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Life Cycle Assessment of Neodymium-Iron-Boron Magnet-to-Magnet Recycling for Electric Vehicle Motors

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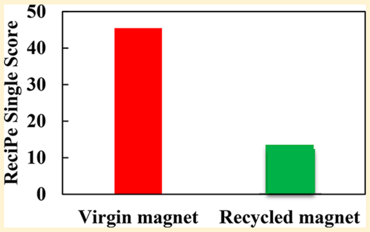
Supporting Information

ABSTRACT: Neodymium-iron-boron (NdFeB) magnets offer the strongest magnetic field per unit volume, and thus, are widely used in clean energy applications such as electric vehicle motors. However, rare earth elements (REEs), which are the key materials for creating NdFeB magnets, have been subject to significant supply uncertainty in the past decade. NdFeB magnet-to-magnet recycling has recently emerged as a promising strategy to mitigate this supply risk. This paper assesses the environmental footprint of NdFeB magnet-to-magnet recycling by directly measuring the environmental inputs and outputs from relevant industries and compares the results with production from "virgin" materials, using life cycle assessments. It was found that magnet-to-magnet recycling lowers environmental impacts by 64−96%, depending on the specific impact categories under investigation. With magnet-to-magnet recycling, key processes that contribute 77−95% of the total impacts were identified to be (1) hydrogen mixing and milling (13−52%), (2) sintering and annealing (6−24%), and (3) electroplating (6−75%). The inputs from industrial sphere that play key roles in creating these impacts were electricity (24−93% of the total impact) and nickel (5−75%) for coating. Therefore, alternative energy sources such as wind and hydroelectric power are suggested to further reduce the overall environmental footprint of NdFeB magnet-to-magnet recycling.



1. INTRODUCTION

Neodymium-iron-boron (NdFeB) magnets have become essential components of electronics, home and medical appliances, electric motors, and defense related applications since their invention in 1983. The acceptance of NdFeB has been driven by their high maximum energy product: up to 52 MGOe (megaGauss Oersteds; 1MGOe ≈ 7.9577 kJ/m^3). This is significantly higher than ferrite (3.5 MGOe), samarium (22 MGOe) and alnico (8 MGOe) based permanent magnets.[1] Accordingly, magnetic assemblies utilizing NdFeB magnets are significantly smaller and/or more powerful than those made using other materials. This is critical in (hybrid) electric vehicles where traction motors must be as compact and lightweight as possible while still providing high torque and power density.[2]

China dominates the NdFeB magnet supply chain, fulfilling over 95% of global NdFeB alloy and powder production.[3] Raw materials for NdFeB, such as the rare earth elements (REEs) neodymium (Nd) and dysprosium (Dy), are also largely mined, separated, and refined in China (80−95%).[3] Chinese export tariffs and other recent policies that restrict the free flow of REEs have created substantial REE and NdFeB magnet supply risk and price volatility. Indeed, REE price uncertainty has caused a number of appliance manufacturers to revert to less efficient ferrite or samarium based magnetic assemblies. Nevertheless, REE demand for NdFeB magnets in clean technologies such as electric vehicles is projected to increase dramatically.[4]

One strategy to mitigate supply risk is through recycling. Conventional pyro or hydrometallurgical methods are energy or chemically intensive as they separate REEs back to pure oxides. An alternative approach is to bulk-recycle all the materials in an NdFeB magnet without separation. This has been termed "magnet-to-magnet recycling". Recently, novel technologies have been developed to process end-of-life (EOL) NdFeB magnets into "new" NdFeB magnets that retain or improve magnetic performance relative to starting materials.[5−7] Magnet-to-magnet recycling has two major advantages: (1) it recovers all the magnet materials and reuses them in new magnets, minimizing waste and resource depletion, and (2) it utilizes mechanical rather than chemical processes, reducing the environmental footprint associated with chemical usage and harmful emissions.

The environmental impacts of NdFeB magnet recycling have not been well studied. The majority of past research has

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focused on life cycle assessments (LCAs) of mining REEs from bastnäsite, monazite, or ion adsorption clays in China. These processes consume chemical acids and solvents and generate hazardous waste.[8−13] Akahori et al. (2014)[14] performed LCA on NdFeB magnet recycling, but their system boundary was confined to REE extraction. Sprecher et al. (2014)[15] performed an LCA for NdFeB magnet recycling, but their work was based on a "hypothetical" lab scale recycling process. Only one study has analyzed commercial-scale recycling to date: Jin et al. (2016).[16] However, this work has several limitations including inadequate reporting of the life cycle inventory (LCI) and a lack of in-depth analysis.

To correct this deficiency, the research described herein provides a comprehensive and reliable LCA on a real, industrial-scale NdFeB magnet-to-magnet recycling process.[5] The material and energy input and output data were obtained from primary measurements, augmented with information from the literature where necessary. With this information, the environmental impacts of NdFeB magnet-to-magnet recycling were assessed and compared with "virgin" production.

2. MATERIALS AND METHODS

LCAs were performed to assess the environmental impact of NdFeB magnet-to-magnet recycling in comparison with their production from "virgin" elements. The goal was to 1) quantify the environmental impacts of producing NdFeB magnets from traditional virgin production routes and compare with magnet-to-magnet recycling, and 2) identify the key processes that contribute most to the environmental footprint of NdFeB magnet-to-magnet recycling to further reduce environmental burden. The geographic region under investigation is the United States. The life cycle impacts of producing 1 kg of NdFeB magnets from virgin materials and 1 kg of equivalent magnets from magnet-to-magnet recycling were compared. Table 1 shows the properties of the two magnet types under comparison. Both are suitable for high temperature applications such as electric vehicles (EVs), offer similar performance, and thus can be used interchangeably.

Table 1. Properties of Virgin and Recycled NdFeB Magnets[16a]

parameters (unit)	virgin magnet	recycled magnet
B_r (T)	1.2	1.3
BHc (kOe)	11.5	12.6
IHc (kOe)	19.0	>20.0
BH_{max} (MGOe)	34.0	40.7
operating temperature (°C)	180	180

[a] B_r stands for residual induction (i.e., flux density) with unit T (tesla; $T = kg{\cdot}A^{-1}{\cdot}s^{-2}$); BHc is coercive field force of flux density with unit kOe (kilo Oersted; 1 kOe ≈ 79 577A·m^{-1}); IHc is coercive field force of polarization with unit kOe; BH_{max} is the maximum energy product with unit MGOe (megaGauss Oersteds; 1MGOe ≈ 7.9577 kJ/m^3).

The starting feedstock material for NdFeB magnet-to-magnet recycling were harvested magnets from EOL hard disk drives (HDDs). HDDs are identified as one of the most feasible ways to collect a substantial amount of NdFeB scrap.[17,18] A small amount of rare-earth rich grain boundary modifier (GBM) alloy was added during the recycling process to enhance the magnetic properties. The material compositions of virgin and recycled magnets under comparison are shown in Table 2. Inductively coupled plasma (ICP) was used to measure each elemental concentration. Besides material composition, microstructure of the magnet is also important in determining magnetic properties.[19] With a novel microstructure formed when using the magnet-to-magnet recycling process, recycled magnets are engineered to offer comparable, or like in this case, better magnetic performance than the virgin magnet, even when the heavy rare earth content (i.e., Dy) of the recycled magnet is 36% lower than the virgin magnet.

Table 2. Material Compositions of Uncoated NdFeB Magnets for EVs (Unit: Weight %)[16]

element	virgin magnet	recycled magnet
Fe	66.88	64.57
Nd	18.0	21.63
Dy	6.15	3.96
Pr	4.60	6.43
B	1.02	0.93
Co	2.84	1.74
Ga	0.21	–
Cu	0.18	0.32
Al	0.12	0.32
Ti	–	0.10

The system boundary of this LCA is cradle-to-gate that measures the environmental impacts of two NdFeB magnet manufacturing routes: virgin production and magnet-to-magnet recycling. The tool for reduction and assessment of chemicals and other environmental impacts (TRACI 2.1 V1.04), which is a midpoint level life cycle impact assessment methodology developed by the U.S. Environmental Protection Agency, was selected since it was specifically designed for use in the United States. The Ecoinvent 3 database was utilized for all unit processes except for electricity. Since NdFeB magnet-to-magnet recycling is operated in Texas, US-EI 2.2 database was applied as it provided more suitable data. Economic allocation was used to separate the environmental impacts associated with coproducts where their values differ significantly. With this background, LCA was performed on SimaPro 8.3 software.

3. LIFE CYCLE INVENTORY

Figure 1 shows the process diagram (i.e., system boundary) for virgin production and magnet-to-magnet recycling. New materials such as iron, REEs, and other metals are required for both processes, but the specific material composition and quantities are very different. As the recycling route utilizes most of the waste materials, only 0.0005−0.001 kg of new materials are required to produce 1 kg of NdFeB magnets, whereas it is 1.3−3.0 kg for virgin production, some of which are lost during sintering, annealing, grinding, and slicing.

3.1. REE Production in China. REEs are the key materials for manufacturing NdFeB magnets, in particular, Nd, Dy, Pr, and sometimes including minor amounts of Gd. As the existing Ecoinvent database does not contain a detailed LCI for REE production, the process data was compiled using Sprecher et al. (2014),[15] Vahidi et al. (2016),[11] Vahidi and Zhao (2017),[20] and Arshi et al. (2018).[13]

For light REEs such as Nd and Pr, Bayan Obo in China is the world's largest production site. As discussed in Sprecher et al. (2014),[15] REE production consists of six major steps: mining, beneficiation, acid roasting, leaching, solvent extraction, and electrolysis. REE-bearing ore such as bastnäsite and monazite is "open-pit" mined. Iron and other minerals are removed using magnetic separation, froth flotation, and table separation to

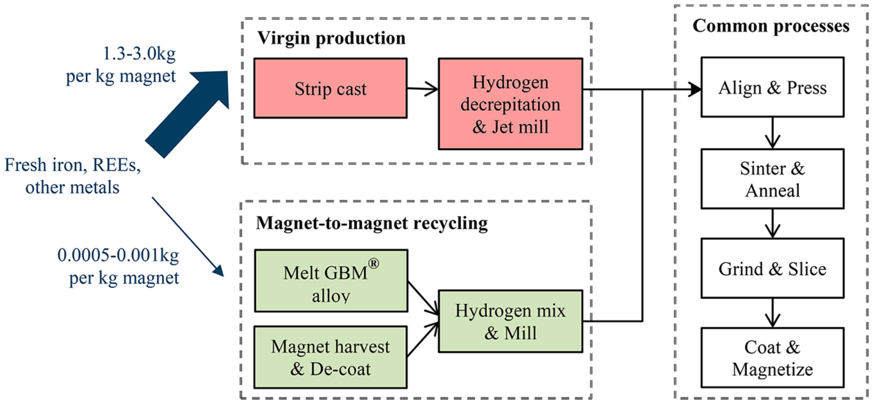

Figure 1. Process flows for NdFeB magnet virgin production and magnet-to-magnet recycling.

obtain 61% rare earth oxide (REO) concentrate. Sulfuric acid is added at the roasting stage to remove carbonate and fluoride from the REO concentrate to obtain water-soluble $RE_2(SO_4)_3$. The mixture is then dissolved in water, and MgO and $CaCO_3$ are added to remove iron and thorium impurities. Caustic soda is used to precipitate REEs, which are then transformed into $RECl_3$ by HCl addition. Finally, individual REOs are separated from each other through solvent extraction with an organic solvent (e.g., P2O4) and kerosene. Impurities are further reduced by adding HCl, and rare earths are precipitated by inorganic salt (e.g., ammonium bicarbonate). The 99.99% pure individual REO is dissolved in a fluoride based molten salt and electrolyzed to obtain pure individual REE metals.

For medium and heavy REEs such as Dy and Gd, ion-adsorption clays are the world's most important source. According to Vahidi et al. (2016),[11] an in situ leaching process with six major steps is employed: site preparation, leaching, precipitation, filtration, mechanical pressing, and calcination to obtain 92% $RE_2(CO_3)_3$ or $RE_2(C_2O_4)_3$. Hydrochloric acid is then added to convert the REO into $RECl_3$. Solvent extraction and metallothermic reduction are applied to attain pure individual REE metals. Stoichiometric calculations were used to estimate the chemical inputs, outputs, and environmental emissions at all stages.

3.2. NdFeB Magnet Production in the U.S.

3.2.1. Virgin Magnet Production. An LCI for NdFeB virgin magnet production was performed using information from Urban Mining Company, Sprecher et al. (2014b),[15] Zakotnik et al. (2016),[21] and Moign et al. (2009).[22] The complete LCI data is available in the Supporting Information (Excel spreadsheet and pdf Table S1).

NdFeB virgin magnet production starts with strip casting. Fresh REEs, electrolytically pure iron, and ferroboron are combined in a crucible and then melted by an inductive element under an inert atmosphere in an industrial strip casting apparatus. Once melted, the total intermetallic mix is slowly poured onto a water-cooled copper wheel to produce "strip-casted" flakes of magnetically anisotropic NdFeB alloy. This process is designed to minimize formation of the α-iron phase.

Strip-cast NdFeB alloy is then hydrogen decrepitated in a "hydrogen reactor" to form a coarse powder of around 4−7 μm average particle size, which is the subjected to jet milling to form fine powders of around 3−4 μm average particle size. Fine powders are then mixed with lubricants, and compacted in a mold under intense pressure and in the presence of a magnetic field; so that the particles are magnetically aligned. The resulting green compacts are then sintered at 1000 °C. During sintering, the RE-rich grain boundary phase forms a liquid and the surface tension of this metallic fluid draws the particles of alloy together and densifies the blocks. The loss of material until this stage is typically 5−15% of total starting mass, and these losses are partially a result of rare earth oxidation. The sintered magnet blocks are typically sliced and diced into two shapes: rectangular and cylindrical with material losses of ~25% and ~65%, respectively.

As the REEs are strongly electronegative, they are reactive and have to be protected from corrosion. The main anticorrosion layers are either an organic or a metallic layer. The metallic layers are usually galvanized nickel, nickel−copper-nickel, tin, or aluminum. Organic coatings include epoxide resins. Anticorrosion layers are most important in locations with high humidity, or that experience frequent exposure to saline conditions, for example, offshore wind turbines. About 92−95% of the NdFeB magnets today are manufactured using a sintering process.[23] This allows the production of specially tailored magnets.

3.2.2. NdFeB Magnet-to-Magnet Recycling. An LCI for NdFeB magnet-to-magnet recycling was performed using information primarily sourced from Urban Mining Company, and augmented with Sprecher et al. (2014),[15] Zakotnik et al. (2016),[21] and Moign et al. (2009).[22] Distinctive LCI for magnet-to-magnet recycling is available in the Supporting Information (SI) (Excel spreadsheet and pdf Table S2).

EOL HDDs are collected from U.S. data centers and transported to the regional consolidation centers, requiring a travel distance of 90km on average. HDDs are degaussed and dismantled for extracting valuable components such as printed circuit boards and NdFeB magnets, and the rest of HDDs are shredded for wiping data and recycling materials. NdFeB "scrap" is then shipped to the production facility in Austin, Texas located up to 1500 km away. As described in Zakotnik and Tudor (2015),[7] EOL HDDs are typically demagnetized in 300 kg batches for 4 h at 400 °C in a vacuum furnace. Any coatings on these waste magnets are then mechanically removed by using a 680 kg/min steel shot blasting apparatus (model 28GL) for 15 min. Uncoated magnets are soaked for 3 min in a 5% (volume/volume %) HNO_3 acid bath to remove any surface oxide layer and residual coating. The resulting surface-clean NdFeB magnets are then divided into 120 kg batches and stored, ready for the next stage.

Batches of EOL NdFeB are placed into a hydrogen mixing reactor with a proprietary GBM alloy to begin powdering the material. Each reactor is first evacuated and heated to 80 °C before admitting hydrogen to a pressure of 0.9 bar. The

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Table 3. Life Cycle Impacts of Producing 1 kg of NdFeB Magnet through Virgin Production Vs. Magnet-to-Magnet Recycling

impact category	unit	virgin (A)	recycled (B)	B/A	distinctive, virgin (C)	distinctive, recycled (D)	D/C
ozone depletion	kg CFC-11 eq	1.8×10^{-05}	8.1×10^{-07}	4%	1.7×10^{-05}	6.4×10^{-08}	0.4%
global warming	kg CO_2 eq	1.3×10^{02}	2.5×10^{01}	20%	1.0×10^{02}	3.8×10^{-01}	0.4%
smog	kg O_3 eq	1.2×10^{01}	1.1×10^{00}	10%	1.1×10^{01}	5.4×10^{-02}	0.5%
acidification	kg SO_2 eq	1.0×10^{00}	3.8×10^{-01}	36%	6.7×10^{-01}	2.7×10^{-03}	0.4%
eutrophication	kg N eq	1.4×10^{00}	1.1×10^{-01}	7%	1.3×10^{00}	5.1×10^{-03}	0.4%
carcinogenics	CTUh	6.8×10^{-06}	1.3×10^{-06}	19%	5.5×10^{-06}	2.8×10^{-08}	0.5%
non carcinogenics	CTUh	3.6×10^{-05}	9.0×10^{-06}	25%	2.7×10^{-05}	9.9×10^{-08}	0.4%
respiratory effects	kg $PM_{2.5}$ eq	2.1×10^{-01}	2.5×10^{-02}	12%	1.9×10^{-01}	3.7×10^{-04}	0.2%
ecotoxicity	CTUe	9.0×10^{02}	2.3×10^{02}	26%	6.6×10^{02}	4.2×10^{00}	0.6%
fossil fuel depletion	MJ surplus	1.6×10^{02}	2.5×10^{01}	15%	1.4×10^{02}	5.4×10^{-01}	0.4%

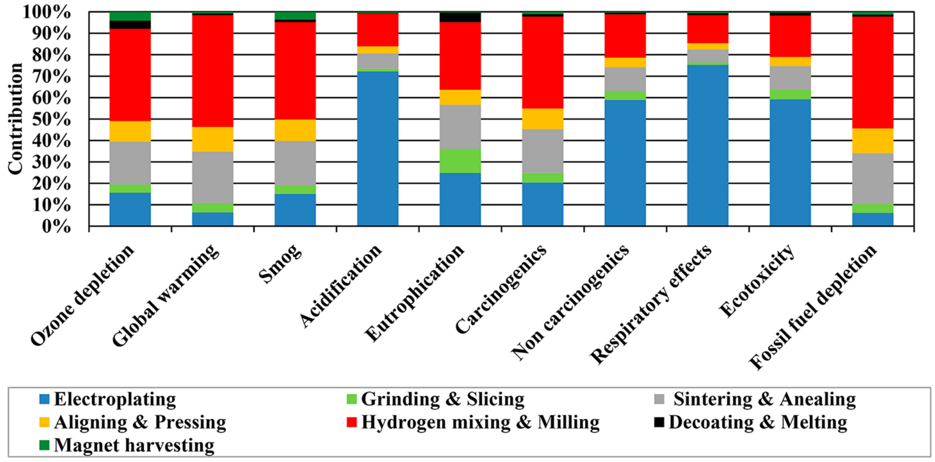

Figure 2. Life cycle impacts of each processing step for NdFeB magnet-to-magnet recycling.

material is then allowed to absorb hydrogen at this elevated temperature until the exothermic reaction is completed, that is, when there is no further change in pressure. At this temperature, hydrogen reacts with the grain boundaries of the NdFeB alloy and only limited sites in the main $Nd_2Fe_{14}B$ crystals, deforming the lattice structure. This results in production of coarse powders from the starting flakes or blocks. The reactor is then evacuated until a vacuum of better than 1×10^{-2} bar is achieved. The batch is then heated in situ to 600 °C to partially degas the material by removing hydrogen.

The resulting powder is then further homogenized into a finer powder by milling to achieve a uniform powder size of ~3.5 μm (monitored by a particle size analyzer) and sieved using a 120 μm stainless-steel mesh to remove large oxidized particles. Powders are then compacted with a ~2500 kN/m^2 compressive force in a magnetic field of ~1.5T to form a "green compact". The magnetic field is present during pressing to magnetically align the particles of powder, so that the resulting magnets are more powerful, as all the magnetic moments are aligned in the same direction. In the absence of a magnetic field, the particles would be randomly aligned and this would reduce the magnetic properties of the resulting magnets.

Once pressed, the green compacts of aggregated powder are transferred to a hydraulic chamber capable of loading ~120 kg of material and subjected to an isostatic (i.e., from all directions) pressure of ~200 bar. The green compacts are then vacuum-sintered at a temperature of 1080 °C for 1 h, followed by furnace cooling, then subjected to an annealing step at 650 °C for 1 h. The densities of the resulting sintered blocks are determined using the Archimedes' principle and a temperature controlled liquid to confirm that complete densification has occurred. The chemical composition of all batches is defined using ICP analysis before, during, and after the process. Similar to virgin production, the loss of material is typically 5−15% of the total starting mass. The sintered magnet blocks are cut or ground into rectangular and cylindrical pieces with material losses of ~25% and ~65%, respectively. About 50−80% of these materials are collected and reused as raw material feedstock in magnet-to-magnet recycling. They are directly fed into the cleaning step of EOL magnets for further processing. Finally, shaped magnets are electroplated and magnetized into NdFeB magnets.

4. RESULTS

4.1. Life Cycle Impact Assessment: Baseline.

Table 3 shows the comparative life cycle impacts of NdFeB magnet virgin production versus magnet-to-magnet recycling. Overall, the recycling route (column B of Table 3) has substantially lower environmental impacts than virgin production (column A of Table 3) in all 10 impact categories (i.e., B/A = 4−36%). In particular, the processes that are distinctive from virgin production in terms of LCI (i.e., magnet harvesting, decoating, and melting for magnet-to-magnet recycling vs strip casting for virgin production) have significantly lower impacts (i.e., D/C = 0.2−0.6%). In other words, common processes for creating NdFeB magnets dominate the overall environmental impact of magnet-to-magnet recycling (i.e., 92−99%, calculated by (B−D)/B). More detailed LCA results and discussions on virgin production are shown in SI Tables S3 and S4 including comparison with other literature, Arshi et al. (2018)[13] and Wulf et al. (2017).[24]

Table 4. Contributions of Each Input and Output to the Life Cycle Impacts of Producing 1 kg of NdFeB Magnet through Magnet-to-Magnet Recycling

impact category	electricity	nickel	transportation	REEs	other inputs	emissions
ozone depletion	77%	14%	4%	4%	0%	1%
global warming	93%	5%	1%	1%	0%	1%
smog	81%	14%	4%	1%	0%	0%
acidification	27%	72%	0%	0%	0%	0%
eutrophication	56%	24%	0%	4%	0%	15%
carcinogenics	77%	19%	1%	1%	0%	2%
non carcinogenics	36%	58%	0%	1%	0%	4%
respiratory effects	24%	75%	1%	1%	0%	0%
ecotoxicity	34%	59%	0%	1%	0%	6%
fossil fuel depletion	93%	5%	1%	1%	0%	0%

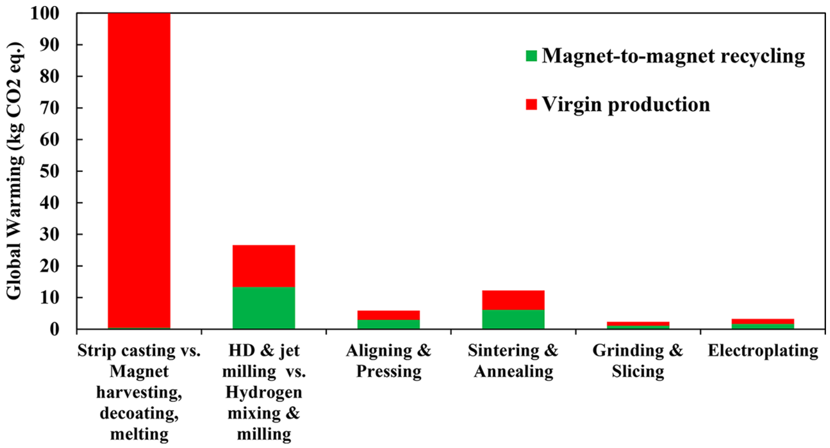

Figure 3. Global warming potential of each processing step in virgin production and magnet-to-magnet recycling for 1 kg of NdFeB magnets.

Table 5. Comparative Life Cycle Impacts of Producing 1 kg of NdFeB Magnet through Magnet-to-Magnet Recycling with Different Energy Sources

impact category	unit	base (A)	natural gas/(A)	wind/(A)	nuclear/(A)	hydro/(A)
ozone depletion	kg CFC-11 eq	8.1×10^{-07}	24%	25%	290%	24%
global warming	kg CO_2 eq	2.5×10^{01}	92%	8%	8%	7%
smog	kg O_3 eq	1.1×10^{00}	47%	20%	22%	20%
acidification	kg SO_2 eq	3.8×10^{-01}	79%	73%	73%	73%
eutrophication	kg N eq	1.1×10^{-01}	45%	45%	45%	44%
carcinogenics	CTUh	1.3×10^{-06}	30%	37%	32%	25%
non carcinogenics	CTUh	9.0×10^{-06}	66%	67%	79%	64%
respiratory effects	kg $PM_{2.5}$ eq	2.5×10^{-02}	82%	78%	81%	77%
ecotoxicity	CTUe	2.3×10^{02}	66%	69%	72%	66%
fossil fuel depletion	MJ surplus	2.5×10^{01}	197%	9%	9%	8%

Figure 2 shows the life cycle impacts of NdFeB magnet-to-magnet recycling at each processing step. Three key processes were identified to be the most impactful: (1) hydrogen mixing and milling (contributing 13–52% of the total environmental footprint), (2) sintering and annealing (6–24%), and (3) electroplating (6–75%). Within hydrogen mixing and milling, electricity contributes 99–100% of the total impact. For sintering and annealing, electricity contributes 70–100% of the total impact. For electroplating, the nickel coating material contributes 73–99% of the total impact.

For the life cycle impacts of virgin magnet production, each processing step is analyzed in SI Figure S1. Notably, strip casting has the highest impact to the environmental footprint of virgin magnet production (64–96% of the total impact), within which REE consumption dominates the overall impact (94–99% of strip casting impact).

To identify the major source of the environmental impacts for NdFeB magnet-to-magnet recycling, Table 4 shows more detailed LCA results for the individual input and output. Two inputs: electricity and nickel were identified to be the environmental hotspots that play key roles in creating the environmental burden. Electricity, as the single largest contributor for six impact categories out of 10, imposes 24–93% of the impact for each impact category. Nickel, as the most impactful material for four different impact categories, contributes 5–75% of the total impact. Transportation, other inputs except for REEs (i.e., iron, copper, and cobalt for creating GBM alloy; hydrogen and chemicals), and the outputs (i.e., emissions) have minimal effects on the overall impact (0–15% in total). REEs, including neodymium and dysprosium, contribute only 0–4% to the total environmental footprint for magnet-to-magnet recycling, which is substantially lower than

Table 6. Life Cycle Impacts of Producing 1 kg of NdFeB Magnet through Magnet-to-Magnet Recycling with Uncertainties

impact category	unit	virgin, China	virgin, U.S.	recycled, China	recycled, U.S.
ozone depletion	mg CFC-11 eq	12–29	13–30	0.4–0.9	0.6–1.3
global warming	kg CO_2 eq	94–222	88–207	25–56	18–41
smog	kg O_3 eq	9–21	8–19	2–4	1–2
acidification	kg SO_2 eq	0.8–1.7	0.8–1.6	0.4–0.6	0.3–0.5
eutrophication	kg N eq	1.0–2.4	1.0–2.4	0.1	0.1–0.2
carcinogenics	CTUh	4.5×10^{-06}–1.0×10^{-05}	4.8×10^{-06}–1.1×10^{-05}	6.4×10^{-07}–1.3×10^{-06}	9.7×10^{-7}–2.0×10^{-6}
non carcinogenics	CTUh	2.6×10^{-05}–5.7×10^{-05}	2.6×10^{-05}–5.8×10^{-05}	6.7×10^{-06}–1.1×10^{-05}	7.2×10^{-6}–1.2×10^{-5}
respiratory effects	kg $PM_{2.5}$ eq	0.2–0.4	0.2–0.3	0.04–0.06	0.02–0.03
ecotoxicity	CTUe	646–1,430	643–1,422	188–327	184–320
fossil fuel depletion	MJ surplus	101–240	113–267	5–10	18–39

their contributions to virgin production (61–95% of the total impact, see SI Table S5). The reason behind this is because NdFeB magnet-to-magnet recycling significantly reduces REE requirements by approximately 99.9% compared to the virgin production (0.0004–0.0009 kg vs 0.4–0.9 kg virgin REEs).

To compare the environmental impacts of producing virgin and recycled magnets by their processing steps, Figure 3 illustrates the global warming potential as a representative example. Due to the extensive REE consumption, strip casting for virgin production has the highest global warming potential, while the counterpart processes for magnet recycling (i.e., magnet harvesting, decoating, and melting) have only about 0.4% of the impact of strip casting. The latter processes have relatively small impacts, and the differences between the two processing routes are minor (as the red and green bars of Figure 3 are stacked).

4.2. Life Cycle Impact Assessment - Alternative Scenarios.

Since electricity is a major contributor to the overall environmental footprint of NdFeB magnet-to-magnet recycling, the effect of replacing the standard energy source with alternative, greener technologies was assessed. The baseline energy (represented by *Electricity, medium voltage, at grid, Texas/US US-EI U*) was replaced by natural gas (*Electricity, natural gas, at power plant/US US-EI U*), wind (*Electricity, at wind power plant/US- US-EI U*), nuclear (*Electricity, nuclear, at power plant/US US-EI U*), and hydro (*Electricity, hydropower, at power plant/US** US-EI U*). Table 5 shows the resulting life cycle impacts of the entire NdFeB magnet-to-magnet recycling process using the different energy sources in comparison to the baseline - column A (same as Table 3 column B). That is, the environmental impacts of NdFeB magnet-to-magnet recycling using natural gas, wind, nuclear, and hydroelectric power are 24–197%, 8–78%, 8–290%, and 7–77% of the total baseline impacts, respectively. Therefore, increasing the electricity share from wind or hydroelectric power would significantly reduce the overall environmental impacts of NdFeB magnet-to-magnet recycling.

It should be noted that there are significant uncertainties surrounding material and energy inputs and outputs during NdFeB magnet manufacturing as was shown in SI Tables S1 and S2 (i.e., low, baseline, and high values for each unit process). A majority of these uncertainties originate from the material losses and their recyclability in NdFeB magnet manufacturing. In addition to the uncertainties in the process, the relative proportion of electricity generated from renewable sources varies between countries and even regions; and so the associated environmental burdens are also uncertain. Here, we examined two geographic locations for NdFeB magnet production – U.S. (Texas) and China. For the three scenarios noted in SI (i.e., low, baseline, and high), the life cycle impact ranges for these locations were shown in Table 6. As is evident, the difference between virgin production and magnet-to-magnet recycling overwhelms the difference between China and U.S. (Texas).

The LCA results confirm that magnet-to-magnet recycling substantially lowers the environmental footprint of NdFeB magnet production, largely due to its minimal use of fresh REEs. By adopting greener electricity sources such as wind and hydroelectric power, the environmental footprint of NdFeB magnet-to-magnet recycling could be further reduced. These results also suggest possible directions for further development of magnet-to-magnet recycling to maximize the environmental benefits of this new technology.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.7b05442.

Life cycle inventory of NdFeB virgin magnet production; life cycle inventory of NdFeB magnet-to-magnet recycling; life cycle impacts of each processing step for NdFeB magnet virgin production; contributions of each input and output to the life cycle impacts of virgin production (PDF)

Life cycle inventory of NdFeB magnet virgin production (XLSX)

Life cycle inventory of NdFeB magnet-to-magnet recycling (XLSX)

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Notes

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