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ARTICLE

Assessment of the Research and Production Bridgehead of the Rare Earth Industry of the People's Republic of China

Aleksandr Kirsanov * , *Semjon Pervykh* , *Anastasia Zdonis*

Institute of Non-Ferrous Metals, Siberian Federal University, Krasnoyarsk 660041, Russian Federation

ABSTRACT

Since 2010, the growth in demand for and consumption of rare earth elements has more than doubled, due to a fairly wide area of their possible use in various high-tech devices and products. Today, the People's Republic of China continues to be the world leader in reserves and production output of this type of minerals due to the presence of large deposits, as well as well-structured production chains, which are often combined to create closed cycles for the extraction and processing of rare earth elements. This study provides a comprehensive assessment of China's rare earth sector by analyzing the structure, specialization, and technological capabilities of major domestic producers. Particular attention is given to their production capacities and innovative technologies. Using publicly available patent data from international sources, the study evaluates the current state of technological development in areas such as mineral extraction, chemical processing, waste minimization, and environmental protection. The analysis confirms that China's innovation potential in the REE industry continues to grow at a high pace. Moreover, the emergence and expansion of strategic industries based on rare earth materials – such as electric vehicles, wind energy, and advanced electronics—further strengthen the country's position as a technological leader. The findings provide useful insights for researchers, policymakers, and industry stakeholders interested in sustainable development, strategic resource management, and the future of rare earth innovation in a global context.

*CORRESPONDING AUTHOR:
Aleksandr Kirsanov, Siberian Federal University, Krasnoyarsk 660041, Russian Federation; Email: AKirsanov@sfu-kras.ru

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1. Introduction

The global demand for rare earth elements (REEs) has increased significantly over the past decades, largely due to their indispensable role in a wide range of advanced technologies—including electronics, renewable energy systems, electric vehicles, aerospace components, and defense applications. These elements possess unique chemical and physical properties that make them critical in the production of permanent magnets, catalysts, batteries, and luminescent materials.

China currently dominates the global REE industry, maintaining leadership in the exploration, mining, processing, and technological development of REEs (**Figure 1**) [1]. This dominance is underpinned by large domestic reserves, favorable state policies, and vertically integrated production chains that enable efficient extraction and transformation of REEs into high-value products.

Despite its advantages, the Chinese REE sector faces several critical challenges, including resource depletion at major deposits, increasing environmental pressure, technological gaps in downstream applications, and fragmentation in innovation networks. These issues raise concerns about the long-term sustainability and competitiveness of the industry.

This paper aims to provide a comprehensive assessment of China's rare earth industry, with a particular focus on its production structure, leading companies, technological innovations, and patent activity. By analyzing industry reports, statistical data, and intellectual property trends, the study seeks to clarify China's strategic position in the global REE market and offer insights into the evolving research and industrial landscape that supports it.

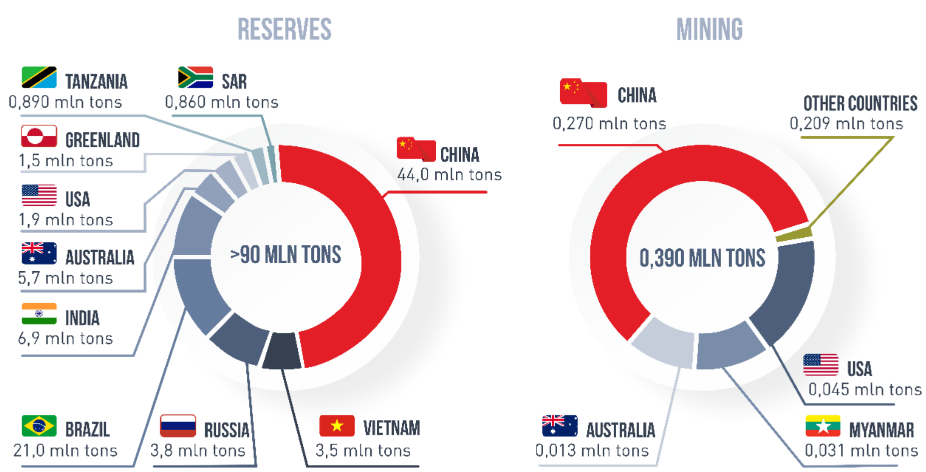


Figure 1. World Reserves and Leading Countries in REE Mining (in 2024).

2. Literature Review

In their free form, rare earth elements (REEs) are metals, so another abbreviation is often found in the literature, REMs (rare earth metals). Despite the fact that in most sources they are considered synonymous, in this work the term REEs will be used to indicate the raw stock from which metal concentrates – REMs – can be obtained.

REEs include 17 components of the periodic table of chemical elements, which are the most in demand in the manufacture of complex goods (**Figure 2**) [2–4]. The structure of the atoms of the elements of the entire REE group is very similar, which gives them almost the same chemical and physical properties [4, 5].

REE reserves on the planet are quite significant and are estimated at the level of tin and copper [7]. Even the rarest element thulium is more common than antimony, bismuth, or mercury [8]. However, they are highly dispersed, which makes it difficult to mine them. For comparison, the content of ordinary iron in ore ranges from 16% to 70%, while a figure of 35% is considered small, REE mining usually begins if their content in mineral placers exceeds 0.5–1.0% [8].

Moreover, REEs are found almost everywhere – in rocks (lanthanum, ytterbium, cerium, etc.) [9], in placers on the seashore and in the seawater (cerium, lanthanum) [10, 11], in fossil bony fishes (scandium, yttrium) [12, 13], in plants and animals [14–18], and even in coal and oil [18].

The total reserves of REEs in the world according to the United States Geological Survey are more than 90 million tons, of which 44 million tons belong to China (**Figure 1**) [1]. It is noteworthy that the BRICS countries (Brazil, Russia, India, China, and South Africa) jointly possess 85.0% of the world's REE reserves discovered today, while the total potential of the USA and Australia is only 7.4%.

Due to the high demand for REEs throughout the world, their mining is growing at an accelerated pace, overtaking many other metals. Thus, in 2024, 390 thousand tons of REEs were extracted, being over 15 times more than 40 years ago, when China was just preparing to enter the rare earth race. For comparison, the average annual gold mining in 2020 worldwide was 3.5 thousand tons (in 2010, 2.83 thousand tons) [19].

It should be noted that China, as a monopolist, has the ability to dictate prices throughout the world, and tense relations with the United States only contribute to their increase. This is because most large Chinese companies are somehow dependent on the government's decisions. Therefore, if China, as it has repeatedly stated, begins to implement its plans to limit the supply of REMs abroad, this will deal a serious blow to European plans for the transition to green energy, because almost 20% of the world production of REMs goes to the creation of solar panels and wind generators [20–23].

At the same time, China will strengthen its technological potential by increasing the manufacture of finished products based on REMs and increasing their added value for other countries.

Such a precedent already existed in 2010, when the PRC imposed an unspoken embargo against Japan due to the arrest of a fishing vessel that was located near the disputed island. Then, the reduction in supplies of REMs from China reached 72%. A more recent example occurred in 2019; against the backdrop of a "trade war" with the United States, China raised tariffs on REEs from 10 to 25%. This sharply increased the cost of REEs – for example, on May 16, 2019, the price of neodymium was about 337,470 yuan per ton, and already on May 19, 490,214 yuan per ton.

China, wishing to maintain its leadership, is constantly increasing its annual quota for REE mining. In 2022, it again increased it by 25%, to 210 thousand tons, which is another record. The quota for REE smelting and separation was also increased to 202 thousand tons, being 24.7% rise on the year earlier.

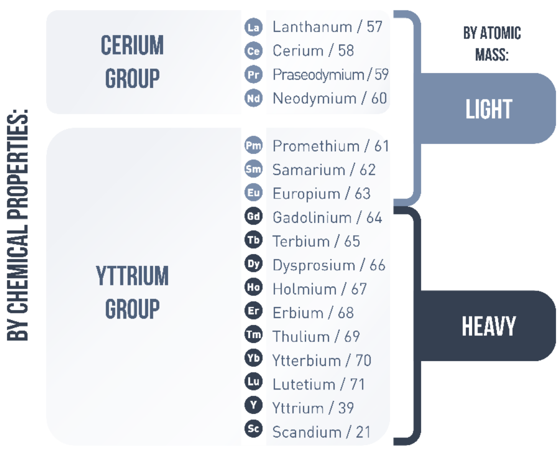


Figure 2. REE Classification by Atomic Weight and Chemical Properties.

3. Materials and Methods

This study employs a mixed-methods approach, combining qualitative analysis of industry reports, policy documents, and scientific literature with quantitative analysis of patent data. Patent data were collected from the World Intellectual Property Organization (WIPO) and Orbit Intelligence databases, focusing on applications filed by Chinese entities from 2019 to 2022. The analysis involved categorizing patents by technological area, identifying key innovators, and tracking trends in patent filings related to mining, processing, and product development. Industry statistics, including resource reserves, production capacities, and industry structure, were obtained from official reports of the US Geological Survey, Chinese government agencies, and industry associations. The literature review included peer-reviewed articles, industry reports, and patent analysis to evaluate technological trends and innovation activity.

The demand for and production of REEs is constantly growing, while reserves remain generally at the same levels (**Table 1**). Thus, in 2013, about 110 thousand tons were mined in the world, and in 2024, this value more than tripled (390 thousand tons). The demand for neodymium oxides (permanent magnets are made from it, it is part of microchips and electric motors) in 2013 was 9,066 thousand tons, and in 2024 – 22,578 thousand tons.

The increase in demand is two-fold:

The first factor is population growth. According to the UN, today the planet's population is 8 billion people [24], leading to increased demand for digital gadgets and advanced technologies. At the same time, the population continues to increase in developing countries such as China, India, and Brazil [25–28].

The second factor is the increasing complexity of the process of creating electronic devices. According to an international study, in the 1980s, only 12 chemical elements were needed to create a microchip. In the 1990s, the number of required elements increased to 16, and by the beginning of the 2000s, it amounted to more than 60 elements.

In 2021, the global rare earth market size reached USD 8.7 billion. It is expected that the average annual growth will be 4.47%, and by 2027, the market size will reach USD 11.6 billion.

The main drivers for the growth in demand for REMs are the increase in the production of modern electronics, as well as research on their use in nano- and biotechnologies.

The scope of REEs is quite wide – production of goods, medicine, power, chemical, semiconductor, space, and other industries (**Figure 3**) [4, 29–32].

Table 1. Ree Mining and Production Dynamics Worldwide in the Period from 2013 to 2024 (excluding China).

Indicator	Year											
	2013	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**
REE reserves, million tons	140	130	130	120	120	120	1200	120	120	130	110	90
REE world mining, thousand tons	110	123	130	129	132	190	220	240	280	300	376	390
Demand for neodymium oxide in the world,thousand tons	9.1	10.3	11.6	13.1	14.6	16.4	18.4	20.7	21.1	21.6	22.0	22.6

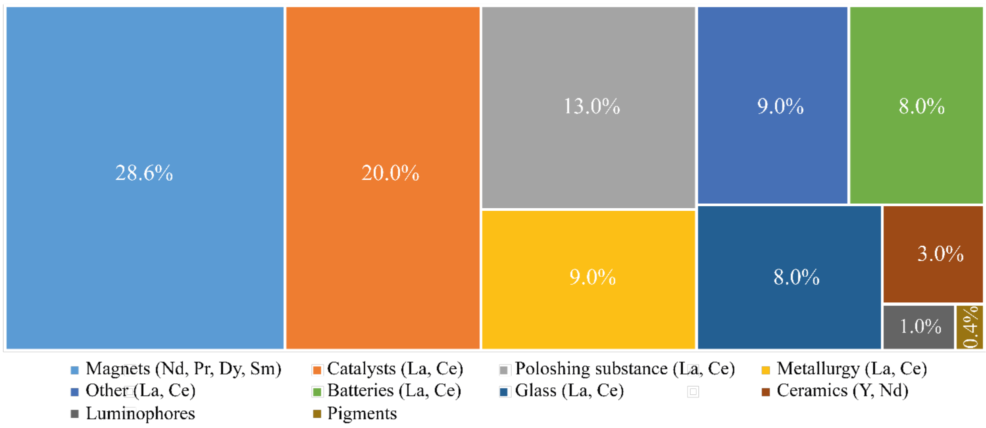
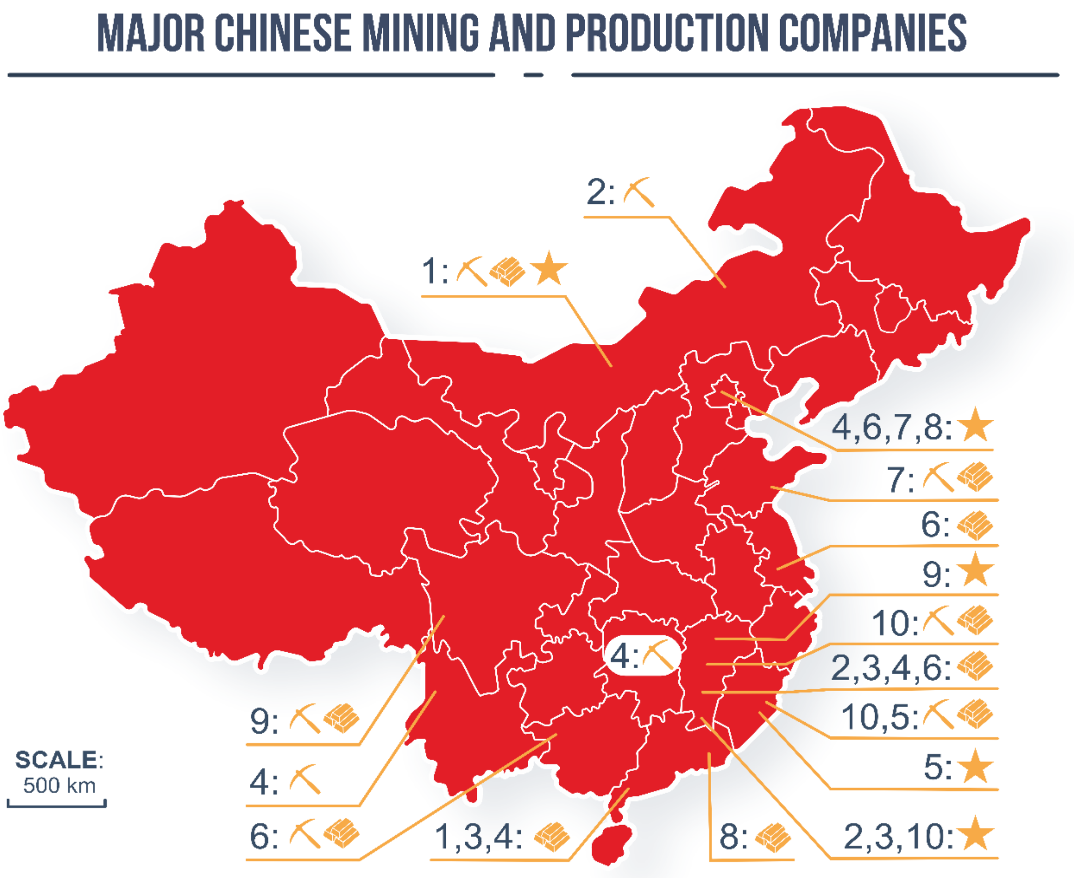


Figure 3. REE Application Areas.

Since the beginning of the 1990s, the People's Republic of China has been the largest miner of REEs, its output is 168 thousand tons/year, being about 60% of the total world mining, while the PRC processes almost 80%. The main provinces for REE mining and REM production are Inner Mongolia, Jiangxi, and Fujian, but works are also carried out in other provinces (**Figure 4**) [33–37].



№	COMPANY	HQ	REE MINING	ENRICHMENT AND SEPARATION
1	Baogang Group	Baotou	Inner Mongolia	Inner Mongolia, Guangdong
2	JL Mag Rare-Earth Co., Ltd.	Ganzhou	Inner Mongolia	Jiangxi
3	China Rare Earth Resources and Technology Co., Ltd	Ganzhou		Jiangxi, Guangdong
4	China Minmetals Corporation	Beijing	Hunan, Yunnan	Jiangxi, Guangdong
5	Xiamen Tungsten Industry Co., Ltd	Xiamen	Fujian	Fujian
6	Aluminum Corporation of China	Beijing	Guangxi	Jiangsu, Jiangxi, Guangxi
7	China Iron and Steel Research Institute Group	Beijing	Shandong	Shandong
8	China Nonferrous Metal Mining (Group)	Beijing		Goangdong
9	Jiangxi Copper	Nanchang	Sichuan	Sichuan
10	Ganzhou Qiandong Rare Earth Group	Ganzhou	Jiangxi, Fujian	Jiangxi, Fujian

Figure 4. Overview Map of Major Chinese REE Mining and Production Companies.

The US ranks second. Its production amounted to approximately 45,000 tons of REM concentrates (11.5%). Next comes Myanmar – 31,000 tons and Australia – 13,000 tons.

Russia has a global share of only 1% in REE production. This is because after the collapse of the USSR (which had a share of 15%), out of 9 enterprises in the rare earth industry, only the Solikamsk magnesium plant in Perm Territory survived (it manufactures only semi-finished products), the others closed or remained in other countries' territories. Today, REEs are mined at the Lovozero loparite deposit in the Murmansk Region [38–41].

4. Results

4.1. Chinese Mining and Production Companies

China is the undisputed world leader in REE mining and production, controlling up to 67% of the world's supply of REE raw stock. About 72% of global REE consumption also accounts for the Chinese industry. All this is possible because of the presence of the entire necessary production chain: from geological exploration to making REM concentrators and their use in creating products.

The creation of such a chain was caused by the characteristics of Chinese companies, which are often merged with each other, creating closed cycles for REE mining and processing. Let us look at the largest of them.

4.2. Baogang Group

This conglomerate has been in business since 1954, and includes CHINA NORTH RARE EARTH (GROUP) HIGH-TECH Co. – the largest REE mining company in China (Official web page of China North Rare Earth (Group). https://www.reht.com/), headquartered in Baotou, Inner Mongolia province.

CHINA NORTH RARE EARTH (GROUP) HIGH-TECH Co. has over 49 branches and holding and joint-stock companies in 12 provinces. Besides, the company owns a number of R&D organizations, including:

- BAOTOU RESEARCH INSTITUTE OF RARE EARTHS;
- STATE LABORATORY FOR RESEARCH AND INTEGRATED USE OF RARE EARTH RESOURCES BAIYUN OBO;
- NATIONAL ENGINEERING RESEARCH CENTER FOR RARE EARTH METALLURGY AND FUNCTIONAL MATERIALS;
- NATIONAL PLATFORM FOR TESTING AND EVALUATING NEW MATERIALS;
- RARE EARTH INDUSTRY CENTER;
- INTERNATIONAL COOPERATION BASE FOR NEW RARE EARTH MATERIALS.

BAOGANG GROUP is the only one in China that fully covers the five main sectors of the REE industry and has a complete production chain. Production capacities are designed for smelting and separation of raw stock (120 thousand tons/year) and REM production (10 thousand tons/year).

At the same time, companies are engaged in the manufacture of various products using REMs, including:

- Nickel-metal hydride (NiMH) batteries (capacity 1 million pcs./year)
- Magnetic resonance imaging with permanent REE magnets (100 pcs./year);
- Luminescent material (100 tons/year);
- Alloys of magnetic materials (41 thousand tons/year);
- Polishing materials (23.5 thousand tons/year);
- Hydrogen storage alloy (8,3 thousand tons/year);
- REE-based flue gas denitrification catalyst (12 thousand m3/year).

The main specializations of the BAOGANG GROUP are REE mining, production of REMs and some REM-based products. In particular, they are engaged in the production of:

- High-quality sintered NdFeB magnets (one of the best magnetic materials from a mixture of neodymium, iron, boron, dysprosium, cobalt, etc.) and fast-hardening thin-sheet NdFeB alloys with a permanent conical crystal structure and uniform phase distribution. The products are used in automobile drives, CNC servo drives, elevators, wind power generation, etc. (BAOTOU STEEL RARE EARTH MAGNETIC MATERIALS Co., Ltd and BEIJING SANJILI NEW MATERIAL Co., Ltd);
- High-efficiency alloy powder for hydrogen storage

(SIHUI DABOWEN INDUSTRIAL Co., Ltd.);

- Carbonates of praseodymium-neodymium, lanthanum-cerium, as well as concentrates of samarium-europium-gadolinium and REE oxides with low aluminum and chloride content (BAOTOU FEIDA RARE EARTH Co., Ltd.);
- Oxides of lanthanum, praseodymium-neodymium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, fluorescent grade terbium, yttrium, yttrium-europium, etc. (XINFENG COUNTY BAOTOU STEEL XINLI RARE EARTH Co., Ltd.);
- Roasted ore and REE chloride salt, as well as 20 types of oxides and carbonates;
- Metal praseodymium neodymium, polishing powder, extractant P507, OPE film;
- Wide range of polishing materials;
- Medical equipment (including magnetic resonance equipment) (BAOTOU XIBAOBOWEI MEDICAL SYSTEM Co., Ltd.);
- The experimental Anta down jacket with heat return technology, which became the first "sports down jacket" that can retain heat at −35 °C;
- SCR flue gas denitrification catalysts based on REEs, as well as technologies for automotive exhaust gas catalysts and their devices.

Each company within the Baogang Group has its own methods and technologies for REE mining and production. However, one can highlight a characteristic feature that is inherent in all of them – the entire chain of mining, processing, and use of REEs is built in such a way as to reduce the percentage of waste. Thus, when mining iron by BAOTOU STEEL (GROUP), tailings are directly sent to CHINA NORTH RARE EARTH (GROUP) HIGH-TECH Co., Ltd, which uses them as raw stock or for flotation.

Let us highlight a number of companies with individual technology features:

- North Rare Earth has a complete industrial chain for the use of REEs: enrichment, smelting, separation, processing, and application. The company also conducts scientific research on the development of new technologies;
- ZIBO BAOTOU STEEL GANODERMA RARE EARTH HIGH-TECH Co., Ltd owns the only alkaline production process in China, which allows for the processing and separation of mixed chloride of REMs (capacity of 25 thousand tons/year);
- BAOTOU FEIDA RARE EARTH Co., Ltd. It uses REE mixed carbonate as raw stock, and the P507 hydrochloric acid system is used for extraction and separation. The resulting solutions of praseodymium-neodymium chloride and samarium-europium-gadolinium chloride are precipitated with ammonium bicarbonate. This allows obtaining concentrates and oxides with low aluminum and chloride content.

4.3. JL Mag Rare-Earth Co., Ltd.

The company is engaged in the research, development, production, and sales of materials based on high-performance third-generation permanent magnets NdFeB. To carry out its operations, the company has a factory for the production of heavy REMs in Ganzhou (Jiangxi province), a factory for the production of light REMs in Baotou (Inner Mongolia province), and a plant for the creation of magnetic materials in Ningbo (Zhejiang province) (Official web page of JL MAG Rare-Earth Co. https://www.jlmag.com.cn/en/).

The main specialization is the production of various materials and parts based on permanent magnets. In addition to independent REE mining and REM production, the company also receives raw stock from CHINA NORTHERN RARE EARTH GROUP and GANZHOU RARE EARTH GROUP.

By mid-2022, the total production capacity of materials based on permanent magnets had reached 23,000 tons/year. By 2025, it is planned to increase capacity to 40 thousand tons/year.

Currently, JL MAG RARE-EARTH Co., Ltd produces mass quantities of sintered magnets and NdFeB magnetic materials of various brands (N58, 56M, 56H, 56SH, etc.). They are distinguished by their high magnetic energy, magnetic field value, and density. Magnetic assemblies, injection molded magnets, and compression joint magnets are also produced.

JL MAG products are widely used in electric vehicles and auto parts, energy-saving air conditioners, industrial motors and elevators, wind power, audio, computers, robotics, etc.

In September 2020, the company signed an agreement with Tesla to supply magnets for their cars.

JL MAG uses the grain boundary diffusion technology (one of the main mechanisms for low-temperature sintering in powder metallurgy production), which has received invention patents in the USA, Europe, and Japan.

JL MAG has R&D institutes in China, the Netherlands, and Japan. Forty-eight patents were received, including 23 for inventions. The company establishes special scholarships for college students and hires staff from poor areas of Ganzhou.

In 2021, the revenue from the sale of permanent NdFeB magnetic materials amounted to 3,766 million yuan. Overall, the company recorded a revenue of 4 billion yuan, an increase of 68.8% compared to the previous year. Production and sales volumes recorded a historical maximum for the entire existence of the company. Due to the general increase in demand, by 2025 the company plans to almost double the annual production volumes reaching 40 thousand tons/year.

4.4. China Rare Earth Resources and Technology Co., Ltd.

The company is headquartered in Ganzhou (Jiangxi province). It has 4 subsidiaries, including the Research Institute of Rare Earth Elements. Products are imported to the USA, Japan, South Korea, and the European Union. Net assets for 2021 are 3.87 billion yuan (Official web page of China Rare Earth Resources and Technology Co. http://www.cmreltd.com/).

The company is focused on the production and trading of high-purity REE single oxides used in the production of high-quality glass, ceramics, magnetic materials, LEDs, fluorescent materials, lasers, superconductors, high-energy batteries, and fiber optic cables.

The company also conducts R&D of new materials and provides consulting services. The products are widely used in magnetic, luminescent, catalytic, chemical, crystalline materials, and high-tech electronic components. Raw stock for separation and processing is purchased from other companies.

The holding company DINGNAN DAHUA NEW MATERIAL RESOURCES Co., Ltd produces 14 kinds of REE compounds and 2 kinds of co-precipitation products. The purity of most of them exceeds 99.99%, including lanthanum and yttrium oxides.

The company's research institute has developed a number of technologies, including:

- Extraction and separation of REE compounds;
- Saponification of the organic phase of calcium;
- Composite saponification of ammonia and calcium;
- Extraction and separation of high-purity europium oxide without recovery;
- Recovery of waste rare earth energy-saving lamp powder.

DINGNAN DAHUA NEW MATERIAL RESOURCES Co., Ltd introduces "green technologies" for purifying liquid REE ore, recycling wastewater, reducing exhaust gas discharge, etc.

4.5. China Minmetals Corporation

The state-owned system-forming enterprise was created in 1950 and is directly managed by the central government. It includes 22 enterprises, headquartered in Beijing. REE mining is carried out in Hunan and Yunnan, with processing and separation occurring in Jiangxi and Guangdong provinces. The company owns 38 Chinese and foreign mines (Asia, Oceania, Africa, South America), which produce more than 70% of the national strategically important metals. Among other things, the company is involved in trade logistics, finance, and real estate (Official web page of China Minmetals Corporation. http://www.minmetals.com/) [42].

At the end of 2021, China Minmetals' total assets exceeded 1 trillion yuan, and operating profit exceeded 850 billion yuan (58th place in the list of the world's 500 largest companies).

The main activity is the mining of metals and minerals. It has the entire REE production chain: from deposit exploration and development to processing and sales.

At the beginning of 2022, the company had 14 research and design institutes and 43 scientific platforms, including national laboratories. The total number of scientific and technical employees exceeds 30,000 people. The number of active patents is almost 43 thousand. In addition, the company acts as editor-in-chief in the preparation of more than 1,400 international and national standards.

4.6. Xiamen Tungsten Industry Co., Ltd.

A group of high-tech enterprises founded in 1958. Main business areas: mining of REEs, tungsten, molybdenum, and other minerals, creation of new materials, and real estate (Official web page of Xiamen Tungsten Industry Co. http://www.cxtc.com/Default.aspx).

It operates a full cycle of REE mining and production, including direct extraction, smelting and separation, deep processing and use in production.

Most of the company's REEs are intermediate or ancillary products. The company's REE production line has a high industry status (the State Council of the People's Republic of China approved its support), but the company works mainly to order, according to specific requests for quantity and quality.

REEs are used to produce permanent magnets, motors for industrial energy and automobiles, cathode materials for lithium-ion batteries and powder anode materials for hydrogen storage, as well as products for agriculture and environmental protection.

The company's total asset value in 2021 was estimated at 32.42 billion yuan, up 29.15% from the previous year. Of this, the rare earth business generated 4.8 billion yuan, an increase by 56.98% compared to 2020. The sales volume and unit price of REE oxides also increased. As on incomplete 2022, the company already had 40.96 billion yuan in assets.

4.7. Other Companies

In addition to the above corporations, there are a number of other companies engaged in the mining and production of REEs in China:

- ALUMINUM CORPORATION OF CHINA. Founded in 2001, headquartered in Beijing. REE mining is carried out in Guangxi province and enrichment and separation is carried out in Jiangsu, Jiangxi, and Guangxi provinces.
- CHINA IRON AND STEEL RESEARCH INSTITUTE GROUP (CISRI). Founded in 1952, headquartered in Beijing. There are subsidiaries in Japan and Vietnam, and offices in the USA and Germany. REE mining, enrichment, and separation are carried out in Shandong province.
- CHINA NONFERROUS METAL MINING (Group). Established in 1983, headquartered in Beijing. The processing and separation facilities are located in Guangdong province. It is also developing REE deposits in China, Central and South Africa.
- JIANGXI COPPER. Founded in 1979, headquartered in Nanchang (Jiangxi province). Mining, enrichment, and separation of REEs take place in Sichuan Province.
- GANZHOU QIANDONG RARE EARTH GROUP. Established in 1988, headquartered in Ganzhou (Jiangxi province). Mining, beneficiation, and separation take place in Jiangxi and Fujian provinces.

4.8. New REE Mining and Processing Technologies Developed in China

In 2021 alone, China filed 1,585,663 patent applications with the World Intellectual Property Organization (WIPO), accounting for 46.6% of all applications worldwide [43]. Most of them relate to computer and audiovisual technologies, digital communications, but many also relate to the mining industry.

In general, registered Chinese patents related to REEs are quite diverse, ranging from mineral mining, mineral processing, and creation of various REE-based products. Thus, China Agricultural University invented an organic complex based on REMs, which has a biostimulating effect on seed germination, growth and development of seedlings, and increases plant resistance to diseases [44].

Below are some patents published over the past 2–3 years, roughly divided into three groups:

4.9. REE Mining

East China Jiaotong University in 2019–2022 registered several patents on a method and system for predicting the content of components in the process of REE extraction. In particular, the following is proposed:

- Creation of an Elman neural network model to control the REE extraction process;
- Receiving data;
- Calculation of optimal values through a process of continuous optimization;
- Making operational forecasts for REE production and

the required amount of reagents.

This forecasting method helps to optimize production and calculate in advance the amount of required reagents and the overall REE yield. It is suitable for working with several variables at once, which increases production efficiency [45].

Another university patent proposes a component content prediction system based on a historical REE database that includes descriptions of the color characteristics of REE solutions under various laboratory conditions and their corresponding REE component content as input to this technical analysis. They and the colors of the target REE solutions are then matched to a predefined condition [46].

CHINA NORTH RARE EARTH (GROUP) HIGH-TECH has registered patents for several devices:

- A device for continuous removal of sulfate radicals from REE solution. It includes feeding equipment, a chain of series-connected settling tanks, a temperature sensor, a filter, a heat exchanger, and a flow regulator—all of which lead to an increase in the yield of the REE product and a decrease in the consumption of materials used [47];
- Devices for processing emulsion together with a method for processing REE-containing raw stock. It has a vacuum filter, vacuum and transfer pumps, and a buffer tank. It allows separating the emulsion, water and organic REE compounds without any chemicals, increasing the product yield [48];
- A device for continuous production of crystalline REE carbonate. The device consists of multiple systems (flow control, seed reflux, sedimentation, thickening) and a supernatant storage tank. The device is capable of continuously producing crystalline REE carbonate of constant quality, which is also easily filtered and washed [49].

Another company, CHINA ENFI ENGINEERING CORPORATION, offers REE oxide extraction devices and REE precipitation devices. The first one is an extraction device for processing REE minerals, which integrates mixing, roasting, leaching, extraction, precipitation, and calcination units. It makes the REE leaching process faster and easier than usual [50]. The second one is a tank with cavities mixing the initial liquid and the deposition agent. The temperature of the supplied liquid can be adjusted, which compensates for its fluctuations during an exothermic reaction (with the release of heat) and ultimately extinguishes the unstable quality of the product that previously existed with this method [51].

4.10. REE Processing

Numerous REE recycling patents have been filed over the past three years. In China, they are registered on behalf of companies, and less often – by research centers and universities. Here are some of them that are relevant today:

- A method for removing fluorine from rare earth chloride mixed solution obtained by acid-base combination treatment. It includes the stages of processing the raw stock with soluble carbonate, mixing the carbonaceous sediment with a REE chloride solution, adjusting the pH value, heating, and filtration. The method helps to reduce the amount of slag produced, reduces thermal energy consumption, speeds up processing time, and reduces overall processing costs. Patent owner: FANGXING RARE EARTH Co., Ltd, Mianning county, Sichuan province [52];
- A kind of method for preparing pure sulfuric acid rare earth solution. A pure solution of REEs in sulfuric acid is obtained from sulfated calcined ore. Extraction occurs in stages and faster than usual. More than 50% of REEs are recrystallized into high-purity sulfates through careful use of the kinetic properties of REE solutions and ore leaching. Patent owner: YOUYAN RARE EARTH NEW MATERIALS Co., Ltd, Beijing [53];
- A method for removing non-rare earth impurities in rare earth hydrometallurgy. According to it, REEs are treated with an acid-base combination method, then precipitated and filtered, and the resulting solution is subjected to extraction to obtain different solutions of REE chlorides. Then they are heated, the pH is adjusted, a solution of sulfur ions is added and filtered. This method removes impurities of heavy metals (barium, radium, lead) without additional costs. Patent owner: FANGXING RARE EARTH Co., Ltd, Mianning county, Sichuan province [54];

A method for recovering organic and rare earth from bastnaesite extraction in three phases. The process steps are as follows: the three-phase emulsion is centrifuged with the addition of solvent to obtain the residue and filtrate. Sulfuric acid is added to the residue, which is transferred to another place – this is how carbonation occurs. Water is added to the reactor and centrifuged again with some steps. This method saves solvent, processing time, and does not generate organic waste in wastewater. Patent owner: FANGXING RARE EARTH Co., Ltd, Mianning county, Sichuan province [55];

- A method for decomposing bastnaesite. The main steps include: oxidation and roasting, low-temperature complex acid leaching, flocculation (liquid separation to produce a fluorine-containing rare earth feed solution and acid leach residue), and defluorination treatment. With this method, the rate of leaching REE oxide concentrates increases by 71.5%, and isolated REE such as lanthanum – by 95%, praseodymium and neodymium – by 97%, compared to standard methods. The method helps to reduce alkali consumption and reduce the discharge of waste into wastewater, saves energy, and produces a high-quality product. Patent owner: JIANGXI COPPER TECHNOLOGY RESEARCH INSTITUTE Co., Ltd, Nanchang, Jiangxi province [56];
- A method of removing iron ions from solutions containing neodymium, praseodymium, dysprosium, and iron. This is achieved by adding glucose and uniform mixing followed by hydrothermal treatment. As a result, iron-containing compounds settle at the bottom. The REE retention rate is over 97%. The same method can be used to treat acidic waste solutions. It is easy to use and inexpensive. Patent owner: Northeast Normal University, Changchun, Jilin province [57].

4.11. Green REE Extraction from Industrial Waste

This category of patents includes developments whose goal is to reduce environmental harm as a result of REE mining or REE extraction from recycled materials/waste.

A method for removing impurities and recovering emulsified organic phase by rare earth extraction. The process includes separation of the organic phase, back extraction with hydrochloric acid, acid washing, and water washing. This method is not only for obtaining REEs but also for taking care of the environment. Wastewater containing REEs treated in this way meets national requirements. Patent owner: Steel Research Group Rare Earth Technology Co., Ltd [58];

Rare earth processing waste water processing method. Consists of the following stages: filtration, distillation with nitrogen and ammonia and their adsorption, adsorption with activated carbon, and electrolysis. The result is REE plus wastewater treatment. A bipolar membrane electrodialysis device is also used, which processes wastewater into alkali, acid and industrial water solutions that meet the standards. The method requires low financial costs and is convenient on an industrial scale. Patent owner: CHINA ALUMINUM RARE EARTH (YIXING) Co., Ltd, Liaocheng, Shandong province [59];

A method for extracting rare earth oxides from polishing powder waste. The process steps include dissolution, evaporation, extraction, washing, distillation, and combustion. This method separates REEs from polishing powder waste, including silicon, aluminum, fluorine, calcium, magnesium, etc. Increases the rate of REE extraction, does not use ammonia water, and supports the environment. Patent owner: Hunan Rare Earth Metal & Material Institute, Changsha, Hunan province [60];

Ecological restoration type rare earth tailings. The patent proposes the creation of green tailings dumps (tailings are waste rocks with low mineral content). It consists of various layers, including clay barrier, vegetation and special REE enhancement layer, as well as flood ditches, clay barrier, etc. Such a tailings dump allows restoring the ecological balance and reduces the concentration of heavy metals in the soil. Patent owner: CHINA ENFI ENGINEERING CORPORATION, Beijing [61];

A method of extracting lanthanum from fly ash. The general process goes as follows: fly ash is dissolved in hydrochloric acid, filtered, and then leached. Next, REEs are isolated and separated. By resorting to extraction and leaching of the resin, a solution of lanthanum is obtained. This method is very simple; the extraction speed and purity of the product are higher than usual. Patent owner: CHINA SHENHUA ENERGY Co., Ltd, Beijing [62].

4.12. REE Mining Problems

The increase in demand, and as a result, in REE production, has begun to lead to faster depletion of rich deposits. Thus, in China, which accounts for more than 60% of REE production, only a third of the original reserves remained at the Baotou mine, and the recovery rate of the useful component decreased to 10%. In the southern region of the country, only 15 deposits of ion absorption ores remain, although 20 years ago there were 50 of them.

High-tech production, as well as raw stock recycling, does not in any way solve the problem of depletion of deposits. Therefore, individual EU countries, the USA, and Australia have already created "scarce" lists of minerals that are critical to industry and national security [63–65]. China, in turn, plans to partially or completely stop the exports of REMs from the country, justifying this by the depletion of internal resources with the growth of domestic needs, as well as environmental damage.

The depletion of known deposits forces to look for new ones; however, there are a number of problems here too. Below are the main ones:

- High economic costs. The development of new deposits requires high costs for the purchase and maintenance of mining equipment, staff payroll, obtaining licenses from the government, deployment of processing plants, creation of transport lines, etc.;
- Remoteness of deposits and lack of infrastructure. As a rule, new deposits are wild areas where there is no basic infrastructure: roads, electricity, and water. Natural conditions have a particular influence: deposits can be located in northern latitudes, such as Tomtorskoye (Russia), where the average annual temperature is −16.3 °C. Infrastructure creation accounts for about 30% of all capital expenditures;
- Shortage of qualified personnel. Often the problem lies in the lack of popularity of the mining sector among graduates. In addition, most companies are forced to independently provide educational programs to improve their skills, since educational institutions do not keep up with rapidly changing mining technologies;
- Illegal mining. Particular damage to reserves is caused by illegal mines, which produce huge amounts of waste with frequent irrational use of subsoil;
- Obtaining licenses and complying with environmental standards. In almost every country, the government imposes strict requirements for companies involved in mining. This imposes additional costs on companies to mitigate the harm that occurs during production.

The above difficulties in REE mining, as well as the dependence of mining companies on the REM market conditions, make the industry unattractive to investors. This creates certain difficulties when developing new deposits, and also affects the final price of REMs.

5. Discussion

According to the data of Orbit Intelligence (Official website of the Orbit Intelligence intellectual property database. https://www.questel.com/) – the leading global intellectual property analysis software, there are 40,196 registered patents worldwide covering the rare earth sector as of the end of 2022. The list of leading countries by received patents related to REEs includes China (10,920 patents), Japan (4,598), USA (3,161), Korea (1,726), Germany (1,497), etc. However, this order of the leading countries in terms of the number of registered patents was not always the case.

The first registered patent that mentioned REEs dates back to 1902 – a German chemist Richard Escales proposed a method for producing explosives of high destructive power, which consisted in using as a combustible ingredient in the production of explosives of the metals whose oxides are difficult to recover, such as boron, cerium, lanthanum, neodymium, didymium, zirconium, and thorium.

Generally, up to 1950, a total of 172 patents were registered, in one way or another related to the REE industry. The main countries registering their intellectual property at that time were the UK, the USA, France, and Germany. Since 1975, Japan has held the lead in the number of registered applications in various REE areas by a large margin, due to its flourishing technology. While the first registered patents of the PRC were published only in 1985, this balance of power continued until 2007, when the strategic policy of the Chinese authorities made the country a leader in the number of registered applications.

It is worth noting that to date, the rights to 13% of all patents received belong to corporations such as Hitachi Metals, Ltd. (Japan), TDK Corporation (Japan), Toshiba (Japan), China Petroleum & Chemical Corporation (Japan), Nippon Steel Corporation (Japan), Shin-Etsu Chemical Co., Ltd. (Japan), Panasonic Corporation (Japan), Sumitomo Metal Mining Co., Ltd. (Japan), Kyocera (Japan), Hitachi Ltd. (Japan).

Table 2 shows the number of registered patent applications in the last 10 years related to the REE sector.

The scale of technological innovation in China's REE industry continues to grow, and the data (**Table 2**) shows that the country is actively promoting the development of the rare earth industry, finding new applications for REEs (**Figure 5**).

A large number of patents are concentrated in the mining and metallurgical industry (**Figure 5**), while in other areas of development in China, REE-based patents are not so widespread. In comparison, in Japan, the application field of REE-based intellectual property results is more homogeneous, and in addition to the mining and metallurgical industry, widespread application is observed in the field of electrical machinery, equipment, and energy. This situation allows Japan to conduct comprehensive development of a number of industries, while China has a more consistent position, and all efforts are now directed to the mining and manufacturing sectors.

Table 2. Number Of Ree-Related Patents by Leading Country in the Last 10 Years.

Country	Year										
	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022*
China	1006	1091	1298	1469	1584	1627	1665	1432	1486	1286	793
Japan	525	451	426	390	407	387	327	277	252	130	28
USA	392	350	354	355	360	321	309	291	250	156	64
EP	210	173	184	148	185	180	142	136	112	28	9
WIPO	331	266	274	221	265	248	227	202	201	176	51
Korea	195	166	147	130	133	134	136	114	106	40	11
Germany	37	37	64	33	53	30	28	24	15	15	1
Canada	55	42	42	37	43	45	30	30	27	9	3
Taiwan	65	57	43	30	53	46	64	42	37	22	6
France	6	10	8	20	11	11	10	7	–	2	–

* Data for 2022 is being processed; EP – Eurasian Patent Office; WIPO – World Intellectual Property Organization.

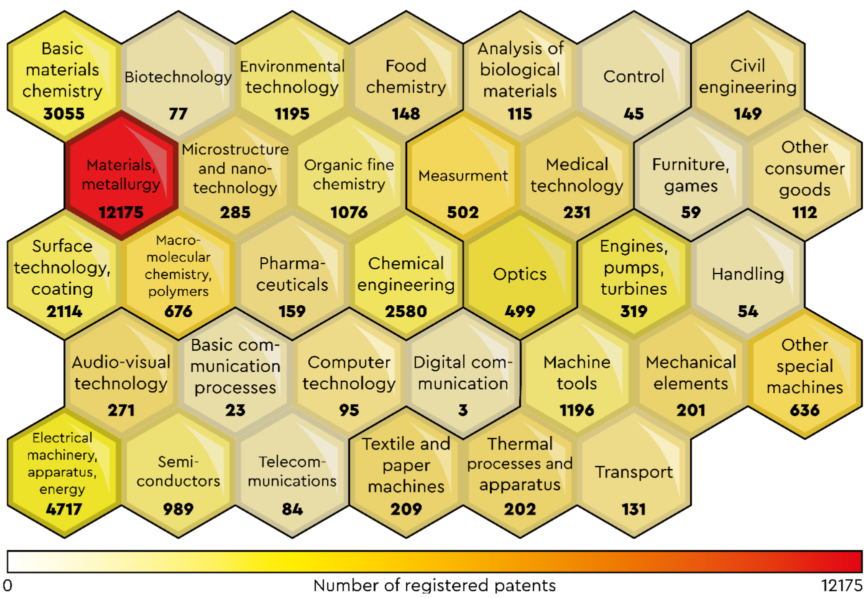


Figure 5. Application Area of REE-Based Chinese Patents.

Considering the above, it can be concluded that with the global increasing attention to rare earth resources and encouraging technological innovation, Chinese patented rare earth technologies are developing rapidly and maintaining a leading position in quantity. However, the main owners are still the largest Japanese companies producing high-tech equipment or products.

In terms of the total number of patent applications for the rare earth industry, after decades of development, China's innovation capabilities have improved significantly. However, just from the absolute number of patents in general, the whole situation of technological innovation in China's REE industry cannot be fully clarified.

In order to build up and strengthen the innovative potential based on REEs, as well as the development of not only mining but also other industries, the Chinese authorities need to think about stimulating the formation of international scientific and technological collaborations that can benefit both existing industry chains and lead to the creation of new chains with diversified and multilateral capabilities.

6. Conclusions

This study provides an assessment of the scientific potential and opportunity of technological growth of China in the REE mining and processing industry, upon the results of which the following conclusions have been drawn:

1. REEs are an indispensable key element for the development of high-tech in any country. Thus, in the future, increased competition between world powers for the ownership of REEs and the possession of their deposits is expected. At the same time, Russia and South Africa are promising countries for REE mining. The first one has rich deposits, including the Tomtorskoye, Chuktukonskoye, Zashikhinskoye, Beloziminskoye, and Katuginskoye fields. South Africa already has the Steenkampskraal mine (Western Cape province), which contains the highest quality REEs (for example, the content of neodymium is more than the total content of all REEs in most other deposits, namely 2.58% or 15.6 thousand tons). However, at the moment, and in the foreseeable future, China will be the leader.
2. China's position as the leader in the rare earth market has been facilitated by strategic government policies and low labor costs.
3. Compared to Japan and the United States, China began to expand its research and development in the REE sector relatively late, but in accordance with the trend of development of patents in this industry and the creation of related technological innovations, at the current time, the country has every chance of long-term taking the lead in this sector.
4. The innovation network of China's rare earth industry is currently in a state of unbalanced and relatively loose connections, so it is necessary to form a new model for the integration and mutually beneficial development of the entire industry chain. Finding new applications of REEs in various fields to establish cooperation in research and development, as well as forming a network structure for diversified multilateral cooperation and innovation development, will enable the comprehensive development of the entire rare earth production chain.
5. In accordance with the innovative status of the entire rare earth industry, China needs to continue to increase investment in scientific research, increase research on the development of new technologies, formulate and improve scientific and technological innovation policies, and create a favorable innovation environment.

Author Contributions

Conceptualization – A. K.; methodology – A. K. and S. P.; validation – A. K., S. P., and A. Z.; formal analysis – S. P., and A. Z.; resources – S. P., and A. Z.; writing – original draft preparation – A. K.; writing – review and editing, S. P., and A. Z.; visualization – A. Z.

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Conflicts of Interest

The authors declare no conflict of interest.

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