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Innovation in rare earths recycling: A quantitative and qualitative analysis of patent data☆

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ABSTRACT

Rare earth elements (REE) are currently essential enablers of the digital and decarbonization transition. However, their supply chain is highly concentrated and their extraction has a high environmental impact. Circular economy solutions could provide a double benefit, reducing supply risk for import-dependent countries and mitigating the impacts of REE mining.

This article focuses on REE recycling and provides a comprehensive global overview of innovation dynamics in this sector using patent data. We propose a two-step patent search methodology to identify REE recycling patents, based on the OECD ENV-TECH classification for green technologies and keyword occurrence. We then develop a set of quantitative and qualitative metrics to explore innovation dynamics at the country, applicant and technology type level.

China clearly emerges as the most attractive market for REE recycling patents and Chinese universities as the most active applicants worldwide. Conversely, patent applications in all other countries showed stagnating trends over the last decade. In particular, Europe has a lower number of both patent applications and patents developed compared to the US and Japan. However, patent quality indicators show a very different picture: US and Japanese applicants, who appear to be at the technological forefront, receive more citations and are more oriented towards protecting their inventions internationally. Our analysis therefore highlights the importance of considering both quantitative and qualitative patent metrics when examining innovation trends in REE recycling.

We discuss the determinants of these observed phenomena, draw policy implications - particularly for REE import-dependent countries - and propose avenues for future research at the intersection of CRM, the circular economy, and innovation studies.

1. Introduction

Digitalization and decarbonization are currently considered by governments as the fundamental strategies to steer economic systems towards economic and environmental sustainability, while striving not to hamper economic growth (Amoroso et al., 2021; Mealy and Teytelboym, 2022; Muench et al., 2022; Stern and Valero, 2021). Nevertheless, digital and green technologies are based on an increasing variety of materials (Ayres and Peiró, 2013; Graedel et al., 2015b) and their massive diffusion entails an exponential growth in the extraction of mineral resources (International Energy Agency, 2021; Kowalski and Legendre, 2023). Consequently, scholars have recently begun to focus their attention on how and with what consequences technological systems rely on scarce and critical materials (Compagnoni and Santini, 2024; Li et al., 2024). Indeed, if "scarcity" is understood as the overall geological rarity of a raw material, "criticality" is a measure of the supply risk of a raw material in relation to its economic importance (Graedel et al., 2015a; Schrijvers et al., 2020). Therefore, the scarcity and, especially, the criticality of certain mineral resources has raised concerns about potential material bottlenecks in the implementation of

☆ Nothing to declare.

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the digital and green transitions (de Koning et al., 2018; Habib and Wenzel, 2014; Valero et al., 2018).

A prime example of what is discussed above is the case of rare earth elements (REE). REE are a group of 17 chemical elements[1] with similar and peculiar chemical and physical properties. Because of these specific properties, REE are currently essential inputs for very important economic sectors and green-tech value chains, although the value of the REE market at the raw material level is relatively small. For example, REE are essential for the production of consumer electronics such as laptops and smartphones (Carrara et al., 2023), of permanent magnets used in electric motors for electric vehicles and wind turbines (Alves Dias et al., 2020; Rosenow and Mealy, 2024), and of fuel cells and electrolyzers, key components for the production of green hydrogen for energy use, which rely on lanthanum, cerium and yttrium (Carrara et al., 2023). In addition to this high economic importance and strategic role for decarbonization, the supply chain of REE is also highly concentrated, both at the raw and processed materials stage (Carrara et al., 2023; Gagarin and Eggert, 2023; Golev et al., 2014; Nanni et al., 2023). In particular, China has a quasi-monopoly on the global production (70%, see F igure A.1) and processing (90%) of REE (Park et al., 2023). The European Union (EU), for example, relies on imports of processed REE from China for 85% (light REE) to 100% (heavy REE) of its needs (European Commission, 2023a). In the short term, the high concentration of REE supply could lead to episodes of price volatility, as it already happened in 2011 in response to China's introduction of REE export quotas (Eggert et al., 2016; Fernandez, 2017). Instead, in the medium to long term, the transition to techno-economic systems based on REE and critical raw materials (CRM) in general may lead to geopolitical dependence of import-dependent countries on suppliers (Abraham, 2015; Brussato, 2024). For these reasons, REE have been included in the CRM lists of the United States, the EU, Japan, South Korea, and Australia (Lee and Cha, 2021).

In addition to supply issues, the surge in CRM mining is also inextricably linked to significant environmental impacts at mining sites, which are typically located in developing countries where sound environmental management practices and labor conditions are often lacking (Luckeneder et al., 2021; Sovacool et al., 2019). On the other hand, the social acceptance of mining activities in developed countries is very limited (Liu et al., 2023; Mateus and Martins, 2021). REE mining, in particular, has been found to be highly impactful (Bai et al., 2022; Sovacool et al., 2020; Zapp et al., 2022), with the now infamous case of the Bayan Obo mine[2] (Zhou and Ge, 2021).

In this picture, Circular Economy (CE) strategies have a dual objective: to reduce the supply risk of raw materials and to reduce their lifecycle environmental impacts. Specifically, CE strategies could focus on REE substitution, efficient use - i.e. reducing REE contents - and recycling (Mertens et al., 2024; Pavel et al., 2017). Unfortunately, the substitution of REE in established technologies has proven to be difficult due to their specific properties (Cenci et al., 2021; Omodara et al., 2019; Pavel et al., 2017). The benefits of reducing the REE composition of technologies are also expected to be limited, as they are already used in very small quantities (Althaf et al., 2021; Compagnoni and Santini, 2024). Finally, the REE recycling sector is still in its infancy, as evidenced by negligible REE recovery rates (European Commission, 2023a). In fact, REE recycling technologies and plants have not yet reached the industrialization stage (Favot and Massarutto, 2019; Omodara et al., 2019) .[3] Moreover, the growing material complexity of electronic devices (Compagnoni and Santini, 2024), i.e. the increasing variety of materials contained, hinders the recycling of REE and other minor metals (Andersson et al., 2019; Hagelüken and Goldmann, 2022; Ljunggren Söderman and André, 2019; Pothen, 2013). Nevertheless, REE recycling, especially from the growing flows of electronic waste generated worldwide (Baldé et al., 2024) which is considered an urban mine for REE and other CRM (Compagnoni, 2022; Mazzarano, 2020), represent an opportunity to extend the materials lifetime as well as to mitigate supply risks (Hagelüken and Goldmann, 2022; Horta Arduin et al., 2020; Rollat et al., 2016). Therefore, technological innovation in REE recycling is needed to achieve significant REE recovery rates and to keep pace with the increasing complexity of recycling processes (International Energy Agency, 2024).

This article examines the global innovation dynamics in REE recycling using patent data. Despite the long tradition in Economics of innovation of using patent data to analyze processes of technological change (Griliches, 1990), patent information has been rarely used to investigate the innovation capacity and trends of the REE industry. Among the few articles in this area, the early study by Fifarek et al. (2008) examined the offshoring of REE production and innovation from the United States. More recently, Zhou et al. (2023) and Leng et al. (2021) linked patents mentioning REE to the corresponding economic sector and the related stage in the value chain, while De Cunzo et al. (2023) investigated the dependence of green technologies on REE and other CRM. Hence, none of these studies focuses on REE recycling processes. Instead, various articles investigated REE recycling, but not based on patent data (Jyothi et al., 2020; Omodara et al., 2019; Sagrillo Pimassoni et al., 2023; Schulze and Buchert, 2016; Silvestri et al., 2021). Finally, to our knowledge, Baldassarre et al. (2023) is the only study using patent data (and scientific literature output) to investigate innovation in the recycling of REE and other critical materials. Nonetheless, Baldassarre et al. (2023) differs from this study in two ways mainly: first, it focuses on circularity processes (not only recycling) only from four specific components with high concentrations of critical materials, namely lithium-ion batteries, permanent (NdFeB) magnets, photovoltaic cells, and hydrogen fuel-cells; secondly, patent data are analysed by means of patent counts only, excluding quality indicators. Therefore, our paper offers a more comprehensive and systematic perspective on the recycling of REE from any type of waste.

In this paper, we propose a two-step search methodology for the identification of REE recycling patents. Firstly, we rely on the OECD ENV-TECH classification for green technologies (Haščič and Migotto, 2015) to select patents related to recycling technologies according to their technological classification codes. Second, we restrict the set of patents of interest based on the occurrence of REE-related keywords in the titles and abstracts of the patents.

The results are based on both quantitative and qualitative metrics. The quantitative analysis sheds light on the most attractive markets for the protection and exploitation of REE recycling inventions and their evolution over time, the most active applicants and their public or private nature, and the most common types of REE recycling technologies. The qualitative analysis complements the previous findings based on two sets of indicators, the first based on information on forward citations and the second on the geographical scope of applicants' filing strategy. The adoption of a qualitative perspective allows us to identify the

[1] Cerium, dysprosium, erbium, europium, gadolinium, holmium, lanthanum, lutetium, neodymium, praseodymium, promethium, samarium, scandium, terbium, thulium, ytterbium, yttrium.

[2] Some online references on the topic: https://www.sciencenews.org/article/rare-earth-mining-renewable-energy-future#:~:text=Rare%20earths%20are%20mined%20by,that%20might%20leak%20into%20groundwaterhttps://hir.harvard.edu/not-so-green-technology-the-complicated-legacy-of-rare-earth-mining/https://ips-dc.org/mapping-the-impact-and-conflicts-of-rare-earth-elements/Some information can also be found on the Global Atlas of Environmental Justice (EJAtlas): https://ejatlas.org/conflict/bayan-obo-world-biggest-rare-earths-mine-baogang-group-baotou-inner-mongolia-china; see Martinez-Alier (2021) for more details on EJAtlas.

[3] EU-funded projects on REE recycling: REE4EU https://ree4eu.eu/overall-results/; SUSMAGPRO https://www.susmagpro.eu/; REEPRODUCE https://www.reeproduce.eu/; HARMONY https://www.harmonyproject.eu/; MAGELLAN https://magellan-horizon.eu/.

nationality of the technological leaders in the studied sector and the direction of knowledge flows. Thus, this article provides a comprehensive investigation of innovation dynamics and capabilities in REE recycling, adopting different levels of analysis: country, applicant and technology type.

Finally, the paper discusses policy implications for supporting innovation processes in REE recycling, especially for countries heavily dependent on REE imports, and venues for future research on REE/CRM recycling innovation.

2. Materials and methods

In this Section, we first briefly discuss the advantages and disadvantages of using patents as a proxy for innovation. In Section 2.2, we present our two-step patent search methodology based on a combination of technological field codes from the OECD ENV-TECH green patent classification and REE-specific keywords. Finally, we describe the indicators developed to explore the obtained dataset and identify relevant innovation trends.

2.1. The use of patent data to measure (green) innovation

Patents are frequently used as an indicator of the rate of invention, which is a crucial precursor to innovation (Higham et al., 2021). Precisely, a granted patent is an exclusive right to exploit (make, use, sell, or import) an invention over a limited period of time within the jurisdiction of the patent office to whom the application is filed. Patents provide a broad protection that extends beyond the specific expression of an invention to the invention itself. In return for intellectual property protection, the applicant must disclose the invention in the text of the application. Indeed, the application is always published, following a secrecy period usually lasting eighteen months, independently of the effective granting of the patent. Patent data offer several advantages over alternative measures of innovation (Fabrizi et al., 2018; Haščič and Migotto, 2015; Oltra et al., 2010).

First, patents are commensurable because they rely on an objective standard. Indeed, patentable inventions must satisfy three requisites: novelty, non-obviousness, and usefulness, i.e. having industrial applicability. Second, they assess the midway results of the creative process, which differs from data on R&D spending that only reflects the economic input for innovation processes or from trade information that might not include innovative technologies (Cvijanovic et al., 2021). Third, as a quantitative data, patents are suited for statistical analyses (Pavitt, 1985). Fourth, patents are fully accessible to the public. Finally, different technological fields can be identified on the basis of IPC (International Patent Classification) and CPC (Cooperative Patent Classification) codes. More generally, patents represent a rich source of information (Griliches, 1990), reporting the applicant, the application country (patent authority), a textual and graphic description of the invention, and a list of references, among other details.

Anyway, flaws in the use of patent data in tracking innovation processes are also acknowledged (Haščič and Migotto, 2015). For the case under considerations, two possible limitations appear to be more significant. First, not all patentable inventions are patented. The process for obtaining a patent is time consuming: it often takes a long time to craft a patent application and a long time (usually ranging between two and three years) before a submitted application can potentially be approved. Moreover, economic costs are connected to patent filing, enforcement and maintenance, i.e. renewal. Finally, the application for patenting entails the disclosure of the invention. For all these reasons, innovators may opt not to legally protect their inventions by means of patents: informal strategies like industrial secrecy and trade secrets can represent a preferred alternative. It is well known that patenting propensity varies across industries (Oltra et al., 2010) making the use of patent data less convenient in the analysis of certain sectors. The availability of previous research using patent data referring to the waste management processes reassures on the sufficient patenting propensity of the sector (Cecere and Corrocher, 2016; Marin et al., 2018a; Nicolli et al., 2012). Secondly, patented inventions vary strongly in quality. The OECD (Squicciarini et al., 2013) defines patent quality as the technological and economic value of patented inventions, and the possible impact these might have on subsequent innovations. The well-known skewness of the patent quality - or value - distribution means that the majority of patents have little relevance in terms of economic exploitation and for subsequent technological progress (van Zeebroeck, 2011). For this reason, quantitative measures of raw patent counts need to be supplemented with qualitative ones in order to measure the relative significance of different innovations (Squicciarini et al., 2013).

2.2. Patent search strategy

The procedure of selection of the patents followed two main steps. The first step relies on the use of technological field codes for the identification of recycling technologies in general. For this purpose, we started by exploiting the well-established ENV-TECH classification for “green patents” developed by the OECD (Haščič and Migotto, 2015). Green (or eco) innovations are innovations that result, throughout their life cycle, in a reduction of environmental risk, pollution and other negative impacts of resources use (including energy use) compared to relevant alternatives (Ghisetti et al., 2015; Rennings, 2000). Over the last three decades, the identification of green innovations through patent data has become well-accepted and increasingly sophisticated, leading to the development of various selection methods (Favot et al., 2023). Among these, the OECD ENV-TECH presents the advantage of considering both IPC and CPC classes, unlike European Patent Office (EPO) Y02/Y04S Tagging scheme and World Intellectual Property Organization (WIPO) IPC Green Inventory (Favot et al., 2023); consequently, it is highly detailed in the identification of the object of innovation (Barbieri et al., 2020; Fabrizi et al., 2018), defining about eighty technological fields. Moreover, the ENV-TECH classification is regularly updated to keep track of the evolution of IPC and CPC codes. Hence, in line with previous research (Compagnoni et al., 2024; Marin et al., 2018b; Zoboli, 2019), our search strategy starts from the selection of patents related to the classes of “material recovery, recycling and re-use” and/or “reuse, recycling or recovery technologies” according to ENV-TECH (April 2022 version). Following the green innovation literature (Barbieri et al., 2020; Bianchini et al., 2022), we defined patents in “recycling” if they include at least one IPC/CPC code belonging to one of the two classes mentioned above. The data were retrieved from PATSTAT[4] online (Spring, 2022). PATSTAT is a widely used, comprehensive patent database covering patent applications filed in more than 70 national and international patent offices (Kang and Tarasconi, 2016). As of the latest editions, it records information on more than 100 million patent applications filed since the late eighteenth century (Caldarola et al., 2024). The extracted sample covers worldwide patent applications[5] and, initially, the period 1980–2022. At this stage, a total of about 220500 patent families were identified.

Because, in principle, the ENV-TECH list of IPC/CPC codes associated to recycling might be incomplete, leading to a bias in the identification of recycling patents, we perform a validation of that list. To this end, we analysed the occurrence of all the technological codes associated to the set of patents identified as described above. By making a ranking of the codes by number of occurrences, we discovered that, besides the ENV-TECH recycling codes, the only one showing a high frequency was the CPC code Y02P10/20. This code, associated by EPO to “technologies related to metal processing and recycling”, is not included in ENV-TECH,

[4] https://www.epo.org/en/searching-for-patents/business/patstat.

[5] Our unit of analysis is the patent application, irrespective of its granting status. For brevity, we might refer to this unit of analysis simply as a “patent” throughout the remainder of the article.

but it is part of an alternative green patent codes list, namely the "Y02/Y04S tagging scheme".[6] Consequently, in order to ensure the selection of the patents tagged by the above-mentioned code, highly related to our scope of analysis, we integrated the code to our previous list obtained from ENV-TECH and we replicated the patent search on PATSTAT. Generally speaking, the practice of integrating multiple green patent identification methodologies is encouraged in order to increase the coverage and reliability of search strategies (Barbieri et al., 2023; Favot et al., 2023).[7] Our final list of IPC and CPC identifying recycling technologies is provided in Appendix.

The second step of our search strategy is aimed at narrowing down the selected set of recycling innovations to the scope of REE. Since no IPC/CPC codes or green technology classifications specifically address REE, keywords are the only viable method for identifying patents mentioning REE among those previously classified as recycling patents. Hence, for this purpose, we restricted the selected patents to those containing the following list of keywords related to REE and synonyms in their title and/or abstract, in English language: "rare earth element*", "light REE*", "heavy REE*", "rare earth metal*", "rare earth oxide*", "lanthan*", "rare earth*".[8] This list of keywords associated with REE is partly different from the ones of Zhou et al. (2023) and Leng et al. (2021), reflecting our purpose of identifying patents referring to any REE element and recycling processes only.

Finally, we also limited our search to the timeframe 2010 to spring 2022. Retrospectively, this temporal criterion was adopted to exclude obsolete technologies and in consideration of the limited number of patent applications filed globally in the decade preceding the selected period, ranging around fifty per year on average. Conversely, we selected patent documents until the most recent available data. Clearly, the last years of observation suffer from incomplete coverage, because of the 18 months secrecy period of patent applications, of the rolling updates of national patent databases, and the upgrading of PATSTAT occurring only twice a year.

The whole patent search strategy, the validation of the IPC/CPC codes list, and the SQL scripts for PATSTAT queries are provided in Priore et al. (2024) in order to ensure the replicability of our selection methodology and of our analysis. The search strategy is also outlined in Fig. 1.

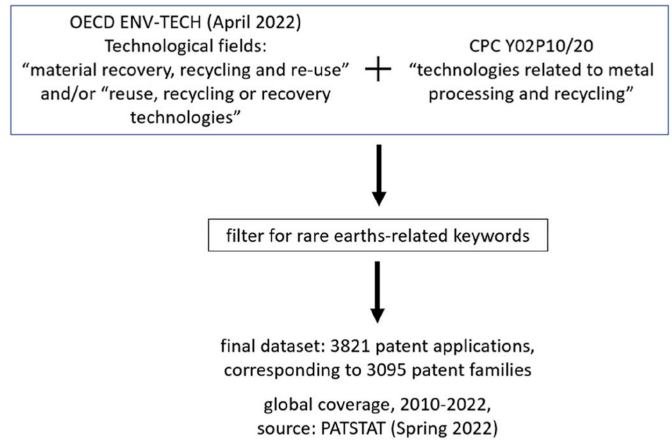

Fig. 1. Scheme for the patent search strategy adopted in this paper.

2.3. Patent analysis

The obtained REE recycling patent dataset is analysed first by the means of quantitative indicators and subsequently through qualitative ones.

The quantitative analysis is structured on three levels. First, patents are counted at a global level and by application patent authority, i.e. application country; these indicators are provided both in a dynamic and static perspective. Here, the aim is to understand the recent interest in innovating in the REE recycling field and what could be the most attractive market for this type of technology. Secondly, we count applications by applicant, not only to identify the names of the most productive innovators in the field, but also to distinguish their private or public nature. Third, applications are counted by the main type of technology. These indicators have been commonly used as intellectual property right statistics (Johnstone et al., 2010; WIPO, 2023).

To account for the heterogeneity of patent quality, as discussed in Section 2.1, we complement raw patent count indicators with a set of qualitative indicators. Indeed, as discussed by Higham et al. (2021), patent 'quality' is an intrinsically multidimensional concept that cannot be reduced to a single best metric. Overall, our aim here is to assess patents' technological impact and patterns of knowledge diffusion. In the qualitative investigation we adopted patent families[9] as the unit of analysis, in order to avoid duplication due to equivalent patent applications, i.e. filed at different patent offices and representing the same invention (Criscuolo, 2006).

A first set of patent quality indicators adopted in this paper is based on forward citations, that is the citations a patent receives from subsequent applications (Squicciarini et al., 2013). They reflect a disclosure regarding knowledge of prior art (Higham et al., 2021). Forward citation counts were one of the first invention-level metrics available to measure technological importance and their use as an indicator of patent quality has become well-established (Jaffe and de Rassenfosse, 2017). Numerous scholars, including Trajtenberg (1990), Hall et al. (2005), and Harhoff et al. (2003), have used forward citations not only to assess technological importance but also to evaluate the economic value of an invention. More precisely, in this paper, forward citations are first used to provide an indicator of overall technological importance of a country's knowledge stock; in this case, we aggregate the forward citations by the country of residence of the cited applicant, as in Alessandri (2023). Secondly, this total count of citations received by the country of residence of the cited applicant is split by country of residence of the citing applicant[10]. This procedure allows evaluating the impact of the prior art on territories that might differ from those in which a given invention is conceived or, in other words, to inspect patterns of knowledge flows among countries.

A second group of metrics related to patents quality is connected to the geographical scope of the applicants' filing strategy. Indeed, the quality of patents is held to be correlated with the geographical scope of patent protection, i.e. with the number of jurisdictions in which patent

[6] This green patent classification methodology is based on CPC codes and it has been developed by EPO in collaboration with United Nation Environmental Program (UNEP) and the International Centre on Trade and Sustainable Development (ICTSD) (Angelucci et al., 2018).

[7] Note that our search strategy for recycling patents differs from the one adopted by Georgakaki et al. (2024) for the calculation of the indicator on the number of "patents related to recycling and secondary raw materials", which is part of the Eurostat Circular Economy Monitoring Framework. Indeed, Eurostat indicator is based on CPC codes only.

[8] Stars represent jolly characters in SQL programming language, required for PATSTAT queries.

[9] Applicants have up to 12 months from the first filing of a patent application (typically in the country of origin) to file applications in other jurisdictions regarding the same invention and claim the priority date of the first application. The set of patents filed in several countries which are related to each other by one or several common priority filings is generally known as patent family (Squicciarini et al., 2013).

[10] Because the country of residence of the applicants might be missing in PATSTAT, in this paper the citations analysis is primarily focused on patents for which both the country of residence of the citing applicant and the one of the cited applicant are known.

protection has been sought (Squicciarini et al., 2013). This is because the patenting process in multiple jurisdictions can be very costly, implying additional patenting fees, attorney costs, and translation costs. Consequently, this filing strategy is adopted by the applicants only if they consider their invention as particularly valuable (Harhoff et al., 2003). In this paper, among patent internationalisation metrics, we make use of triadic patent families (TPF), including patent applications filed to the EPO, to the JPO (Japanese Patent Office), in addition to patents granted by the USPTO, all sharing one or more priorities" (Dernis and Khan, 2004). This common quality indicator serves various purposes. First, the use of TPF helps exclude the "home advantage" bias in the comparison of countries' innovative performance (van Zeebroeck, 2011). This bias arises when international comparisons are based on the raw count of filed patents due to the fact that national patent offices receive a disproportionately large number of domestic patent applications, i.e. patent applications from residents (Criscuolo, 2006). Second, TPF offers a partial solution to the challenge of assessing the "quality of the patent system" (De Saint-Georges and Van Pottelsberghe De La Potterie, 2013), because they are filed to three different patent offices. Finally, moving to the applicant level, we select a set of most productive applicants, in terms of number of REE recycling inventions, from different countries and we assess their "territorial protection strategy", that is the potential of territorial enforceability of the exclusive right. More specifically, for each selected applicant, we calculate the share of patent applications by application authority over the total number of patent applications for that specific applicant. In this case we are particularly interested in comparing the share of domestic and international patents, i.e. patents filed abroad (Schmoch and Gehrke, 2022), across top applicants of different nationality.

3. Results

3.1. Quantitative analysis

Our search strategy led to the identification of a total of 3821 patent applications filed worldwide over the period 2010–2022. Fig. 2 shows the time trend for global REE recycling patents, which increased significantly in the period 2010–2018 at a compound annual growth rate of 12.5%, starting from 177 and reaching 472 applications. The drop observed after 2018 is probably largely due to the incompleteness of the data, as previously discussed; moreover, from 2020 on, the series is affected by the drop in R&D and patenting activities determined by the COVID-19 pandemic. In consideration of these two factors, the temporal analysis of global REE recycling patents would suggest an increasing interest for innovations in this field, as it in general for REE-related inventions (Leng et al., 2021). However, moving to a country-level analysis, strong imbalances are observed.

Table 1 shows the number of REE recycling patent applications received by patent authorities between 2010 and 2022, regardless of the

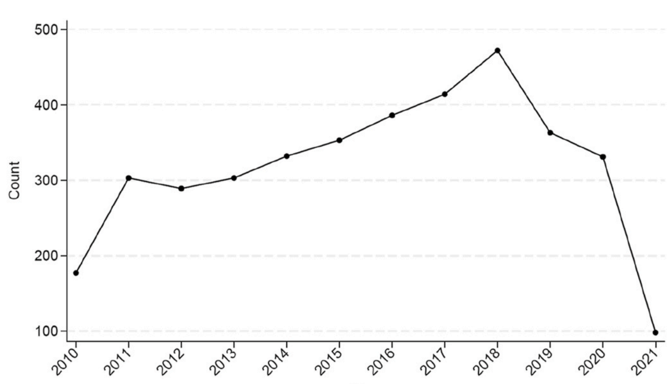

Fig. 2. Time trend of global patent applications in REE recycling (2010–2022).

Table 1
Top authorities by total number of patent applications, 2010–2022.

Authority	Patent applications
China	2517
WIPO	252
United States	238
Japan	227
Russia	141
EPO	123
Canada	72
South Korea	68
Australia	68
Taiwan	23
United Kingdom	12
South Africa	10

applicant's or inventor's country of residence. China received the highest number of applications globally, overtaking the second-highest, the US, by a factor of ten. Table 1 also includes two international authorities, WIPO and EPO.[11] The latter scored consistently less applications with respect to the US and Japan. Finally, the list in Table 1 includes other REE extracting countries, such as Australia, and countries with a strong position in REE-intensive value chains, such as South Korea (Carrara et al., 2023; Zhou et al., 2023). Korea's Rare Metals Supply Plan 2.0 is one of the rare examples of comprehensive roadmap with long-term strategies for recycling critical minerals, together with China's 14th Five Year Plan on Circular Economy (International Energy Agency, 2024). The volume of patent applications indicates the interest of applicants to protect and possibly exploit their invention in a specific jurisdiction. In other words, the patent application count reflects countries' attractiveness as a market. Hence, the result presented in Table 1 is coherent with the geographical distribution of the global share of REE production, which is dominated by China, followed by the US (see Fi gure A.1 in Appendix). This finding suggests that the most attractive markets for REE recycling technologies are countries that can directly recycle pre-consumer manufacturing REE scraps and residues, rather than those that (potentially) rely on urban mining of post-consumer end-of-life products as a feedstock (Binnemans et al., 2013).

Nonetheless, this count could in principle reflect a home bias due to the numerosity and relative patenting propensity of national applicants, in addition to foreign applicants. This case might be especially relevant when analysing the data from CNIPA/SIPO, the Chinese patent office (see Fig. 4).

Adopting a dynamic perspective, the country-level analysis reveals that China appears by far as the most attractive country for the legal protection for REE recycling inventions since at least 2010 (Fig. 3 Panel A). Since then, the gap between China and the following countries has increased hugely, especially starting from 2012. Indeed, if in 2010, the patent applications filed in China were about four times those of the second authority, i.e. Japan, in 2018 the gap reached a factor of 17 with respect to applications to the US patent office, which overtook Japan in 2015. Overall, applications filed at the CNIPA/SIPO, increased about four times between 2010 and 2018.

This trend appears to be correlated to two other dynamics occurring in China. The first is represented by the Chinese government's policies in the REE field. In order to tackle the substantial illegal production of REE

[11] In the case of the EPO, patent application and publication counts may differ significantly. This is primarily because the EPO procedure allows applicants to extend the coverage of patent applications filed in any European country to the EPO level within one year from the priority date registered by the national authority. Our analysis focuses on patent applications rather than subsequent publications, as publication delays could negatively impact the evaluation of innovation dynamics.

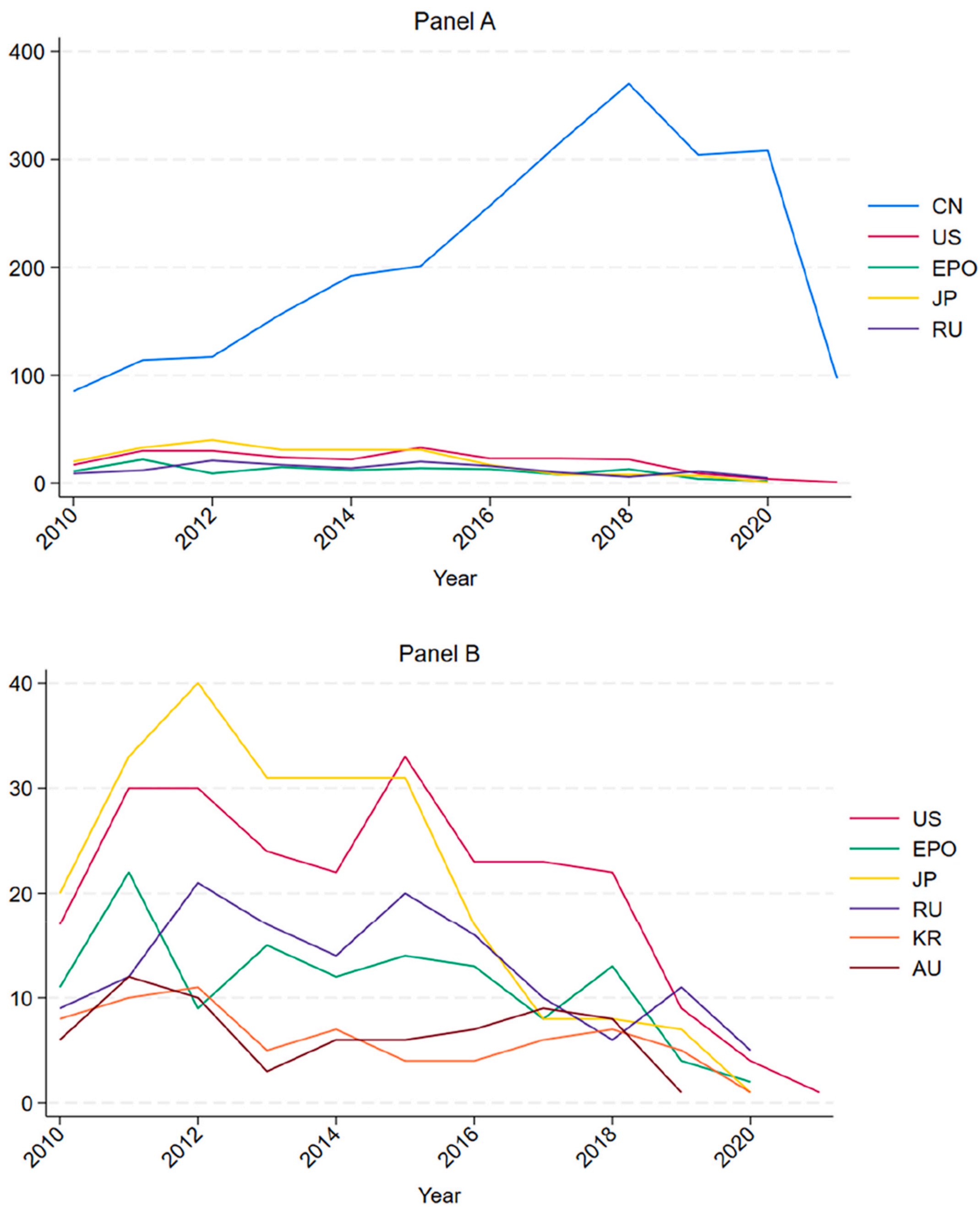

Fig. 3. REE recycling patent applications trend by top application authorities, 2010–2022. Legend: CN China, US United States, EPO European Patent Office, JP Japan, RU Russia, KR South Korea, AU Australia.

(Packey and Kingsnorth, 2016) and the massive pollution generated by REE extraction and refining (Zapp et al., 2022; Bai et al., 2022), on the one hand, China gradually enacted environmental protection laws and, on the other hand, it consolidated all REE production companies into six big state-owned enterprises[12] (Chai et al., 2020; Mancheri et al., 2019). Export licenses have been allocated directly by the Chinese Ministry of Commerce, and applying firms must meet several conditions to be eligible, including compliance with environmental and social security standards, a minimum firm size, and proof of REE origin from licensed mining operations (Pothen and Fink, 2015). The process of consolidation intensified in 2014, following China's debacle in the WTO dispute on Chinese REE export quotas[13] (Mancheri, 2015). The government supported the six state-owned enterprises by allowing them to merge and acquire small operations and illegal mines, and by allocating over 90% of production quotas to these groups (Mancheri et al., 2019). Hence, Chinese environmental and production concentration policies might have increased interest in REE recycling technologies, both to improve REE production environmental outcomes and to exploit alternative sources of REE. Environmental regulation is a well-known

[12] The companies are: China Minmetals, Chinalco, Baotou Steel, Xiamen Tungsten, Ganzhou Rare Earths, and Guangdong Guangsheng Rare Earths (Mancheri et al., 2019).

[13] Chinese defence in the WTO dispute settlement on REE was also primarily based on two arguments of environmental nature, namely moving towards a sustainable extraction path of REE and controlling mining environmental damages (Hayes-Labruto et al., 2013; Pothen and Fink, 2015).

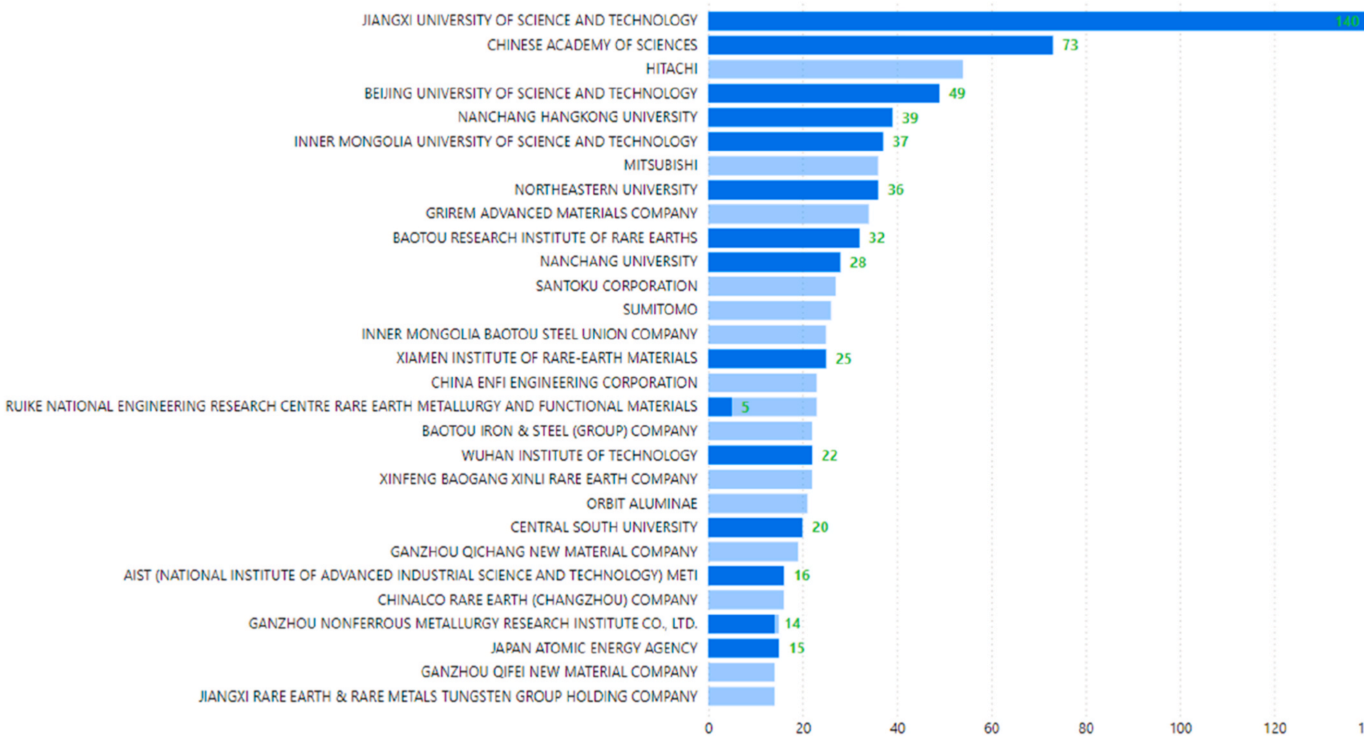

Fig. 4. Top applicants by number of filed applications in REE recycling; universities in dark blue, companies in light blue. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

determinant of eco-innovation (Ambec et al., 2013; Ghisetti and Pontoni, 2015), also supporting international collaborations (Corrocher and Mancusi, 2021) and technology transfer in this field (Verdolini and Bosetti, 2017).

The second Chinese-specific dynamic that should be taken in consideration when analysing the trend in REE recycling patents filed in China is the generalised booming of patenting activities in that country. This phenomenon, occurring over the last two decades, has been examined in the literature and ascribed to the surge in R&D investment, foreign direct investments, and substantial patent subsidies (Chen and Zhang, 2019; Dang and Motohashi, 2015; Eberhardt et al., 2017). Thus, these factors have probably inflated the patenting activity also in the REE recycling field. In addition, China, as various other developing countries, has substantially increased its level of protection of intellectual property rights (Chen et al., 2024; Park, 2008; Zhao, 2010). Patent protection, as other institutional and legal factors (EPO, 2017; Papageorgiadis and McDonald, 2019), has been shown to be positively linked to the growth of patenting and innovation ecosystems (Chen et al., 2024; Reis et al., 2022), especially in the case of developing countries (Arza et al., 2023; Chen and Puttitanun, 2005; Sharma et al., 2018). Hence, this patent policy might have positively affected patenting trends in China also in the REE recycling field.

Comparing Panel A and B in Fig. 3, it is possible to observe how the impressive growth of applications in China is opposed to an equally striking stagnation of the trends registered everywhere else in the world. Applications filed in countries other than China reached a peak in 2011–2012 (2015 for the US) and are currently decreasing. On average, between 2016 and 2018 the EPO and the Japanese patent authority (JPO) received 11 patents per year, which is about half compared to the US. Hence, Europe currently does not seem to be an attractive market for REE recycling technologies, despite the specific funding opportunities in this field provided by the EU (Baldassarre et al., 2023) and the efforts to establish resource efficiency-oriented (electronic) waste policies (Barteková and Kemp, 2016; Compagnoni, 2022; Favot et al., 2022). According to Baldassarre et al. (2023), EU funded projects connected to CRM circularity have mainly focused on lithium-ion batteries (LIB), with €425 million in funding between 2014 and 2021. In that period, 3140 patents on LIB recycling were filed in the EU, indicating a significant interest of the market in this area. The strong focus on LIB is confirmed by the creation of the European Battery Alliance, while other critical products, such as magnets, fuel cells, electrolysers, have not been addressed with the same emphasis. In the field of NdFeB magnets, for example, the growth of R&I intensity—measured by patents, scientific articles, and innovation projects—has been modest since 2014. This decline can be partially explained by fluctuations in EU investments, which peaked in 2015 at €22.5 million but dropped by half or more in the following years, with an average funding of €10.5 million (Baldassarre et al., 2023). Rizos et al. (2024) investigate barriers to develop a European value chain for permanent magnets recycling; by interviewing industry experts and academics, the following barriers are identified: limited information about the type of magnets included in end-of-life products, lack of recycling targets, lack of eco-design requirements, difficulty in moving products across borders, lack of certification systems, high costs involved in the recycling processes, competition with magnets sourced from non-EU countries and missing segments of the REE value chain. Japan, which has a similar legislative environment to the EU as well as REE scarcity (Barteková and Kemp, 2016), has been quite dynamic in the early 2010s, especially thanks to the activity of national firms (see Fig. 4). To secure its minerals supply, Japanese government and industries have invested in measures for demand control, such as substitution and recycling (British Geological Survey, 2011), but also in mineral resource entitlements abroad, especially in Australia (Hatayama and Tahara, 2015; Kannan et al., 2025). In the case of REE, following the 2011 REE crisis, Japan managed to gradually decrease its import dependence from China by securing its supply from diverse countries (Schmid, 2019). The decreasing vulnerability of Japanese REE supply might have disincentivized investments in REE recycling. The US also show a stagnation in REE recycling inventions, besides being a relevant player in the REE value chain, both as the second global producer and as a final-stage manufacturer of

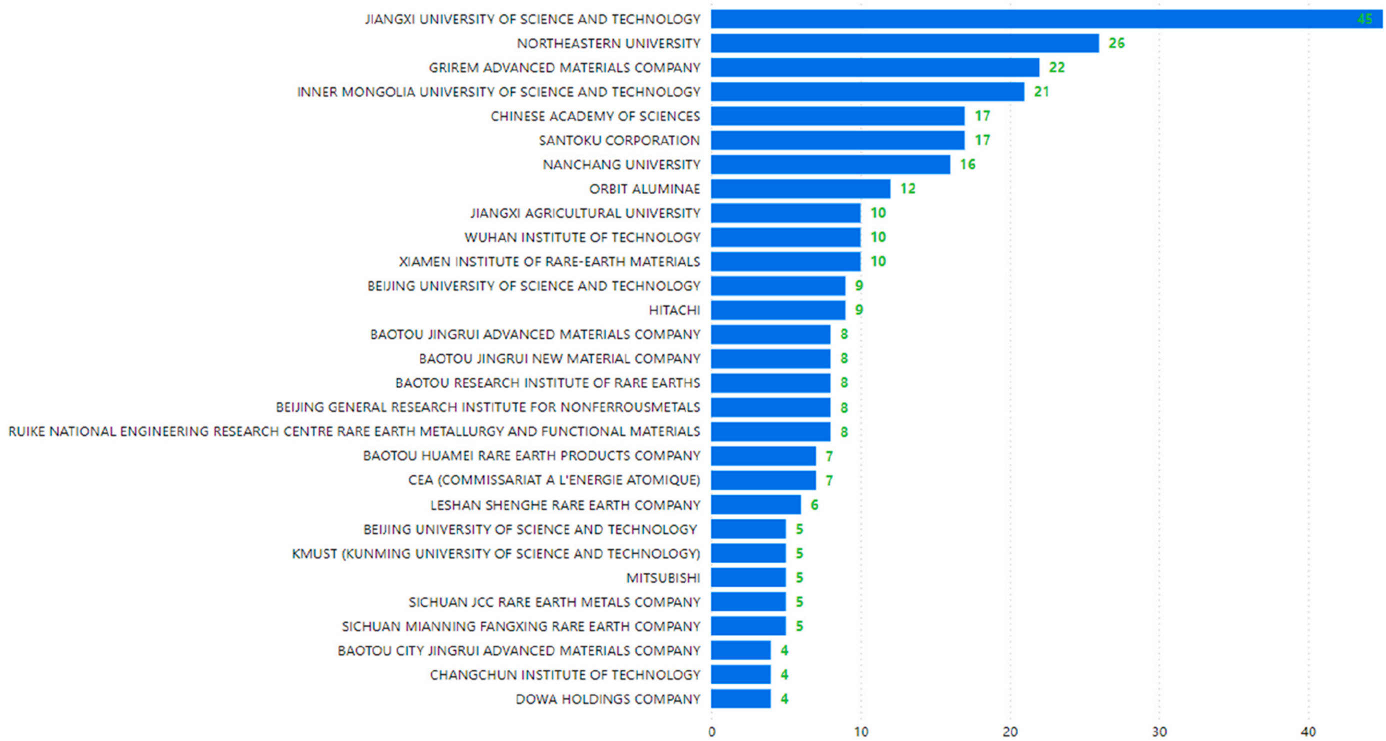

Fig. 5. Top applicants in hydrometallurgical REE recycling processes.

REE-intensive products. This trend seems to be a consequence of the long process of transfer of REE-related intellectual property and knowledge towards China (Fifarek et al., 2008; Park et al., 2023). In general, developed countries present stagnating patenting dynamics since the 2000s when considering the whole waste management sector (Nicolli et al., 2012; Zoboli et al., 2019).

Shifting the analysis at the applicant level, we find that most REE recycling patent applications are submitted by companies (2053). These are followed by universities, governmental non-profit universities, and governmental non-profit institutes, which together account for 1185 applications. Individual applicants comprise only 534 of the total.

Fig. 4 provides the names of the most active applicants globally and it classifies them as public or private institutions. The analysis reveals that the major players are Chinese universities or Chinese institutes. This finding, referring to the specific case of REE recycling, is consistent with the general surge in patent activity from Chinese universities (Fisch et al., 2016; Lin et al., 2024). Most of the Chinese organizations listed in Fig. 4 appear to be located in some of the major Chinese REE mining provinces, such as Jiangxi and Inner Mongolia/Baotou (Mancheri et al., 2019). In contrast, the most significant private companies are based in Japan, with Hitachi, Mitsubishi, and Sumitomo filing altogether 117 patent applications. Sumitomo was the original developer of sintered NdFeB permanent magnets in 1984 (Alves Dias et al., 2020); this type of magnet accounted for about 90% of NdFeB market production in 2018, being generally used in electric motors and wind turbine generators, and thus they make up the bulk of the demand for REE magnets (Gagarin and Eggert, 2023). Santoku has been active in the recycling of neodymium and dysprosium for use in permanent magnets and in 2018 it was acquired by Hitachi, with the explicit aim of having a branch specialised in REE recycling (Alves Dias et al., 2020). In 2010, Hitachi developed a method for recycling REE magnets from various types of electronic waste (Hitachi, 2010); this is representative of the company's strategic involvement in recycling (Baba et al., 2011). Interestingly, Mitsubishi and Sumitomo also invested in various mining projects abroad (Hatayama and Tahara, 2015); this suggests that, even in the case the Japanese companies that are more active in REE recycling innovation, the recycling strategy either accompanies or is secondary to securing mineral supplies through foreign direct investments. European applicants lag behind in terms of number of patent applications, with the French "Commissariat à l'énergie atomique et aux énergies alternatives" (11 patents), the German Siemens (10), and the British Seren Technologies (7), now Ionic Technologies, as the three most active applicants.

The final analysis examines the technology landscape to identify the most prominent techniques for REE recycling. Several studies address the recycling methods of REE (Binnemans et al., 2013; Sethurajan et al., 2019; Yuksekdag et al., 2022; Ramprasad et al., 2022; Sagrillo Pimassoni et al., 2023), identifying hydrometallurgical and pyrometallurgical processes, typically preceded by mechanical pre-processing, as the primary methods for recycling REE. According to Balaram (2019) the chemical similarities among REE make their separation a major challenge and a key barrier to widespread recycling. Hydrometallurgical methods require the use of various chemicals, but have the advantages of low temperature and therefore less energy consumption, reduced gas and dust emissions, and ease of separation from base metals (Sethurajan et al., 2019; Ramprasad et al., 2022). Therefore, it is considered a less costly and more environmentally friendly process than the pyrometallurgy (Yuksekdag et al., 2022). Additionally, the hydrometallurgical method has the advantage of using the same processing steps as the separation of REE from primary ores (Binnemans et al., 2013). Consequently, the method is the most patented process with a total of 642 patent applications filed during the time frame of our investigation. Fig. 5 reports the most prominent contributors in the hydrometallurgical processes by the number of filed applications. Jiangxi University of Science and Technology[14] takes the leading role with 45 applications, followed Northeastern University,[15] located in the US.

Pyrometallurgical processes have some advantages: they can handle

[14] Jiangxi University is now part of Nanchang University.

[15] Articles proving the activity of Northeastern University in the REE field: https://coe.northeastern.edu/news/developing-alternatives-to-rare-earth-materials/https://news.northeastern.edu/2022/10/17/rare-earths-crisis/.

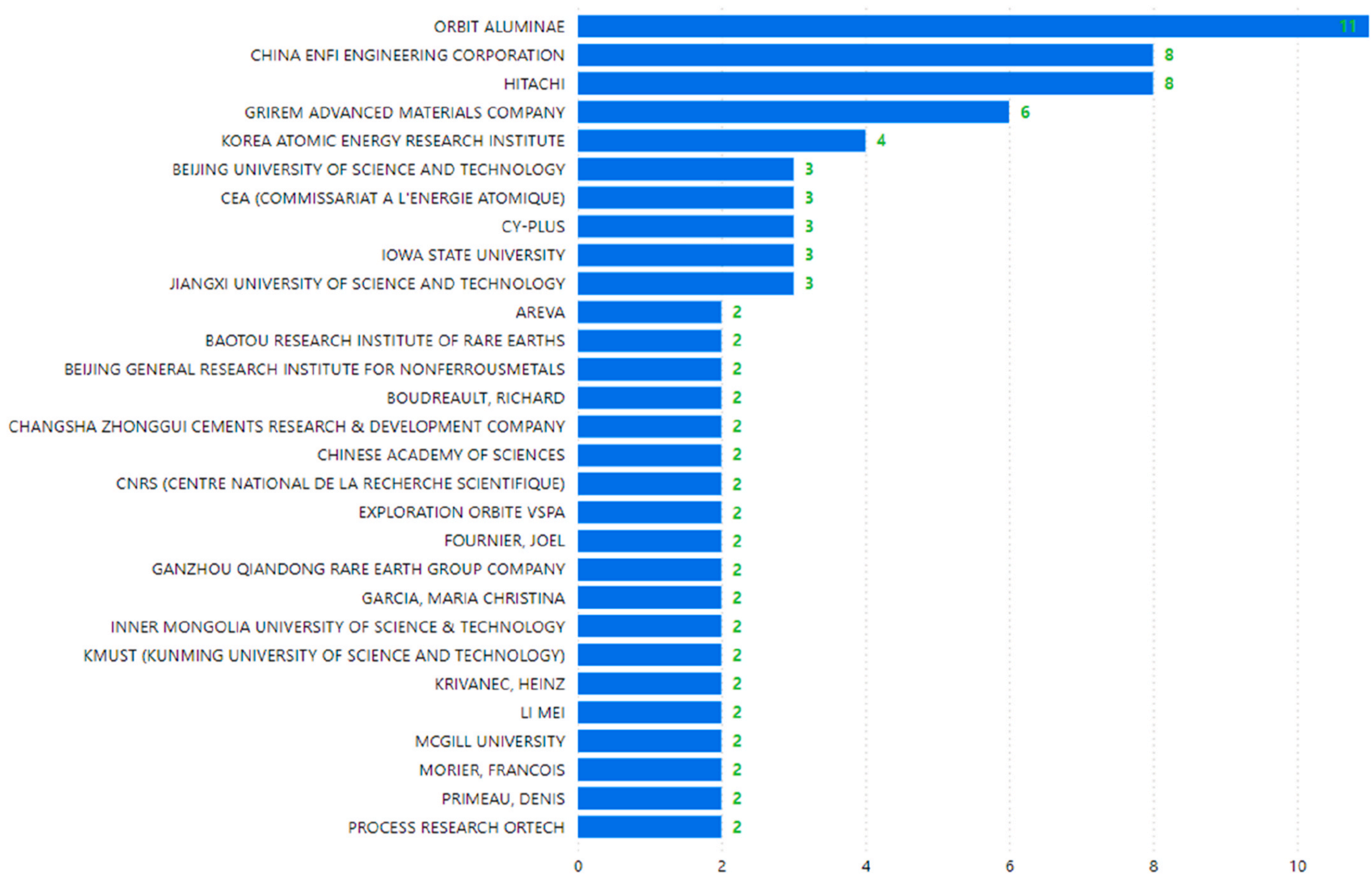

Fig. 6. Top applicants in Pyrometallurgical REE recycling processes.

relatively large or coarse materials (Sethurajan et al., 2019) and they do not generate waste water (Binnemans et al., 2013). A total of 133 global patent applications in REE recycling pyrometallurgical processes were identified in the period of analysis. In the context of REE recycling, inventions related to pyrometallurgical processes more often originate from companies compared to those related to hydrometallurgy. Fig. 6 ranks the top applicants in pyrometallurgical REE recycling processes.

3.2. Qualitative analysis

In this Section we propose various quality indicators in order to assess patents' technological impact and patterns of knowledge diffusion. We start by exploring forward citations, which allow us to inspect the relevance of the prior art from a geographical perspective, and subsequently we analyze the applicants' propensity to patent internationally by means of triadic patent families and the territorial protection strategy.

In Fig. 7, we aggregate the citations received by REE recycling patents by country of residence of the cited applicant, irrespectively of the citing country, i.e. the origin of citations. This first bar chart provides an indication on the nationality of the technological leaders in the field. Besides the very high number of patents filed in China (Table 1) and the fact that Chinese research institutes are the most productive applicants globally (Fig. 4), patents filed (anywhere) by Chinese applicants received a lower number of citations with respect to their American, Japanese and European (French and, mainly, German) competitors. This provides a preliminary indication of the relatively modest average technical quality of Chinese patents. This issue has been discussed in the literature and it has also been connected to China patent policies (Boeing and Mueller, 2016; Lin et al., 2024). Since 2000, the Chinese government has stimulated patent applications with subsidies and pressure

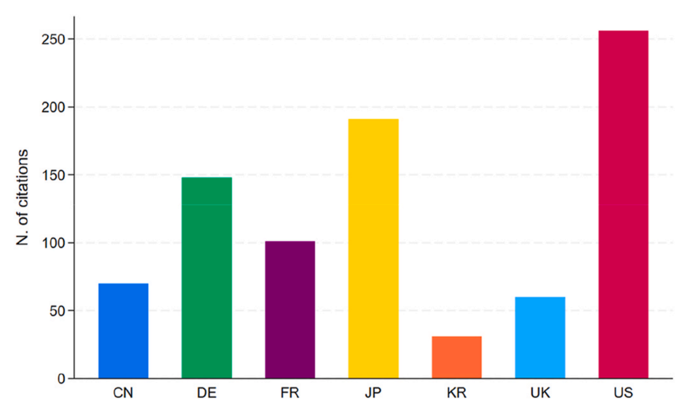

Fig. 7. Total forward citations by applicants' country of residence (selected).

mechanisms leading to a rapid rise in the number of patent applications (Schmoch and Gehrke, 2022). However, according to various scholars, these policies affected negatively patent quality (Boeing and Mueller, 2016; Long and Wang, 2019), particularly in the case of Chinese universities. Indeed, quantitative patent goals, career incentives and subsidies on patenting costs for scholars in universities boosted patent applications, but not patent quality, i.e. forward citations (Fisch et al., 2016; Lin et al., 2024). Lin et al. (2024) have gone so far as to speak of a "patent bubble" in Chinese universities occurring in the last decade.

To explore more in detail the patterns of knowledge flows, we investigate the origin of the citation counts displayed in Fig. 7. To

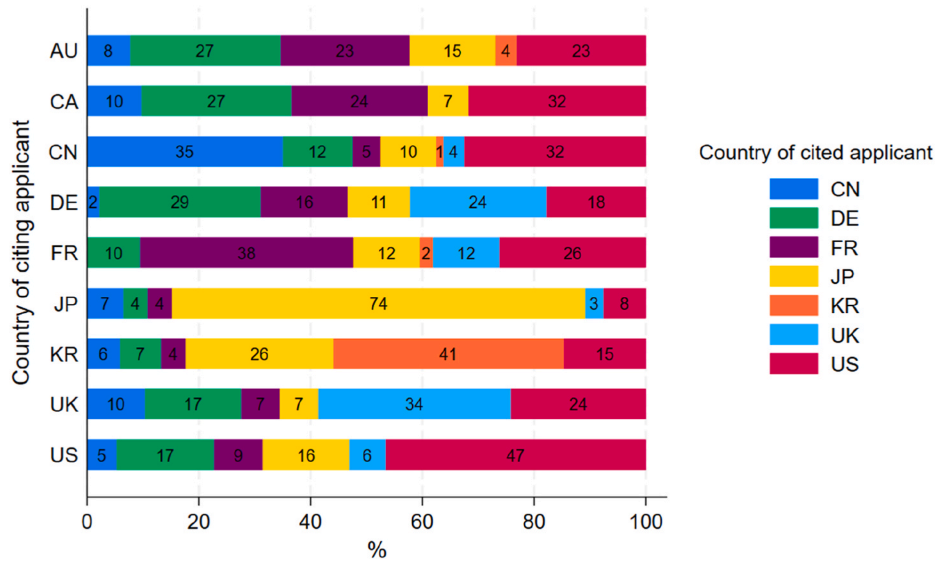

Fig. 8. Countries of forward citing applicants over countries of cited applicants. Note: AU Australia, CA Canada, CN China, DE Germany, FR France, JP Japan, KR South Korea, UK United Kingdom, US United States.

generate Fig. 8, first we select citing countries as the same list of cited countries of Fig. 7 plus Australia and Canada.[16] The selected countries are those receiving and making the highest number of citations, thus representing the core innovators and knowledge generators in REE recycling. Then, we calculate the total number of forward citations towards the seven selected cited countries (same as in Fig. 7).[17] Finally, for each citing country we calculate the share of forward citations by country of the cited applicant. In other words, Fig. 8 represents the allocation of citations of a citing country across cited countries. This elaboration immediately reveals that, for each citing country, the highest share of forward citations is in favour of patents filed by applicants of the same nationality, that is country of residence. In particular, the share of citations towards applicants of the same nationality is the lowest for Germany and the highest for Japan. Hence, here we discover that the REE recycling field is affected by a clear home bias in citations (Jaffe et al., 2000; Kwon et al., 2017). To account more clearly for this phenomenon, we compare the rate of citations received by applicants of a certain country from applicants of the same country and the rate of citations received by applicants of that country from foreign applicants. For instance, even though the Chinese rate of home citations is close to the average rate of within-country citations, the rate of citations towards Chinese applicants falls dramatically to about 6% on average - that is an 83% drop in received citations[18]- when we look at the other citing countries represented in Fig. 8. Very similar gaps between internal citations and citations received from foreign applicants are observed for Japan and South Korea. For a comparison, even though the US has a higher rate of internal citations with respect to China, American applicants receive a higher rate of citations from abroad, with a gap between non-US to US and US to US citations that is about −47%. For European countries, German, French and British applicants are respectively cited 46%, 70% and 75% less from foreign applicants than from applicants with the same nationality. Summarising, all analysed countries present significant home biases in citations, but these are particularly strong for East Asian countries, as already observed for different technological sectors (Brem and Nylund, 2021). The home bias phenomenon affecting citations has been ascribed to the fact that knowledge flows tend to be geographically localised (Criscuolo et al., 2005; Peri, 2005), to biases in patent examination processes (Bacchiocchi and Montobbio, 2010), to a possible higher chance to win patent litigations in the home country (An et al., 2023; Mai and Stoyanov, 2018), and to the so-called Not-Invented-Here syndrome, i.e. the persistent decision-making error arising against external knowledge (Hannen et al., 2019).

Overall, from the analysis of forward citations we can draw a number of conclusions and implications. First, home biases in the sourcing of knowledge for innovation indicate that firms tend to use knowledge from the innovation system in which they are embedded, leading to the possibility to miss key technological developments in the REE recycling field developed by external innovators and markets (Brem and Nylund, 2021). Higher home biases suggest a possible lower absorptive capacity from foreign innovators (Cohen and Levinthal, 1990); in particular, higher geographical and technological distances are associated with lower probabilities of knowledge flow (Verdolini and Galeotti, 2011). Secondly and in the opposite vein, very high citation rates towards foreign applicants may indicate the availability of a limited knowledge stock on REE recycling, or a growing dependence on external knowledge

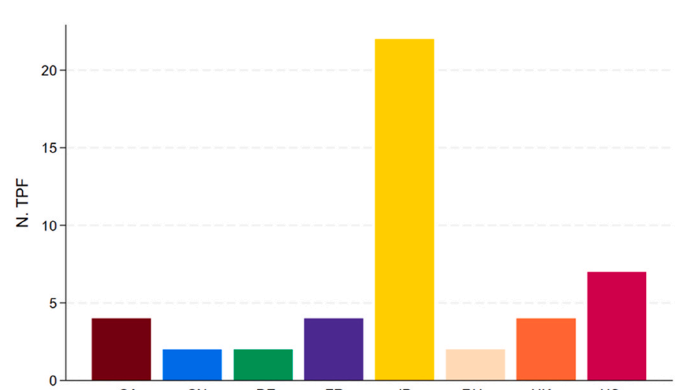

Fig. 9. Total number of triadic patents by applicants' country of residence (selected).

[16] By "citing country", here we mean the country of residence of the applicant of a citing patent (family). Conversely, by "cited country", we mean the country of residence of the applicant of a cited patent (family).The analysis of forward citations by applicants' country of residence is not performed for EPO patents because of their supranational nature.

[17] This count is based on patent applications receiving at least five citations.

[18] The drop is calculated as: [(average citations from country *i* to country *j*/ citations from *j* to *j*) - 1] * 100. For example, in the case of China: [(average citations from non-CN to CN/citations from CN to CN) - 1] * 100.

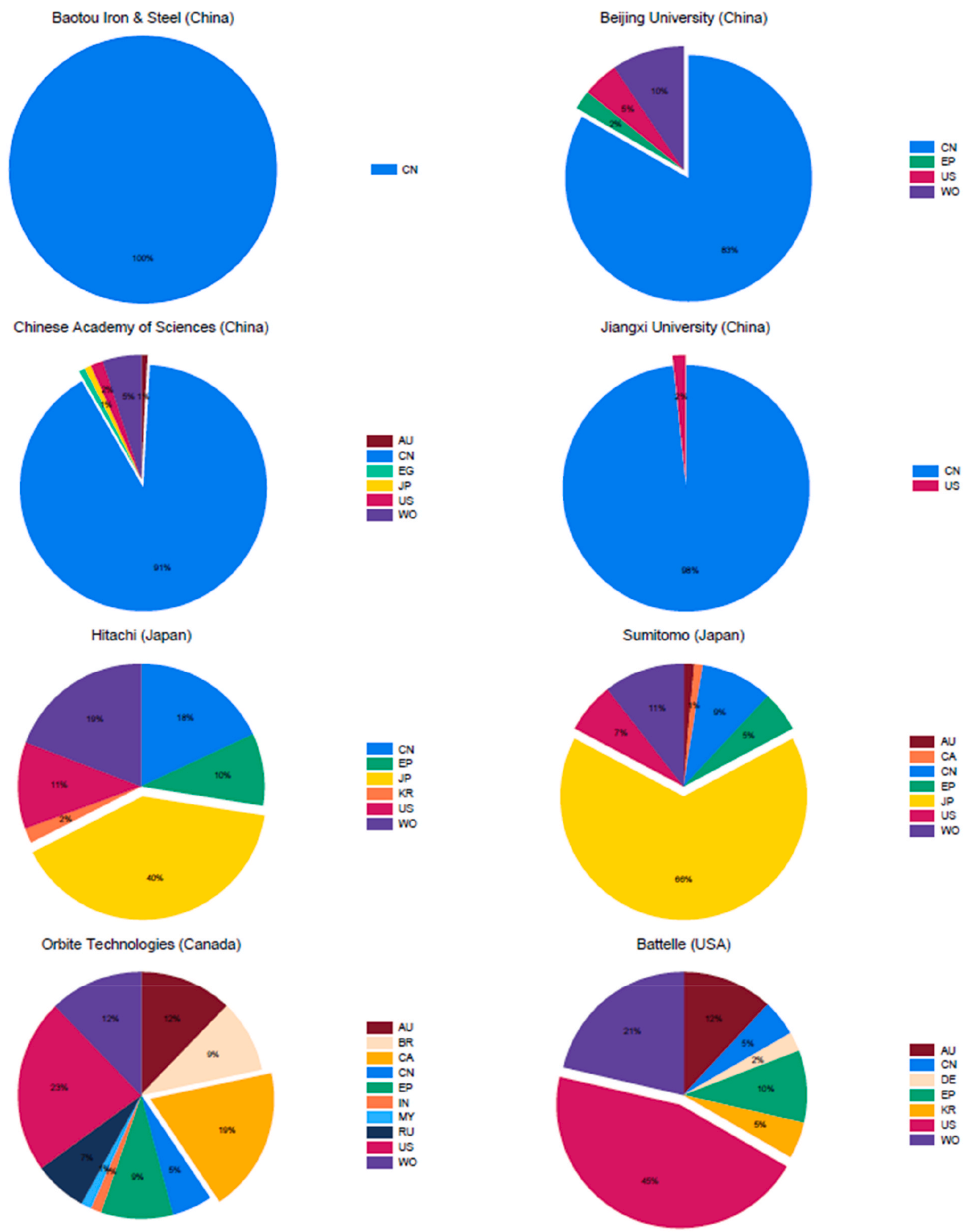

Fig. 10. Territorial protection strategy: share of international patent applications over total applications by applicant (selected) filed in 2010–2022.

flows, and a limited or shrinking competitiveness of internal R&D (Fifarek et al., 2008). Finally, the allocation of forward citations suggests that, while China dominates in terms of the number of REE recycling inventions developed and protected, the US (applicants) appear to be at the knowledge frontier, receiving the highest number of citations from foreign applicants.

A further common set of patent quality indicators is related to the geographical scope of applicants' filing strategy. We start by analysing triadic patent families (TPF). Fig. 9 shows the count of TPF by applicants' country of residence filed between 2010 and 2022. Japan leads with 22 triadic patent families, reflecting a proactive international patenting strategy and its efforts to secure its REE supply, especially after the 2010 dispute with China (Schmid, 2019). US applicants rank second in terms of TPF, followed closely by Canada, France and the UK, which show a relatively high orientation to international patenting in consideration of their low total number of REE recycling patents. China, with only 2 triadic patent families, demonstrates limited international market protection for its inventions, suggesting Chinese patents may not consistently meet the standards required by the EPO, JPO, and USPTO. This is also reflected in the average size of Chinese patent families – i.e. the number of authorities covered on average by patent families with Chinese priority – which indicates that only about 0.5% of Chinese patent families are extended outside China; for a comparison, the average size of patent families including one application filed to the USPTO is about 1.5 (about one third of such patent families cover more than one country) and the one of the patent families including one EP publication is 7. This result is in line with the ones of Alessandri (2023) and Fernandez (2021), referring specifically to the mining sector, demonstrating the low propensity of Chinese applicants to protect their inventions internationally. Our findings for the specific REE recycling sector find general support in Schmoch and Gehrke (2022).

Finally, we inspect the territorial protection strategy of some top applicants, with the aim to compare their propensity to patent in their home country and abroad. For applicants from China, we selected Jiangxi University, the Chinese Academy of Sciences, Beijing University, and Baotou Steel. For Japanese applicants, Sumitomo Ltd and Hitachi Ltd were chosen, while for Western applicants, Battelle Ltd (USA) and Orbite Technologies[19] (Canada) were selected.

Thus, for each selected applicant, Fig. 10 illustrates the share of REE recycling patent applications filed either at the national level or abroad with respect to the applicant's country of residence over the total number of patent applications in any authority, in the same technological field. Even though, for seven out of eight applicants the majority of applications were directed to the respective national authority, confirming once again a generalised home bias, this choice of territorial protection strategy is particularly strong for Chinese applicants. For instance, for Jiangxi University and the Chinese Academy of Sciences, the two applicants with the highest numbers of REE recycling patent applications globally, only about 10% and 2% of their patent applications are addressed to foreign authorities. This finding demonstrate that Chinese top applicants choose to protect their inventions almost exclusively in their home country and this explains the extremely limited number of Chinese TPF identified in Fig. 9. Conversely, the non-Chinese applicants considered in Fig. 10, not only chose to protect their inventions internationally much more often, but their territorial protection strategy is also wider, reaching a higher number of countries. An alternative and more detailed representation of the territorial protection strategy of the eight selected top applicants is provided through Sankey diagrams in Fi gure A.2 and A.3 in Appendix.

To conclude, Section 3.2 proved the importance of integrating qualitative patent indicators to quantitative ones when assessing the innovation dynamics of the REE recycling sector. Indeed, while Chinese applicants, especially universities, dominate in terms of number of patent applications, applicants from other countries seem to be at the technological forefront. This result is suggested *in primis* by the number of citations received and by their geographical distribution, with Chinese patents rarely included in foreign innovators' prior art. Secondly, this general result is supported by the geographical scope of applicants' protection strategy, showing a significantly higher propensity of Japanese, USA and, to some extent, Canadian and European innovators in REE recycling to protect their inventions internationally.

4. Conclusions

The *twin transitions*, encompassing both a green and a digital techno-economic shift, rely heavily on rare earth elements (REE), which are currently essential for various high-tech and renewable energy applications. Europe, the US, Japan, South Korea and Australia have included REE in the list of critical minerals due to their strategic economic importance and the supply risk posed by China's quasi-monopoly in REE mining and processing. Circular economy strategies, such as REE recycling, offer an alternative to primary mining by mitigating supply chain risks, reducing geopolitical dependence on suppliers, and mitigating the environmental impacts associated with mining. However, innovation is needed to achieve economically viable and technically efficient REE recycling, which is currently very limited.

This study examines global innovation trends in REE recycling through a comprehensive analysis of patent data. The study presents a two-step patent search methodology: first, selection of recycling technologies based on IPC and CPC codes according to OECD ENV-TECH, and second, employing text mining of REE-related keywords in patent abstracts and titles (Priore et al., 2024).

Our results are based on both quantitative and qualitative patent indicators. Globally, REE recycling patent applications increased steadily reaching the 472 units in 2018, about 2.7 times more than in 2010. However, strong imbalances are observed at the country level. Indeed, China clearly emerges as the most attractive market for REE recycling invention protection, receiving about 17 times more applications than the following patent authority, the US. This gap has widened enormously since 2010, also due to stagnating innovation dynamics in all countries except China. A first possible explanation for this finding is that the most attractive markets for REE recycling technologies are countries that either already refine virgin materials or that have the possibility to recycle pre-consumer manufacturing REE scraps and residues—since the technology is similar—, rather than those that may depend on urban mining of post-consumer end-of-life products. This is due to the greater economic efficiency of recovering REE from pre-consumer scraps and residues, as they are readily available at production and recycling sites, have higher REE concentrations, and exhibit lower material complexity compared to electronic waste. A second possible determinant of the impressive trend of patent applications in China is represented by REE production policies enacted in this country. These policies have progressively tightened environmental regulations on REE production and concentrated it in a few state-owned enterprises (Mancheri et al., 2019; Pothen and Fink, 2015), which may have increased interest in REE recycling to improve the environmental outcomes of production and tap into alternative REE sources. Finally, China's patent policies, based on patenting incentives (Chen and Zhang, 2019) and the strengthening intellectual property rights protection (Chen et al., 2024), also possibly supported the patenting in REE recycling in China. At the applicant level, Chinese universities are the most productive in terms of number of patent applications, while, among private organizations, Japanese companies are the most prolific. Hydrometallurgical processes are patented more frequently than pyrometallurgical processes. The hydrometallurgical processes used to extract REE from both primary and secondary sources remain largely the same, giving an advantage to players already involved in primary extraction, i.e., once again, Chinese ones mainly.

The picture is quite different when looking at patent quality

[19] Today the company is called Advanced Energy Minerals.

indicators. US applicants are the most cited, followed by Japanese applicants. Analyzing the distribution of forward citations across cited countries, we find a general home bias, but this is particularly strong in the case of East Asian countries; for example, US and, to some extent, European applicants are cited significantly more often by foreign applicants than Chinese applicants. The results of this qualitative assessment are confirmed and reinforced by the analysis of the propensity of applicants to patent internationally, which is very low for Chinese innovators and highest for Japanese and US innovators.

It can be concluded that US and Japanese innovators in REE recycling seem to be at the technological forefront, while knowledge transfer (prior art) from Chinese innovators to foreign innovators is limited. This picture of the quality of Chinese patents is consistent with the existence of a "patent bubble" in Chinese universities (Lin et al., 2024), driven by government pressure and incentives to patent. In principle, a partial alternative explanation for the geographically limited relevance of Chinese patents could be the low absorptive capacity (Cohen and Levinthal, 1990) of other countries. These countries may lack the knowledge base on REE separation processes possessed by Chinese producers of virgin REE, which could be an advantage for the latter. For instance, European countries largely rely on imports of already refined REE or product components containing REE (European Commission, 2023a), thus they might lack knowhow on REE refining industrial processes. This knowledge and industrial gap in REE processing is also indicated by the presence of EU-funded projects in this field. [20]

4.1. Policy recommendations and future research

Major global economic players, such as the EU and the US,[21] have acknowledged the importance of establishing resilient supply chains for CRM, as it can be discerned from the recent discussions on “friend shoring” (Vivoda and Matthews, 2023) and “strategic autonomy” (Amighini et al., 2023; Tagliapietra and Veugelers, 2023). We argue that these strategies should not merely represent a shift of extraction activities and associated trade flows to politically aligned countries, but should instead promote a transition to circular models of natural resource management. Having recognized the role of the circular economy in the supply of CRM (Blengini et al., 2017; Mathieux et al., 2017), the EU Critical Raw Materials Act moves more concretely in this direction. It stipulates that the EU’s recycling capacity should be able to produce at least 25% of the Union’s annual consumption of CRM by 2030, aims to support the market for recycled materials, and, with respect to REE, introduces a “product passport” for permanent magnets (European Commission, 2023b). This last measure would improve the availability of data on REE flows throughout their life cycle: this is fundamental information for investment decisions in the field of CRM recycling (Compagnoni et al., 2024; Huisman et al., 2017; Rollat et al., 2016). Many challenges remain in the implementation of the CRM Act (Hool et al., 2023), as evidenced by the current REE recycling rates. Our analysis demonstrates the need for further support for innovation in REE recycling technologies in Europe, which lags behind the US and Japan. Indeed, the peak in REE prices in 2011 did not provide a stable boost for innovation in REE recycling in Europe. In the absence of this stable demand-pull factor, public investments are necessary to support the accumulation of knowledge and the advancement of REE recycling technologies, as it has often been the case for green technologies (Costantini et al., 2015; Ghisetti and Pontoni, 2015). Public investments should also more strongly support international collaborations and research transfers; indeed, for instance, EU-funded projects have stimulated the development of environmental innovations (Fabrizi et al., 2018, 2025). Public research centers and universities might play a key role in knowledge creation and transfer, especially in lagging behind countries.

Recycling technologies are only one among the factors affecting the economic efficiency of REE recycling. Other factors are: the electronic waste collection rates and its low concentration of REE, which affect economies of scale; the material complexity and design of electronic devices, affecting the recoverability of REE (Althaf et al., 2021; Andersson et al., 2019; Bookhagen et al., 2020; Favot and Massarutto, 2019; Zhang et al., 2017). Consequently, the improvement of policies in these two areas, such as eco-design regulations and extended producer responsibility (Babbitt et al., 2021; Compagnoni, 2022; Favot et al., 2022), should accompany those for technological innovation in REE recycling. On the other hand, for the supply of recycled REE to be absorbed by the market, it seems necessary to promote the production of components containing these materials, which is often concentrated in China as well as REE production (Carrara et al., 2020; Rosenow and Mealy, 2024). The significant role of demand in green technological development and catch-up has been demonstrated in previous literature (Corrocher et al., 2021; Landini et al., 2020). Finally, the harmonization of waste management and trade policies would greatly benefit the development of international circular economy networks, fostering the achievement of economies of scale in REE recycling, innovation development and transfer, and efficient secondary markets (Compagnoni et al., 2024; International Energy Agency, 2024; Yamaguchi, 2018).

Our explorative analysis paves the way for a number of future research directions. Primary and secondary data at the firm and university levels should be used to assess the impact of environmental regulations on REE mining and the effect of national patent policies on both the quantity and quality of patents, particularly in China and developing countries. Future research should evaluate the benefits and limitations of policies for electronic waste management and for electronic equipment circularity (e.g. eco-design, recycled content targets, environmental standards), especially in the case of developed countries. Economic complexity methods (De Cunzo et al., 2023; Mealy and Teytelboym, 2022; Valverde Carbonell et al., 2023) could be used to explore the suitability of countries and regions to develop REE/CRM recycling value chains based on their pre-existing knowledge and industrial capabilities. The spillover innovation effects of EU-funded projects (Fabrizi et al., 2018) on REE/CRM circularity should be explored. Future research could also combine different types of data on innovation and scientific development on REE/CRM circularity, such as scientific publications.

CRediT authorship contribution statement

Riccardo Priore: Writing – review & editing, Validation, Methodology, Investigation, Formal analysis, Data curation. **Marco Compagnoni:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Marinella Favot:** Writing – review & editing, Writing – original draft, Validation, Supervision, Investigation, Conceptualization.

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.

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[20] SUPREEMO https://www.supreemo-project.eu/.

[21] Among the US initiatives for the security of CRM supply there are the Inflation Reduction Act (Romani and Casoli, 2024), the Minerals Security Partnership (Vivoda and Matthews, 2023) and the Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals (Executive Order 13817, 2017).

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Appendix

List of IPC and CPC codes identifying "material recovery, recycling and re-use" and/or "reuse, recycling or recovery technologies" according to ENV-TECH:

A23K10/26–28, A23K10/32–33, A23K10/37–38, A43B1/12, B03B9/06, B22F8, B29B7/66, B29B17, B30B9/32, B62D67, B65H73, B65D65/46, C03B1/02, C04B7/24–30, C04B11/26, C04B18/04–305, C04B33/132, C08J11, C09K11/01, C10M175, C22B7, C22B19/28–30, C22B25/06, D01G11, D21B1/08–10, D21B1/32, D21C5/02, D21H17/01, H01B 15/00, H01J 9/52, H01M 6/52, H01M 10/54, Y02W30/52, Y02W30/56, Y02W30/58, Y02W30/60, Y02W30/62, Y02W30/64, Y02W30/66, Y02W30/74, Y02W30/78, Y02W30/80, Y02W30/82, Y02W30/84, Y02W30/91.

The final list of codes used in the first step of our patent search strategy also includes the CPC Y02P10/20.

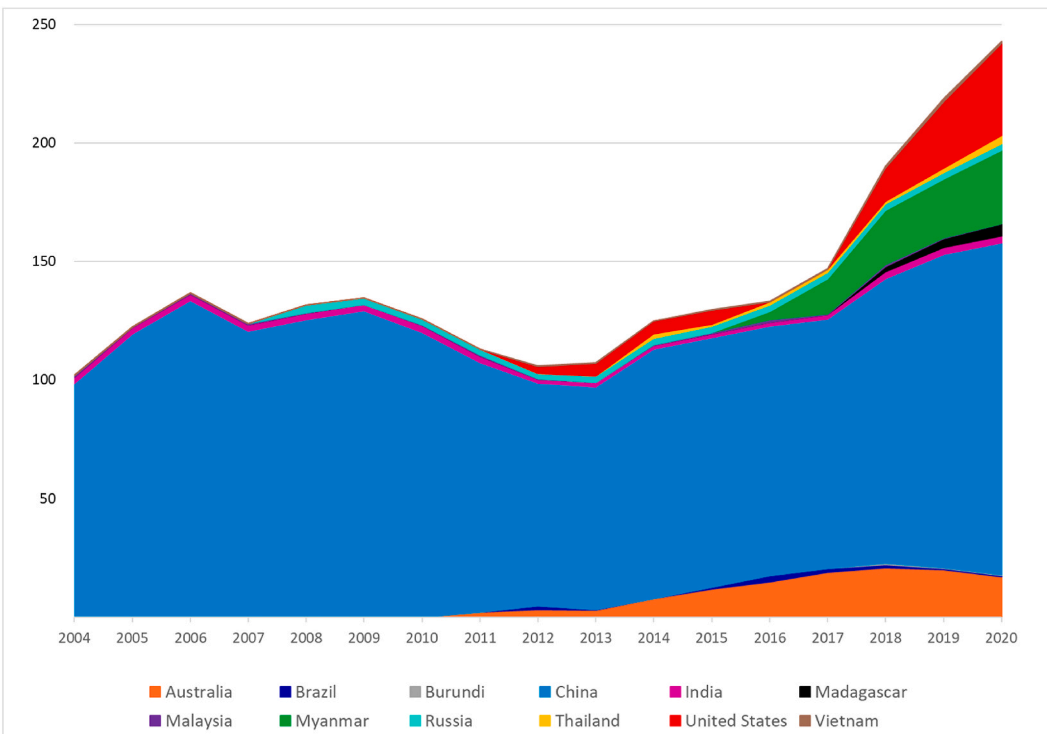

Fig. A.1. Global mine production of REE, 2004–2020. Y axis unit: thousand metric tons, REE-oxide equivalent. Own elaboration on US Geological Survey data.

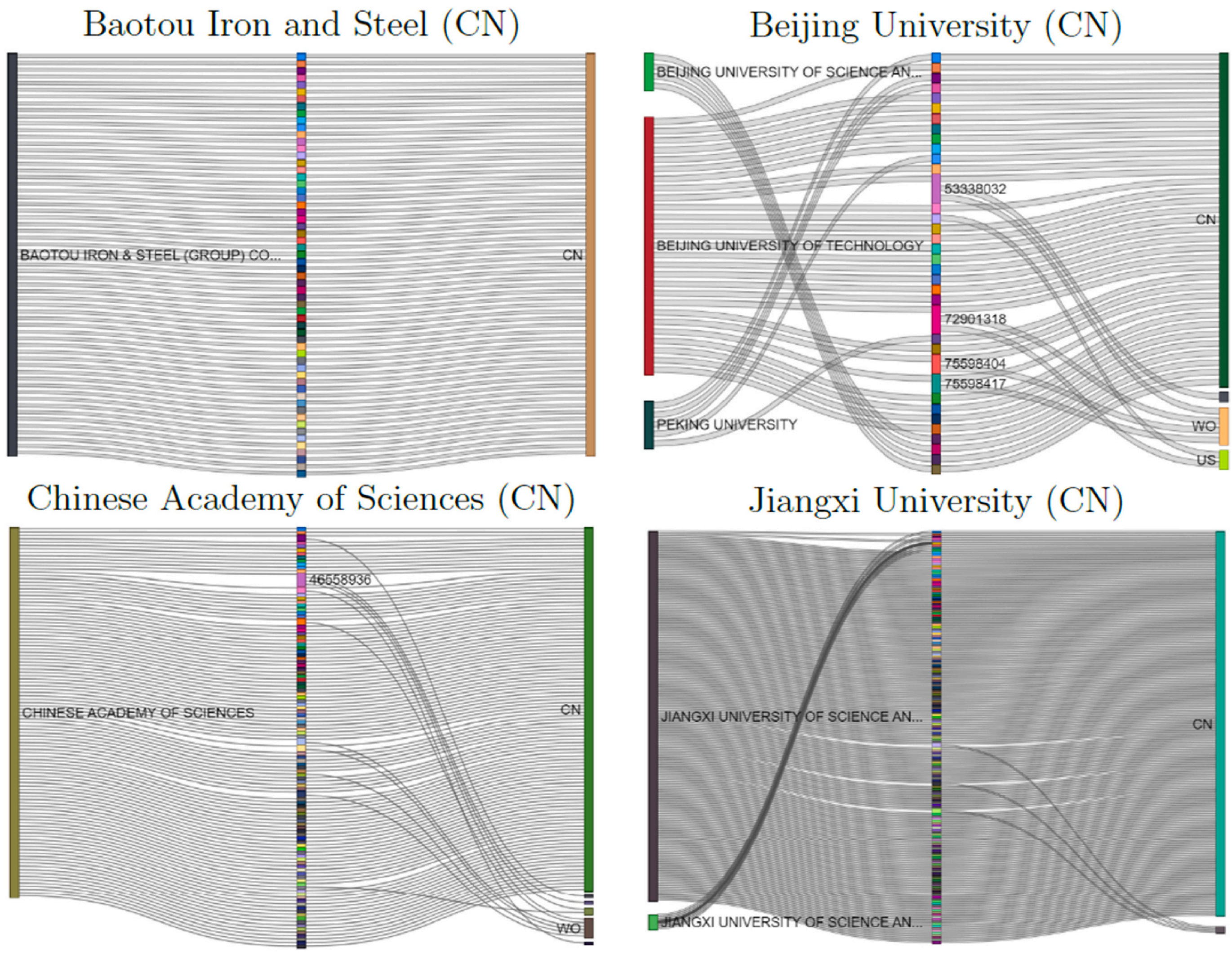

Fig. A.2. Sankey diagrams illustrating the territorial protection strategy of Chinese applicants.The diagrams link, from left to right: the name of a specific applicant (possibly including the applicant's subsidiaries and its different names present in PATSTAT); the applicant's patent applications (number); the application authority.

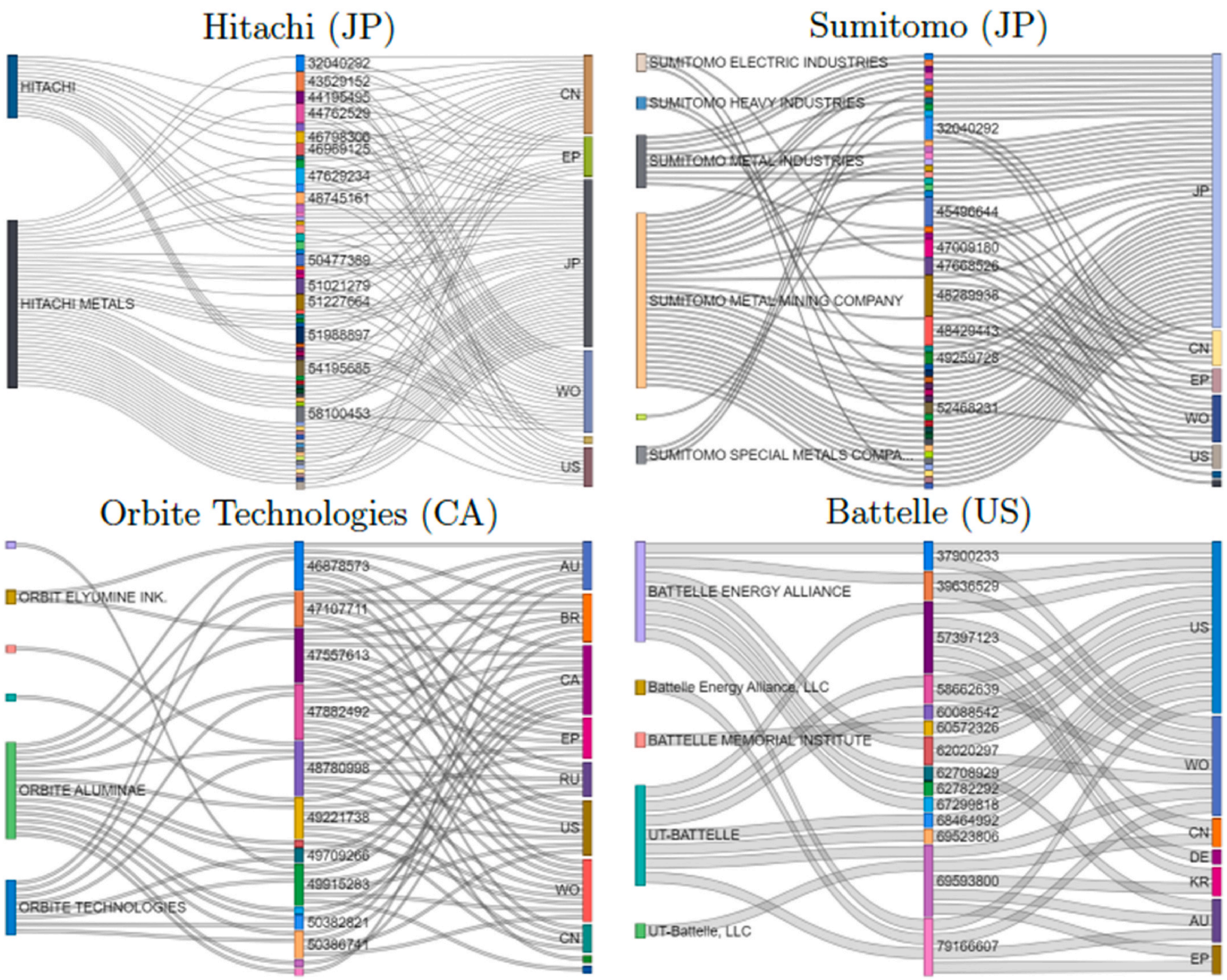

Fig. A.3. Sankey diagrams illustrating the territorial protection strategy of non-Chinese applicants.The diagrams link, from left to right: the name of a specific applicant (possibly including the applicant's subsidiaries and its different names present in PATSTAT); the applicant's patent applications (number); the application authority.

Data availability

See Attached files.

Rare Earth Elements (REE) recycling analysis of patents' data (Original data) (Mendeley Data).

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