Strategically, converting the environmental potential quantified in this study into realized reductions will require OEM commitment to design for disassembly and recyclability, timely scale-up of short-loop and long-loop recycling infrastructure, and development of EU-based PM manufacturing capacity to reduce dependence on imported virgin material (CEPS, 2023).

4.3 Mitigating REE supply risks

Beyond recycling, the wind industry and policymakers can pursue complementary strategies to reduce reliance on primary REEs, particularly the heavy REEs dysprosium (Dy) and terbium (Tb), which are the scarcest and most costly given the supply

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concentration described above (IEA, 2025). Materials innovation offers one lever: metallurgical advances such as grain boundary diffusion technology allow magnets to maintain coercivity with a lower Dy/Tb fraction (ZhongwuLiu, JiayiHe, & RajuV.Ramanujan, 2021). Generator design offers a second lever: manufacturers are exploring hybrid drivetrain concepts, such as the medium (MSPMG) and high-speed (HSPMG) geared systems with smaller permanent-magnet generators, as well as hybrid generator topologies, including Hybrid Excited Permanent Magnet Generators (HEPMGs), which combine electromagnetic excitation with permanent magnets to reduce REE PM demand while maintaining high generator performance. Direct-drive high-temperature superconducting (HTS) generators could potentially eliminate the need for PMs in future large wind turbines, although this technology has not yet been commercially deployed (Song, Bergen, Winkler, Wessel, & Brake, 2019).

These technical strategies require policy support to scale in time with projected demand growth: funded R&D for recycling efficiency and REE-free technologies, workforce training for new mining, separation, and recycling facilities, and streamlined permitting for both mining and recycling capacity. Combined with the recycling pathways discussed in Section 4.2 diversifying supply through materials innovation, generator design, and policy support forms a more resilient basis for meeting future REE demand than reliance on any single strategy.

4.4 Wind turbine PM EoL scenarios

Recycling reduces the environmental footprint of NdFeB magnets primarily by avoiding energy-intensive virgin production of REEs. This benefit is far less visible at the turbine (per-kWh) level, where the small relative differences (<5%) reflect the dilution of a magnet-level intervention by non-magnet life cycle stages (Section 3.4) rather than a genuine limit on recycling's effectiveness. This distinction matters for how the results should be used: evaluated in isolation, the per-kWh figures could understate the case for prioritizing short-loop recycling, whereas the magnet-level results make clear that, as long as virgin Nd, Pr, and Dy production continues to dominate the global supply chain, short-loop recycling remains the single most effective lever available for reducing the climate impact of NdFeB magnets specifically, though, as Section 4.2 shows, not yet the only lever needed to reduce total wind turbine impact at scale. Future work extending this analysis to resource depletion, alongside climate change, would strengthen this case further, given the direct relevance of REE resource criticality to the recycling routes evaluated here.

4.5 Limitations and outlooks

This study only uses GWP100 and does not capture trade-offs across other impact categories relevant to PM production and recycling. In particular, long-loop recycling's higher chemical and energy intensity is likely to carry a disproportionately larger burden in categories such as marine and freshwater ecotoxicity, eutrophication, and resource depletion than in climate change alone, given the acid leaching, solvent extraction, and waste treatment steps involved (Mugion, Elmo, Ungaro, Di Pietro, & Martucci, 2025); a global-scale OWE assessment found that while manufacturing dominates climate change impacts (~75-98% of cumulative impact), the relative contribution of different life cycle stages and processes shifts noticeably across

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categories such as marine ecotoxicity and metal depletion (Li, Mogollón, Tukker, & Steubing, 2022). Extending the M0/M1/M2 comparison to a broader impact category set, e.g., ReCiPe or a comparable multi-indicator method, would evaluate whether short-loop recycling's environmental advantage holds, narrows, or reverses outside of climate change, and is a priority for future work.

The inventories used in this study treat the PM itself with limited resolution. Precise alloy compositions, particularly Dy and Tb content, vary substantially by magnet grade and are often proprietary (Alves Dias, Bobba, Carrara, & Plazzotta, 2020),), yet this composition directly determines both the magnet's recyclability via the short-loop route and the REE recovery burden of the long-loop route. The M0/M1/M2 datasets used here represent a single, generic sintered NdFeB composition rather than the grade-specific range actually deployed across the Dutch offshore fleet; as higher-grade, heavy-REE-containing magnets become more common in larger turbines, the recycling routes and associated impacts modeled here may not remain representative. Coating type and thickness, similarly treated as a single input within the M0/M1/M2 sintering dataset rather than a separate, grade- or manufacturer-specific process, is a further simplification worth resolving in future inventory work.

Modern wind turbines use PM grades with compositions that may differ substantially from those applied in first-generation PM generators, including lower Dy contents enabled by advances in alloy design and grain-boundary diffusion. These grade-specific differences may influence coercivity, thermal stability, demagnetization resistance and degradation behavior, and should therefore be evaluated in relation to lifetime electricity production and generator maintenance requirements. For scenarios involving substantial lifetime extension or reuse over a second operational period, future assessments should quantify the effects of PM grade and ageing on production losses, failure risk, inspection frequency and component replacement, rather than assuming unchanged generator performance throughout the extended lifetime.

Rather than conducting a separate parameter-based sensitivity analysis, this study examines key decision-relevant PM variations through predefined scenarios covering generator configuration, recycling route and recycled-content shares (2%, 25% and 100%). Additional parameter variations were not assessed because available data are insufficient to define robust, grade- and process-specific ranges for magnet composition and recovery efficiencies. A comparably sensitivity analysis for this study's magnet-specific results could vary: (i) PM mass per MW (±20% around the 650/160/80 kg/MW, reflecting uncertainty in generator-type-specific magnet loading), (ii) recycled content share within the D and E scenarios beyond the three levels evaluated (2/25/100%), to identify whether impact reduction scales linearly or shows diminishing returns at intermediate content, (iii) magnet grade mix (e.g., higher-Dy vs. lower-Dy grades), given its direct effect on both short-loop recyclability and long-loop REE recovery burden, and (iv) the assumed EoL recycling rate itself, since the 8.2–26 kt volume estimates in Section 3.1 assume magnets are available for recovery but do not model actual collection or recycling rates achieved in practice. Given that extraction/production dominates total impact across all scenarios evaluated (~73-79%), and that PM mass per MW and recycled content share are the two parameters most directly linked to this stage, these two variables would likely yield the largest sensitivity of the parameters listed, and are recommended as the starting point for future sensitivity analysis of this system.

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5 Conclusions

The projected expansion of the Dutch North Sea and IJsselmeer offshore wind fleet towards 2050 will create substantial additional demand for PMs, estimated at 17.2 kt for turbines installed between 2020 and 2046, based on an assumed 50/50 split between PMSG and MSPMG configurations for wind turbine types that have not yet been selected. Supplying this demand from virgin REEs remains exposed to significant geopolitical and market concentration risks, as primary REE mining, separation and processing are concentrated in a limited number of regions. EoL PM recovery therefore represents an important domestic opportunity: decommissioned PM mass from Dutch offshore wind farms is projected to increase from negligible volumes in 2030 to 2.1 kt in 2050, after which the available EoL volume could exceed the sector's projected annual demand for new PM material.

The environmental assessment shows that circular EoL routes can reduce the impact of permanent magnet use, but that the magnitude of this benefit depends strongly on the recycling route and assessment level. At the turbine level, short-loop recycling with 100% post-consumer recycled content (E3) achieved the lowest total impact of all evaluated scenarios, approximately 2% below the virgin-magnet baseline (A). Long-loop recycling at the same recycled-content level (F3) achieved a smaller reduction of less than 1%, while reduce by drivetrain choice for MSPMG (B). reuse (C) and remanufacture (D) showed little or no net benefit in this assessment. For scenario B, the reduced PM mass was offset by a higher O&M burden associated with the geared drivetrain. At the material level, the advantage of short-loop recycling is much clearer: it reduces GWP by approximately 73% compared with virgin PM production, more than double the approximately 27% reduction achieved by long-loop recycling. This reflects the ability of short-loop recycling to preserve the alloy structure, whereas long-loop recycling requires more energy- and chemical-intensive separation of REEs before reprocessing.

Short-loop recycling is therefore the best-performing EoL route quantified in this study, but its applicability is not universal. It is most suitable for simpler PM grades or homogeneous scrap streams, while the complex, high-grade PMs used in modern wind turbines currently have more limited short-loop recyclability. Meeting future Dutch offshore wind PM demand with EoL material will therefore require a differentiated circular strategy: prioritising short-loop recycling where PM grade and batch homogeneity allow; using long-loop recycling for complex, degraded or mixed scrap unsuitable for direct reprocessing; and complementing both with lifetime extension, repair, remanufacturing, reuse and modular magnet design to enable higher-value circular pathways. Achieving this at the scale of projected 2050 decommissioning volumes will require parallel investment in recycling capacity, collection and dismantling systems, material traceability, and permanent magnet design for recyclability. These measures can reduce reliance on virgin REE supply while strengthening circularity and supply resilience in the Dutch offshore wind sector.

Data availability

Source data (in Excel) is provided with the paper.

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Supporting Information

Supporting Information (SI) is provided with the paper.

Author contributions

HvdMM and CL jointly prepared and revised the manuscript. CL, KJ and AB performed the LCA and analyzed the results. HvdMM developed the PM material volume projections and collected and integrated data from the Global Offshore Wind Farms Database and relevant stakeholders.

Competing interests

The contact author has declared that none of the authors has any competing interests.

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Acknowledgements

The authors thank Bakker Magnetics and De Leeuw Metalen for their cooperation and valuable input. This research was supported by TNO's Knowledge Innovation Project (KIP) 2025 and the Re2Mag project, 'Reuse and Repurposing of Wind Turbine Permanent Magnets'.

Financial support

This research has been supported by co-financing by TKI-Energy from the 'Toeslag voor Topconsortia voor Kennis en Innovatie (TKI's)' of the Ministry of Economic Affairs and Climate (grant no. 'TKITOE_ WOZ_2519 _Re2Mag').

Declaration of competing interest

The authors declare no competing financial interest. The authors thank Microsoft Copilot for its assistance in language polishing.

https://doi.org/10.5194/wes-2026-201
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