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High-Quality Development Strategy for the Supply Chain of Critical Minerals and Its material industry in China

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Abstract: Critical minerals and materials are fundamental to national economy, national defense construction, and residents' lives; therefore, it is of great significance to ensure the stability of their supply chain. This study associates mineral resources with the material industry and analyzes the strategic needs and development status of China's key minerals and their raw material industries from the perspective of the entire industrial chain including resource exploration, mining, smelting, material processing, manufacturing, and product recycling. Moreover, problems are summarized including blocked industrial chain; insufficient supply of key minerals at the resource end; high energy consumption and excessive scale at the smelting end; insufficient support capacity, inadequate innovation ability, and weak industrial foundation at the material end; and lagging development at the recycling end. Focusing on exploration, mining, and basic raw material preparation, a three-step goal by 2035 is proposed, and technological development priorities are summarized from the aspects of mining, smelting, and basic raw materials. Furthermore, we propose suggestions for the high-quality development of China's key minerals and material industry supply chain, including promoting the supply guarantee capacity of domestic mineral resources, improving the technical competitiveness of new materials, and unblocking the resource–smelting–material–recycling industrial chain.
Keywords: critical minerals; materials; entire industrial chain; supply chain; high-quality development; recycling

1 Introduction

Critical minerals and materials are the material basis for national economy, social development, national defense construction and residents' life. At present, the international situation has undergone profound changes [1]. Developed countries attach importance to the security of the supply chain of critical minerals and its material industry and make plans and layout. China also emphasizes on improving the stability and competitiveness of the industrial chain and supply chain and strengthening the independent and controllable capabilities of them.

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Governments and scholars in China and abroad attach great importance to the security and stability of the supply chain of critical minerals and its material industry. Countries worldwide strengthen both the construction of local supply chain and international cooperation. Critical minerals and related materials have become the focus of competition of the international supply chain. Some countries try to build a supply chain of mineral resources and related materials that is independent of China, and control global strategic resources through many methods, such as political, economic, military, transportation channels, international rules, equity investment, and social media. China's supply chain of critical minerals and material industry is facing huge risks under the current complex international environment. First, China's minerals and raw materials are highly dependent on foreign countries, and the gap is increasing. Second, some countries have formed alliances to contain and blockade the overseas supply of China's critical minerals and raw materials. Third, the development and utilization level of China's advantageous minerals is low, the high-value utilization degree of raw materials is low, the high-quality raw materials of advantageous minerals are still dependent on imports, and the resource advantage hasn't transformed into industrial advantage. China is in a disadvantageous position of exporting primary products and importing high-quality processed products in the international division of labor.

In recent years, Chinese scholars also attached great importance to the study of supply chain of critical minerals and materials. They summarized the development strategies of foreign countries and their enlightenment to China [2,3], analyzed and evaluated the supply risks faced by China's critical minerals and materials, and proposed corresponding development suggestions [4–9]. The Chinese Academy of Engineering has organized strategic studies on developing a strong country in the fields of mineral resources and materials. For example, the "Strategic Research on Strengthening China with Mineral Resources" project team has systematically analyzed the major problems faced by the development of China's mineral resource industry, proposed relevant development strategies, and raised relevant development paths for different kinds of minerals [10,11]. The "Strategic Research on Strengthening China with New Materials by 2035" project team has systematically analyzed the development status and problems of the material industry, and formulated the technology roadmap for the strategic needs of 2035 [12]. However, no previous consulting projects has carried out series research of mineral resources and the material supply chain. In fact, mineral resources are the basis of the material industry, and the material industry is the downstream of mineral resources. Therefore, connecting the mineral resources and the material industry in series and conducting interdisciplinary strategic researches are more conducive to analyzing the current development status of the industrial and supply chains, investigating the major problems faced from the perspective of the whole chain, and systematically proposing relevant development strategies from the perspectives of ensuring supply chain security, unblocking the industrial chain, and promoting the domestic circulation and the international & domestic dual-circulation.

The critical minerals and its material industry involved in this study refer to the industrial system that contains the entire supply chain of mineral raw materials such as resource exploration, mining, smelting, processing, manufacturing, and recycling. High-quality development of critical minerals and its material industry refers to (1) the high-quality development of the entire chain involving the resource, smelting, product manufacturing, and recycling ends; and (2) providing high-quality raw materials for the high-quality development of the national economy and society. The high-quality development of critical minerals and its material industry is characterized by sound industrial chain, strong industrial international competitiveness, high green development level, international leading science and technology, and safe and controllable supply of critical raw materials. Based on China's mineral resource endowment and the development status of the material industry, this paper systematically clarifies the critical minerals and their smelting, material preparation, and recycling chains, analyzes the products and their supply status of each link, analyzes the situation, problems, and strategic needs faced by the development of China's critical minerals and its material industry, and proposes a high-quality development strategy.

2 Strategic demand of China's critical minerals and their materials against the background of high-quality development

China is the largest importer of mineral resources worldwide. In 2020, the import amount of mineral products in China was 1.8 trillion CNY. The dependence on critical minerals will continue to increase in the next 15 years. China is also the largest consumer of raw materials in the world. As industrial transformation and new industrialization converge, the demand for high-end materials in critical national strategic areas such as means of delivery, energy power equipment, information display, and life and health has become increasingly prominent.

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2.1 Demand for energies and resources

2.1.1 Fossil energy

Against the background of high-quality economic development and achieving carbon peak and carbon neutralization (dual carbon) goals, energy demand in China will continuously grow, requiring the country to contain the total carbon emissions and adjust its energy consumption structure. From 2020 to 2035, the energy demand will maintain overall growth and the energy structure will change rapidly. The demand for renewable energies will surpass that of fossil energy by 2035–2040. The total energy consumption is expected to reach the peak around 2035 (about 6.2×10^9 tce), up 25% from 2020 (4.98×10^9 tce). The consumptions of fossil energies will reach their peaks one after another. For example, coal will reach its peak during the 14th Five Year Plan period, oil will reach its peak around 2028, natural gas will reach its peak before 2040, and nuclear and hydropower will continue to grow.

2.1.2 Ferrous metals

The demand for steel and ferrous metals maintain high. In terms of steel consumption, it was 1.03×10^9 t in 2020, and is estimated to be 1.02×10^9 t, 1×10^9 t and 9.5×10^8 t in 2025, 2030, and 2035, respectively; that is, by 2035, the overall consumption will be running high and declining slowly. The demand for iron ore and manganese ore will decline slowly. The refined iron ore (62% grade) consumption was approximately 1.38×10^9 t in 2020, and is estimated to be 1.32×10^9 t and 1.1×10^9 t in 2025 and 2035, respectively. The manganese ore consumption was 1.3×10^7 t in 2020, and is estimated to be 1.08×10^7t and 8.5×10^6t in 2025 and 2035, respectively.

2.1.3 Other critical minerals

The strategic emerging industries have driven the demand growth for copper, aluminum, lithium, cobalt, nickel and other critical minerals. Corresponding to the rapid development of new energy vehicles, new energy industry, and other strategic emerging industries, copper, aluminum, lithium, cobalt, nickel, and other new energy industrial minerals maintain a growing trend. The demand for copper maintains a growth trend and will rise from 1.3×10^7 t to 1.96×10^7 t during 2020–2035. With the lightweight development of transportation, aerospace, machinery, and other equipment, the demand for aluminum will continue to grow and will rise from 3.686×10^7 t to 5.738×10^7 t during 2020–2035. The demand for lithium, cobalt, nickel, and rare earth will increase from 2.3×10^5 t, 7×10^4 t, 1.35×10^6 t, and 1.85×10^5 t in 2020 to over 2×10^6 t, 2×10^5 t, 2.9×10^6 t, and 1×10^6 t in 2035, respectively.

2.2 Demand for high-end materials in critical strategic areas

2.2.1 Means of delivery

Large transport planes demand many high-end materials, such as composite materials, ultra-high-strength steel, high-strength stainless steel, aluminum/titanium/magnesium light alloy, polymer materials, battery materials, rare earth permanent magnet materials, sealing damping materials, anti-icing materials, transparent cabin materials, and radome (window) materials. High-speed trains are in urgent need of precision bearing steel, gear steel, industrial die steel, wheel rail steel, axle steel, aluminum/titanium/magnesium light alloy, and heat-resisting alloy. It is estimated that by 2030, the number of domestic large transport plane will exceed 1000, the number of aero engine will be 3×10^4, and the demand for heat-resisting alloy will reach 7×10^4 t; the annual demand for bearing steel, gear steel, and die steel for basic parts of high-speed trains will reach 3×10^6 t, 2×10^6 t, and 5×10^5 t respectively.

2.2.2 Energy power field

Nuclear power, oil and gas exploitation, and other major projects in the energy field are in urgent needs of special alloys, rare earth materials, amorphous materials, super-conducting materials, and composite materials. It is estimated that, by 2030, China will build over 1000 sets of 600℃ and 700℃ ultra-supercritical thermal power units, the demand for heat-resisting steel and heat-resisting alloy will be 10 million tons, and the annual demand for steel and corrosion-resistant alloy for marine resources prospection, exploration, storage, transportation, and relevant infrastructure construction will reach 6×10^5 t.

2.2.3 Information display field

The new generation of information technology urgently demands large-size silicon, the third-generation semiconductor materials, new display materials, rare earth luminescent materials, graphene, and meta-materials. It is estimated that, by 2030, the annual demand for advanced semiconductor polished sections in the information display field will be 7.5×10^8 pieces, in which, the annual demand for epitaxial chips—a third-generation semiconductor material—for lighting and industrial energy saving will be approximately 6×10^8 in^2 (1in = 25.4 mm), and the annual demand for new display materials will be 3.5×10^8 m^2.

2.2.4 Life and health field

The biomedicine and medical equipmen fields are in urgent needs of bio-based high-performance nylon, bio-based polyurethane, orthopedic implants, cardiovascular and cerebrovascular implants, dental materials, and oral materials. It is estimated that, by 2035, the demand for fillers (mineral nano materials) for commonly used drugs for stomach and intestinal diseases and skin diseases will reach 3×10^5 t.

3 Development status of critical minerals and the material industry in China

3.1 The scale of mineral resources and the material industry is huge and has become the footstone of industrialization and urbanization of China.

Compared with other countries, China has advantages in the scale of mineral sources production, smelting, processing, and recycling, and has formed a mineral resource and material industry with the largest scale in the world. For example, China's total output and output value of mineral resources are at the forefront, and the total output value of smelting and processing industries accounts for over 50% of the world. The output of over 100 types of materials such as advanced energy storage materials, photovoltaic materials, organic silicon, super-hard materials, and special stainless steel, and the recycling scale of metals such as scrap steel and scrap aluminum are among the highest in the world.

The critical mineral and material industries include: coal, oil and gas, ferrous metal, non-ferrous metal, and non-metal mining industry; smelting and processing industries such as petroleum processing, coking and nuclear fuel processing, chemical raw material and chemical product manufacturing, ferrous metal smelting and rolling industry, and non-ferrous metal smelting and rolling industry; and the new material industry and secondary metal mineral resources recycling industry which cannot be found in the standard classification. According to the output and prices of the products in 2020, the output values of the mining, smelting, new material, and secondary metal mineral resource recycling industries were approximately 6 trillion CNY, 40 trillion CNY, 5 trillion CNY, and 0.8 trillion CNY, respectively. The total amount of these four industries was about 51.8 trillion CNY, accounting for over one third of the total industrial output value.

The critical mineral and material industries provide various kinds of raw materials for the national infrastructure construction and the manufacturing of equipment and products such as airplanes, high-speed trains, automobiles, ships, electronic communication equipment, and home appliances. The industries support the manufacturing and construction industries with a total output value of approximately 90 trillion CNY (prices in 2020) and have become the footstone of China's economic development. The next 15 years will be an important period for China to develop strategic emerging industries and construct a powerful country in mineral resources and new materials, and also a critical period for economic and industrial transformation and upgrading. The stable supply of mineral raw materials and the independent supply of critical materials will ensure the stable development of critical industrial sectors such as national defense equipment, aerospace, information and communication, and new energies, and drive the high-quality development of economy and society.

3.2 China has become the world's largest producer and consumer of mineral resources

The geological prospecting work in China is progressing well. By 2020, 173 kinds of mineral resources had been discovered, reserves of 189 kinds of minerals had been identified. China ranks third in the world in terms of mineral resources endowment. Ten minerals (including ilmenite, vanadium, tungsten, tin, and molybdenum) rank first, and 14 minerals (including zinc, graphite, fluorite, and lithium) rank top five. At present, China is the world's largest producer of mineral resources, the output of 36 kinds of minerals (including coal, vanadium, lead, zinc, tungsten, tin, molybdenum, antimony, gold, rare earth, graphite, and fluorite) ranks first. Except for gold and boron, the output of the other 34 kinds of minerals accounts for over 20% of that in the world, the output of nine kinds of minerals (including gallium, magnesium, mercury, bismuth, and tungsten) accounts for over 70% of that in the world, and the output of 12 kinds of minerals (including silicon and germanium) accounts for over 50% of that in the world. The huge production capacity of mineral resources has strongly supported the rapid industrialization of China.

China has entered the middle and later stage of industrialization, and its demand for mineral resource is diverse and large. The fundamental and supporting status of mineral resources in the national economy will remain for a

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long time. In 2020, China's consumption of coal, oil, natural gas, iron ore, and copper core was 4.98 × 10^9 tce (54% of the world), 6.9 × 10^8 tce (17%), 3.28 × 10^{11} m^3 (9%), 1.43 × 10^9 tce (67%), and 1.453 × 10^7 t (49%), respectively. In the next 15 years, China's consumption of bulk minerals such as coal, iron, and manganese will remain high, while the demand for strategic minerals such as oil, natural gas, lithium, cobalt, and nickel will continue to grow moderately.

3.3 China has built a large-scale and relatively complete smelting & processing industry

China has stepped into the rapid development period of industrialization and formed a metallurgical industry with large scale, complete industrial chain, complete product types, and high technical level since 2000. In 2020, the output of crude steel, refined steel, primary aluminum, refined lead, refined nickel, refined tin, primary magnesium, and refined cobalt in China were 9.3 × 10^8 t, 7.28 × 10^6 t, 3.708 × 10^7 t, 6.44 × 10^6 t, 7.3 × 10^5 t, 2 × 10^5 t, 8.9 × 10^5 t and 9 × 10^4 t, respectively, accounting for 51%, 40%, 40%, 49%, 30%, 55%, 89% and 68% of the world, respectively. China's processing capacity of gas and oil ranks among the top in the world. In 2020, the crude oil processing capacity was 6.7 × 10^8 t, and the annual output of gasoline, diesel, and kerosene was approximately 1.3 × 10^8t, 1.6 × 10^8t, and 4.05 × 10^7 t, respectively.

3.4 China's industrial system is complete and has partial international competitiveness

China has formed a material industrial system with the most complete categories and the largest scale in the world. The output of around 100 kinds of materials (such as iron and steel, non-ferrous metals, rare earth metals, cement, glass, chemical fiber, advanced energy storage materials, photovoltaic materials, organic silicon, super-hard materials, and special stainless steel) rank first worldwide. In recent years, the output value of the new material industry in China has grown rapidly. Focusing on the critical leap of new materials, China has launched the construction of a number of national demonstration platforms for the production and application of new materials (such as nuclear energy, aero-engine, aviation, and integrated circuit materials), which has significantly improved the application of new materials; and independently developed topological insulator materials, high temperature super-conducting, bulk nano materials, bionic and meta-materials, semiconductor lighting materials, photovoltaic materials, deep UV and other artificial lens materials, separation membrane materials, and high-end biomedical materials for organ replacement and rapid virus detection . The research and development (R&D), production and application technologies are generally close to the international level, and some of them lead the world [12].

3.5 China has preliminarily established a resource recycling industrial system

China has preliminarily established an industrial system for recycling of waste resources covering recovery, processing, and reuse. The recovery scale of crap steel, scrap non-ferrous metals, and other resources has become the first of the world. In 2020, the recovery volumes of scrap steel and scrap non-ferrous metals in China were 2.6 × 10^8 t and 1.3 ×10^7 t, respectively, much higher than that of traditional developed countries and areas. According to the research data of the China National Resources Recycling Association, in 2019, there were about 1 × 10^5 recycling enterprises for renewable resources in China with around 1.5 ×10^7 employees [13].

4 Major problems faced by the development of critical minerals and material industry

4.1 The competition and instability of international supply chain threaten the high-quality development of the industry

Currently, the international geopolitical situation is highly unstable and has entered a turbulent period of old and new order adjustment, resulting in the instability in the international supply chain of energy, bulk commodities, critical technologies, and products. Traditional developed countries and areas have significantly increased their international competition strength and continue to adjust the strategic layout of their critical products and technology supply chains. While strengthening the stability and independent control of their own supply chain, they gain competitive edges by focusing the vulnerability of the critical minerals and materials of other countries through international surveys and other methods. Therefore, the safety and stability of the supply chain of China's critical minerals and materials have become an important factor affecting the industrial development, economic development, and even national security. It is particularly urgent to build a high-quality development mode for minerals and material industries that focuses on domestic supply and is supplemented by international circulation.

4.2 The industrial chain presents a spindle shape, resulting difficulties in upstream and downstream products and technologies

The output value of the whole minerals and material industries in China is concentrated in the smelting and processing industry, while the proportions of resource, material, and recycling ends are small, resulting in a spindle shape development trend of “large in the middle and small at both ends” in the whole industrial chain. China has long been the “world’s processing plant” and focused on the midstream of the industrial chain. Therefore, the upstream and downstream of the industrial chain in China still faces obstacles even though the material and recycling industries develop rapidly in recent years. China’s economy has transferred from rapid to high-quality development. High-end, smooth, green, and low-carbon development of the industrial chain of critical minerals and materials is the essential requirement of economic and social development. The spindle shape is no longer suitable and urgently require adjustment and transformation.

4.3 Insufficient domestic supply guarantee ability of critical minerals

Owing to long time and high-intensity development and utilization and the influence of policy guidance and environment protection, the development space of China’s mineral resources is limited, the investment in the mining market is depressed, the domestic mineral reserves are hard to grow, and the output is significantly reduced. China’s demand for critical mineral resources keeps growing, but the decline of domestic supply capacity has resulted in further incease in external dependence. Insufficient domestic supply guarantee ability of critical minerals is mainly reflected in the following three aspects: (1) The prospecting investment declines and the growth rate of mineral reserves declines. In 2020, China’s investment in solid prospecting was only 16.2 billion CNY, which is 68% less than that of 2012. The growth rate of identified resources reserves of 23 kinds of minerals (including iron, copper, potassium salt, and fluorite) declined. (2) The investment environment is bad and the prospecting development activities are shrinking. From 2011 to 2021, the number of prospecting rights in China reduced from 3.6×10^4 to 1.1×10^4 (down by 69%), and the number of mining rights reduced from 1.01×10^5 to 3.6×10^4 (down by 64%). (3) The fixed assets investment in the mining industry reduced, and the output of important minerals reduced significantly. From 2013 to 2020, the fixed assets investment in China’s mining industry reduced from 1.46 trillion CNY to 1.02 trillion CNY, and the output of 16 kinds of minerals (including oil, iron, manganese, chromium, molybdenum, tin, antimony, phosphate rock, and fluorite) reduced by 10%–60%.

4.4 Insufficient level of green development at the smelting end due to high energy consumption and high emission

As one of the intermediate links in China’s mineral and material industries, the smelting and processing link has a large scale of development, a high level of industrial technology, and certain international competitiveness. The output of major smelting products account for about 50% of world, and most of the smelting and processing products can meet the demand of downstream. However, owing to the large scale of the industry, large consumption of upstream resources, and the difficulty in fully converting raw materials into high-end products, the abundant smelting and processing capacity has caused high-energy consumption and high emission, leading to the weak link in the green development of the industrial chain. In 2020, the energy consumption of China’s iron and steel industry was about 4×10^8 tce, and the energy consumption of non-ferrous metal industry was about 2×10^8 tce, accounting for around one fifth of China’s industrial energy consumption in total. The carbon emission of the smelting and processing industry accounted for over 20% of that of the country, of which, the CO_2 emission of iron and steel industry was about 1.5×10^9 tce (accounting for 15% of the national total), and the CO_2 emission of non-ferrous industry was about 7×10^8 t (accounting for 7% of the national total).

4.5 The critical material industries fail to fully satisfy the demand of critical areas owing to insufficient innovation ability and weak foundation

In the critical areas representing China’s high manufacturing level, the supply of high-end materials is insufficient and the support capacity is not strong. For example, the scale of display industry has ranked the world, while most of new display materials still rely on imports. High speed railway trains have become the “business card” of high-end manufacturing in China, but most of the chips used in traction motors and converters are imported. The overall innovation ability in the material field is not strong. Although good process has been made in many directions of basic research in material science, the contribution to the creation and breakthrough of major materials is out of proportion to the scale of the field. For example, Invar alloys and Elinvar alloys, semi-conductor

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materials, fullerenes and graphene, optical fibers, blue light emitting diodes, topological phase change and topological materials, and other epoch-making new materials were not first discovered by Chinese scientists. The critical foundation of China's material industry is still weak, and the critical raw and auxiliary materials, analytical instruments, and some manufacturing equipment are heavily dependent on imports. The R&D of domestic equipment still adopts the mode of tracking and following the international advanced level. Most of them are in the prototype stage without industrial application. These technologies face potential intellectual property risks.

4.6 The development of recycling end lags behind, becoming the largest short board of the whole chain

The recycling industrial system of resources and materials in China is deficient, and the recycling level is far lower than that of traditional developed countries. In 2020, scrap steel accounted for only 22% of China's steel raw materials, compared with over 70% in the United States, 55%–60% in the European Union, over 50% in South Korea, and over 35% in Japan. China's secondary resource supply (new and old wastes) of aluminum, copper, and lead accounted for 18%, 16%, and 39% in consumption, respectively, which were significantly lower than that of traditional developed countries. At present, the recovery rates of all kinds of waste products in China are not high. For example, the recovery rate of scrap car is only 0.7% (the international level is 4%–6%), and the recovery rate of home appliances, electronic products, and waste batteries is also lower than the international level. In addition, the laws and standards system for the recycling of metal resources in China are not sound, the standardization level is low, the generating intensity of bulk solid waste is high, the utilization is insufficient, the products added value of comprehensive utilization is low, and the technical, digital, and refined management levels need to be improved urgently [13].

5 Targets and measures for high-quality development of supply chain of critical minerals and material industries

5.1 Basic strategies and development targets

China should plan the development of the supply chain for critical minerals and related material industries considering the new development pattern, focus on ensuring the bottom line of mineral resources in the country and expanding the international mineral resources, to systematically improve the supply capacity and strengthen the independent innovation ability of the metallurgy and material industries. It is necessary to focus on improving the development quality and efficiency, practicing the green and low-carbon circular development model, and ensuring that the strategic mineral resources can be found (for exploration), mined, and used (for preparation of basic raw materials). (1) For basic raw materials in short supply which are urgently needed for the development of strategic emerging industries and major equipment, such as iron, copper, aluminum, uranium, lithium, cobalt, nickel, chromium, potassium salt, manganese, gold, tantalum, and niobium, the prospecting and exploration should be promoted to achieve major breakthroughs and reserves and production substantially increased, thereby significantly improving the supply capacity of domestic basic raw materials. (2) For indium, gallium, germanium, tellurium, bismuth, and other rare metals and petrochemical materials that are urgently needed in the new-generation information technology, new energy, life and health, and other critical areas, breakthroughs should be achieved in the critical technologies and equipment for high-quality, high-purity, and high-value preparation of materials and recycling of secondary resources, thereby improving the guarantee ability of high-end applications and the comprehensive competitiveness of the industry. (3) For superior resources such as rare earth, tungsten molybdenum, graphite, vanadium titanium, and fluorite, focus should be placed on meeting the demand of high-end applications, breakthroughs need to be achieved in the high-value technology system of materials, and critical technologies and equipment should be developed based on the resource characteristics, thus to form strong international market competitiveness.

China should adhere to independent innovation, optimize industrial structure, improve quality and efficiency, pursue green and low-carbon in the next 15 years to achieve the independent control of critical minerals and materials, expand a number of enterprises with international market competitiveness, and comprehensively realize the high-quality development of China's mineral and material industries for the weak links in the supply chain, such as resource supply, scientific and technological level, green development, and recycling. (1) By 2025, the critical minerals and material industries should preliminarily form a new pattern of high-quality development with a relatively smooth industrial chain and significantly improved development level of all links. The supply capacity at the resource end should be significantly improved. The critical technologies in short supply at the material end should achieve brokenthroughs. The recycling efficiency should be significantly improved. (2) By 2030, the supply chain of critical mineral and material industries should preliminarily achieve high-quality development, the independent guarantee ability and international supply of the mineral resources should be significantly strengthened, the industrial scale of smelting should become more reasonable and achieve green and efficient development, and the critical technologies at the material end should be developed, and the recycling industrial system should be initially built so as to basically realize the independent control of critical materials. (3) By 2035, the supply chain of critical minerals and related material industry should entirely achieve high-quality development, the resource supply should be fully independent and controllable, the quality and achievements of industrial development at the smelting end should greatly improved, critical products and technologies should be fully self-supplied, and the recycling industrial system should be perfect.

5.2 Major breakthroughs of critical technologies

Intelligent prospecting and exploration technology should be developed. The prediction theory of prospecting should be innovated and advanced prospecting and exploration technology and equipment should be developed to support the prospecting work in new areas with high altitude, deep cutting, and shallow coverage and improve the prospecting efficiency.

Resource development and utilization technologies which are compatible with China's resource endowments should be developed. High-efficiency dressing and smelting and comprehensive utilization technologies should be developed for paragenetic and associated minerals of large mineral resource and applied to the vanadium titanium-magnetite in Panzhihua and Xichang areas, Bayan Obo iron niobium rare earth mine in Baotou, and Jinchuan copper nickel cobalt mine in Aba Prefecture, to improve the comprehensive utilization level of resources. Research should be conducted on critical technologies such as precision mining and separation, green and low-carbon smelting and separation, material recycling, preparation of high-purity and high-quality basic raw materials, large-scale equilibrium application of high abundance rare earth elements, and comprehensive recovery and utilization of secondary resources, to solve the problems of low resource utilization, low grade of smelted and separated products, and unbalanced application of rare earth elements in the process of rare earth extraction and separation.

Advanced material purification technology should be developed. R&D should be conducted on purification and preparation technology of raw materials such as high-purity and ultra-high-purity iron, copper, aluminum, titanium, cobalt, tungsten, molybdenum, tantalum, nickel, germanium, antimony, indium, gallium, beryllium, quartz, graphite, fluorine, phosphorus, and matrix resin so as to match the high-quality development of new-generation information technology and high-end equipment manufacturing for the demand of high-purity raw materials such as high-quality silicon single crystal, high-grade photo-resist, packaging substrate, high-end sputtering target, and precursor.

New energy materials and environmental friendly materials should be developed. High-performance and scaled process and technology should be developed for basic raw materials such as nuclear graphite, basalt fiber, and resin materials for power battery diaphragm. Research should be conducted on frontier basic materials such as grapheme, hydrogen storage materials, and polypropylene resin for ultra-high-voltage cables. The recovery and recycling system mainly for power batteries and photovoltaic batteries should be improved. The preparation technology and equipment should be developed for petrochemical basic raw materials such as polyolefin, polyester, polyamide, and polyurethane with the characteristics of low precipitation, low odor, and high biocompatibility so as to form a large health synthetic resin basic raw materials system.

The process manufacturing technologies of materials should be developed. Breakthroughs should be achieved in the technical system of critical processes such as long/short process of iron and steel metallurgy, short process for special smelting, near final manufacturing of advanced materials, and petrochemical process, thus to realize the green and intelligent manufacturing process of bulk raw materials, and form an advanced manufacturing process of bulk raw materials that reaches the international advanced level and features dynamical order and coordination.

5.3 Critical measures for improving industrial supply chain

5.3.1 Improving the supply and guarantee ability of domestic mineral resources

It is necessary to increase the investment in mineral resource exploration, implement a new round of actions for achieving breakthroughs in mineral prospecting, focus on strengthening the deep edge resource exploration of old mines and existing large- and medium-sized mines, and try to improve the reserves of mineral resources. While maintaining the commonweal exploration investment, commercial exploration investment should be encouraged.

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The production of domestic mines should be guaranteed to ensure a stable supply of large- and medium-sized mines. The current supply capacity of large- and medium-sized mines accounts for more than 80% of China's total. Investigation and analysis should be conducted to identify the problems faced by development, and support measures should be actively implemented in finance and taxation, banking, mining right approval and other aspects, so as to accurately strengthen the corresponding resource supply and guarantee ability.

The total consumption of mineral resources should be controlled. China should control the total energy consumption and reduce the energy consumption and carbon emission intensity corresponding to unit output value. The energy consumption structure should be optimized and the clean and efficient utilization of coal should be actively promoted. It is necessary to promote the development of deep thermal energy resources and orderly improve the proportion of nuclear, wind, biomass and other renewable energies in the primary energy supply structure. It is also necessary to ensure the demand for strategic minerals, scientifically determine the upper limit of mineral resource consumption, intensively and economically utilize mineral resources, and promote the transformation of production and life styles.

Research on mining, dressing and smelting technologies should be conducted for minerals in short supply. Technical breakthrough projects should be set up in the links of prospecting, dressing, separation, and smelting for crisis minerals that has poor resource endowment and is restricted by dressing and smelting technologies, such as potassium salt, lithium, cobalt, chromium, nickel, zirconium, hafnium, niobium, tantalum, beryllium, and rhenium. This can achieve breakthroughs in development and utilization of resources that have a low grade and are difficult to process, thereby improving the domestic supply capacity of related minerals.

The construction of the reserve capacity of mineral resources should be strengthened. It is necessary to enlarge the emergency reserve scale of mineral products in short supply, appropriately reserve ore-fields and mine production capacities. Research on substitute technologies for minerals in short supply should be strengthened, such as substituting copper with aluminum, aluminum with magnesium, and lithium with sodium magnesium vanadium. It is also necessary to build a reserve system covering exploration, smelting, materials, equipment manufacturing, and recycling.

It is necessary to optimize the national resource management policies and boost the confidence in the mining market. It is suggested to adjust the equity fund system, appropriately reduce the equity fund of exploration right, and collect the equity fund of mining right (priced by output and paid together with taxes in the production process) later. The transfer system of mineral resources should be optimized, and detailed rules formulated for the transfer system that is conducive to the prospecting and reserve increase of the geological prospecting units and the independent exploration of enterprises.

5.3.2 Improving the technical competitiveness of materials

Long-term and stable support should be provided to materials with great international influence and high technical difficulties. It is suggested to launch and implement major technical projects for new materials to achieve breakthroughs in a number of critical core technologies, explore pathways that can guide development and achieve sustainable development, and form a collaborative innovation system for new materials R&D and application.

It is necessary to improve the material science and technology innovation system, reorganize and optimize national critical laboratories in material field. Centering on the national strategic needs and major innovation tasks, China should adjust the positioning and research direction of the original national critical laboratories considering the demand for new materials by new-generation information technology, dual-carbon goals, high-end equipment manufacturing, and life and health field, thus to improve medium- and long-term technology research through overall planning, systematic layout, and classified management.

A firm foundation of material technology should be established. Learning from the successful experience in developed countries, considering universities and research institutes as the research objects, and increasing the sustainable investment of public resources are inducive to improving the original innovation ability and achieving major original breakthroughs in the material, common, interdisciplinary, and forward-looking fields. In the industrial basic fields such as critical basic raw materials, basic processes and equipment, basic parts and components, basic inspection and testing instruments, and basic industrial software, advantageous enterprises should be considered as the main body, and the industry, universities, and research institutes should be closely integrated to implement innovation of the entire industrial chain, thereby improving the basic industrial capacity and providing a sustainable motive power for the development of the material industry.

Innovation in the R&D and management modes should be promoted. The scientific research evaluation mechanism should be reformed, and results evaluation should be shifted from papers to comprehensive evaluation of innovation, practicality, and social benefits, to encourage young researchers to conduct application-oriented researches. China should boost the transformation of scientific research achievements, promote the high-end equipment manufacturing field to provide verification and application opportunities for domestic materials, and focus on practical application to drive the evolution and upgrading of material technologies. It is necessary to strengthen the talent team construction in the material field and promote international exchange.

5.3.3 Unblocking the industrial chain of resource, smelting, material, and recycling

Complying with the dual-carbon goals and considering the high-quality development status, China should focus on promoting the structural adjustment of critical minerals and material industries. The development scale of primary smelting and processing industries with high energy consumption, high raw materials consumption, and low industrial added value (such as crude steel, coal power aluminum, and primary chemical industry) should be strictly restricted.

The international market competitiveness of domestic enterprises should be improved. It is necessary to promote industrial integration and ensure that the concentration of strategic resource industries is no less than 70%. Enterprises should strengthen independent and original innovation. Leading enterprises should extend the industrial chain and optimize the entire industrial chain.

The green transformation of the resource industry should be promoted to improve the green development level of the industry. We should raise the green access threshold for industries, construct green mines and green resource-based enterprises, and guide enterprises to transform toward the resources needed for supporting new energy, new materials, and new-generation information technologies. It is necessary to accelerate the construction of carbon emission and carbon transaction standards and guide the standardized transformation of industries through standards and rules. We should also implement an enterprise carbon emission management account system, manage the carbon emissions of enterprises according to international standards, and cooperate with downstream smelting and transportation enterprises, so as to coordinately reduce the carbon emissions in the value chain.

We should construct the supply system for secondary resources and improve the supply capacity. It is necessary to perfect the secondary resources recycling system and optimize the secondary resources recycling policies; build a resource recycling management platform through information technologies to improve the secondary utilization level of iron, non-ferrous metals, and rare and precious metals; use the whole process tracking technology of product manufacturing and utilization and the technology of product recovery, disassembly, and re-utilization to significantly improve the recycling rate of metals in domestic product, increase the recycling amount of lithium, cobalt, nickel, and other metal resources in scrap steel, scrap copper, scrap aluminum, and waste batteries to 30% of their consumptions (2035), so as to effectively relieve the pressure on resource security. We should fasten the construction of resource recycling bases, and promote the construction of a number of comprehensive waste disposal demonstration bases with high environmental protection standards and high technology level, so as to make up for the weaknesses of urban green development and help the construction of new urbanization.

6 Conclusion

Currently, China's critical mineral resources and material industries are in the initial stage of high-quality development with the following characteristics. They are large but not strong, relevant technologies are only following the international advanced level, and the green development of the industries remain a low level. Among the entire industry chain, the resource end is weak and has not entered into a high-quality development stage. The smelting end develops well and has entered the high-quality development stage. The material end is catching up with the international advanced level with several areas progressing well. However, the material industry has a weak foundation, is uncompetitive, and lacks a system for critical core technologies. The recycling end is relatively weak and has not entered into the high-quality development stage. It is recommended to deploy the following three engineering projects.

A project of constructing a red line for strategic mineral resource supply aims to prevent major risks in mineral resource security. The security bottom lines for China's mineral resources should be defined by comprehensively considering the external dependence, domestic resource conditions, resource demand, substitution, and supply of secondary resource. These bottom lines include resource self-sufficiency, output, incremental resource reserve, and reserve bottom lines. Red lines for mineral resource development and exploration should be scientifically designated.

A major project of R&D and application of critical new materials focuses on high-temperature alloys, special alloys for high-end equipment, high-performance fibers and composite materials, special polymer materials,

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electronic information materials, rare earth new materials, and material genetic engineering. Efforts will be made to establish a critical core technology system, form a collaborative innovation system for the entire process, and explore a high-quality development path of the industry.

A project of building the supply system of secondary resources and improving the supply capacity. A resource recycling management platform should be developed by constructing a recycling system of secondary resources, thus to form an entire process tracking and recycling technology system. The pressure on resource security can be relieved by improving the recycling rate of metals, and the construction of resource recycling bases represented by the demonstration bases of comprehensive waste disposal should be accelerated.

The above major projects can promote the coordinative development of the supply chain of critical mineral resources and material industries and provide a solid material support for the high-quality development of China's economy and society. It is worthy pointing out that this study mainly is based on the current status of domestic mineral resources and material industries. We will focus on the new international situation and conduct research on the global mineral resource plan and layout, hoping to provide references for national macroeconomic research and management.

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