The dynamics of accelerating end-of-life rare earth permanent magnet recycling
A technological innovation systems approach

Koese, Maarten; van Nielen, Sander; Bradley, Jessie; Kleijn, René

DOI
10.1016/j.apenergy.2025.125707

Publication date
2025

Document Version
Final published version

Published in
Applied Energy

Citation (APA)
Koese, M., van Nielen, S., Bradley, J., & Kleijn, R. (2025). The dynamics of accelerating end-of-life rare earth permanent magnet recycling: A technological innovation systems approach. *Applied Energy*, *388*, Article 125707. https://doi.org/10.1016/j.apenergy.2025.125707

Applied Energy 388 (2025) 125707

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

The dynamics of accelerating end-of-life rare earth permanent magnet recycling: A technological innovation systems approach

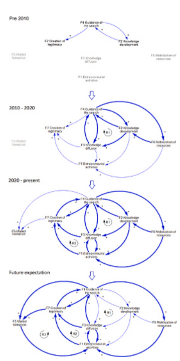
Maarten Koese [a,*], Sander van Nielen [a], Jessie Bradley [b], René Kleijn [a]

[a] Institute of Environmental Sciences (CML), Leiden University, Leiden, the Netherlands
[b] Faculty of Technology, Policy & Management, Delft University of Technology, Delft, the Netherlands

HIGHLIGHTS

- Technological Innovation System framework was applied to recycling permanent magnets;
- Identifying rapid growth of activity in the system around magnet recycling;
- Reinforcing loops were identified, indicating the system dynamics over time;
- Tapping into magnet waste flows is a critical challenge for scaling up recycling.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Rare earth permanent magnets
Recycling
Technological innovation systems
Circular economy
Supply chain resilience
Critical minerals

ABSTRACT

Demand for rare earth permanent magnets (REPMs) has grown drastically the past decades and is expected to increase further due to their use in electronics, electric vehicles and wind turbines. Rare earth supply challenges have increased the urgency to recycle End-of-Life (EoL) REPMs. This paper examined the development of global EoL REPM recycling by applying the Technological Innovation Systems (TIS) framework, assessing temporal development and dynamics between different aspects of the system. The analysis showed an acceleration of recycling innovation activities since 2013, evidenced by e.g. research and development initiatives, (commercial) pilot plants and media and policy attention. Activities were identified globally, with regional concentration of some functions. Innovation in EoL REPM recycling is mainly driven by policies and positive expectations, while entrepreneurial activities also contribute. The EoL REPM recycling TIS holds potential for further growth, if sufficient supplies of recyclable material are secured and a demand for recycled magnets is created. These goals can be achieved by developing the capacity to handle a diversity of waste products, by making recycling cost-effective, or by finding other marketing approaches for recycled magnets. This would enable the emergence of

Abbreviations: CLD, causal loop diagram; EoL, end-of-life; EU, European Union; EV, electric vehicle; HD, hydrogen decrepitation; NdFeB, neodymium-iron-boron; PM, permanent magnet; R&D, research and development; REE, rare earth element; REPM, rare earth permanent magnet; SD, system dynamics; TIS, technological innovation system.

* Corresponding author.
E-mail address: j.m.koese@cml.leidenuniv.nl (M. Koese).

https://doi.org/10.1016/j.apenergy.2025.125707
Received 20 February 2024; Received in revised form 12 February 2025; Accepted 9 March 2025
Available online 17 March 2025

an independent market. Together with other circular economy solutions, EoL REPM recycling can contribute to a more sustainable and resilient magnet supply.

1. Introduction

Rare Earth Elements (REEs), the 17 elements in the periodic table consisting of the lanthanides plus scandium and yttrium, are essential in many crucial technologies. They are used in various applications, ranging from lighting and military applications to electronics [1]. Demand for REEs has increased drastically the past decades and is expected to grow even more in the future, due to the energy transition [2,1,3]. Contrary to what their name suggests these elements are relatively abundant in the earth's crust. Several governments have labelled REEs as critical materials, e.g. the European Union (EU) [4], the US [5], Japan, China, Canada and Australia [6]. Materials are classified as critical when they are associated with supply risk, and they are considered essential for a country's economy at the same time.

REE supply is linked to both sustainability issues and supply risks. Regarding sustainability, mining and processing of REEs is associated with detrimental effects on the local environment and human health [7]. Extraction and purification of REE ores is energy-intensive [8], and may lead to radioactive and chemical pollution [9]. Regarding supply risk, China currently dominates the supply chain of these materials, accounting for around 70 % of primary production [10] and approximately 90 % of refined production [11]. This leads to potential supply risks for countries in the rest of the world. In 2010/2011, China installed an export ban on REEs following a conflict with Japan, which lead to a sharp increase in prices [12,13].

The detrimental impacts of REE production combined with the risk of supply disruption demands a holistic approach to increase sustainability and resilience of REE supply. Numerous strategies can enhance resilience and sustainability, albeit with their respective set of challenges. These strategies include supply diversification, stockpiling, and circular economy strategies; reduce, reuse, and recycle [14,8,13]. Diversifying supply of REEs has proven to be challenging – people are not keen on mines in their backyard [15], and building a whole mining or processing industry from scratch is difficult and time-consuming. Increasing stockpiles may lead to undesired price increases [12]. Reducing the use of REEs seems improbable – even if the amount per product is reduced, this is offset by the rapidly growing demand [16]. Substitution is difficult because of the specific material properties the REEs have; replacing them by other elements often reduces product performance [17]. Designing more durable products and making them fit for reuse seems to be a more promising approach [18,19]. The final strategy, i.e. increasing recycling rates of REEs, is the focus of this paper. Recycling is an important piece of the puzzle that reduces the demand for more environmentally damaging primary production [20,21].

One of the most important applications of REEs are rare earth permanent magnets (REPMs) made of neodymium-iron-boron (NdFeB), which are used in, among others, electronics, electric vehicles (EVs) and wind turbines. Because of the projected growth in EVs and wind turbines, demand for REPMs will show a similar upward trend. REPMs are the main driver behind REE demand growth [1]. Considering the challenges of environmental impacts and potential supply disruptions of REEs, awareness regarding recycling of these REPMs is increasing.

Although the political attention for REPM recycling is high [22,23,24], a clear view on the emerging recycling industry is lacking. Multiple technology options for recovering REEs from EoL REPMs recycling have been researched [25] and some are used in industrial applications today (e.g. Noveon [26]). However, there is very little insight in the recycling capacity and recycling rate of REPMs; many papers cite the poorly supported number of 1 % REE recycling [27,28,29]. It is expected however that the recycling rate will increase.

The aim of this research is to map and analyze the development of EoL REPM recycling technology, including its institutional embedding. In our research, we mainly focus on recycling of REPMs derived from EoL products, not on the recycling of manufacturing scrap. We used the concept of Technological Innovation Systems (TIS) [30] to analyze the innovation of REPM recycling technology as a whole, and the institutional infrastructure in which it is developed and deployed. Currently it is not fully clear how this innovation emerged, what the dynamics of the surrounding system are, and what this can tell us about its potential implementation in the future. Considering the increasing volumes of magnet waste, it is crucial to understand how REPM recycling can be developed and diffused as effectively as possible. This research aids in comprehending the progression and dissemination of EoL REPM recycling technology, consequently offering valuable insights for policymaking in the realm of a circular economy.

2. Theoretical background

In this section we present the key concepts employed in this paper. We first describe the concept of the Technological Innovation System (TIS), including its seven functions and its dynamics. Then, we provide an overview of the technology this paper focuses on, namely REPM recycling.

2.1. Technological innovation systems

The concept of a Technological Innovation System was first defined by Carlsson and Stankiewicz [30] as a '*dynamic network of agents interacting in a specific economic/industrial area under a particular institutional infrastructure and involved in the generation, diffusion, and utilization of technology*'. These systems promote innovation and the development of new technologies [31]. Analyzing the structure and dynamics of a TIS is essential for adequate innovation policy [32]. In TIS literature, innovation is considered as a mutual activity, emerging from interactions between various actors and organizations that are influenced by a particular institutional context [33]. A TIS thus focuses on a particular innovation or technology and the system surrounding it. The TIS framework is used to analyze innovation at the *meso* level on a local, national or global scale [31,33].

A TIS consists of a structure and functions. The structure of a TIS – the actors, institutional and physical infrastructure, and their interactions - can be considered its foundation, and remains relatively stable over time [33,32,34,35]. The functions of a TIS, however, are more dynamic. These functions refer to processes that should occur for innovation systems to perform well. This paper focusses on these TIS functions and their dynamics rather than the systems' structural elements, although the latter are accounted for implicitly. The seven functions are: *entrepreneurial activities; knowledge development; knowledge diffusion; guidance of the search; market formation; resources mobilization;* and *creation of legitimacy* [36,37]. A more elaborate overview of the functions can be found in section 3.2., Table 1. If policy makers want to influence the overall performance of the TIS, intervening in these functions is often the first step [38].

For a TIS to perform well and an innovation to be successful all seven functions should be fulfilled, leading to inter-function reinforcement and positive feedback loops [32]. These positive feedback loops, or virtuous cycles, ideally lead to widespread implementation of the new technology [34]. On the other hand, these feedback loops may also work the other way, with functions depreciating each other and thus weakening the TIS [37]. It is important to note that fulfilment of one function does not necessarily drive the innovation development directly, but the synthesis and interplay of different functions in the system does. Hekkert et al. [37] state one function often forms the basis of these feedback loops, also referred to as '*motors of change*'. Suurs and Hekkert [39] define four motors of sustainable innovation: the *Science and Technology Push Motor Motor (driven by guidance of the search)*, the *Entrepreneurial Motor (driven by entrepreneurial activities)*, the *Systems Building Motor (also driven by entrepreneurial activities)* and the *Market Motor (driven by market formation)*. Empirical studies suggest these motors follow each other in the order as discussed, in a so-called 'Succession Model of Innovation' [40]. The motors of innovation can be mapped to the phase of development of a technology. Hekkert et al. [40] identify five phases of development: pre-development, development, take-off, acceleration, and stabilization. A technology switches from pre-development to development when there is a working prototype, and from development to take-off when there is a commercial application. When there is fast market growth, the phase switches to acceleration, and finally, after market saturation, stabilization occurs. Pre-development can be linked to the *Science and Technology Push Motor*, development to the *Entrepreneurial Motor*, take-off to the *Systems Building Motor* and acceleration to the *Market Motor* [41].

2.2. REPM recycling technology and challenges

Various technologies have been explored for the recovery and recycling of EoL REPMs (see Fig. 1) [25]. The shortest recycling loop is through powder metallurgy, which recovers NdFeB powder from scrap magnets. This is often based on Hydrogen Decrepitation (HD), through which magnetic materials are broken down by using hydrogen's ability to cause lattice expansion and material embrittlement. Most hydrogen-based REPM recycling processes go even further and also include grain boundary engineering, in which additives are strategically incorporated at the grain boundaries to improve the magnetic properties of the final recycled magnet [42,43]. Other recycling technologies return materials to earlier steps of the supply chain. These technologies include pyrometallurgy, resulting in alloys or separated metals; electrorefining, yielding individual REE metals; gas-phase extraction, converting the metals into chlorides; and hydrometallurgy, turning the material into rare earth oxides [44,25]. The latter resembles the recovery of rare earths from primary ores and has been a foundational element of NdFeB production since its origin. These methods have been used successfully in industrial settings for decades [45], but for recycling of manufacturing scrap and waste rather than EoL REPMs [25].

Both the recycling after manufacturing and the recycling after use (Fig. 1) can play an important role in a circular economy. However, EoL

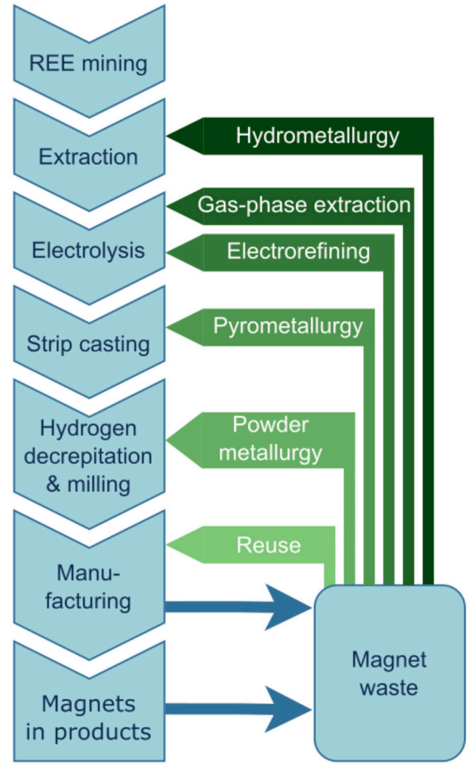


Fig. 1. Overview of NdFeB recovery methods, and the point of entry of material into the primary supply chain.

recycling better reflects efficiency improvements and contributes more to supply security [46,47] and is therefore the main focus of this research. EoL recycling is also less common and more difficult to realize than manufacturing scrap recycling. Although commercial-scale short loop recycling of EoL NdFeB-magnets is possible [48], multiple challenges remain. These challenges relate to e.g. EoL magnet waste collection and disassembly, lacking economies of scale due to small magnets and small waste flows, and uncertainty from volatile prices [49]. Still, the environmental benefits of magnet recycling are clear. Direct recycling involves less energy-intensive processing steps than magnet production with virgin materials [50] or other longer loop recycling methods, resulting in magnets with similar properties but

Table 1
The different functions of the Technological Innovation System and the indicators to assess them, based on Hekkert et al. [37], Hekkert and Negro [36] and Suurs et al. [34].

Function	Description	Indicators used in this study	Data sources, search engines
1. Entrepreneurial activities	Activities that turn new knowledge into business opportunities. These experiments lead to increased insight into the functioning of the technology under different circumstances, and how actors react to it.	Number of (pilot) plants	Extensive Google search, company websites, expert interviews
2. Knowledge development	This function entails both learning by searching as well as by doing.	Patents, academic publications	Patentscope, Web of Science
3. Knowledge diffusion through networks	Exchange of information among stakeholders is necessary to guarantee policy decisions are aligned with recent technological developments and R&D agendas are incorporating current norms and values.	Collaborative research projects, conferences, networks	Web of Science, extensive Google search, expert interviews
4. Guidance of the search	Specific technological options should be chosen to allocate sufficient time and resources to further explore this technology, dictated by preferences in society.	Policy documents, regulations	Governmental policies and regulations, research institutes reports, expert interviews
5. Market formation	Market formation, e.g. through creating niche markets or a competitive advantages through taxes or quotas, is essential since innovations often cannot compete with incumbent technologies.	Standards, regulations	ISO, governmental policies and regulations, expert interviews
6.Resources mobilization	Capital (financial and human) is essential for all activities within innovation systems. Resources are especially crucial for knowledge production.	Public and private investments	Public announcements and public government spending accounts
7. Creation of legitimacy	To become part of or overthrow the existing regime, innovations have to be legitimate. This legitimacy can be catalyzed by advocacy coalitions, through influencing agenda-setting, resources allocation and market formation.	Media coverage: news articles, lobby activities	NexisUni, expert interviews, lobby reports

lower environmental impacts [51]. Magnet-to-magnet recycling causes significantly lower environmental impacts than virgin magnet production [52,53]. Although we focus on EoL recycling of magnets in this paper, manufacturing scrap recycling still forms a relevant part of the EoL REPM recycling TIS, as this type of recycling contributes to the initial emergence of the TIS functions that are needed to further develop EoL REPM recycling.

Technology characteristics and maturity also play a role in the functions of a TIS [36]. The more mature a technology, the more likely the functions will be fulfilled. Following this, we expect a limited fulfilment of the functions related to REPM recycling, since the technology is relatively immature [44,54]. However, the technology is considered as an important solution to (future) pressing societal problems such as critical material supply constraints [16,21], and leading scholars call for market intervention to stimulate viability of recycling [55]. In this paper we will explore in what stage of the Succession Model of Innovation the technology around EoL REPM recycling currently is, in this way enabling focused policy action and a successful TIS in the future.

3. Methodology

This section presents the methods used for this research. First, we describe the sequence analysis method, followed by the data collection approach and a definition of indicators for each of the seven TIS functions. Finally, we discuss how we assess the functions, their interactions and how we synthesize the results. The geographical scope of our research is global, but we also zoom in on some prominent regions where possible. These regions are China, the EU, Japan and the US, since they are the most influential players in the rare earth landscape [56,57]. However, there might be a bias towards Western countries, since only sources written in English are used in this work. The main focus of our research is EoL REPM recycling, but we also assess manufacturing scrap recycling where relevant, as it forms part of the TIS for EoL recycling.

3.1. Sequence analysis

The development of a TIS can be assessed through a sequence analysis, in which change processes are analyzed as sequences of events [37]. The basis of this approach is the event: what central actors do or what happens to them. In the TIS context, Alkemade & Suurs [58] define an event as '*an instance of change with respect to actors, institutions and/or technology which is the work of one or more actors and which carries some public importance with respect to the system under investigation*'. Sequence analysis can capture cumulative causation, incidents, contextual effects and other dynamics of a system, which can be derived from the patterns of events [37,59]. The events serve as indicators of the functions of the scrutinized system, which enables the operationalization of system functions [60]. We adapted the approach of Hekkert et al. [37] and Suurs [60], which will be described in section 3.2 and 3.3.

3.2. Data collection

For the data collection, we combined two approaches: an explorative inductive approach and a deductive approach. For the first we collected data from general sources and subsequently categorized this to the different system functions (see Appendix (A) 1). For the deductive approach, we specifically searched for data for each function based on the operationalization of the different functions as proposed by Hekkert et al. [37] and Suurs et al. [34] (Table 1) (e.g. by conducting a patent search for the *knowledge development* function). Events were collected from various sources, i.e. academic journals, company/industrial/government reports, industry magazines, and the WIPO patent database [61]. A more elaborate description of the data collection per function can be found in A1.

3.3. Assessing functions, defining interactions and synthesizing results

After the data collection, the events were sorted by system function in case they were found through the inductive approach. If found through the deductive approach, the system function under which they should be categorized was evident. This enabled the plotting of indicators and thus the assessment of the functions over time [37,33]. An overview of the system functions, the events and their plots is provided in the results section of this paper. The approach per function is described in more detail in A1.

Subsequently, cause and effect relationships among functions were explored and identified, resulting in an overview of the dynamic system using causal Loop Diagrams (CLD). These CLDs highlight the main causal relationships between functions for the different stages of development. CLDs come from the field of System Dynamics (SD) modelling, and can be used to represent both qualitative and quantitative models [62]. In this research, we take a purely qualitative approach. CLDs have been used before in TIS literature, both as a general illustration [40] and for specific technologies [63,39,64]. What is noteworthy here is that the causal relations differ per technology. So, although theoretically almost all functions could cause a change in another function, this does not seem to happen in the same way for different technologies. In this paper, we explore which relationships are specifically relevant for the REPM recycling TIS at different points in time. The identified events and system dynamics were validated by conducting expert interviews. The experts were selected to broadly represent the field of REPM recycling, with various areas of expertise and nationalities. An anonymized overview of the respondents can be found in A1.8.

4. Results

This section describes the results of our research, categorized per system function and supported with figures. Subsequently we describe the narrative we distilled from these results, supported with CLDs showing the dynamics of the TIS over time.

4.1. F1. Entrepreneurial activities

The number of pilot plants for magnet recycling increased in the past 15 years. 32 pilot plants have been established or announced, with a

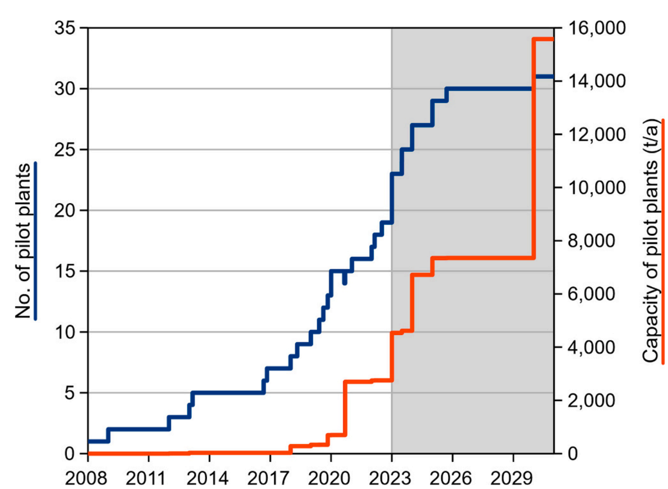


Fig. 2. Number of new plants (blue) and their total recycling capacity (red) for REE magnet recycling. The (expected) start of operation is displayed; when only the starting year was communicated, January 1st was assumed. For 11 of 32 facilities, no (estimated) capacity was released. The shaded area indicates future years. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

cumulative capacity of over 15,000 t/a (Fig. 2 and Table A2). The sector refers to pilot plants as facilities that test at a scale of around 100 t/a. When successful, these plants will enter in operation at full capacity, which is also indicated in Fig. 2 (when disclosed). The installed capacity lags behind the number of plants, because the first plants had a small capacity. The largest plants are still in the design and construction phase, and are expected to become operational over the coming years. Based on the announcements, the capacity is expected to increase from 2750 t/a at the end of 2022 to 15,578 t/a in 2030. Canada is expected to be the largest contributor with a capacity of around 10,000 t/a, followed by the EU (around 2900 t/a) and the US (around 2300 t/a). The UK and Japan will have a relatively small recycling capacity (140 t/a and 29.33 t/a respectively). A total recycling capacity of 15,578 t/a in 2030 would imply an EoL recycling rate of 17 % of the estimated 90 Mt. global NdFeB waste (total waste flow, calculated from [65]). This is a significant rate. Still, it should be noted that initially the plants will not operate at full capacity, and their actual recovery efficiency will also influence the results. Reported recycling potential lies around 90 % [66,65].

Most pilot plants employed hydrometallurgy (15 of 32), followed by powder metallurgy (11 plants). Almost all plants are located in the EU and North America. An overview of all plants can be found in the Appendix Table A2. In addition to the announced plants as depicted in Fig. 2, there is mention of 79 plants across five Chinese provinces, i.e. Jiangxi, Anhui, Jiangsu, Hunan and Guangdong. These plants only recycle manufacturing waste originating from Chinese magnet factories, most likely using hydrometallurgical technology. It is unclear when these plants were established and their total capacity was estimated at 170 kt/a in 2015 (XFA [67]).

Among the operators of recycling plants, three types can be distinguished: new entrants (companies that are founded with the purpose of magnet recycling), incumbents (producers of REEs or magnets that add recycling to their business model), and 'switchers' (companies that shift from another business to magnet recycling). 15 incumbents, 15 new entrants, and 2 switchers were counted. University spin-offs have played a significant role in the development of the recycling industry, illustrating the importance of academic research for the development of new technologies for REPM recycling. An important limiting factor for the emerging entrepreneurs is the access to end-of-life (EoL) magnets. Several challenges regarding access to EoL magnets and some examples of how companies tried to address these can be found in A2.1.

4.2. F2. Knowledge development

4.2.1. Academic research

Recycling of REPMs has received increasing attention in academic research in the past three decades (Fig. 3). While the number of papers published about the topic in the early nineties was very limited, this number has gradually increased to around 45 per year in the past three years. The papers vary in their focus and scope. Most papers describe a full process of REPM recycling, from EoL magnet to new magnet [48] or zoom in on one specific step of the process, such as decrepitation of the magnets to prepare them for further recycling [68]. A few papers consider REPM recycling from a systems perspective, like Sprecher et al. [21], who assess the potential contribution of Nd recycling to reduce supply scarcity or Deng and Ge [69], who explore different scenarios for wind power implementation and their effect on Nd demand and recycling. Finally there are papers focusing on the environmental impacts and benefits of REPM recycling, e.g. Karal et al. [70] finding lower impacts for magnets produced with recycled Nd instead of virgin material or Schulze et al. [71] and Jin et al. [72] who assess the impacts of several potential new recycling routes.

The status of knowledge regarding magnet recycling has been reviewed more extensively by Yang et al. [25] and Ormerod et al. [73]. In a recent study, the recycling barriers for various EoL magnets were studied [74]. The identified bottlenecks include product design, alignment between recycling chain partners, and willingness to pay for recycled magnets. Depending on the type of waste, either the content of NdFeB is low, or the total volume is limited [49]. Moreover, small-scale recycling can be costly, among others due to labour costs of manual disassembly [75]. Large-scale and automated recycling are estimated to be cost-competitive [66,76].

4.2.2. Patents

The number of patents related to REPM recycling has increased drastically since 2010 (Fig. 3). No patents from before 1994 were found. The total number of identified patents (excluding members of the same family) is 313 (based on Patentscope). The majority of patents originate from China (A2.2). These patents also provide insight into the different recycling technologies that are under development (Fig. 4). We distinguish five technology types, complemented by preprocessing of waste (See Fig. 1, and A1.3 for a definition of these processes). Hydrometallurgy is the most common recovery technology (38 % of patents), with roasting as an important sub-technology. The second largest group of

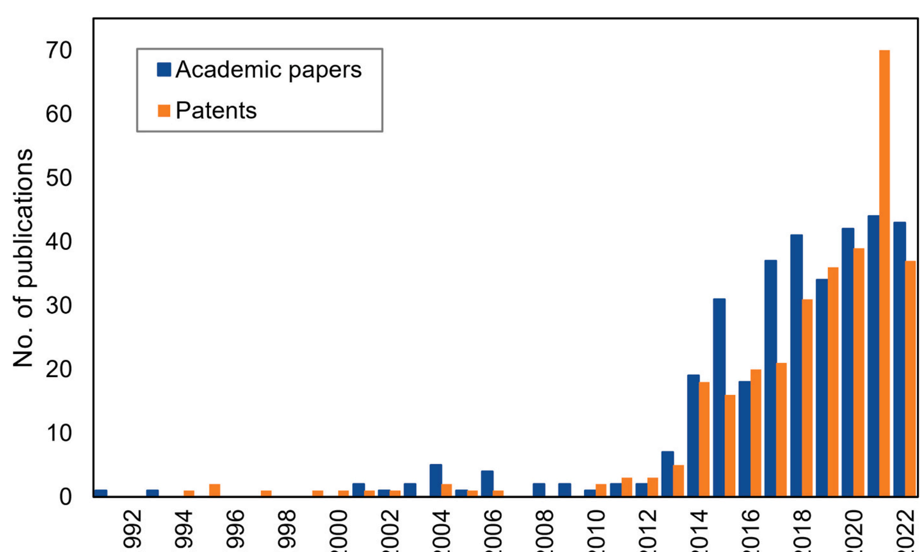


Fig. 3. Journal articles published regarding REPM recycling based on Web of Science and number of patents related to REPM recycling in the past decades. Patents of the same family are counted as one.

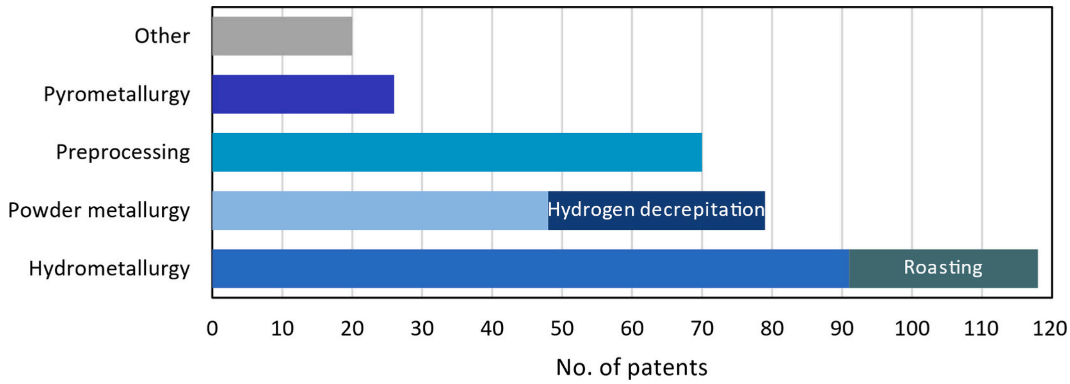


Fig. 4. Technology types of patents for REPM recycling, from 1994 to 2022. Preprocessing occurs in the magnet waste part of Fig. 1.

patents are related to powder metallurgy (25 %), many of which apply hydrogen decrepitation. This process is not only used for recycling, but also for primary magnet alloy production. Besides recovery techniques, 70 patents (22 %) described preprocessing, i.e. methods to liberate or sort EoL magnets. The small remainder of patents (6 %) is grouped as 'Other'. This category includes patents on gas-phase recovery, electrorefining, and unspecified technologies. Only 7 patents consider the recycling of bonded REPMs. The method of 71 patents (23 %) was explicitly applicable to manufacturing waste.

4.3. F3. Knowledge diffusion

4.3.1. Collaborative projects

The number of collaborative projects in magnet recycling research increased in the past decade (Fig. 5). In these projects, different stakeholders including knowledge institutes, companies, and governmental actors work together to create and diffuse knowledge related to magnet recycling. Such projects seem to be implemented especially in the EU and the UK; comparable initiatives were not found in other places. Examples of projects are SUSMAPGRO [77] or REEsilience [78], both aiming to establish a supply chain for magnet recycling and funded by the EU and/or the UK.

4.3.2. Conferences

Although the first conference sessions about EoL REPM recycling occurred in the late 1990s and early 2000s already, the amount of conferences with sessions about the topic increased slightly in the past decade (see A2.3). So far no conferences specifically dedicated to the topic of EoL REPM recycling have taken place; rather, sessions about the topic were organized as part of broader conferences related to magnets, metals, or rare earths. E.g. the Rare Earths Industry Association 2023 conference discussed rare earth supply chains in general, but some sessions were focused on magnet recycling. This indicates that the topic is considered important enough to devote some attention to, but not urgent enough to organize a separate conference for. See the Appendix A2.3 for more examples. The relatively low number of conference activities after 2020 can be explained by the COVID-19 pandemic, causing a pause in the organization of events. Due to the increase in academic papers and patents published (section 4.2.), more growth in diffusion activities is expected the coming years.

4.3.3. Networks

In addition to collaborative projects and conferences, networks are an indicator of *knowledge diffusion* around an innovation. Several (EU-funded) networks have been active in the rare earth sector (etn-DEMETER, n.d.; [79,67]). A considerable, still active network in the field is the *Rare Earths Industry Association* [80], an international non-profit organization representing the global rare earth industry. REIA's goal is to contribute to a more resilient rare earth industry, which includes recycling of REPMs. To achieve this, the network brings together relevant partners, and representatives of REIA are participating in various EU projects related to magnet recycling (e.g. [78,77]).

4.4. F4. Guidance of the search

We assessed guidance of the search based on policy documents. Several reports, policies and action plans clearly consider magnet recycling as an important aspect of increasing REE supply resilience

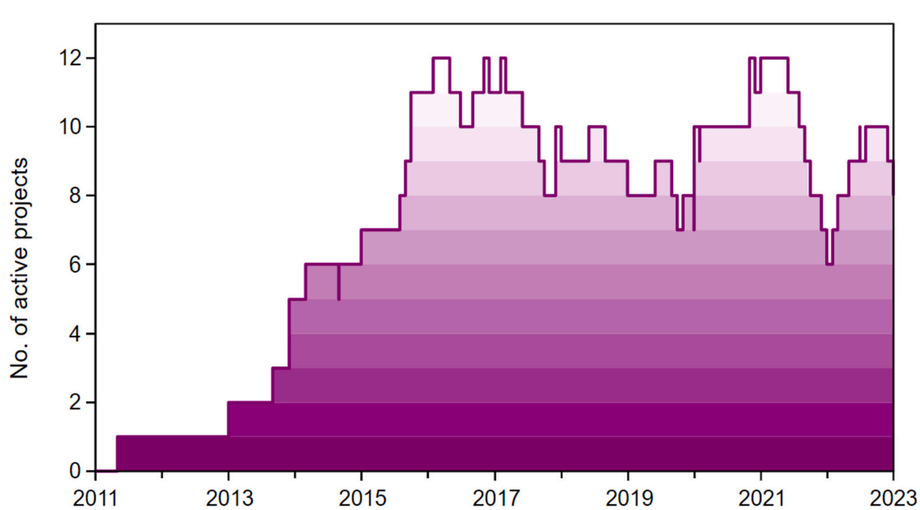


Fig. 5. Number of active collaborative projects in magnet recycling research, in the EU and the UK.

[81,82,83]. Magnet recycling also receives considerable attention in reports written by research institutes [16], or as part of EU funded projects [84,85]. Based on expert interviews, we found that in China recycling efforts for EoL magnets are not widespread, even though recycling of manufacturing waste and swarf is common practice. As mentioned before, 79 swarf recycling plants exist in China, with 170 kt/a capacity in [67] (XFA, [67]). Yet, economic and geopolitical incentives for EoL REPM recycling are lacking, due to the wide availability of cheap virgin material. This is different for Japan, which already invested in critical mineral recycling technology and diversification of its supply chain from the 1980s onward, establishing their first list of critical minerals in 1984. Their measures first focused on stockpiling but later also on supporting R&D on substitutes and recycling. In Japan's 2009 *Strategies to Secure Rare Metals*, securing resources overseas, recycling, substitute development and stockpiling were four main pillars. After the 2010/2011 Chinese export ban the priority to derive rare earths from non-Chinese sources was added, resulting in a reduced reliance on Chinese supplies from 85 % in 2009 to 58 % in 2018 [86].

The policy context and timeline in A2.4. show that attention for critical minerals in general has increased in the past decade. Awareness for this topic seems to be accelerated by the COVID19 pandemic in 2020 and the Russian invasion in Ukraine in 2022, which both contributed to recognition of global supply chain vulnerability and strategic autonomy. The pandemic caused severe shocks to both supply and demand of raw materials [87], and disrupted global trade and transportation leading to increased costs of products and reduced access to raw materials. As a consequence of the invasion in Ukraine, the USA, the EU and other countries and regions imposed sanctions against Russia disrupting global markets and causing increased prices for oil and consumer products [88]. The conflict caused concerns about the supply chains of critical metals as well [89] resulting in persistently higher prices than projected, i.e. a 36 % increase for nickel and 15 % for lithium [90]. The newly enacted EU's Critical Raw Materials Act [23] marks a milestone by introducing, for the first time, the target of establishing a minimum recycled content requirement for permanent magnets. However, specific targets for this requirement have not yet been determined and will likely be implemented before 2030.

The policy support for recycling appears to be high compared to other circular economy strategies. Circularity is increasingly embedded in policies, with Japan as the frontrunner (2000), the EU and China following in 2008 and finally the US (2021) (see A2.4.). Recycling plants and researchers receive financial support, recycled content targets are considered and waste collection directives are implemented. Policies are less specific when it comes to e.g. lower resource consumption, service life extension and more repairable and shareable products. These 'reduce and reuse' strategies could also be supported by generic policies, but it is clear that recycling receives more attention.

The *guidance of the search* for magnet recycling seems to be limited when it comes to the type of specific EoL REPM recycling technology. As described in Fig. 1 and Fig. 4, a range of recycling technologies is under development. Since different recycling technologies vary in their magnet outputs and treated waste streams, the existence of multiple technologies does not reflect a lack of consensus but different optimization goals and various market needs and applications. Scientific publications have contributed to some extent to the *guidance of the search* for technology type, i.e. manufacturing waste mainly being recycled through hydrometallurgical methods, while short loop hydrogen-based routes emerged later targeting magnet-to-magnet recycling (see section 2.2). Still, this level of detail is not reflected in policies yet. Generally *guidance of the search* seems to be present for critical mineral recycling, but it is less prominent for EoL REPM recycling and even less distinct for the specific recycling technology type.

4.5. F5. Market formation

4.5.1. Regulations

Several recently developed regulations contribute to market formation for recycled materials. In the proposed EU Critical Raw Materials Act [23] permanent magnets are described as *'a priority product for increasing circularity'*. Moreover, the mentioned recycled content requirement for magnets stimulates a business case for magnet recycling. Similar efforts are made in other countries, e.g. in Japan's recent Five-Point Plan for Critical Minerals Security [91] which specifically aims at promoting recycling of REPMs both in Japan as well as in developing countries. The market for recycled magnets is currently not stimulated by specific regulations, although generic policies exist. An interviewee confirmed that new transparency regulations have a big influence on the market, increasing the demand for recycled magnets.

4.5.2. Standards

In addition to regulations, standards can also be an indicator of market formation. ISO has prepared five standards that are relevant for REPM recycling. Three of these are published already, and provide standards for information sharing on and measurement of REE content in industrial and consumer/electronic waste. Two are currently under development, providing standards on the analysis of REPM scrap and the classification of recyclable NdFeB resources (see Appendix 2.5). This indicates that the industry calls for definitions and quality requirements. Standardization enables further growth of the recycling industry, because it gives buyers certainty about the quality of their purchases. An ISO working group (ISO/TC 298) has been in place since 2015 to internationalize these industrial standards.

4.6. F6. Resource mobilization

Between 2012 and 2022, more than €230 million was invested into EoL REPM recycling, both by public and private investors. It is important to note that we only include funding for projects directly related to the recycling of EoL REPMs. The largest share is invested in the US, entailing almost €120 million of investments. The US government provided funding to 12 individual organizations, of which almost 80 % was granted to Urban Mining Company (now called Noveon Magnetics), receiving $30 million. Almost €90 million was invested in the EU, with the European Commission funding 18 research projects. In the UK a total of €13.5 million was invested, with 6 research projects supported by the UK government. These EU and UK projects also serve as an indicator for *knowledge diffusion*, as discussed in section 4.3 (Fig. 5). Based on our expert interviews the Japanese government also invested in REPM recycling technology from around 2006/2007 onwards, although it is not clear to what extent. Data on Chinese investments were not accessible to us.

For private investments we rely on public announcements of investments in (pilot) plants. JLMag made the largest investment, investing $100 million in a magnet production and recycling facility in Mexico. However, due to the recent export ban on Chinese magnet production technologies, it is unclear whether this facility will be realized [92]. An overview of funding and investments is provided in Fig. 6, a full list can be found in A2.6. Projects often run for multiple years and their number is rather limited, explaining the fluctuations in funding provided to magnet recycling development over the past decade.

The outcomes of the investments are knowledge diffusion and pilot plants (section 4.1–4.2). In this context, it is remarkable that the majority of the (promised) recycling capacity is located in northern America. Facilities are being built by single companies. In contrast, the EU funds have mostly supported R&D consortia, where subsidies are divided across multiple organizations and resulting in smaller pilot facilities.

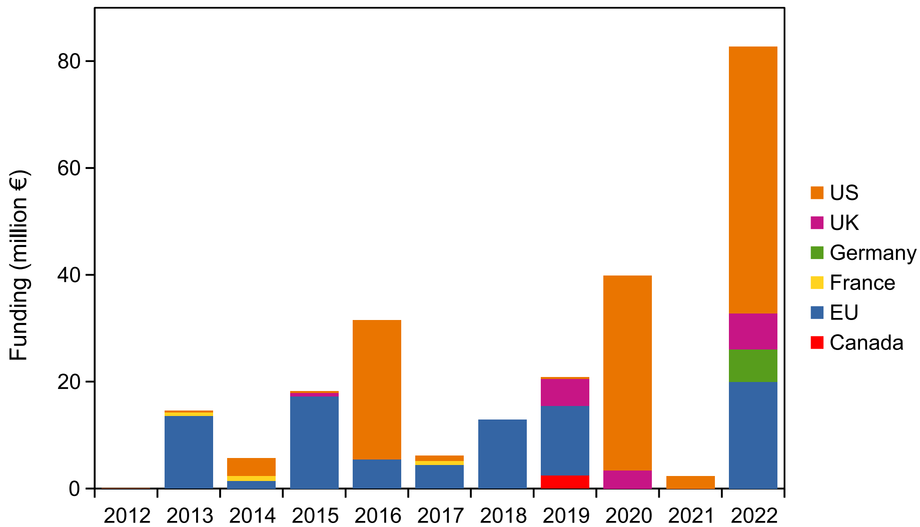


Fig. 6. Funding and investments provided to magnet recycling development and deployment, by country of destination and award date. Besides investing indirectly through the EU, Germany and France have also invested directly in magnet recycling, thus mentioned separately.

4.7. F7. Creation of legitimacy

The media coverage of rare earth recycling peaked first in 2010–2011 (Fig. 7), coinciding with the export ban from China to Japan and a REE price spike. We found only one publication from before 2008 [93]. News articles analyzed the rare earth market situation and discussed the need for recycling [94,95]. Three Japanese companies publicly announced plans for recycling activities: Hitachi, Mitsubishi and Shin-Etsu [96,97,98]. In the years after, the sentiment towards recycling was either neutral or mixed positive/negative. Market analyses continued to be published, as well as analyses of challenges and opportunities for recycling. Some news and opinion articles were critical about the effectiveness of recycling (e.g. [99,100]).

From 2020 onwards more listed companies and start-ups entered the magnet recycling market, as indicated by the amount of press releases from companies (in Newswires and Industry Trade Press). These companies announced investments, research findings, partnerships, acquisitions, pilot plants, and subsidies [101,102]. After the rise of attention in 2010–11, the media coverage was low or absent for several years. From 2019, newspapers have started to report again, from the angle of REE criticality and the geopolitical perspective [103]. In the last two years (2021–2022), newspapers shifted towards reports on solutions, such as recycling technologies and pilot plants [104,105]. A brief assessment of lobby activities, which also contribute to legitimacy, can be found in A2.7.

4.8. Synthesis of results

In this section we describe the fulfilment of the different functions over time, distinguishing several time periods. The interactions between the different functions in the last three time periods are illustrated through explorative causal loop diagrams (CLDs) (Fig. 8).

4.8.1. Pre-2010

Before 2010, there was very limited attention for EoL REPM recycling, despite pioneering technical research. REPMs were invented in the early 1980s [106]. In the period of 1980–2000, marked by globalization, security of mineral supply received little attention, particularly in the US and Europe. China directed some attention towards the topic by installing a Mineral Resources Law in 1982 [107], as did Japan by establishing a critical minerals list in 1984 [86]. Magnet recycling was hardly happening in this period and recycling rates for EoL rare earths were < 1 % [28]. During this period one news article was published about the topic, in addition to a handful of academic papers and patents. In the decade from 2000 to 2010, the first circular economy policies were implemented, in Japan, China and the EU. These three also guided attention towards mineral supply in their policies. Recycling of EoL REPMs did not receive considerable attention yet, although a very limited amount of *entrepreneurial activities*, patents and research papers appeared. Predating many policy initiatives, pioneering technical work in EoL REPM recycling was conducted, such as the development of hydrogen-based recycling processes providing a basis for practical

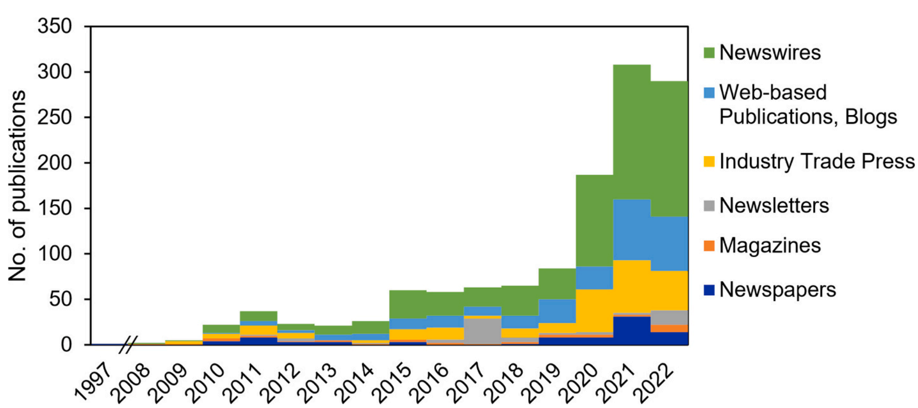


Fig. 7. Number of news articles on REPM recycling per news medium, as identified using Nexis Uni.

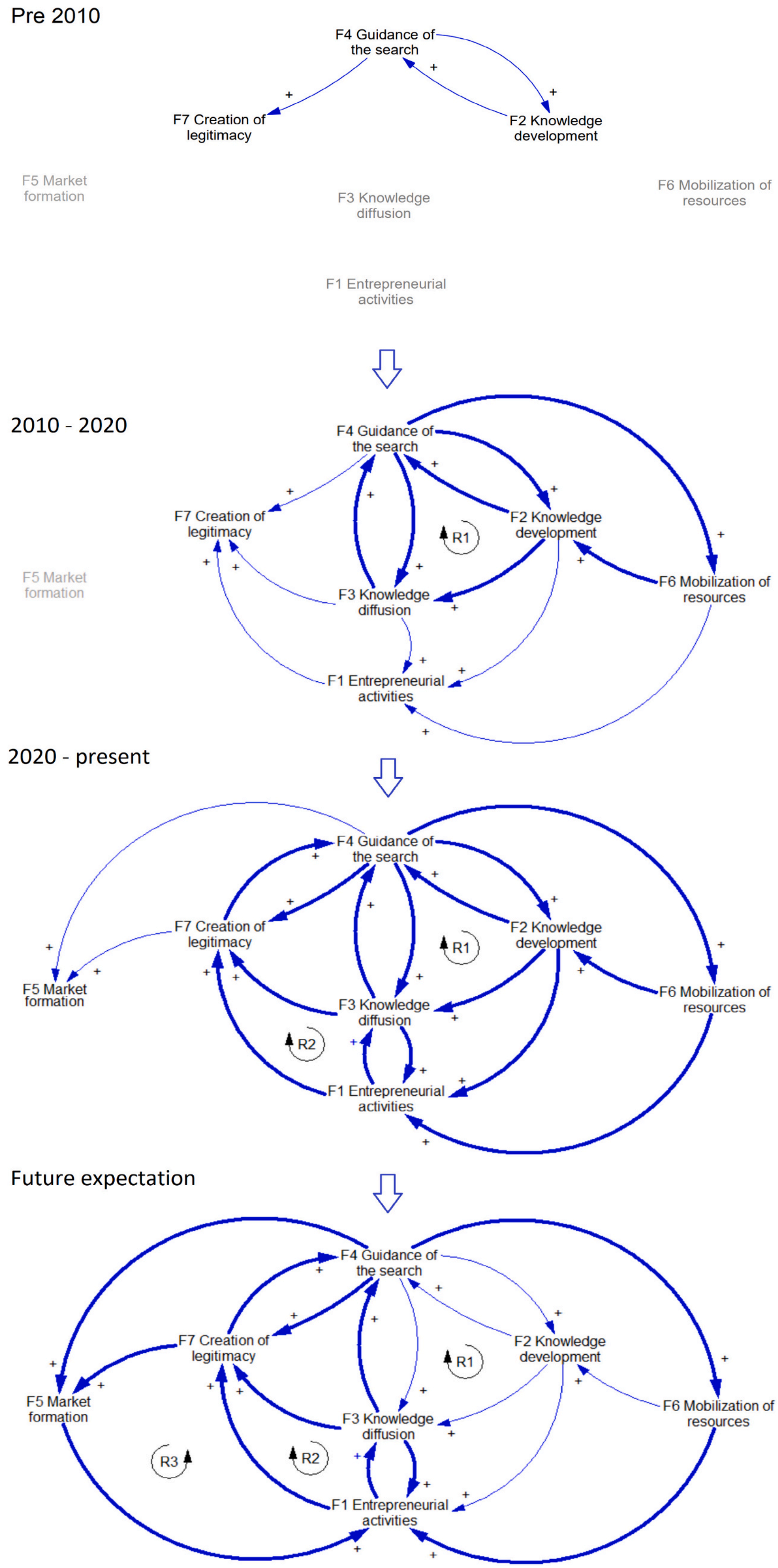


Fig. 8. CLDs of the REPM recycling TIS for three time periods. 2010–2020: pre-development. 2020 – present: development. Present – future: take-off (expectation). R1 = Science & Technology Push Motor. R2 = Entrepreneurial Motor. R3 = Systems Building Motor. The Market Motor is not shown, although it may emerge in the future. Gray = inactive function. Black = active function. Thicker connections are stronger.

recycling pathways in the future [108,109]. At the end of this period, the first subsidies to support recycling technology development were given by the Japanese government. Despite some technological groundwork, the pre-2010 era is marked by very limited *guidance of the search*, *creation of legitimacy* and *knowledge development*, without prevalent connections between these three functions. No motors of change were active in this period.

4.8.2. 2010–2020: pre-development

In the years 2010–2015 the concept of mineral criticality emerged in the US, and received increasing attention in China, the EU and Japan, accelerated by the growing demand of minerals for the energy transition. Geopolitical tensions arose regarding REEs, as illustrated by the Chinese export ban of REEs to Japan in 2010. Following this ban, REE prices rose considerably, which further increased awareness for circularity strategies. This triggered the attention for REE recycling and EoL REPM recycling, resulting in a steep growth in the publication of academic papers and patents, as well as an expansion in the amount of *entrepreneurial activities*. These developments were supported by investments. It seems in this period *the guidance of the search* function served as a trigger for the *Science and Technology Push Motor* [39].

From 2015 onwards a further growth in *knowledge development* and *entrepreneurial activities* regarding REPM recycling occurred. *Knowledge diffusion* also increased, through collaborative research projects and conference sessions. The resources invested in the innovation grew further and legitimacy was enhanced by a surge in news articles. *Guidance of the search* continued to drive the other functions, as indicated by an increase in supporting policies, flagship reports and strategies, all underlining the role of magnet recycling to enhance REE supply resilience. This indicates the continuation of the *Science and Technology Push Motor* in these years (feedback loop R1 in Fig. 8).

4.8.3. 2020-present: development

Awareness of supply resilience increased even further due to supply chain problems during and following the COVID-19 pandemic (2020) and the Russian invasion in Ukraine (2022). This lead to a strengthened *guidance of the search*, since EoL REPM recycling can contribute to strategic autonomy and supply resilience. The growth trend in patents and academic publications continued, and was accompanied by more investments in R&D related to EoL REPM recycling. The innovation gained traction in the public debate as indicated by the growth in published news articles. The amount of resources directed towards the innovation grew considerably, which could be the result of successful lobby for funding by entrepreneurs. This in turn supported *entrepreneurial activities*. Ongoing regulatory activities, like the Critical Raw Materials Act in the EU [23], aim to create a market for recycled magnets. It seems the *Science and Technology Push Motor* was still in force, indicated by strong *guidance of the search*. At the same time, the *Entrepreneurial Motor* seems to be emerging; entrepreneurs increasingly engage in magnet recycling and more private investments are mobilized, which leads to greater *legitimacy*, *guidance of the search*, *knowledge development* and *diffusion*, *resource mobilization*, and in turn a further increase in *entrepreneurial activities* (feedback loop R2 in Fig. 8).

4.8.4. Future expectation: Take-off

In the near future, the *Entrepreneurial Motor* is expected to gain traction, with more and more business activities and funding directed towards (pilot) plants. This will increase knowledge on how to deploy the EoL REPM recycling technology on an industrial scale. Technology demonstrations may then justify higher expectations, leading to increased legitimacy. If policy makers continue to provide *guidance of the search* and support *market formation*, the *Systems Building Motor* may emerge where *entrepreneurial activities* increase *knowledge diffusion* and *legitimacy*, further strengthening *guidance of the search* and *market formation* and in turn more *entrepreneurial activities* (feedback loop R3 in Fig. 8). Finally, the innovation may develop to the point where a market is established, with a demand independent of financial support, founding the *Market Motor*.

If the TIS develops as outlined here, it supports the hypothesis of the Succession Model of Innovation [39]. The speed of this Succession Model of Innovation is expected to depend on contextual factors as well, such as geopolitical tensions, developments in the energy transition and virgin material prices.

5. Discussion and conclusions

5.1. Key findings

To our knowledge, this research is the first to give a dynamic overview of the EoL REPM recycling TIS. We assessed all seven TIS functions by combining a wide range of data sources. We have identified a rapid growth of activity in the TIS around EoL REPM recycling for all functions, especially over the past decade. Some TIS functions, such as *guidance of the search*, are equally present in the main regions that we assessed, while other functions seem to hold a distinct geographical focal point. Most patents (*knowledge development*) are filed in China, while private *resource mobilization* is largest in the US. *Knowledge diffusion* emerges more in Europe, but can reach international audiences. Most functions have an effect that extends beyond borders, highlighting the benefit of the adopted global scope. Actors within the TIS could strengthen the innovation system by intensifying their international collaborations.

Pre-development of the REPM recycling TIS started in 2010, with the *guidance of the search* function triggering the *Science and Technology Push Motor*. This motor seems to be in force to this day, although the *Entrepreneurial Motor* is gaining momentum. While Hekkert & Suurs (2012) argue these motors generally succeed each other, in this case we see they are partly working at the same time, or at least have some overlap. With the *Science and Technology Push Motor* and the E*ntrepreneurial Motor* active, EoL REPM recycling is currently in the development phase, as defined by Hekkert et al. [40].

To transition to the take-off phase with a functioning market, EoL REPM recycling must become economically viable. Proposed policies have taken an initial step towards supporting EoL REPM recycling, but it is not yet evident whether they have had a discernible impact on *market formation.* Although entrepreneurs are increasingly engaging in recycling activities, most plants are still in the pilot phase and most businesses still depend on government subsidies. This corresponds to the findings of Binnemans et al. [55], who state that REPM recycling currently requires a lot of government involvement and funding, and the market is still artificial. To create a functioning market, both supply and demand are essential.

First, supply of recyclable EoL REPMs needs to be established. To achieve this, a few preconditions and technology characteristics which are not directly covered by the TIS functions are required. The growth potential of a recycling TIS partly depends on the availability of suitable feedstocks, but it also relies on the ability of the system to deal with these waste flows. Proper collection of magnet-containing waste needs to be realized to establish substantial recyclable waste flows. In addition, design of products needs to be adjusted in such a way that the magnets can be removed from products with little efforts or energy consumption [49]. The ability of the system to deal with these inputs is determined by the technology characteristics. A recycling TIS has more growth potential if it succeeds in handling a diverse range of feedstocks, from different sources and EoL products. This can be achieved by combining complementary recycling technologies, as developed for REPM recycling [44,25]. Rather than focusing on a specific recycling technology, policymakers should be aware of this complementarity and support recycling in general.

Second, sufficient demand of these recycled magnets should be assured. Demand could follow organically from external developments, such as geopolitical tensions or higher REE prices due to increased demand for magnets in the transitioning energy sector [69,12]. These developments would result in the natural emergence of a market for recycling, thus serving as an 'on' switch for *entrepreneurial activities* [32]. However, with China as a dominant actor actively guiding the magnets and rare earths prices, a business case for recycling emerging naturally is unlikely [110]. The demand for recycled magnets could be stimulated by further policy measures, e.g. by favourable taxes or subsidies, or setting standards for a minimum amount of recycled content in products [55].

5.2. Limitations and suggestions for further research

While some indicators gave a clear picture of the development of the TIS functions, others were more difficult to quantify or more distant from the corresponding function. For example, the measurement of the *knowledge development* function was effectively conducted due to readily available data on patents and academic publications. Conversely, gauging the *knowledge diffusion* function proved more challenging as data on networks, workshops and conferences is difficult to obtain systematically, and collaborations and other diffusion activities might be invisible in quantitative data and thus easily overlooked. To overcome the limitations of certain quantitative indicators, future research could benefit from more extensive expert interviews to gain additional insight into the diffusion of knowledge regarding REPM recycling. Moreover, connections between functions are even more difficult to measure than the functions themselves. We have used CLDs to provide insight into this, but direct connections cannot be determined. This research thoroughly explored these connections, but future research could place more emphasis on expert interviews to further validate these results. A stronger emphasis on interviews with experts from non-Western countries could also alleviate potential bias towards the Western world in this research. Since the searches were conducted in English, and data from countries like China is not always available, this research may have overlooked activities in non-Western countries. Although we tried to limit this bias by conducting interviews with experts from all the assessed regions, further research should incorporate the non-Western perspective better.

Future research providing more in-depth analysis into the different system functions would also be of value. E.g. for *resources mobilization*, there is considerable variety in funding strategies and outcomes. It would be interesting to further examine the effectiveness of the different strategies, and the policy implications for future funding choices. It would also be worthwhile to examine how one actor dominating patents (i.e. China) influences global collaboration and access to and adoption of new technology in other parts of the world.

Although recycling manufacturing waste is also crucial, this research focused on EoL recycling, since it is the most important approach to increase supply security [46,47]. Still, recycling should be part of a broader resource management strategy, also including other circular economy solutions. Despite the high expectations for EoL REPM recycling, it is still a relatively new technology which is not yet widespread. As explored in the System Dynamics model of Guzzo et al. [111], recycling can slow down resource depletion, but it is only one element of a circular economy. Recycling alone cannot fulfil a growing demand [112] and too much focus on recycling can create a dependency on EoL and waste materials and lead to lock-in situations in which consumption of products is encouraged [113]. Other circular economy solutions may be more effective in reducing the rare earth demand, while increasing resilience more directly. Resilience can be fortified by prolonging product lifespans, engaging in the remanufacturing of used magnets, redesigning products to function without REPMs, or reconsidering the societal need for products containing magnets.

In future research, the connections between functions could be quantified in a quantitative SD model. Such models have provided additional insights for other innovation systems [41,114,63,115]. The assessment could be combined with other SD models of the NdFeB supply chain (as proposed by e.g. [8,13]) to dynamically connect the TIS with other supply chain elements that can influence the TIS (and vice versa). Also for the magnet recycling TIS, SD can help to identify the effect of external developments, disruptive events and policies. We expect that most relevant insights can be gained if these SD models cover not only recycling, but also REE demand (including demand reduction by other circular strategies), supply, price and sustainability impacts. This approach would enable the study of dynamic interactions between recycling and other system elements.

CRediT authorship contribution statement

Maarten Koese: Writing – original draft, Visualization, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Sander van Nielen:** Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Jessie Bradley:** Writing – original draft, Visualization, Methodology, Formal analysis. **René Kleijn:** Writing – review & editing, Supervision, 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.

Acknowledgements

We would like to thank all interviewees for taking the time to talk to us. Furthermore, we would like to thank Benjamin Sprecher & Brenda Miranda Xicotencatl for the fruitful discussions about permanent magnets and recycling them.

Funding information

This research is funded by the European Union through the REEsilience project (grant agreement No. 101058598) and SUSMAGPRO project (grant agreement No. 821114) and UK Research and Innovation (UKRI) under the UK government's Horizon Europe funding guarantee grant number 10038960 as part of the Horizon Europe HORIZON-CL4-2021-RESILIENCE-01-07.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2025.125707.

Data availability

Data will be made available on request.

References

[1] Goodenough KM, Wall F, Merriman D. The rare earth elements: Demand, global resources, and challenges for resourcing future generations. Nat Resour Res 2018; 27(2):201–16. https://doi.org/10.1007/s11053-017-9336-5.

[2] Filippas A, Sempros G, Sarafidis C. Critical rare earths: the future of Nd & Dy and prospects of end-of-life product recycling. Materials Today: Proceedings 2021;37: 4058–63. https://doi.org/10.1016/j.matpr.2020.09.210.

[3] Imholte DD, Nguyen RT, Vedantam A, Brown M, Iyer A, Smith BJ, et al. An assessment of U.S. rare earth availability for supporting U.S. wind energy growth targets. Energy Policy 2018;113:294–305. https://doi.org/10.1016/j.enpol.2017.11.001.

[4] Blengini GA, El Latunussa C, Eynard U, De Matos CT, Wittmer DMAG, Georgitzikis K, et al. Study on the EU's list of critical raw materials (2020). Publications Office of the European Union; 2020. https://rmis.jrc.ec.europa.eu/uploads/CRM_2020_Report_Final.pdf.

[5] USGS, United States Geological Survey (2022). 2022 Final List of Critical Minerals. Retrieved from: https://www.usgs.gov/news/national-news-release/us-geological-survey-releases-2022-list-critical-minerals on 23-02-2023.

[6] Su Y, Hu D. Global dynamics and reflections on critical minerals. E3S web conference, 352, 7th international conference on energy science and applied technology (ESAT 2022). 2022. https://doi.org/10.1051/e3sconf/202235203045.

[7] Zapp P, Schreiber A, Marx J, Kuckshinrichs W. Environmental impacts of rare earth production. MRS Bull 2022;47(3):267–75. https://doi.org/10.1557/s43577-022-00286-6.

[8] Salim H, Sahin O, Elsawah S, Turan H, Stewart RA. A critical review on tackling complex rare earth supply security problem. Res Policy 2022;77:102697. https://doi.org/10.1016/j.resourpol.2022.102697.

[9] Weng Z, Haque N, Mudd GM, Jowitt SM. Assessing the energy requirements and global warming potential of the production of rare earth elements. J Clean Prod 2016;139:1282–97. https://doi.org/10.1016/j.jclepro.2016.08.132.

[10] USGS, United States Geological Survey (2023). Rare Earths Statistics and Information. Retrieved from: https://pubs.usgs.gov/periodicals/mcs2023/mcs2023-rare-earths.pdf on 23-03-2023.

[11] IEA. The role of critical minerals in clean energy transitions. Paris: International Energy Agency; 2021. https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions.

[12] Mancheri NA, Sprecher B, Bailey G, Ge J, Tukker A. Effect of Chinese policies on rare earth supply chain resilience. Resour Conserv Recycl 2019;142:101–12. https://doi.org/10.1016/j.resconrec.2018.11.017.

[13] Sprecher B, Daigo I, Murakami S, Kleijn R, Vos M, Kramer GJ. Framework for resilience in material supply chains, with a case study from the 2010 rare earth crisis. Environ Sci Technol 2015;49(11):6740–50.

[14] Ghisellini P, Cialani C, Ulgiati S. A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. J Clean Prod 2016;114:11–32. https://doi.org/10.1016/j.jclepro.2015.09.007.

[15] De Launey, G. (2022). Serbia revokes Rio Tinto lithium mine permits following protests. BBC News, *retrieved from* https://www.bbc.com/news/world-europe-60081853 on 23-02-2023.

[16] Gregoir L, van Acker K. Metals for clean energy: Pathways to solving Europe's raw materials challenge. KU Leuven: Eurometaux; 2022.

[17] Omodara L, Pitkäaho S, Turpeinen EM, Saavalainen P, Oravisjärvi K, Keiski RL. Recycling and substitution of light rare earth elements, cerium, lanthanum, neodymium, and praseodymium from end-of-life applications – A review. J Clean Prod 2019;236:117573. https://doi.org/10.1016/j.jclepro.2019.07.048.

[18] Blomsma F, Pieroni M, Kravchenko M, Pigosso DC, Hildenbrand J, Kristinsdottir AR, et al. Developing a circular strategies framework for manufacturing companies to support circular economy-oriented innovation. J Clean Prod 2019;241:118271. https://doi.org/10.1016/j.jclepro.2019.118271.

[19] Watari T, Nansai K, Nakajima K. Major metals demand, supply, and environmental impacts to 2100: A critical review. Resour Conserv Recycl 2021;164:105107. https://doi.org/10.1016/j.resconrec.2020.105107.

[20] Miranda Xicotencatl B, Kleijn R, van Nielen S, Donati F, Sprecher B, Tukker A. Data implementation matters: Effect of software choice and LCI database evolution on a comparative LCA study of permanent magnets. J Ind Ecol 2023;27(5):1252–65.

[21] Sprecher B, Xiao Y, Walton A, Speight J, Harris R, Kleijn R, et al. Life cycle inventory of the production of rare earths and the subsequent production of NdFeB rare earth permanent magnets. Environ Sci Technol 2014;48(7):3951–8.

[22] EPA, United States Environmental Protection Agency. Using Standards to Promote the Reuse of Rare Earth Materials. United States Environmental Protection Agency 2023. Retrieved from, https://www.epa.gov/vcs/using-standards-promote-reuse-rare-earth-materials. on 11-10-2023.

[23] European Commission. Critical Raw Materials Act (Proposal). https://single-market-economy.ec.europa.eu/publications/european-critical-raw-materials-act_en; 2023.

[24] Kaneko, S. (2023). G-7 eyes joint effort to turn e-waste into rare earths, other metals. Nikkei Asia. Retrieved from: https://asia.nikkei.com/Business/Materials/G-7-eyes-joint-effort-to-turn-e-waste-into-rare-earths-other-metals on 11-10-2023.

[25] Yang Y, Walton A, Sheridan R, Güth K, Gauß R, Gutfleisch O, et al. REE recovery from end-of-life NdFeB permanent magnet scrap: A critical review. Journal of Sustainable Metallurgy 2017;3:122–49. https://doi.org/10.1007/s40831-016-0090-4.

[26] Noveon Magnetics (2025). Our process. Retrieved from: https://noveon.co/ on 12-02-2025.

[27] Balaram V. Rare earth elements: A review of applications, occurrence, exploration, analysis, recycling, and environmental impact. Geosci Front 2019;10(4):1285–303. https://doi.org/10.1016/j.gsf.2018.12.005.

[28] Graedel TE, Allwood J, Birat JP, Buchert M, Hagelüken C, Reck BK, et al. Recycling rates of metals: A status report. United Nations Environment Programme; 2011.

[29] Jowitt SM, Werner TT, Weng Z, Mudd GM. Recycling of the rare earth elements. Current Opinion in Green and Sustainable Chemistry 2018;13:1–7. https://doi.org/10.1016/j.cogsc.2018.02.008.

[30] Carlsson B, Stankiewicz R. On the nature, function and composition of technological systems. J Evol Econ 1991;1(2):93–118. https://doi.org/10.1007/BF01224915.

[31] Ghazinoory S, Nasri S, Ameri F, Montazer GA, Shayan A. Why do we need 'problem-oriented innovation system (PIS)'for solving macro-level societal problems? Technol Forecast Soc Chang 2020;150:119749. https://doi.org/10.1016/j.techfore.2019.119749.

[32] Negro SO, Suurs RA, Hekkert MP. The bumpy road of biomass gasification in the Netherlands: Explaining the rise and fall of an emerging innovation system. Technol Forecast Soc Chang 2008;75(1):57–77. https://doi.org/10.1016/j.techfore.2006.08.006.

[33] Huang P, Negro SO, Hekkert MP, Bi K. How China became a leader in solar PV: An innovation system analysis. Renew Sust Energ Rev 2016;64:777–89. https://doi.org/10.1016/j.rser.2016.06.061.

[34] Suurs RA, Hekkert MP, Kieboom S, Smits RE. Understanding the formative stage of technological innovation system development: The case of natural gas as an automotive fuel. Energy Policy 2010;38(1):419–31. https://doi.org/10.1016/j.enpol.2009.09.032.

[35] Wieczorek AJ, Hekkert MP. Systemic instruments for systemic innovation problems: A framework for policy makers and innovation scholars. Sci Public Policy 2012;39(1):74–87. https://doi.org/10.1093/scipol/scr008.

[36] Hekkert MP, Negro SO. Functions of innovation systems as a framework to understand sustainable technological change: Empirical evidence for earlier claims. Technol Forecast Soc Chang 2009;76(4):584–94. https://doi.org/10.1016/j.techfore.2008.04.013.

[37] Hekkert MP, Suurs RA, Negro SO, Kuhlmann S, Smits RE. Functions of innovation systems: A new approach for analysing technological change. Technol Forecast Soc Chang 2007;74(4):413–32. https://doi.org/10.1016/j.techfore.2006.03.002.

[38] Bergek A, Jacobsson S, Carlsson B, Lindmark S, Rickne A. Analyzing the functional dynamics of technological innovation systems: A scheme of analysis. Res Policy 2008;37(3):407–29. https://doi.org/10.1016/j.respol.2007.12.003.

[39] Suurs R, Hekkert M. Motors of Sustainable Innovation: Understanding transitions from a technological innovation System's perspective: Roald Suurs and Marko Hekkert. In: Governing the energy transition. Routledge; 2012. p. 163–90.

[40] Hekkert M, Negro S, Heimeriks G, Harmsen R. Technological innovation system analysis: a manual for analysts. Utrecht University 2011;16.

[41] Azad SM, Ghodsypour SH. Modeling the dynamics of technological innovation system in the oil and gas sector. Kybernetes 2017;47(4):771–800. https://doi.org/10.1108/K-03-2017-0083.

[42] Zakotnik M, Harris IR, Williams AJ. Possible methods of recycling NdFeB-type sintered magnets using the HD/degassing process. J Alloys Compd 2008;450(1–2):525–31.

[43] Zakotnik M, Harris IR, Williams AJ. Multiple recycling of NdFeB-type sintered magnets. J Alloys Compd 2009;469(1–2):314–21.

[44] Binnemans K, Jones PT, Blanpain B, Van Gerven T, Yang Y, Walton A, et al. Recycling of rare earths: A critical review. J Clean Prod 2013;51:1–22. https://doi.org/10.1016/j.jclepro.2012.12.037.

[45] Huang XW, Long ZQ, Wang LS, Feng ZY. Technology development for rare earth cleaner hydrometallurgy in China. Rare Metals 2015;34:215–22.

[46] Bradley JE, Auping WL, Kleijn R, Kwakkel JH, Sprecher B. Reassessing tin circularity and criticality. J Ind Ecol 2024;28(2):232–46.

[47] Helbig C, Bruckler M, Thorenz A, Tuma A. An overview of indicator choice and normalization in raw material supply risk assessments. Resources 2021;10(8):79. https://doi.org/10.3390/resources10080079.

[48] Zakotnik M, Tudor CO. Commercial-scale recycling of NdFeB-type magnets with grain boundary modification yields products with 'designer properties' that exceed those of starting materials. Waste Manag 2015;44:48–54. https://doi.org/10.1016/j.wasman.2015.07.041.

[49] van Nielen SS, Sprecher B, Verhagen TJ, Kleijn R. Towards neodymium recycling: Analysis of the availability and recyclability of European waste flows. J Clean Prod 2023;394:136252. https://doi.org/10.1016/j.jclepro.2023.136252.

[50] Zakotnik M, Tudor CO, Peiró LT, Afiuny P, Skomski R, Hatch GP. Analysis of energy usage in Nd–Fe–B magnet to magnet recycling. Environ Technol Innov 2016;5:117–26. https://doi.org/10.1016/j.eti.2016.01.002.

[51] Burkhardt C, van Nielen S, Awais M, Bartolozzi F, Blomgren J, Ortiz P, et al. An overview of Hydrogen assisted (Direct) recycling of Rare earth permanent magnets. J Magn Magn Mater 2023;588:171475.

[52] van Nielen SS, Xicotencatl BM, Tukker A, Kleijn R. Ex-ante LCA of magnet recycling: Progressing towards sustainable industrial-scale technology. J Clean Prod 2024;458:142453.

[53] Wang QQ, Wang L, Zhao S, Li FP, Chen WQ, Wang P. A critical life cycle assessment of present and potential rare earth circularity routes from permanent magnets. Resour Conserv Recycl 2025;215:108106.

[54] Swain N, Mishra S. A review on the recovery and separation of rare earths and transition metals from secondary resources. J Clean Prod 2019;220:884–98. https://doi.org/10.1016/j.jclepro.2019.02.094.

[55] Binnemans K, McGuiness P, Jones PT. Rare-earth recycling needs market intervention. Nature Reviews Materials 2021;6(6):459–61. https://doi.org/10.1038/s41578-021-00308-w.

[56] Hu X, Sun B, Wang C, Lim MK, Wang P, Geng X, et al. Impacts of China's exports decline in rare earth primary materials from a trade network-based perspective. Res Policy 2023;81:103321. https://doi.org/10.1051/e3sconf/202235203045.

[57] Zhou L, Xiao W, Yan N. International comparative research on the relevance of science and technology and the innovation ability of the rare earth industry-from the perspective of technology-industry mapping based on patent information. Res Policy 2023;80:103257. https://doi.org/10.1016/j.resourpol.2022.103257.

[58] Alkemade F, Suurs RA. Patterns of expectations for emerging sustainable technologies. Technol Forecast Soc Chang 2012;79(3):448–56. https://doi.org/10.1016/j.techfore.2011.08.014.

[59] Suurs RA, Hekkert MP. Cumulative causation in the formation of a technological innovation system: The case of biofuels in the Netherlands. Technol Forecast Soc Chang 2009;76(8):1003–20. https://doi.org/10.1016/j.techfore.2009.03.002.

[60] Suurs RA. Motors of sustainable innovation: Towards a theory on the dynamics of technological innovation systems. Utrecht University; 2009.

[61] WIPO. *Patentscope*. World intellectual property organization. Available at: https://patentscope.wipo.int/search. [Accessed 19 January 2023].
[62] Sterman J. Business dynamics. Irwin/McGraw-Hill, Boston: Systems Thinking and Modeling for a Complex World; 2000.
[63] Sadabadi AA, Rahimi Rad Z, Azimzadeh H. Photovoltaic technological innovation system (PV TIS) in Iran: identifying barriers, incentives, dynamics and developing policies. J Environ Plan Manag 2022:1–24. https://doi.org/10.1080/09640568.2022.2043837.
[64] Wicki S, Hansen EG. Clean energy storage technology in the making: an innovation systems perspective on flywheel energy storage. J Clean Prod 2017;162:1118–34. https://doi.org/10.1016/j.jclepro.2017.05.132.
[65] Schulze R, Buchert M. Estimates of global REE recycling potentials from NdFeB magnet material. Resour Conserv Recycl 2016;113:12–27. https://doi.org/10.1016/j.resconrec.2016.05.004.
[66] Beylot A, Menad N-E, Seron A, Delain M, Bizouard A, Ménard Y, et al. Economic assessment and carbon footprint of recycling rare earths from magnets: evaluation at lab scale paving the way toward industrialization. J Ind Ecol 2020;24(1):128–37. https://doi.org/10.1111/jiec.12943.
[67] ERECON. European Rare Earths Competency Network. Strengthening the European rare earths supply chain; 2015. Retrieved from: https://ec.europa.eu/docsroom/documents/10882.
[68] Kaplan V, Feldman Y, Gartsman K, Leitus G, Wachtel E, Lubomirsky I. Electrolytic hydrogen Decrepitation of NdFeB magnets under ambient conditions. Journal of Sustainable Metallurgy 2022;8(3):1290–8. https://doi.org/10.1007/s40831-022-00574-0.
[69] Deng X, Ge J. Global wind power development leads to high demand for neodymium praseodymium (NdPr): A scenario analysis based on market and technology development from 2019 to 2040. J Clean Prod 2020;277:123299. https://doi.org/10.1016/j.jclepro.2020.123299.
[70] Karal E, Kucuker MA, Demirel B, Copty NK, Kuchta K. Hydrometallurgical recovery of neodymium from spent hard disk magnets: A life cycle perspective. J Clean Prod 2021;288:125087. https://doi.org/10.1016/j.jclepro.2020.125087.
[71] Schulze R, Abbasalizadeh A, Bulach W, Schebek L, Buchert M. An ex-ante LCA study of rare earth extraction from NdFeB magnet scrap using molten salt electrolysis. Journal of Sustainable Metallurgy 2018;4:493–505. https://doi.org/10.1007/s40831-018-0198-9.
[72] Jin H, Frost K, Sousa I, Ghaderi H, Bevan A, Zakotnik M, et al. Life cycle assessment of emerging technologies on value recovery from hard disk drives. Resour Conserv Recycl 2020;157:104781. https://doi.org/10.1016/j.resconrec.2020.104781.
[73] Ormerod J, Karati A, Baghel APS, Prodius D, Nlebedim IC. Sourcing, refining and recycling of rare-earth magnets. Sustainability 2023;15(20):14901. https://doi.org/10.3390/su152014901.
[74] van Nielen SS, Kleijn R, Sprecher B, Xicotencatl BM, Tukker A. Early-stage assessment of minor metal recyclability. Resour Conserv Recycl 2022;176:105881. https://doi.org/10.1016/j.resconrec.2021.105881.
[75] Jones, W. (2017). Final environmental and economic report: Considerations and future guidance. In resource efficient production route for rare earth magnets (issue 7.6).
[76] Talens Peiró L, Castro Girón A, Gabarrell i Durany, X.. Examining the feasibility of the urban mining of hard disk drives. J Clean Prod 2020;248:119216. https://doi.org/10.1016/j.jclepro.2019.119216.
[77] SUSMAGPRO. Sustainable Recovery, Reprocessing and Reuse of Rare Earth Magnets in a European Circular Economy. https://www.susmagpro.eu/about-susmagpro; 2023.
[78] REEsilience. Resilient and sustainable REE supply chains for the e-mobility and renewable energy ecosystems and strategic sectors. https://reesilience.eu/; 2023.
[79] EREAN. European Rare Earth (Magnet) Recycling Network. https://fp7-erean.eu/index.php; 2017.
[80] REIA. Rare Earth Industry Association. Available from: https://www.global-reia.org/; 2023.
[81] Bobba, S., Carrara, S., Huisman, J., Mathieux, F., Pavel, C. Critical raw materials for strategic technologies and sectors in the EU -A Foresight Study 2020. European Commission Joint Research Centre. https://rmis.jrc.ec.europa.eu/uploads/CRMs_for_Strategic_Technologies_and_Sectors_in_the_EU_2020.pdf.
[82] Gauß R, Burkhardt C, Carencotte F, Gasparon M, Gutfleisch O, Higgins I, et al. Rare earth magnets and motors: A European call for action. A report by the rare earth magnets and motors cluster of the European raw materials Alliance, Berlin. https://erma.eu/app/uploads/2021/09/01227816.pdf; 2021.
[83] Gislev M, Grohol M, Mathieux F, Ardente F, Bobba S, Nuss P. Report on critical raw materials and the circular economy. European Commission: Brussels, Belgium; 2018. https://op.europa.eu/en/publication-detail/-/publication/d1be1b43-e18f-11e8-b690-01aa75ed71a1.
[84] Boissenin C, Ferrara F, Hanen S, Prek M. Obstacles, impacts and recommendations for the future of European rare earth elements value chain. Prospex Insitute: SecREEts Fourth Policy Council; 2022. https://www.sintef.no/contentassets/9bb7bf0272ad4f7996943f341be5b875/pi_secreets-report_september_final_v2.pdf.
[85] Rizos V, Righetti E, Kassab A. Developing a supply chain for recycled rare earth permanent magnets in the EU. INSPIRES project, CEPS In-Depth Analysis; 2022. https://www.ceps.eu/ceps-publications/developing-a-supply-chain-for-recycled-rare-earth-permanent-magnets-in-the-eu/.
[86] Nakano J. The geopolitics of critical minerals supply chains – Japan. In: Center for Strategic and International Studies (CSIS); 2021. Retrieved from: https://www.jstor.org/stable/resrep30033.8.
[87] Habib K, Sprecher B, Young SB. COVID-19 impacts on metal supply: How does 2020 differ from previous supply chain disruptions? Resources, Conservation and Recycling; 2021. p. 105229.
[88] Allam Z, Bibri SE, Sharpe SA. The rising impacts of the COVID-19 pandemic and the Russia–Ukraine war: energy transition, climate justice, global inequality, and supply chain disruption. Resources 2022;11(11):99.
[89] OECD. The supply of critical raw materials endangered by Russia's war on Ukraine. OECD 2022. https://doi.org/10.1787/e01ac7be-en.
[90] Khurshid A, Chen Y, Rauf A, Khan K. Critical metals in uncertainty: How Russia-Ukraine conflict drives their prices? Res Policy 2023;85:104000. https://doi.org/10.1016/j.resourpol.2023.104000.
[91] METI, Japan''s Ministry of Economy Trade and Industry. Five-Point Plan for Critical Minerals Security. https://www.meti.go.jp/information/g7hirosima/energy/pdf/Annex005.pdf; 2023.
[92] Liu, S. & Patton, D. (2023). China bans export of rare earths processing tech over national security. Reuters Retrieved from: https://www.reuters.com/markets/commodities/china-bans-export-rare-earths-processing-technologies-2023-12-21/ on 24-05-2024.
[93] Adams B. S.L. flutist adds new composition to her lyrical life. Salt Lake City: Deseret News; 1997. https://advance.lexis.com/api/document?collection=news&id=urn:contentItem:3SCG-N0B0-00DS-91BG-00000-00&context=1516831.
[94] Clenfield J, Yasu M, Biggs S. Japan turns to recycling to ease rare earth squeeze. South Africa: The Star; 2010. https://advance.lexis.com/api/document?collection=news&id=urn:contentItem:51ND-30G1-JCV0-12MM-00000-00&context=1516831.
[95] Tabuchi H. Mining trash for rare earths. Yukon: Yukon News; 2010. https://advance.lexis.com/api/document?collection=news&id=urn:contentItem:516D-0JJ1-JCDW-F147-00000-00&context=1516831.
[96] Jiji. Mitsubishi materials to establish rare earth magnet recycling. Jiji Press Ticker Service; 2010. https://advance.lexis.com/api/document?collection=news&id=urn:contentItem:5162-V8S1-JCF4-K4G1-00000-00&context=1516831.
[97] Jiji. Shin-Etsu chemical to start rare earth recycling. Jiji Press Ticker Service; 2010. https://advance.lexis.com/api/document?collection=news&id=urn:contentItem:516G-SMB1-JCF4-K0GM-00000-00&context=1516831.
[98] TNS. Hitachi develops recycling technologies for rare earth metals. Targeted News Service 2010. https://advance.lexis.com/api/document?collection=news&id=urn:contentItem:5211-7PV1-JC11-11JK-00000-00&context=1516831.
[99] Riley A. Even with recycling and substitution, there's only so far rare earth consumers can stretch available supplies. American Metal Market Monthly 2010. https://advance.lexis.com/api/document?collection=news&id=urn:contentItem:7YKR-PXC1-2SG3-S0GY-00000-00&context=1516831.
[100] Worstall T. An amazingly sensible decision on recycling rare earths from DoD: don't. PandoDaily; 2014. https://advance.lexis.com/api/document?collection=news&id=urn:contentItem:5BYF-GF71-F03R-N09X-00000-00&context=1516831.
[101] Hotter A. HyProMag sets up German unit to recycle rare-earth magnets. Metal Bulletin Daily Alerts 2021. https://advance.lexis.com/api/document?collection=news&id=urn:contentItem:643R-S6W1-F0GS-H35V-00000-00&context=1516831.
[102] Impact Financial News. Geomega resources signs LOI with Everwin Magnetics. Impact Financial News, https://advance.lexis.com/api/document?collection=news&id=urn:contentItem:61XV-NVT1-JDG9-Y0G0-00000-00&context=1516831; 2021.
[103] Peel M, Sanderson H. Brussels sounds alarm on critical raw materials. London, England: Financial Times; 2020. https://advance.lexis.com/api/document?collection=news&id=urn:contentItem:60R8-1VR1-JCBW-N51D-00000-00&context=1516831.
[104] Daily Telegraph Reporter. Nissan finds cheaper way to recycle motors. London: The Daily Telegraph; 2021. https://advance.lexis.com/api/document?collection=news&id=urn:contentItem:63HS-2GB1-JCBW-N4RB-00000-00&context=1516831.
[105] Page Bailey M. Rare-earth recovery from magnet scrap is being scaled up. Chem Eng 2022. https://advance.lexis.com/api/document?collection=news&id=urn:contentItem:66GP-X9C1-JCB9-8008-00000-00&context=1516831.
[106] Sagawa M, Fujimura S, Togawa N, Yamamoto H, Matsuura Y. New material for permanent magnets on a base of Nd and Fe. J Appl Phys 1984;55(6):2083–7.
[107] Barteková E, Kemp R. National strategies for securing a stable supply of rare earths in different world regions. Res Policy 2016;49:153–64. https://doi.org/10.1016/j.resourpol.2016.05.003.
[108] Rivoirard, S.Noudem, J.G de Rango, P. Fruchart, D. Liesert, S, and Soubeyroux, J. L. (2000) Proceedings of the 16th international workshop on rare-earth magnets and their applications, Sendai, Japan, p. 347.
[109] Zakotnik M, Williams AJ, Harris IR. Possible methods of recycling NdFeB-type sintered magnets using the HD/degassing or HDDR process. In: Proceedings of the 18th workshop on high performance magnets and their applications. Grenoble France; 2004. p. 267.
[110] Tukker A. Rare earth elements supply restrictions: Market failures, not scarcity, hamper their current use in high-tech applications. Environ Sci Technol 2014;48(17):9973–4. https://doi.org/10.1021/es503548f.
[111] Guzzo D, Rodrigues VP, Mascarenhas J. A systems representation of the circular economy: transition scenarios in the electrical and electronic equipment (EEE) industry. Technol Forecast Soc Chang 2021;163:120414. https://doi.org/10.1016/j.techfore.2020.120414.
[112] Espinoza LAT. Critical appraisal of recycling indicators used in European criticality exercises and circularity monitoring. Res Policy 2021;73:102208.

[113] Syberg K. Beware the false hope of recycling. Nature 2022;611(7936):S6. https://doi.org/10.1038/d41586-022-03645-0.
[114] Phirouzabadi AM, Blackmore K, Savage D, Juniper J. Modelling and simulating a multi-modal and multi-dimensional technology interaction framework: the case of vehicle powertrain technologies in the US market. Technol Forecast Soc Chang 2022;175:121412. https://doi.org/10.1016/j.techfore.2021.121412.
[115] Zolfagharian M, Walrave B, Romme AGL, Raven R. Toward the dynamic modeling of transition problems: The case of electric mobility. Sustainability 2020;13(1): 38. https://doi.org/10.3390/su13010038.