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Towards neodymium recycling: Analysis of the availability and recyclability of European waste flows

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ABSTRACT

The world is facing a growing neodymium demand, creating the need for developing a recycling system to handle future waste flows. Recycling technologies are emerging, but the recycling system around them can only be established with knowledge about available end-of-life (EoL) products. Therefore, this study quantified neodymium waste in European countries using material flow analysis, and assessed the recyclability of major EoL products. For 2019, we find a waste flow of 7.7 kt Nd, consisting mostly of NdFeB magnets. HDDs represent a large current waste flow, while the demand for magnets in industrial applications is increasing. In the future, electric vehicle motors and wind turbines likely provide a source of neodymium with good recyclability. Consequently, there will be different product groups that determine the future waste volumes. To manage the changing waste flows, a neodymium recycling system should be developed with the product properties of future waste flows in mind. Meanwhile, the recyclability of products can be improved by addressing bottlenecks in the recycling chain.

1. Introduction

1.1. Neodymium: A critical material

Neodymium is a strategically important resource and an essential element in modern societies. It is a key enabler of the energy transition due to its application in electric motors and wind turbines (Constantinides, 2018). If global climate ambitions are realized, the neodymium demand could increase tenfold (Elshkaki, 2021; Alves Dias et al., 2020). The European Union (EU) is a frontrunner in the energy transition, and therefore the challenge of neodymium waste treatment is expected to arise here first (Alves Dias et al., 2020). Consequently, the EU has developed strategies to create a circular economy for neodymium and other critical raw materials (Schäfer et al., 2020).

Recycling reduces the criticality and narrows the gap between supply and demand (Binnemans et al., 2013). Several neodymium recycling technologies are under investigation (Yang et al., 2017). Three major technologies are pyrometallurgical recovery, hydrometallurgical processing, and direct recycling of rare earth alloys (Walton et al., 2015). The latter technology is particularly attractive due to the low environmental impact (Sprecher et al., 2014; Miranda Xicotencatl et al., Submitted for publication). However, these recycling technologies have not yet been applied on large scale. To further develop neodymium recycling technologies through practical experience, suitable neodymium-containing wastes need to be identified and captured.

1.2. Research on neodymium flows

Recycling is enabled by material flow studies (MFAs) that map neodymium flows in society. Regarding the flows of neodymium in the EU, four recent studies have contributed to an understanding at aggregated level. The historic flows were mapped by Guyonnet et al. (2015) for 2010, while Ciacci et al. (2019) modeled flows in the past until 2016. Future flows were explored by Reimer et al. (2018), drawing

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Abbreviations: BEV, Battery electric vehicle; EU, European Union; EoL, End of life; FCC, Fluid catalytic cracking; HDD, Hard-disk drive; HEV, Hybrid electric vehicle; MRI, Magnetic resonance imaging machine; NdFeB, Neodymium–iron–boron; NiMH, Nickel-metalhydride; PHEV, Plug-in hybrid electric vehicle; SSD, Solid-state drive; WEEE, Waste electric and electronic equipment

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attention to the expected large waste flows of electric vehicle motors. Finally, the neodymium flows associated with batteries, electronics and passenger vehicles were mapped by Huisman et al. (2017). These studies show diverging results due to differences in scope. For example, only one study included industrial motors (Reimer et al., 2018). A comparison with global neodymium flows indicates that motors (other than traction motors) and pumps could be a significant source of secondary neodymium (Schulze and Buchert, 2016), but several motor types were not considered in the studies with EU-focus.

Neodymium is used in neodymium–iron–boron (NdFeB) magnets, NiMH batteries and catalytic materials. All three of these components compete with alternative components, e.g. ferrite magnets and Li-ion batteries. Therefore, MFA studies should account for the market share of neodymium-containing components, which shows both changes over time and regional variation. For conventional cars, the content of NdFeB magnets was found to increase (Restrepo et al., 2017). Regional differences were observed for example in passenger cars, that contain larger amounts of NdFeB magnets in Japan than in the United States (Nguyen et al., 2019). For end of life (EoL) magnetic resonance imaging machines (MRIs) in Europe, two sources report very different waste flows: 10 t NdFeB was reported in 2016 (Ciacci et al., 2019) and 1000 t NdFeB in 2018 (Reimer et al., 2018). This difference can partly be traced back to the assumed market shares of 10% and 100%, respectively. For other products, snapshots of their composition and NdFeB market share are provided by waste analysis studies (e.g. Menad and Seron, 2017; Dańczak et al., 2018; Lixandru et al., 2017; Böni et al., 2015).

To set up an effective waste collection and processing system, it is key to know the type of available waste products. Since various products contain Nd, the ease of recycling can vary markedly between products (Habib, 2019; Yang et al., 2017). These differences are assessed in only few studies, with a focus on technical characteristics. A comparison of some waste electric and electronic equipment (WEEE) types identified hard-disk drives (HDDs) as a suitable waste flow for Nd recovery (REMANENCE, 2017). Besides, Habib (2019) discussed how product properties affect recycling.

The information on total volumes of neodymium flows in previous MFAs is insufficient for finding recycling opportunities for three reasons. First, inconsistencies in market shares and scope definition create uncertainties. Second, no country-specific analysis of waste flows is available, although Huisman et al. (2017) provide a starting point by analyzing certain waste flows in Europe. Third, the focus on total volumes ignores many important factors that determine the viability of recycling. Factors like product design and technology availability often prevent recycling from being implemented (Van Nielen et al., 2022).

1.3. Insights to support recycling

As argued above, existing literature on neodymium flows in society is patchy at best and a systematic overview on the level of EU members states and product groups is lacking. This is problematic for policy makers and industries that aim to build a recycling system within the EU. In this study we address this by providing detailed information about past and present waste flows. We aim to evaluate the potential for neodymium recovery, and to identify promising EoL products for recycling. To that end, neodymium waste was quantified per product group in EU member states. The analysis used a dynamic material flow model that accounts for the lifespan distribution of products, diffusion of new products and the time-dependent market share of neodymium-containing components. In addition, the barriers and drivers for recycling were evaluated. Major waste flows were compared regarding their recyclability using a framework for recyclability assessment (Van Nielen et al., 2022). This framework addresses product properties, policies and other aspects that determine the recyclability of neodymium.

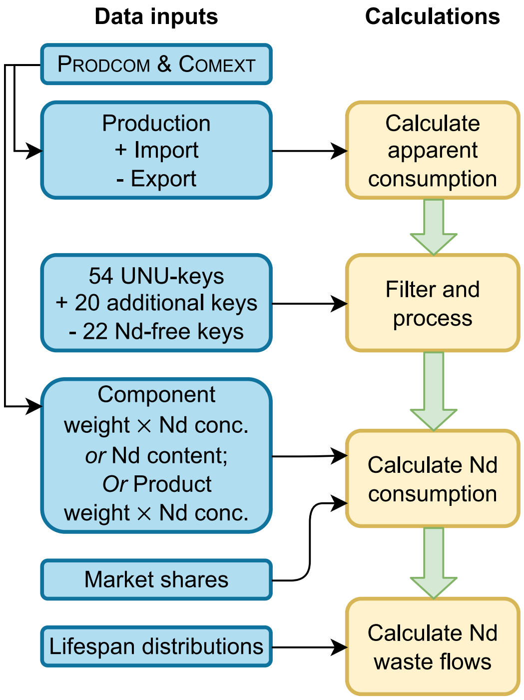

Fig. 1. Overview of calculation steps in this study.

2. Materials & method

2.1. Overview & scope

Material flow analysis and a recyclability assessment framework were used to quantify secondary neodymium resources over time. The waste quantities were calculated using a 4-step approach, as described in the sections below and shown in Fig. 1. First, the production and trade flows were derived from statistics (Apparent product consumption). Next, input data were collected for the Market trends and Product composition, allowing to calculate the European consumption of Nd. Finally, Waste generation was modeled using a distributed lifespan approach. For five products with major Nd waste flows, the recyclability was assessed using a Recyclability assessment framework.

The geographical scope is limited to the current EU-27 and the UK (EU-28). The temporal scope ranges from 1990 to 2018, since for this range EU-wide statistical trade data is available. Given the focus on recycling, this study is limited to the flows that enter and leave the use phase.

For the recyclability assessment, the geographic scope is in line with the MFA, and the reference year is 2019. As recycling technology, we considered hydrogen decrepitation of sintered magnets, an environmentally benign option (Sprecher et al., 2014; Miranda Xicotencatl et al., Submitted for publication). This process recovers Nd alloys and is applied in magnet-to-magnet recycling (Zakotnik and Tudor, 2015) and hydrogen processing of metallic scrap (HPMS) (Walton et al., 2015).

2.2. Apparent product consumption

As a first step, the consumption of Nd-containing products over time is quantified. For this step, we followed the dynamic material flow approach of the ‘Waste over Time’ script developed in ProSUM (Huisman et al., 2017). Both the original source code and modified script are available online (van Straalen et al., 2016).

The ‘Waste over Time’ script implements the apparent consumption method, implying that the consumption in a country is calculated as the sum of production and imports minus exports. The data inputs were obtained from Eurostat statistics on production (Eurostat, 2019c) and international trade (Eurostat, 2019a). Since some statistical data points are missing or erroneous, the script makes several modifications (van Straalen et al., 2016). The calculation involves six steps.

1. Several Prodcom data points were confidential and withheld by Eurostat. These gaps are filled using interpolation from other years and countries.
2. Missing data for product weight are derived from the number of products and the average product weight.
3. Outliers are replaced by interpolations.
4. CRT monitor data are derived from the PC sales volumes.
5. Data for before 1995 are extrapolated with a linear trend starting at the introduction year of each product.
6. Data for 2019 are extrapolated from the trend in recent years.

To match the scope of the present research, four adjustments were made to the input files and calculation procedures. Additional goods were included, statistical data covering 2016–2018 were included, consumption data from other sources were added, and average product weights were updated. The products were grouped using the UNU-Key classification system (Forti et al., 2018). Within this system, 54 UNU-Keys cover all WEEE. The classification was extended with 18 keys, covering vehicles, industrial applications and wind turbines. Although the UNU-Keys are intended to have homogeneous material compositions (Forti et al., 2018), we considered 8 keys as inhomogeneous with respect to Nd content. Therefore, these categories were divided in subcategories, indicated by a suffix in Table 1. Ultimately, our analysis included 53 product categories, which we believe covers almost the whole range of neodymium-containing products.

The statistical dataset was extended to recent years, using the same sources as the original method (Eurostat, 2019c,a). For three products, more specific sales data were obtained from dedicated sources: MRIs (OECD, 2019), passenger vehicles (ACEA, 2021; ICCT, 2018), and wind turbines (EurObserv'ER, 2019; Eurostat, 2019b).

The product weights were updated to better capture the change over time. For each product type and year in the Comext dataset, the product weight was determined as the median value of the weight in all countries. These updated weights were used in step 2 to derive mass flows from numbers of products. Whenever possible, this conversion used weights specific for each year.

2.3. Market trends

The neodymium flows associated with each product category were derived from the apparent consumption while accounting for market penetration dynamics. The demand for Nd D_{Nd} was calculated by multiplying the demand for a product, D_p, by both the Nd content of the product M_{Nd} and the market share of Nd-containing products s_p (Eq. (1)). This calculation is applied to each product, country and year.

$$D_{Nd} = D_p \times M_{Nd} \times s_p \tag{1}$$

In Eq. (1), s_p is a crucial factor because of the existence of substitutes to Nd-containing components. In fact, either a NdFeB magnet or a ferrite magnet can be used in many applications, and NiMH batteries exist next to several other battery technologies.

As a basis, we created an overview of market shares of Nd-containing components in different years and applications based on scientific literature and technical reports. For some applications, this overview contained sufficient data points to interpolate the market share evolution over time. For applications with no or few data points, the market share was assumed to follow the average permanent magnet market trend depicted in Fig. 2 (see Supplementary information A, B).

In the model, we explicitly modeled the diffusion of solid-state drives (SSDs), smartphones and tablets. These consumer electronics have shown a large sales growth, which is untraceable in statistic reports. These electronics are aggregated with products with a significantly different NdFeB magnet content (HDDs, mobile phones and laptops, respectively), justifying a disaggregation based on market share data. The market share trend for HDDs and SSDs was based on global shipment data (Robinson, 2020; Alsop, 2019, 2017; Sprecher et al., 2014). This trend is approximated by Eq. (2). For the data storage market excluding datacenters (Alsop, 2019), Eq. (3) was derived. A full overview of the data is given in Supplementary information C. As a proxy for the share of smartphones in the mobile phone market, the penetration of smartphones in the United States was used (ComScore, 2017). The trend after 2015 was extrapolated using a fitted logistic function, see Eq. (4). The ratio between tablet and laptop sales were obtained from global sales figures (Ubrani and Nataraj, 2019).

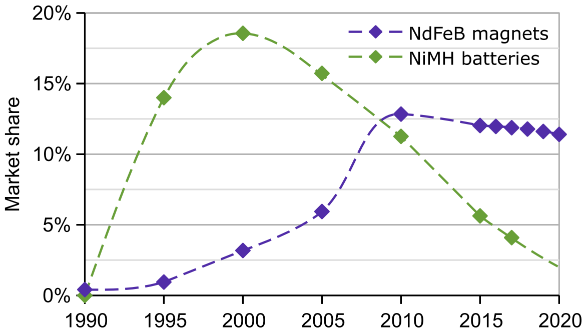

Fig. 2. Volumetric market share of NdFeB magnets in the global permanent magnet market, and NiMH batteries in the portable battery market (Pillot, 2018). See Supplementary information A for data sources.

$$S_{HDD,all} = \frac{0.7}{1+e^{0.4\cdot(y-2018)}} + 0.3 \tag{2}$$

$$S_{HDD,PC} = \frac{1}{1+e^{0.4\cdot(y-2018)}} \tag{3}$$

$$S_{smartphones} = \frac{0.92}{1+e^{-0.57\cdot(y-2011.66)}} \tag{4}$$

2.4. Product composition

The demand for each product category induces a neodymium demand, which was calculated using the average application properties. Eq. (1) indicates the need for data on the Nd content per product M_{Nd}, which was obtained from literature and manufacturer information. Since the Nd content is not directly available for most products, additional data were gathered on Nd-containing components. We distinguish between three of these components: NdFeB magnets, NiMH batteries and catalytic materials. When only the component weight M_c was known, we used the Nd concentration in the component $C_{Nd,c}$ to calculate the Nd content (Eq. (5)). When the Nd weight fraction $C_{Nd,p}$ was available, it was multiplied by the category-average product weight M_p[2] to obtain the Nd content (Eq. (6)). The product compositions are listed in Table 1.

$$M_{Nd} = M_c \times C_{Nd,c} \tag{5}$$

$$M_{Nd} = M_p \times C_{Nd,p} \tag{6}$$

2.5. Waste generation

After calculating the consumption of products as described above, we derived the waste flows. The waste flows were modeled using a distributed lifespan approach to account for differences in the service life of products. This approach is preferred over a constant lifespan assumption, since most applications under study have a changing demand

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[2] The product weight was derived from Comext as described in Section 2.2.

Table 1
Average product properties per product group. The listed product weights are weighted averages.[b]

UNU-Key	Product group	Product weight M_c (g)	Nd in product $C_{Nd,c}$ (g/g)	Component weight M_p (kg)	Nd in component $C_{Nd,p}$ (g/g)	Data source
	NdFeB magnets					
0001	Central heating (household)	30.85		200	0.2231	[1]; [2]
0102	Dishwashers	45.49		35	0.228	[3]; [4, 5]
0104	Washing machines	71.39	$1.11 \cdot 10^{-4}$	130	0.228	[6]; [3]; [4,5]
0105	Dryers	43.19		102	0.228	[3]; [4,5]
0106	Heating and ventilation (household)	12.14	$1.23 \cdot 10^{-4}$		0.228	[6]
0108	Fridges	38.18	$1.04 \cdot 10^{-4}$	112.5	0.228	[6]; [3,5]; [4,5]
0109	Freezers	43.91	$1.69 \cdot 10^{-5}$	112.5	0.228	[6]; [3,5]; [4,5]
0111	Air conditioners	26.7		152	0.228	[5,7,8]
0112	Other cooling	41.7		200	0.228	Own assumption
0113	Cooling (professional)	102.82		350	0.228	[7]
0114	Microwaves	20.52	$2.20 \cdot 10^{-5}$	110	0.228	[6]; [4]
0201b	Fans	1.97	$2.75 \cdot 10^{-5}$	0.6	0.228	[6]
0204	Vacuum cleaners	3.27	$3.16 \cdot 10^{-5}$	16.8	0.228	[6]
0205	Personal care	1.89	$4.18 \cdot 10^{-4}$	1	0.228	[4]; [4]
0205b	Shavers	5.52	$6.20 \cdot 10^{-4}$	1	0.228	[4]; [4]
0205c	Toothbrushes	0.55		1	0.228	[4]
0301b	HDDs	0.49	$5.65 \cdot 10^{-3}$	15.03	0.2868	[9]; [9,10,11,12]; [4,9]
0302	Desktop PCs	9.33	$4.35 \cdot 10^{-4}$	18.86	0.2698	[6]; [13,14,15]; [4,5,16,17]
0303a	Laptops	1.81	$1.77 \cdot 10^{-3}$	11.4	0.27	[6,17]; [14,15,17,18]; [4,5,17,18]
0303b	Tablets	0.5		2.4	0.2245	[19]
0304	Printers	9.12	$3.63 \cdot 10^{-4}$	15	0.228	[6]; [15]
0305	Telecom	0.58		0.48	0.2105	Assumed identical to mobile phones
0306a	Mobile phones	0.10	$3.85 \cdot 10^{-3}$	0.48	0.2105	[17,20]; [4,17,18,21,22]; [4,17]
0306b	Smartphones	0.10	$1.10 \cdot 10^{-3}$	0.2008	0.2245	[6,23]; [17,19]; [4,17]
0309	Flat screen monitors	5.32		3.95	0.1648	[24]; [24]
0401	Small consumer electronics	0.39	$4.69 \cdot 10^{-4}$	2.10	0.177	[6]; [21]
0401b	Headphones, earphones	0.09	$5.59 \cdot 10^{-3}$	0.93	0.177	[20]; [14]; [17]
0403	Music instruments, radio, HiFi	3.88	$8.07 \cdot 10^{-3}$	1.33	0.3305	[6]; [5,20]
0404b	Video players	3.51	$1.13 \cdot 10^{-3}$	1.21	0.3305	[6]; [4,5]; [4,5]
0405	Speakers	2.45	$4.41 \cdot 10^{-5}$	47.19	0.2330	[6]; [15,17]; [16,17]
0406	Cameras	0.54		0.20	0.2245	Assumed identical to smartphones
0408	Flat screen TVs	10.46		11.48	0.1795	[14,25,24]; [24]
0702	Game consoles	0.48		10	0.3305	[15]
0802b	MRIs	16000	$6.87 \cdot 10^{-4}$	1.6E+6	0.2290	[6]; [4,8,16]; [4,16]
1002	Cooled vending machines	92.22		112.5	0.2280	
1101	Cars	1293	$1.25 \cdot 10^{-5}$	273	0.26	[6]; [5,13,26–28]; [5]
1102a	BEVs	1131		2000	0.1964	[4,8,16,29,30–33]; [2]
1102b	PHEVs	1801		2000	0.1964	[4,8,16,29,30–33]; [2]
1103	HEVs	1510		1316	0.2275	[16,30,34,35]; [5,16]
1104	Snowmobiles, golf cars etc.	3779	$1.72 \cdot 10^{-4}$		0.26	[6]; [16]
1105	Trucks	3475		39.8	0.26	[3,36]
1106	Buses	3705		39.8	0.26	[3,36]
1107	Motorhomes	2349		39.8	0.26	[3,36]
1108	Electric bikes	33.60		266	0.2320	[7,8,13,15,16,21,37]
1201	Industrial machines & motors	3468	$9.57 \cdot 10^{-5}$	175	0.2513	[6]; [38]; [5,16]
1202	Industrial pumps	9.28	$7.42 \cdot 10^{-5}$	350	0.2231	[6]; [1]; [2]
1203	Lifting and conveying machines	134.62	$1.87 \cdot 10^{-4}$		0.2513	[6]
1204	Shaping machines	657.68	$4.21 \cdot 10^{-4}$		0.2513	[6]
1205a	Wind turbines, onshore, low speed[a]	38.22		625	0.294	[8,16,39,40]; [16,39,41]; [2]
1205a	Wind turbines, onshore, high speed[a]	38.22		134	0.294	[8,16,39,40,42]; [16,39,41]; [2]
1205b	Wind turbines, offshore, low speed[a]	38.22		625	0.294	[8,16,39,40]; [16,39,41]; [2]
1205b	Wind turbines, offshore, high speed[a]	38.22		134	0.294	[8,16,39,40,42]; [16,39,41]; [2]
1206	Industrial robots	30.81		1990	0.27	[5]; [5]
	Catalysts					
1101	Catalytic converter			1.114	0.0157	[43]; [44]
1301	FCC catalyst		$1.95 \cdot 10^{-3}$	1	0.0035	[6]; [45,46]
	NiMH batteries					
0201	Other small household: wrist-watches	1.1		0.5	0.0109	[c]
0204	Vacuum cleaners	3.27		490.5	0.0109	[47];[c]
0205	Personal care	1.89			0.0109	[c]
0205b	Shavers	0.312		78	0.0109	[47];[c]
0205c	Toothbrushes	0.55		137.5	0.0109	[47];[c]

(*continued on next page*)

Table 1 (*continued*).

UNU-Key	Product group	Product weight M_c (g)	Nd in product $C_{Nd,c}$ (g/g)	Component weight M_p (kg)	Nd in component $C_{Nd,p}$ (g/g)	Data source
0305	Telecom	0.582		105	0.0109	[47];[c]
0306a	Mobile phones	0.099			0.0109	[c]
0406	Cameras	0.545		62	0.0109	2 AA batteries;[c]
0601	Power tools	2.53	$9.57 \cdot 10^{-5}$	598	0.0109	[47,48];[c]
0602	Tools (professional)	23.17	$9.57 \cdot 10^{-5}$	598	0.0109	[c]
0701	Toys	0.45		93	0.0109	3 AA batteries;[c]
1103	HEVs	1510	$2.02 \cdot 10^{-4}$	38467	0.0109	[28,34,35,49,50]; [28,35,51];[c]

BEV: battery electric vehicle; FCC: fluid catalytic cracking; HEV: hybrid electric vehicle; PHEV: plug-in HEV.

[1] Personal communication, Grundfos, 2020, [2] SUSMAGPRO (2020), [3] Seo and Morimoto (2014), [4] Habib et al. (2014), [5] Sekine et al. (2017), [6] Nansai et al. (2014), [7] Morimoto et al. (2019), [8] Schulze and Buchert (2016), [9] Dańczak et al. (2018), [10] Tecchio et al. (2018), [11] Sprecher et al. (2014), [12] Auerbach et al. (2017), [13] Yang et al. (2017), [14] Hobohm and Kuchta (2015), [15] Glöser-Chahoud et al. (2016), [16] Reimer et al. (2018), [17] Böni et al. (2015), [18] Buchert et al. (2012), [19] Manhart et al. (2016), [20] REMANENCE (2017), [21] Ciacci et al. (2019), [22] Bandara et al. (2014), [23] Wu et al. (2008), [24] Lixandru et al. (2017), [25] Thiébaud et al. (2018), [26] Peck et al. (2017), [27] Restrepo et al. (2017), [28] Fishman et al. (2018), [29] Constantinides (2018), [30] Elwert et al. (2017), [31] Hofmann et al. (2013), [32] Gutfleisch (2013), [33] de Haan and Zah (2013), [34] Bauer et al. (2010), [35] Yano et al. (2016), [36] Widmer et al. (2015), [37] Habib and Wenzel (2014), [38] Buchert et al. (2014), [39] Viebahn et al. (2015), [40] Goodenough et al. (2018), [41] Fishman and Graedel (2019), [42] Barteková (2015), [43] Belcastro (2012), [44] Thermo Fisher Scientific (2012), [45] Topete (2014), [46] Hsu and Robinson (2019), [47] Sommer et al. (2015), [48] Pillot (2018), [49] GEUS and D'Appolonia (2017), [50] Moss et al. (2013), [51] Davies (2006).

[a] Quantities are reported per MW installed capacity.

[b] In the model, a product weight specific for each year and country was used when possible. The values listed here are the weighted averages.

[c] Nd content in NiMH batteries was calculated as the mean of reported values (GEUS and D'Appolonia, 2017; Fishman et al., 2018; Restrepo et al., 2017; Sommer et al., 2015; Guyonnet et al., 2015; Rombach and Friedrich, 2014; Schüler et al., 2011; Yano et al., 2016).

over time. The approach was applied to obtain the waste flow of both applications and incorporated Nd.

The lifespans of products were modeled as Weibull functions ($L(t)$), which approach practical lifespan distributions (Forti et al., 2018). The lifespan distribution function in Eq. (7) describes the expected lifespan using parameters α and β. Then for each model year t and product p, the waste flow $W(t)$ is determined from the consumption D in all previous years n:

$$L(t) = \frac{\alpha}{\beta^{\alpha}} \cdot t^{\alpha-1} \cdot e^{-(t/\beta)^{\alpha}} \tag{7}$$

$$W(t) = \sum_{n=t_0}^{t} D(n) \cdot L_p(t-n) \tag{8}$$

The Weibull parameters and data sources are provided in Supplementary information D.

Flows were quantified per country because waste can be transported freely within national borders, and waste policies differ. The average Nd waste density was calculated per square kilometer, using land area (FAOSTAT, 2021).

2.6. Recyclability assessment

A further assessment of the suitability of products for recycling was performed for five selected flows. This selection was based on the magnitude of current and future waste volumes, which are large for battery electric vehicle (BEV) motors, HDDs, speakers, wind turbines, and industrial pumps. For these waste flows, the recyclability was assessed using a framework recently developed by Van Nielen et al. (2022). That paper has reviewed existing methods to assess the recyclability of materials and developed a combined framework, which covers the major factors that determine the recyclability of minor metals in waste flows (Van Nielen et al., 2022). THe framework provides 35 indicators, grouped by steps in a product's life cycle (Table 2).

The indicators are evaluated using various data sources. For indicators that refer to material flows, numbers from this study were used. When possible, product properties were obtained from waste dismantling studies (Talens Peiró et al., 2020; Habib et al., 2014; Lixandru et al., 2017, e.g.). A full overview of data sources in provided in Supplementary information E. To allow for a better overall comparison of waste flows, the results were aggregated by taking the simple mean of indicator values.

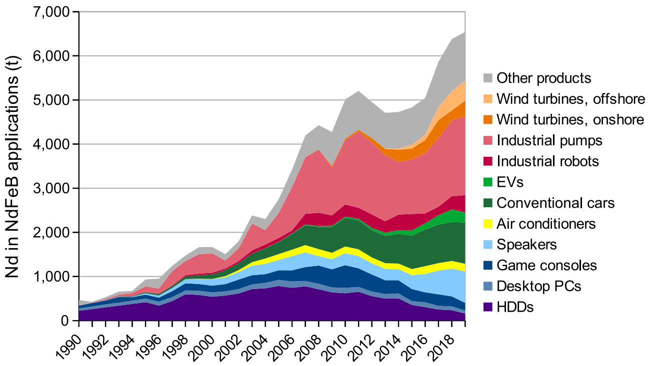


Fig. 3. Increasing demand for Nd in EU-28 countries, grouped by application types.

3. Results

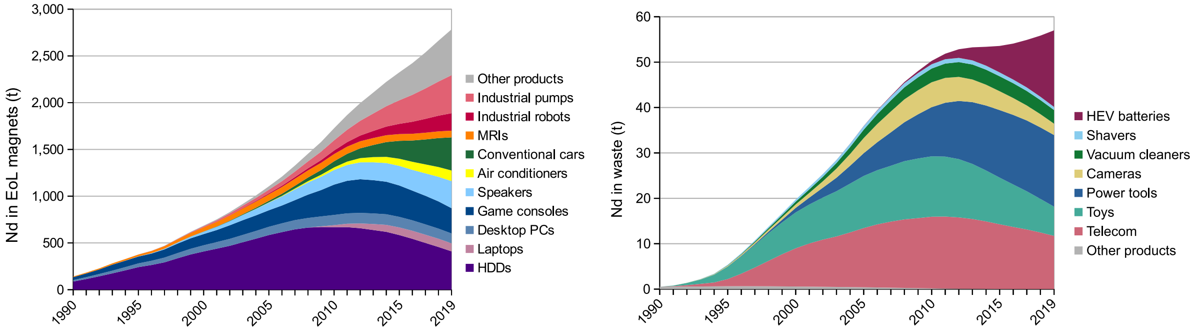
3.1. Neodymium demand

This section analyzes the amount of neodymium contained in consumed products. The demand for neodymium in the EU-28 was found to grow rapidly, due to both rising consumption and market penetration of Nd components. In 2000, only 1.7 kt neodymium was consumed, which grew by 300% to 5.3 kt in 2010. The growth has continued since then, up to a demand of 7.7 kt in 2019. Most of the neodymium was consumed in the form of NdFeB magnets, accounting for over 97% of the total demand. The combined demand for other applications amounted to 90–100 t/a in the last decade.

For NdFeB magnets as the major neodymium consumption driver, Fig. 3 shows a disaggregation of demand. This diagram shows that new magnet applications emerged over time, creating successive *waves* of neodymium demand. Initially, magnet demand was driven by consumer electronics, such as HDDs and game consoles. From 2004 onwards, NdFeB magnets rapidly penetrated the industrial market, with applications in pumps and robots, and also in cars. A third wave appears to emerge in recent years, consisting of clean energy applications, i.e. EVs and wind turbines. The combined effect of these waves is an almost continuous and rapid demand growth trend.

Table 2
Indicators to assess recyclability, grouped by step in the product life cycle.
Source: Adapted from Van Nielen et al. (2022).

Life cycle step	Factors	Indicators
Overarching	Supply chain alignment	Fraction of actors involved in exchange
	Uncertainty	Standard deviation of future waste flow
	Economic drivers	Annual waste flow; Disposal and raw material tax; Recycling subsidy
	Social benefits	Avoided health and safety hazard; Labor rights indicator
Manufacturing	Design for disassembly	Material joint types; Metal content per component; Number of component designs; Number of product designs
Use & collection	Collectability	Annual waste generation; Ownership; Product weight
	Policy	EPR legislation; Export restrictions
	Collection rate	Collected fraction of EoL products; Distance between collection points; Consumer awareness
Preprocessing	Preprocessing performance	Dismantling time; Identification accuracy; Liberation efficiency
	Safety risk	Content of restricted substances
Recovery	Environmental effects	GHG emissions; Toxic process chemicals
	Recovery performance	Concentration after preprocessing; Recovery efficiency; Value fraction of recoverable metals
	Technology availability	Expertise required; Technology readiness level
Secondary market	Demand	Demand growth rate; Price premium or discount; Price volatility
	Revenues	Target metal value; Co-recovered metal value



(a) Neodymium contained in EoL magnets.

(b) Neodymium contained in EoL batteries and catalysts.

Fig. 4. Neodymium waste generated in EU-28 countries, grouped by application type.

3.2. Neodymium waste flows

In contrast to the demand flow, the dominant source of Nd in waste is consumer electronics (Fig. 4(a)). In 2019, 15% of the Nd waste flow originated from HDDs. Yet this amount has been declining from its peak in 2011, a trend also found for laptops, desktops and game consoles. Another important waste flow concerns speakers, which includes various audio devices such as professional loudspeaker systems, home audio, and smart speakers. Contrary to other consumer electronics, the demand for Nd in speakers has increased in recent years, with waste following with delay.

The last few years show an increase in Nd flows associated with EoL industrial robots and pumps. These waste flows represented 7% and 15% of all Nd waste in 2019. Due to the longer lifespan of these products as well as the increasing demand, these waste types are expected to continue to grow in the future. Over the whole range, a shift to product groups with longer lifespans is observed. Automotive and industrial applications are in use longer than consumer electronics, therefore the stock increases even with constant influx.

Compared to EoL NdFeB magnets, other Nd-containing components contribute only little to the European Nd waste flows. Fig. 4(b) shows a waste flow of 57 kt Nd in 2019, which represents 2% of the total in that year. Among the battery and catalyst applications, an increasing amount of Nd originated from hybrid electric vehicle (HEV) batteries. This concerns NiMH batteries found in older generations of HEVs. Since the market for HEVs and BEVs is overtaken by Li-based batteries (Pillot, 2018), this increase is only temporary.

While the emergence of wind turbines and EVs is apparent in Fig. 4(a), these categories are virtually absent in the overview of waste flows. Based on the long lifespan of wind turbines and EVs, significant waste flows are expected several years in the future. Such a delay due to the lifespan was also observed for Nd from conventional cars.

3.3. Country comparison

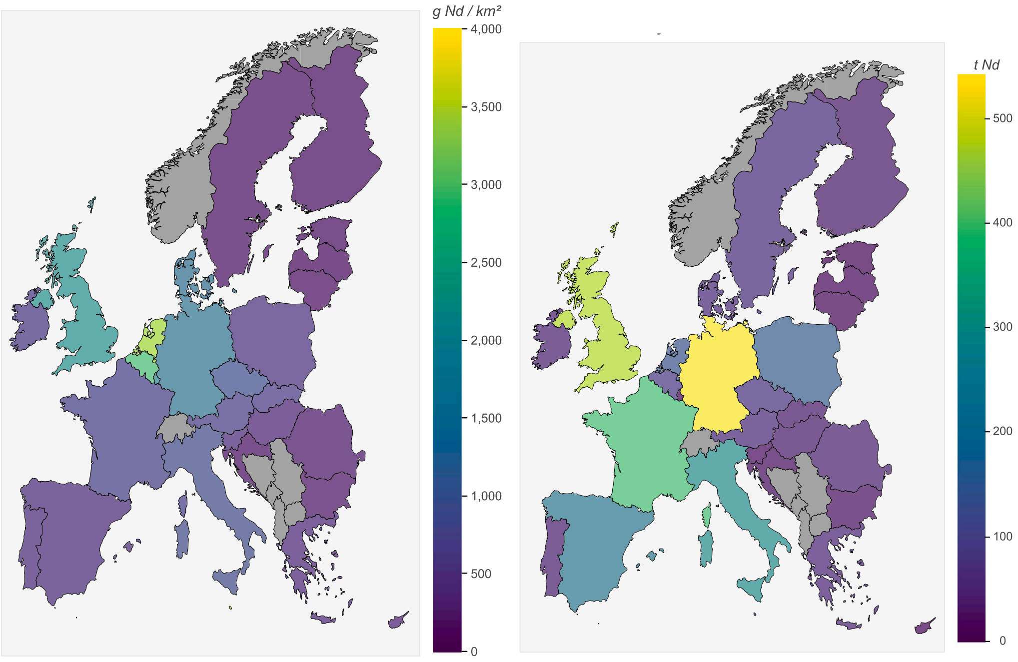
A comparison of annual Nd waste flows of European countries revealed large differences, as illustrated by Fig. 5. The waste density varies with almost two orders of magnitude, amounting to 75 g/km^2 for Latvia and 6.5 kg/km^2 for Malta. Besides Malta, high waste densities are found in other densely populated countries, Belgium and the Netherlands. The variation is also high for the absolute volume of Nd waste, coinciding with differences in population size (Fig. 5(b)). Unsurprisingly, the total Nd waste flow was largest in countries with a large population, such as Germany, France and the UK.

3.4. Neodymium stocks

Lastly, Nd stocks and flows were examined from a macro-level perspective. Since 2000, Nd flows increased annually by on average 112 t for waste and 225 t for consumption. Besides, Fig. 6 reveals an accumulating in-use stock, which results from a growing demand of long-lived products. The stock accumulation is mostly driven by industrial and automotive applications, see Fig. 6(b). This figure illustrates a contrast between stock build-up in various emerging technologies, and a net outflow of HDDs. In 2019, the stocks contained almost two thirds (63%) of all Nd resources consumed from 1985 onwards. The historic Nd waste flows are most likely dissipated to slags and steel alloys (Guyonnet et al., 2015; Thiébaud et al., 2018).

3.5. Recyclability assessment

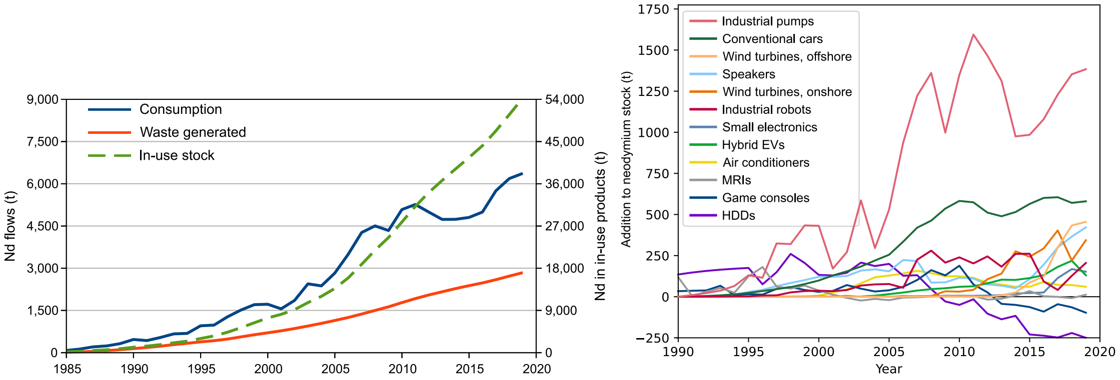
The recyclability assessment framework (Section 2.6) was applied to the product groups of BEV motors, HDDs, speakers, wind turbines and industrial pumps. By evaluating a set of indicators, drivers and barriers for recycling were identified, as described below. Table 3



(a) Waste flow density.

(b) Total waste flow.

Fig. 5. Geographic distribution of neodymium in waste per European country in 2019. Supplementary information F provides a data table.



(a) Totals for the period 1985-2019. Demand for Nd exceeds Nd in waste flows.

(b) Net addition to Nd stock, for products with a stock change greater than 150 t/a.

Fig. 6. Neodymium stock and flow trends for EU-28 countries.

summarizes the results per life cycle stage. All data and sources used in the assessment are reported in Supplementary information G.

Overarching. The recyclability of all five products is supported by the overarching social benefits. These benefits stem from avoiding primary mining of rare earths, and the associated safety hazards (Yang et al., 2017; Bailey, 2019) and labor rights violations (Kucera and Sari, 2020). A distinguishing economic driver is economies of scale. This limits the recyclability of emerging applications (wind turbines and BEVs) at present, whereas sufficient waste quantities are available from products used in mature markets. Financial barriers can be overcome by economic policy incentives, which do exist but not for magnet recycling specifically. All five products have a low supply chain alignment, lowering the recyclability score. A mixed picture is seen for uncertainty, with a remarkably high uncertainty for the future waste flow of industrial pumps and speakers and low uncertainty for wind turbines.

Manufacturing. None of the products is fully designed with recycling in mind, as can be seen from the way components are integrated. Magnets are often glued in place in pumps and speakers (Lixandru et al., 2017), while at best metal casings and screws are used in the other product designs (Talens Peiró et al., 2020; Walachowicz et al., 2014). On the other hand, many components have very similar designs, like HDDs and wind turbine rotors, which is favorable for routinized disassembly.

Use & collection. The collection rate of EoL products varies a lot. It is high for wind turbines (Reimer et al., 2018), as expected from the high collectability. Collection of wind turbines as well as pumps is enabled by their weight and company ownership. Speakers, HDDs and BEVs have a moderate collection rate. While their collectability is lower and uncontrolled export is a threat (Huisman et al., 2015), this is counterbalanced by strong waste policies. The lowest collection rate was found for industrial pumps, which were until recently

Table 3
Recyclability of selected waste flows. Aspects scores are normalized to the range 0–5, where 5 is most favorable for recycling.

Life cycle stage		EV motors	HDDs	Industrial pumps	Speakers	Wind turbines
Overarching	Supply chain alignment	1.3	1.0	0.5	0.5	3.0
	Uncertainty	3.3	4.0	1.7	1.6	4.5
	Economic drivers	1.4	1.9	3.0	3.0	2.4
	Social benefits	4.4	4.4	4.4	4.4	4.4
Manufacturing	Design for disassembly	1.6	2.8	2.0	2.3	4.2
Use & collection	Collectability	2.2	1.6	3.5	2.2	3.6
	Policy	3.0	2.3	0.5	2.3	3.8
	Collection rate	3.1	3.5	0.8	3.0	4.5
Preprocessing	Preprocessing performance	4.3	4.0	2.9	3.2	5.0
	Safety risk	3.5	3.0	5.0	4.5	4.5
Recovery	Environmental effects	4.8	4.8	4.8	4.8	4.8
	Recovery performance	4.9	3.9	4.4	4.9	4.4
	Technology availability	2.3	2.3	2.3	2.3	2.3
Secondary market	Demand	1.9	1.9	1.9	1.9	1.9
	Revenues	5.0	5.0	4.2	3.6	3.9

excluded from the WEEE directive (European Commission, 2012; Andersen, 2022). Although some pump manufacturers offer take-backs,[3] extensive collection systems are missing.

Preprocessing. Wind turbines have the most effective preprocessing, since the magnets are large, can be identified with ease and liberated effectively. For speakers and pumps, the challenge is to distinguish units with NdFeB magnets, as these products have a high market share of ferrite magnets.[4] All five waste flows have the advantage that they are free from hazardous substances. However, the waste treatment of HDDs is often subject to data protection regulations.

Recovery. Since the hydrogen decrepitation process is assumed to be used, the recovery performance is almost identical for all waste flows. Hydrogen decrepitation has several advantages, such as a high recovery efficiency, no toxic process chemicals (Walton et al., 2015), low GHG emissions (Miranda Xicotencatl et al., Submitted for publication), and no interference with recovery of other metals. On the other hand, the technology needs expertise and has intermediate maturity. Hydrometallurgical and pyrometallurgical technologies have a similarly high recovery. These alternatives are more mature, but also have higher environmental impacts.

Secondary market. All recycled magnets share the same secondary market. This market is characterized by a steady demand growth (Elshkaki, 2021) and a high price volatility (Bastian, 2020). The latter presents a barrier for long-term business planning. Recovered magnet alloys can generate relatively large revenues, even though a weak price premium is expected on top of the commodity price. The products differ regarding the co-recovered metals, which are valuable for HDDs and EVs and smaller for speakers.

Contrasting the five EoL products, significant differences exist in both product characteristics and value chains. These differences translate to diverse bottlenecks or barriers for recycling. As also observed in the MFA, the waste flows differ in annual quantity. Besides, big differences exist in product weight, design variation, and waste collection policies.

Aside from these differences, common drivers and barriers for Nd recycling can be identified. Prominent bottlenecks appear in the overarching factors, notably supply chain alignment. Additional bottlenecks are the metal price volatility and product design. A common driver is the recovery step, owing to the good performance and compatibility.

4. Discussion

4.1. Promising waste flows

This study has shown that a large share of neodymium is currently used for magnets in industrial applications. We identified pumps and robots as significant and growing contributors to Nd waste flows, as opposed to most previous studies on the EU level. Also, HDDs were identified as a major source for the near future, which is in line with earlier work (Thiébaud et al., 2018). We calculated a total Nd demand of 7.7 kt in 2019, while a previous study (Huisman et al., 2017), which disregarded industrial applications, found a much lower value. For other application groups such as vehicles, the results are in agreement.

Surprisingly, the recyclability assessment revealed that the recovery process – although immature – was not the main bottleneck for recycling. Instead potential bottlenecks are in design, waste collection and other steps that are product-dependent. This implies that the experience gained with one product might not be transferable to other products. Further R&D efforts on recycling should define target products and focus on these to develop relevant solutions.

In line with previous findings, a good recyclability was found for wind turbine magnets (Habib, 2019). Wind turbines scored above average for many recyclability indicators, except for the current waste flow. This implies that if the growth of wind energy follows the political ambitions, it becomes a highly attractive source of EoL magnets.

The rapid growth of Nd demand observed in this study has two major implications. First, the growth creates a large gap between Nd demand and the potential secondary supply (Fig. 6(a)). Even when Nd recycling is expanded to its full potential, virgin input is needed to meet the demand. Therefore, Nd recycling is unlikely to be hindered by limits to recycled content in magnets. Second, the in-use stock is growing, especially for long-lasting products. This stock creates an urgency to establish a recycling system soon, thereby avoiding dissipation through improper waste treatment.

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[3] Grundfos, personal communication

[4] Personal communication, B&C Speakers and Grundfos.

Countries differ considerably in terms of total Nd waste volume and waste density $(\mathrm{kg/km^2})$. This implies a trade-off for recycling industries, with the outcome depending on business characteristics. Pilot plants could best be established in countries with a high Nd waste density such as Belgium and the Netherlands. When upscaling opportunities are important, a country with a large total volume available would be preferred. Having access to material within a single jurisdiction avoids permitting procedures for waste export. Further upscaling is possible by importing waste flows from other countries.

4.2. Limitations & uncertainties

The dynamic MFA approach delivered results with a high level of detail, but also has some limitations. The strength of the followed approach, based on trade statistics, is the ability to model dynamic markets. Compared to a stock-driven approach, it allows to study products that are weakly linked to population size, e.g. industrial equipment. The statistical data were processed to correct for reporting errors. Still, some errors could remain, presenting a source of uncertainty.

The results are sensitive to the market penetration of NdFeB magnets, therefore this study considers market shares to be time-dependent. This approach leads to results that differ from other studies, as highlighted in a comparison for auxiliary vehicle motors (i.e. outside the drivetrain). These motors are identified as the presently largest source of EoL NdFeB magnets by two previous studies (Reimer et al., 2018; Ciacci et al., 2019). For 2018, Reimer et al. (2018) reported ~ 2600 t EoL auxiliary vehicle motor magnets (or 776 t Nd). Ciacci et al. (2019) calculated a similar amount for the year 2016. Our value for auxiliary motors is smaller (310 t in 2018), because we correct for the market share of NdFeB magnets based on Restrepo et al. (2017) and Habib et al. (2014). In fact, cars manufactured before 2000 only contain minor Nd quantities (Restrepo et al., 2017).

4.3. Future research

Market shares of permanent magnets are also expected to differ between countries, although it has been little researched. Only for passenger vehicles and wind turbines, regional differences were indicated (Nguyen et al., 2019; Carrara et al., 2020). Among EU countries, wealthier countries are expected to consume more high-end ('premium') versions of applications, featuring rare earth magnets more often. Tightening energy efficiency standards are expected for pumps and other motors, triggering a wider use of lightweight and strong NdFeB magnets. To understand the differences between countries, further research is needed.

This study investigated recyclability from a value chain perspective. As a next step, recyclers could investigate specific technical characteristics of waste flows. Relevant characteristics for NdFeB magnets include the type of coating and corrosion level (Burkhardt et al., 2020). In addition, feasibility studies could address the prevalence of sintered and bonded NdFeB magnets, since the magnet type determines what recycling technologies are applicable (Yang et al., 2017).

4.4. Improving the recycling system

The recyclability assessment complemented the MFA insights by broadening the perspective. The framework comprises both key material flow indicators and indicators of product properties and organizational structures. Besides, it allows to identify possible improvements to the recycling system of products. During the further development of neodymium recycling, the recyclability framework is useful for monitoring changes in recycling technologies, product properties and societal settings. Then trends can be identified that make recycling more worthwhile.

To optimize the recycling system, sufficient scales are needed and can be achieved through consolidation, i.e. combined processing of waste flows. The need for consolidation is most apparent for consumer electronics. In this waste flow, a shift is ongoing from HDDs to a diverse mix of appliances. Combined collection and sorting seems feasible in existing recycling centers, although each application needs different handling. For some industrial products, growing volumes could justify a dedicated collection system in the future. Such B2B take-back has organizational advantages.

Consolidation of disassembly is highly challenging due to the identified design variation and evolution. This could explain why disassembly pilots focus on single products (Bast et al., 2014; Zakotnik and Tudor, 2015; Baba et al., 2013). A possible solution is design standardization, which would facilitate e.g. EV motor recycling (Bast et al., 2014). Alternatively, an adaptive process could be developed, using sensing and detection tools. Metallurgical recovery processes are already capable of combined processing. To ensure the output quality, it is essential to characterize and monitor the inputs.

5. Conclusions

This research underlines the urgency for developing a neodymium recycling system in Europe, both to meet the growing demand for raw materials and to avoid resource losses. Our analysis identified a rising Nd consumption, which leads to growing waste flows in the future. We identified HDDs as a major Nd waste flow, providing attractive input for recyclers for some years. Nd waste associated with industrial pumps and robots, and conventional cars are becoming more significant. In one to two decades from now, it is expected that EoL EVs and wind turbines will become the major source of secondary Nd. These large and/or growing waste flows should be targeted first to achieve significant recycling.

The growth of NdFeB magnet waste flows enables new business opportunity due to economies of scale. However, the application of neodymium is dispersed over many products, which complicates standardized recycling. The recycling industry should adapt to the expected changes in quantities of EoL products. Most flexibility would be needed in sorting and disassembly facilities. For emerging products, appropriate dedicated recycling routes need to be developed in time to accommodate for their future waste flows. This involves the development of processes for each part of the recycling system, and can be informed by a recyclability assessment. To improve on recyclability, it is suggested to focus on the design and secondary market steps of the recycling chain.

This study has explored the neodymium waste flow dynamics in European countries and the recyclability of EoL products, thereby providing insight into the recycling potential and differences between countries. Our research has shown that new magnet applications emerged over time, creating successive waves of neodymium demand. Consequently, there will be different product groups that determine the future waste volumes. The availability and product properties of these future waste flows should be kept in mind when developing neodymium recycling systems.

Meanwhile, current waste flows provide an opportunity for the developing neodymium recycling industry. EoL products with good recyclability can be used to gain experience in Nd recovery. Before starting, companies should choose consciously which waste flows to process and in which countries to start, as large differences exist between them. These findings support the development of effective recycling technologies and systems to close neodymium resource loops.

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CRediT authorship contribution statement

Sander S. van Nielen: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Benjamin Sprecher:** Conceptualization, Writing – review & editing, Supervision, Funding acquisition. **Teun J. Verhagen:** Writing – review & editing. **René Kleijn:** Conceptualization, Methodology, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.jclepro.2023.136252. Supporting data for material flows and recyclability of neodymium waste: market share data, product lifespan, and spatial density of waste flows.

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