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1 Introduction

1.1. Background and objectives

Securing mineral resources is a critical issue from a national security aspect. Mineral resources are essential for people's modern, comfortable daily lives and are used in a wide range of industrial products (Figure 1). The volumes and numbers of mineral resources used have increased [1], [2], [3], [4], [5], [6], [7], [8], [9], [10]. Their significance lies in their contribution to developing and manufacturing advanced technologies across high-tech industries. Some mineral resources are essential for transitioning to a low-carbon society [11], [12], [13]. Copper is needed for renewable energy transmission and distribution and electric vehicles. Lithium and cobalt are needed in rechargeable batteries for storing renewable energy. In addition, semiconductors are needed in large quantities for various control systems for efficient decarbonization, which require silicon, indium, gallium and others. Many countries regard these mineral resources as critical minerals (detailed in Chapter 2). Mineral resources are increasingly needed for countries to achieve stable economic growth and to advance sustainability considerations [14].

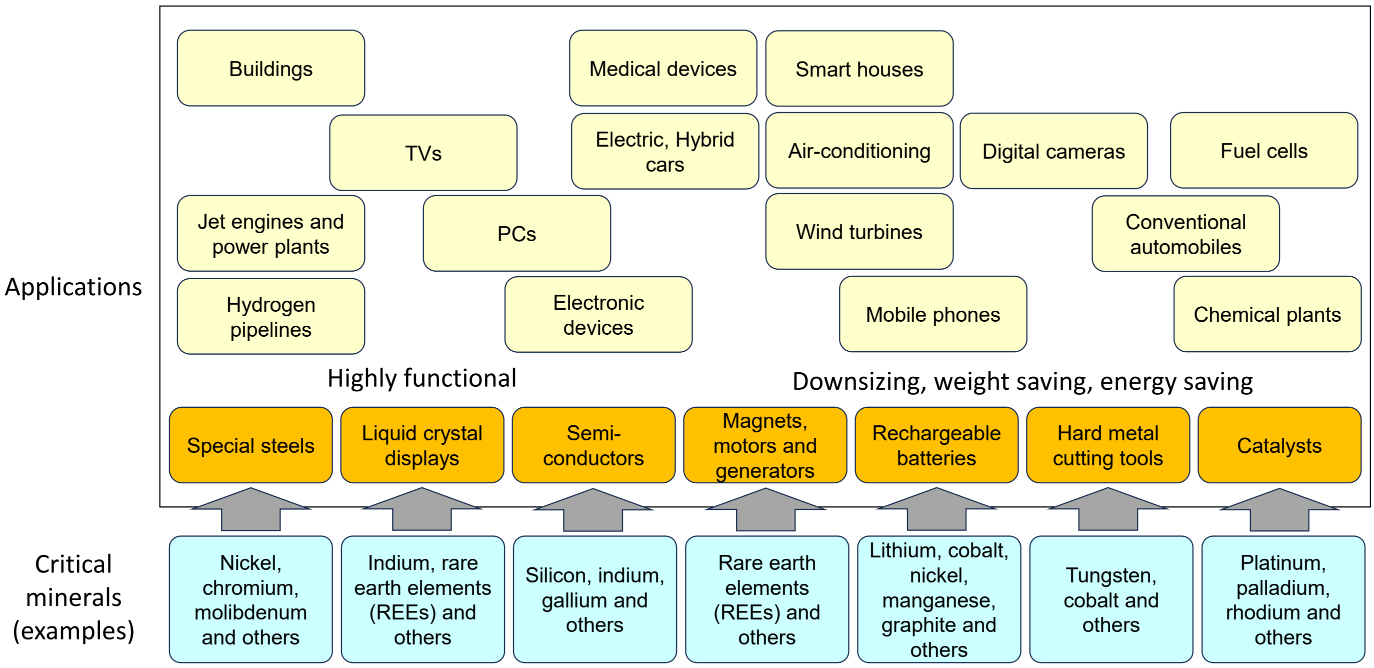

Figure 1 Mineral resources and their applications

Note: In this dissertation, "critical mineral" includes “metallic and non-metallic elements, which are compounds or alloys in many cases [15]”. In some cases, “mineral resources” also include metallic and non-metallic elements if not otherwise specified.

Mineral resources are essential to national economies and have a high supply risk and vulnerability, referred to as critical minerals, critical metals or critical materials [16], [17], [18], [19], [20], [21], [22]. The initial concept of critical minerals was originally used to refer to strategic materials needed for warfare before and during the Second World War [23], [24], [25]. However, in the 2000s, as the economic development of the so-called BRICS countries progressed and economic friction with these countries became a concern, the stable procurement of critical minerals became more important [16]. The research of the NRC (U.S.) (2008) [16] contains important implications despite lacking a quantitative assessment. It proposes an assessment on two axes: supply risk and vulnerability. Until then, critical minerals had been assessed by policymakers and experts as vague strategic commodities, based on which governments selected critical minerals.

The concept of critical minerals is intricately tied to the modern economies' dependence on specific raw materials vital for the production of key goods and services. Key features and concepts associated with critical minerals include their strategic importance, which is essential for vital technologies and industries such as defense, energy, electronics, and telecommunications.

Countries express concern over the vulnerability of their supply chains for critical minerals, given the reliance on a limited number of sources, mitigating risks in the face of geopolitical tensions or supply disruptions. The economic value of critical minerals is substantial, driven by their role in advanced technology production, particularly in industries like electric vehicles, renewable energy, electronic devices, and advanced manufacturing.

These mineral resources find application in diverse technological uses, including mobile phones, electric vehicles, renewable energy technologies (such as solar panels and wind turbines), and advanced medical devices. The global competition for access to and control over critical minerals has intensified, leading to geopolitical considerations and dynamics in international trade. Nations strive to secure a stable supply of these minerals to maintain their technological competitiveness. Critical minerals encompass a diverse range of elements and compounds, including rare earth elements, lithium, cobalt, indium, and graphite.

Governments often institute mineral resources policy and related implementation to ensure a stable and secure supply of critical minerals, involving domestic production incentives, international partnerships, or strategic stockpiling. Addressing the challenges associated with critical minerals requires the development of sustainable mining practices, diversification of sources, recycling, and investment in research and development for alternatives or improved efficiency in their use.

Addressing the security of mineral resources is a crucial concern from a national security perspective. Numerous countries have formulated policy documents to ensure the protection of their mineral resources. These nations identify their critical minerals through expert assessments and uniquely devised methodologies. Examples include Japan [26], [27] and Korea [28] in the Asian region, Australia [29], Canada [30] and the United States (US) [31] in the North American region, the European Union (EU) [32] and the United Kingdom (UK) [33] in the European region.

While the primary focus of policy documents has traditionally centered on national security, recycling has emerged as a crucial policy implementation for both national security and waste management since the late 2000s [16], [34], [35], [36]. Recycling post-consumer products is highlighted as a key circular economy strategy in the mineral resources policies of some countries [28], [37], [38], [39], [40], [41], [42]. The low self-sufficiency in raw materials drives this emphasis on recycling. Fostering the circular economy is essential to decrease primary materials consumption and rely on secondary materials to shape expected mineral resource governance [43], [44], [45]. Consequently, mineral resources policy objectives are increasingly incorporating recycling as a circular economy strategy alongside the traditional focus on national security.

The present mineral resources policy adheres to a defined decision flow framework, involving steps such as 1) identifying critical minerals for national economies based on multiple dimensions (e.g., supply risk and vulnerability to supply disruption), and 2) implementing mineral resources policies (e.g., exploration, mine development, substitution, circular economy practices like recycling and reusing, and stockpiling) to mitigate supply risks and the impacts of supply disruption. However, in numerous policy documents, the determination of each mineral's criticality often does not consider the evaluation of supply risks and potential economic damage resulting from restrictions on mineral resource supply.

In the instance of the EU [32], [40], [46], a prominent mineral resources policy document, critical minerals are determined by assessing both supply risk and the economic importance of each mineral to the EU economy. Economic importance is calculated based on the value added by each end-use application (industrial sector) and each mineral's demand share in these applications. Schrijivers et al. (2020) indicate that most criticality assessment methodologies lack cause-and-effect mechanisms [20]. The EU methodology does not incorporate cause-and-effect mechanisms, such as direct impacts on intermediate industries and other indirect impacts on end-use and service industries, nor does it address the relationship between current possible damages and strategic future importance.

Beyond these considerations, the latest policies plan for achieving multi-objectives, including national security and sustainability. Some of the present policy implementation does not necessarily align with circular economy goals. Policymakers must adopt a comprehensive approach to policy that facilitates the transition to a circular economy and addresses national security concerns.

1.2. Structure of the dissertation

This study reviews the existing policy documents and their limitations (Chapter 2). Based on the review, the study examines the possible economic damages of critical minerals' supply disruption as a vulnerability evaluation (Chapter 4) and estimates the final destination of critical minerals for creating their circular flows (Chapter 5). For these analyses, a high-resolution input-output approach is adopted (Chapter 3). This study proposes a new decision flow framework for a comprehensive mineral resources policy from national security and sustainability perspectives (Chapter 6). The concept and research domains are shown in Figure 2.

In this thesis, "critical mineral" includes "metallic and non-metallic elements, which are compounds or alloys in many cases [15]". In some cases, "mineral resources" also include metallic and non-metallic elements if not otherwise specified.

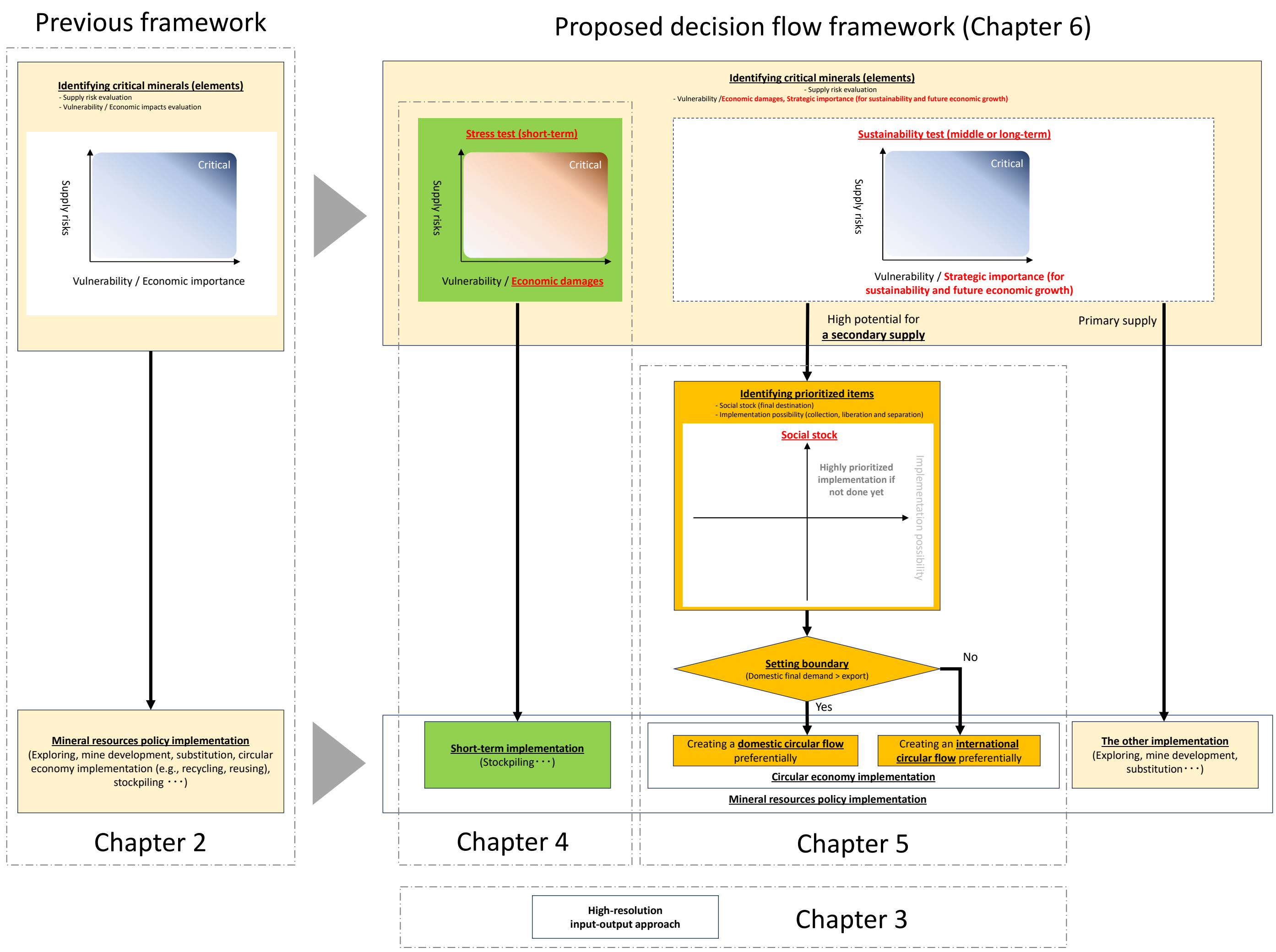

Figure 2 Concept and research domains of the study

2 Overview of mineral resources policy on critical minerals

2.1. History of mineral resources policy on critical minerals

The term "critical minerals," also referred to as "critical materials," "important materials," or "critical products," originated in the late 1930s to early 1940s [23], [24], [25], [47] within legal systems geared toward wartime considerations. The National Research Council (U.S.) introduced a contemporary and practical concept of "critical minerals" in 2008 [16]. Policymakers adopt this or a similar concept to designate their critical minerals and publish policy documents outlining actions for securing mineral resources. Examples of countries implementing such policies include Australia [29], [48], Canada [30], [49], China [50], [51], the EU [17], [34], [40], [52], [53], [54], [55], France [39], Germany [41], [56], Japan [27], [35], [36], [38], [57], [58], [59], Korea [28], Spain [42], the UK [37], [60], and the US [31], [61], [62]. These policy documents encompass strategies and action plans for securing mineral resources, involving activities such as exploration, mine development, substitution, circular economy practices like recycling and reusing, and stockpiling.

Post-World War II, the trend of mineral resources policy underwent substantial transformations as nations endeavored to reconstruct their economies and industries. The war's immediate aftermath heightened industrialization, technological advancements, and surging global demand for mineral resources for a significant recalibration of policy approaches. Countries, in their pursuit of reconstruction and recovery, experienced a heightened demand for minerals as industries sought raw materials for rebuilding infrastructure and manufacturing. The US's initiation of the Marshall Plan in 1948 further provided these demands by providing financial assistance and resources to Western European countries, Japan and other related countries [63].

During the Cold War, the conflict between the US and the Soviet Union accentuated the strategic importance of specific mineral resources, notably uranium, essential for the development of nuclear weapons and space technologies. Behind the development of nuclear technologies, research and development of rare earths, as a by-product of uranium ore, has also been pursued [64]. In the 1950s, the establishment of strategic stockpiles of critical minerals gained prominence, particularly in the US, aiming to ensure a stable supply during times of conflict or disruption. This policy aimed to reduce dependency on foreign sources and enhance national security. Resource conservation was reconsidered in the late 1960s [65].

After the publication of “The Limits to Growth” by the Club of Rome in 1972 [66], researchers and policymakers brought about heightened environmental awareness regarding mineral extraction, leading to the introduction of environmental regulations and guidelines in several countries, addressing concerns about pollution, habitat destruction, and the impact of mining activities on local communities. Eggert (2008) reviews trends in mineral economics from 1989 to 2006 from an editorial perspective and indicates that “sustainability” appeared for the first time in the title fo mineral development in 1993 [67]. In the 1990s, countries and companies shifted toward globalization in the mineral sector, marked by increased international trade and cooperation. Sustainable development principles gained prominence, influencing policies to balance economic growth with environmental and social considerations.

In the 2000s, emerging economies such as Brazil, Russia, India and China (BRIC countries) grew rapidly and are considered favorable investment areas [68]. At the same time, these economies were recognized as potentially significant consumer countries of mineral resources [16]. As an emerging economy, China was regarded as a competitive producer country as well as a rapidly expanding consumer country [16].

The 21st century has been characterized by a rapid technological boom, driving increased demand for mineral resources such as rare earth elements, lithium, and cobalt. Concerns over supply chain vulnerabilities, particularly dependence on specific countries, led to renewed interest in diversification and responsible sourcing. Governments increasingly recognize the significance of sustainable mineral resource management in addressing environmental, social, and economic well-being. After World War II, geopolitical considerations, economic requirements, environmental awareness, and technological advancements characterized and shaped mineral resources policy. The ongoing challenges for resource security and sustainability continue to steer contemporary mineral resources policy.

2.2. Mineral resources policy from the circular economy aspect

Following the practical concept of the circular economy proposed by the Ellen MacArthur Foundation Foundation in 2013 [69], policymakers and researchers extensively covered this approach. Several review papers affirm that recycling is a fundamental component of circular economy strategies [70], [71], [72]. These strategies, also known as circular actions, encompass reducing, reusing, repairing, refurbishing, remanufacturing, repurposing, recycling, recovering, and more. Recycling is a circular economy strategy that derives value recovery [73]. Individuals and organizations are urged "to maintain a circular flow of resources by recovering, retaining, or adding to their value while contributing to sustainable development [73]".

The conventional mineral resources policy documents include strategies and actual actions to secure critical minerals, such as exploration, mine development, and stockpiling. A key aspect of new strategies is related to sustainability. Building a sustainable supply chain, which covers from mining to recycling, is emphasized in most countries and regions. Many countries respect the idea that recycling is a potential supply of mineral resources for national security and sustainability (detailed in Chapter 2.3). Circular economy implementation is included in these policy documents as mineral resources policy implementation. The origin of the circular economy concept is the Club of Rome's prediction that the world would run out of minerals and other resources sooner rather than later [66]. In 2011, the United Nations Environment Programme (UNEP) / International Resource Panel (IRP) proposed to decouple the natural resource use and environmental impacts from economic growth [74].

Some mineral resources policy implementations (e.g., substitution) are not harmonized with the other policy implementations. In the case of substitution, a cause-and-effect mechanism is not considered in the relationship between substituting and recycling critical minerals. Additionally, existing waste management policies do not coincide with circular economy implementations in the context of mineral resources policy. Policymakers need a comprehensive decision flow framework in mineral resources policy for multiple goals.

2.3. Mineral resources policy documents in major countries

Mineral resources policy and its structures exhibit evolutionary patterns, necessitating regular updates from official sources for the latest information (Table 1). Generalized descriptions of mineral resources policy features and structures for the European Union (EU), France, Germany, the United States (USA), and Japan underscore some key aspects. The EU Raw Materials Initiative focuses on sustainable raw material supply, emphasizing resource efficiency, recycling, and responsible sourcing [34], [40], [46]. EU's circular economy strategy promotes a shift towards sustainable resource management, reducing dependence on primary raw materials. The EU emphasizes a circular economy for specific raw materials to ensure a sustainable supply.

France conducts geological surveys through the National Geological and Mining Service (BRGM) and emphasizes a sustainable development approach in mineral resources policies, balancing economic, environmental, and social considerations [39]. France integrates sustainable development principles, leveraging the BRGM's role in research and resource management. Germany's strategy emphasizes sustainable resource use and technological innovation, administered by the Federal Ministry for Economic Affairs and Energy and complemented by the Federal Institute for Geosciences and Natural Resources (BGR) [41]. Germany's policies focus on technological advancements and innovation to optimize efficient resource use. The US addresses national security and economic growth concerns [31], [75]. The U.S. Department of Energy (DOE) oversees mineral resource policies, with agencies like the US Geological Survey (USGS) playing a role. Japan focuses on resource security for high-tech industries, recycling as a production of secondary materials, and engaging in international cooperation through the Ministry of Economy, Trade and Industry (METI) and the Japan Organization for Metals and Energy Security (JOGMEC).

These unique policy features align with each country's circumstances, priorities, and supply chains of mineral resources.

Table 1 Designation method for critical minerals and policy implementation in policy documents

Country / Region	Designation method (Criticality assessment)	Policy implementation
Australia [29], [76]	Expert judgment based on the evaluated criticality of different countries and the resource potential for Australia	Stable supply through the development of new sources; sovereign capability development; creating regional jobs and growth; creating international partnerships; government investment initiatives; research and innovation; accelerator initiatives and environmental and social governance standards.
Canada [30]	Expert judgment	New exploring; accelerating mine development; establishing sustainable infrastructure; harmonization with indigenous people; diversified workforce and wealthy communities; global leadership and security.
China [50], [51]	Expert judgment	Enlarging and strengthening rare earth enterprises; merging and reorganizing rare earth enterprises; supporting rare earth enterprise groups to extend their industrial chains further downstream; encouraging exploration; controlling minerals production; securing mineral resources for strategic application; establishing the dynamic balance mechanism (REEs) on demand and supply; building a traceability system.
EU [40], [46]	Evaluating supply risks and economic importance to the EU	Developing resilient supply chains; relying on secondary materials with circular economy implementation, sustainable products market; strengthening the sustainable and responsible mining and processing; diversifying sustainable and responsible

		procurement; rules-based open market and international trade without barriers.
France [39]	-	Mapping the needs for critical minerals regarding the energy transition; recycling as a potential production; researching secondary mineral resources; including sustainability criteria in the production chain of critical minerals to preserve industrial competitiveness.
Germany [41]	-	Increasing primary materials for EVs and energy transition in EU member countries; providing companies financial support for feasibility studies in raw material supply; monitoring the market of raw materials for key industries; considering secondary materials and products with higher added value; ensuring sustainable supply chains of mineral resources for the energy transition; promoting research and development in processing and metallurgy for recycling; strengthening the supply and use of secondary materials; international guidance for sustainable management in the supply chains of mineral resources.
India [77]	Evaluating supply risks and economic importance to India	Enhancing exploration; research and development in mining and mineral processing technologies; research and development in recycling technologies; finding substitutes for critical minerals; enhancing international trade and diplomatic agreements regarding critical minerals.
Japan [38], [57], [78]	Expert judgment	Financing upstream mining overseas; accelerating secondary materials usage; promoting research and development of recycling technologies; and stockpiling for short-term supply disruptions.
Korea [28]	Expert judgment?	Improving import dependency on critical minerals; increasing recycling; increasing international resource cooperation; expanding stockpiles; and establishing an early warning system for supply disruption.
UK [33], [37]	Evaluating supply risks and economic vulnerability to the UK	Accelerating the growth of the UK's domestic production; accelerating a circular economy of critical minerals through recovery, reuse nd recycling; collaborating with international partners to diversify supply; supporting UK companies overseas to participate in diversified and transparent supply chains; developing diplomatic and trading relationships to improve the resilience of supply in the UK; making international markets more responsive, transparent and responsible; improving data and traceability and making London as the global center of responsible finance for critical minerals.
US [31], [75]	Evaluating supply risk, production growth and market dynamics and other "deep-drive" studies (e.g., production concentration, net import reliance and byproduct commodities)	Driving scientific innovation and developing technologies for securing critical minerals; improving import dependence on foreign adversaries; supporting capacity for sustainable domestic supply chains of mineral resources; building the long-term innovation ecosystem for mineral resources; deriving new capabilities to mitigate future supply disruptions; international partnership to improve the diversity of supply chains and to promote sustainable mining and processing; collaborating with international partners to establish global industry standards.

2.4. Critical minerals selected by countries

Based on the concept of "critical minerals" proposed by the National Research Council (U.S.), policymakers carry out criticality assessments and create policy documents in mineral resources policy (see Table 1). Some review papers outline criticality assessment [18], [19], [20], [21], [22], [33], [79], [80], [81], [82], [83], [84]. Some studies develop a farm- and products-level criticality assessment [85], [86], [87], [88], [89], [90], [91], [92], [93], [94], [95], [96], [97]. The criticality assessment supports policymakers in designating critical minerals for a national economy, which varies with countries' and regions' supply chains and industrial structures (Table 2). Some academic papers review a trend in the determination of critical minerals [8], [98], [99]. These policy documents commonly emphasize that "battery materials (e.g., lithium, cobalt, nickel, manganese, graphite)" and "rare earth elements" are essential for transitioning to a low-carbon society. "Battery materials" are essential raw materials for lithium-ion batteries. Some rare earth elements, such as lanthanum, samarium, neodymium, dysprosium and terbium, are used for high-performance permanent magnets in advanced electric generators, motors, electric vehicles and wind turbines.

Table 2 Critical minerals designated in each country's policy document

Commodity	Australia [29]	Canada [30]	China [51]	EU [32]	France [39]	Germany [41]	India [77]	Japan [27]	Korea [28]	UK [33]	US [100]
Aluminum		X	X						X		(X)
Antimony	X	X	X	X				X	X	X	X
Arsenic											X
Barium								X			
Baryte				X				(X)			X
Bauxite				X							X
Beryllium	X			X			X	X			X
Bismuth	X	X		X				X	X	X	X
Borate				X							
Boron								X			
Cesium		X						X			X
Chromium	X	X	X				X	X	X		X
Cobalt	X	X	X	X	(X)			X	X	X	X
Coking coal			(X)	X							
Copper		X	X		(X)	(X)			X		
Fluorspar		X	(X)	X				(X)			X
Gallium	X	X		X		(X)		X		X	X
Germanium	X	X		X		(X)	X	X			X
Gold			X								
Graphite	X	X	X	X			X	X	X	X	X
Hafnium	X			X				X			X
Helium	X	X									X
Indium	X	X		X		(X)		X	X	X	X
Iron			X								
Limestone							X				
Lithium	X	X	X	X	(X)	(X)		X	X	X	X
Magnesium	X	X		X				X		X	X
Manganese	X	X						X	X		X
Molybdenum		X	X					X	X		
Nickel		X	X			(X)		X	X		
Niobium	X	X		X			X	X	X	X	X
Platinum	X	X		X				X	X	X	X

Group Metals (PGMs)											
Phosphate				X				(X)			
Phosphorus			X	X				X			
Potash		X	X								X
Rare earth elements (REEs)	X	X	X	X	(X)	(X)	X	X	X	X	X
Rhenium	X						X	X			X
Ruthenium	X										
Rubidium								X			X
Selenium								X	X		
Silicon				X			X	X	X	X	
Strontium				X			X	X	X		X
Tantalum	X	X		X			X	X	X	X	X
Tellurium		X						X		X	X
Thallium								X			
Tin		X	X						X	X	X
Titanium	X	X		X				X	X		X
Tungsten	X	X	X	X				X	X	X	X
Uranium		X	X								X
Vanadium	X	X		X				X	X	X	X
Zinc		X							X		
Zirconium	X		X				X	X	X		X

Note: A bracketed description (X) is considered applicable through the documents' context. The Chinese Government additionally designates petroleum, natural gas, shale gas and coal bed methane as critical materials other than the above [51].

Considering the vulnerability of national economies to critical minerals supply disruption and restriction, current assessment methodologies do not necessarily distinguish possible economic damages from strategic importance for building sustainable supply chains and future economic growth. The first methodical attempt to evaluate the criticality of mineral resources is made by the National Research Council (U.S.) [16]. It adopts two parameters to determine criticality: supply risk and the impact of supply disruption or vulnerability (Figure 3). This determination follows expert judgments.

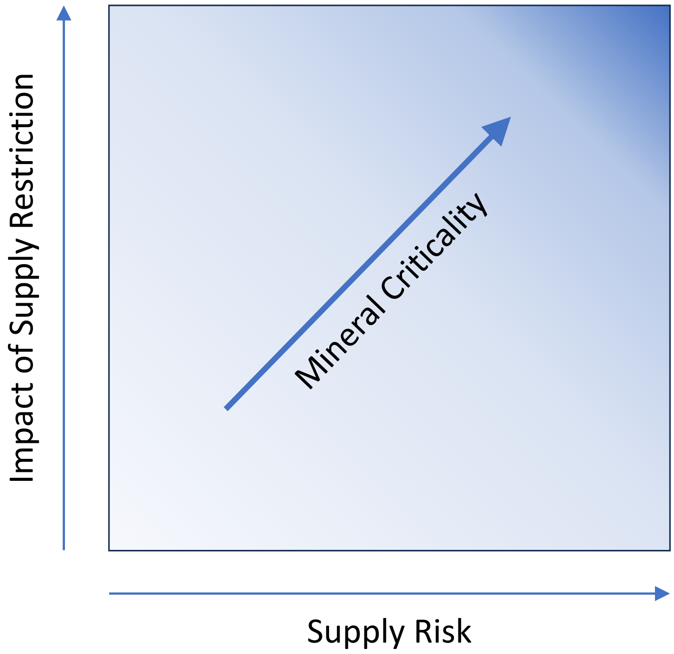

Figure 3 Conceptual image of the criticality matrix proposed by the NRC (U.S.) [16]

The following major assessments, as quantitative methodologies, are made by the EU and the UK [17], [33], [46], [53], [101]. The EU also uses two dimensions: economic importance and supply risk (Figure 4). The economic importance is calculated with 1) the end-use share (sector) of raw materials, 2) the sector's value-added and 3) the substitution index (Figure 5). The supply risk is calculated with the country concentration index (Herfindahl-Hirschman Index is used as a proxy), country governance index (scaled World Governance Index is used as a proxy), import reliance, end-of-life recycling input rate and substitution index (Figure 6). The UK also determines the criticality of each mineral resource to the UK economy with similar dimensions: global supply risk and UK economic vulnerability [33].

These quantitative methodologies still require a cause-and-effect mechanism to evaluate the damages or impacts of the disruption of mineral resources's supply. The quantitative criticality assessment and derived research act as a policymaking tool to mitigate the supply risks and vulnerability of mineral resources' supply disruption [81], [83], [90], [102], [103], [104], [105], [106], [107], [108], [109], [110]. Schrijvers et al. (2020) indicate that researchers should develop an increased understanding of the cause-and-effect mechanisms between risk factors and indicators [20]. Compared with evaluating supply risks, evaluating the vulnerability or economic importance faces technical issues because of limited data availability in each country or region [20], [22]. Policymakers need to consider missing damages or impacts on national economies with the current methodologies of criticality assessment.

For the improvement of vulnerability evaluation, this study examines the possible direct economic damages on intermediate manufacturing industries and indirect impacts on other industries, such as finance and service industries. In terms of harmonizing the multiple goals of national security and sustainability, like circular economy, this study attempts to estimate the final destination of critical minerals possibly accumulated as social stocks and discuss the correlation between the results and current policy implementation.

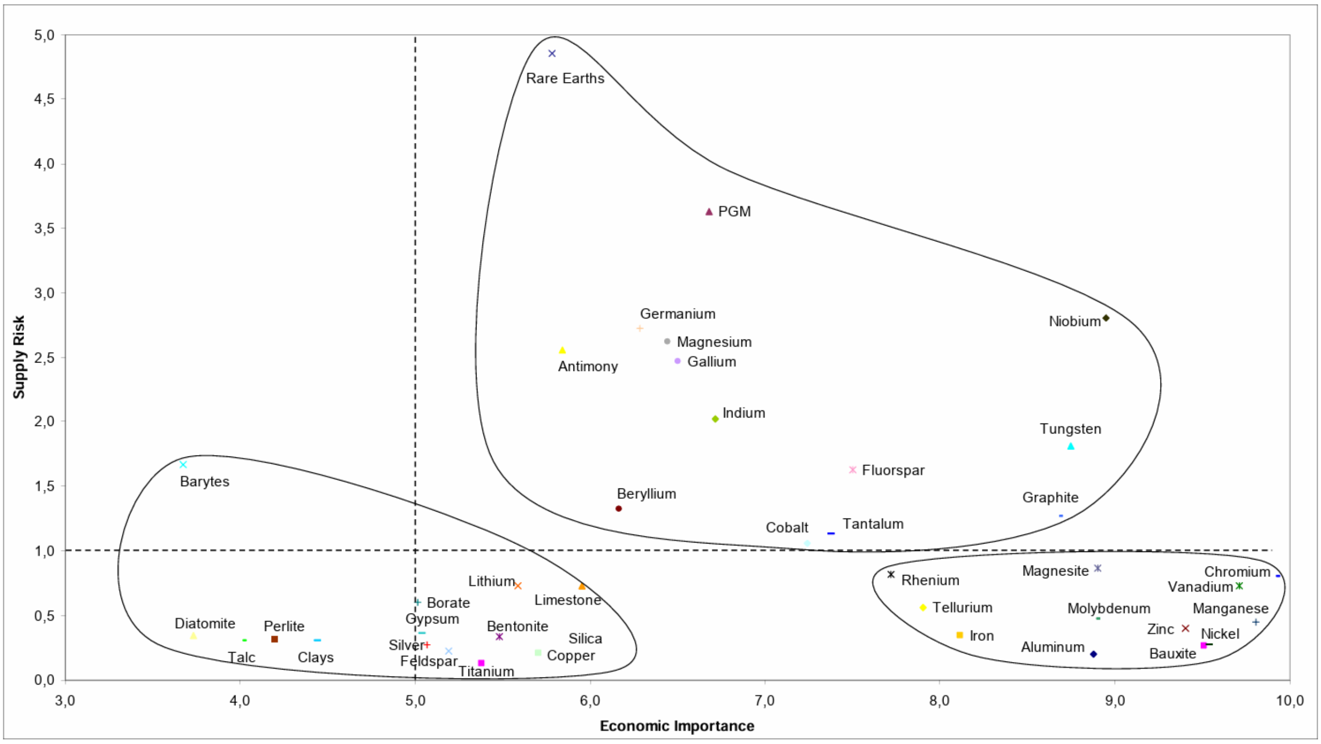

Figure 4 Criticality matrix evaluated by the EU [17]

$$EI = \sum_{s} (A_s * Q_s) * SI_{EI}$$

where:

- *EI = economic importance;*
- *As = the share of end use of a raw material in a NACE Rev. 2 (2-digit level) sector;*
- *Qs = the sector's VA at the NACE Rev. 2 (2-digit level);*
- *SI_{EI} = the substitution index of a raw material related to economic importance;*
- *s denotes sector.*

Figure 5 Equation to calculate the economic importance (EI) in the EU criticality matrix [46]

$$SR = \left[\left(HHI_{WGI,t} \right)_{GS} \cdot \frac{IR}{2} + \left(HHI_{WGI,t} \right)_{EUsourcing} \left(1 - \frac{IR}{2} \right) \right] \cdot (1 - EoL_{RIR}) \cdot SI_{SR}$$

Where:

- *SR = supply risk;*
- *GS = global supply, i.e. global suppliers countries mix;*
- *$EU_{sourcing}$ = actual sourcing of the supply to the EU, i.e. EU domestic production plus other countries importing to the EU;*
- *HHI = Herfindahl-Hirschman Index (used as a proxy for country concentration);*
- *WGI = scaled World Governance Index (used as a proxy for country governance);*
- *t = trade parameter adjusting WGI;*
- *IR = import reliance;*
- *EOL_{RIR} = end-of-life recycling input rate;*
- *SI_{SR} = substitution index related to supply risk.*

Figure 6 Equation to calculate the supply risk (SR) in the EU criticality matrix [46]

3 High-resolution input-output (IO) approach

3.1. Input-output (IO) analysis

An input-output (IO) analysis is an economic modeling technique that analyzes the complicated interdependencies among different economic sectors. This method provides a systematic approach to anatomizing the relationships between various industries, capturing the repercussions that alterations in one sector may have on others. Some studies apply the IO approach to evaluating environmental impacts [111], [112], [113]. This analysis aims to quantify the flow of goods, services, and monetary transactions within an economy. The applications of IO analysis extend to economic forecasting, impact assessment of policy changes, and regional economic analysis. This tool aids policymakers in understanding the potential effects of alterations in government spending, investment, or external shocks on different sectors and the overall economy.

The IO table lies at the core of IO analysis. The IO table, described as a matrix, illustrates the transactions between diverse sectors of an economy. Each row and column corresponds to a specific industry or sector, while the entries signify the monetary value of transactions (output, intermediate inputs, and final demand) exchanged between sectors. Sectors constitute various industries or economic activities, including many industrial sectors, such as agriculture, manufacturing, and services. These sectors produce goods and services either for domestic consumption, use as intermediate inputs in other sectors, or for exportation.

Transactions in the input-output table embody the flow of goods and services between sectors, classified into three primary categories: output, representing the production of goods and services by each sector; intermediate inputs, denoting goods and services purchased for use in the production process; and final demand, reflecting the consumption of goods and services by households, government, and exports. Coefficients within the IO table signify the proportion of a sector's output used as intermediate inputs by other sectors. The coefficients explain an interdependence between sectors in the production process.

The analytical framework of IO analysis facilitates the calculation of multiplier effects, indicating how changes in one sector can affect the entire economy. Various types of multipliers, such as output, employment, and income multipliers, measure the impact of supply disruption in final demand on diverse economic variables. The Leontief inverse, derived from IO tables, stands as a mathematical concept representing the matrix inverse of the coefficients matrix (detailed in Chapter 3.4). It is useful in calculating the direct and indirect repercussions for a sector's output.

An input-output (IO) analysis is a model to examine the economy-wide implications of products or sectors that capture economic interdependencies. Each government produces an input-output table for analysis every few years. A few governments prepare high-resolution input-output tables. The Japanese Government is one of the few governments to provide one of the most high-resolution input-output tables in the world, having over 400 endogenous sectors [114]. The latest table as of 2015 was published in 2019 for 2015 in Japan [114]. The table is prepared in a competitive import type and producer price evaluation. Import data is merged with domestic production in this type of IO table. The IO table describes the import and domestic production values as one in all output rows and input columns. Import values are deducted from the domestic production value at the end of rows. When subdividing sectors, this type of IO table does not require individual output/input data on domestic production and imports, respectively.

The IO table describes the interdependency between industrial sectors, as shown in Figure 7. A sector's sales (outputs) are described horizontally in a row. The total sum of sales is shown as the domestic production at the end of the row. The sector's buys (inputs) are described vertically in a column. The total sum of buys is also shown as the domestic production at the bottom of the column. The total sums of the domestic production shown in the outputs and inputs are the same. The volumes of domestic final demand, such as household consumption, governmental consumption, fixed capital formation and export, are shown in final demand sectors. These sectors are also described as the final destination of products. The volumes of value-added sectors, such as salaries, companies' surplus and tax burden, are shown in value-added sectors. The tola value-added equals a country's Gross Domestic Product (GDP).

Each input value is divided by the domestic production value in an input coefficients vector. In the case of a hybrid input-output table, which is described in monetary and physical units, the input values of the sector's output values described in a physical unit are divided by the domestic production value in physical units, such as "kg," "t," "unit," and "m^2". The squared input coefficients matrix is the basis of the input-output analysis.

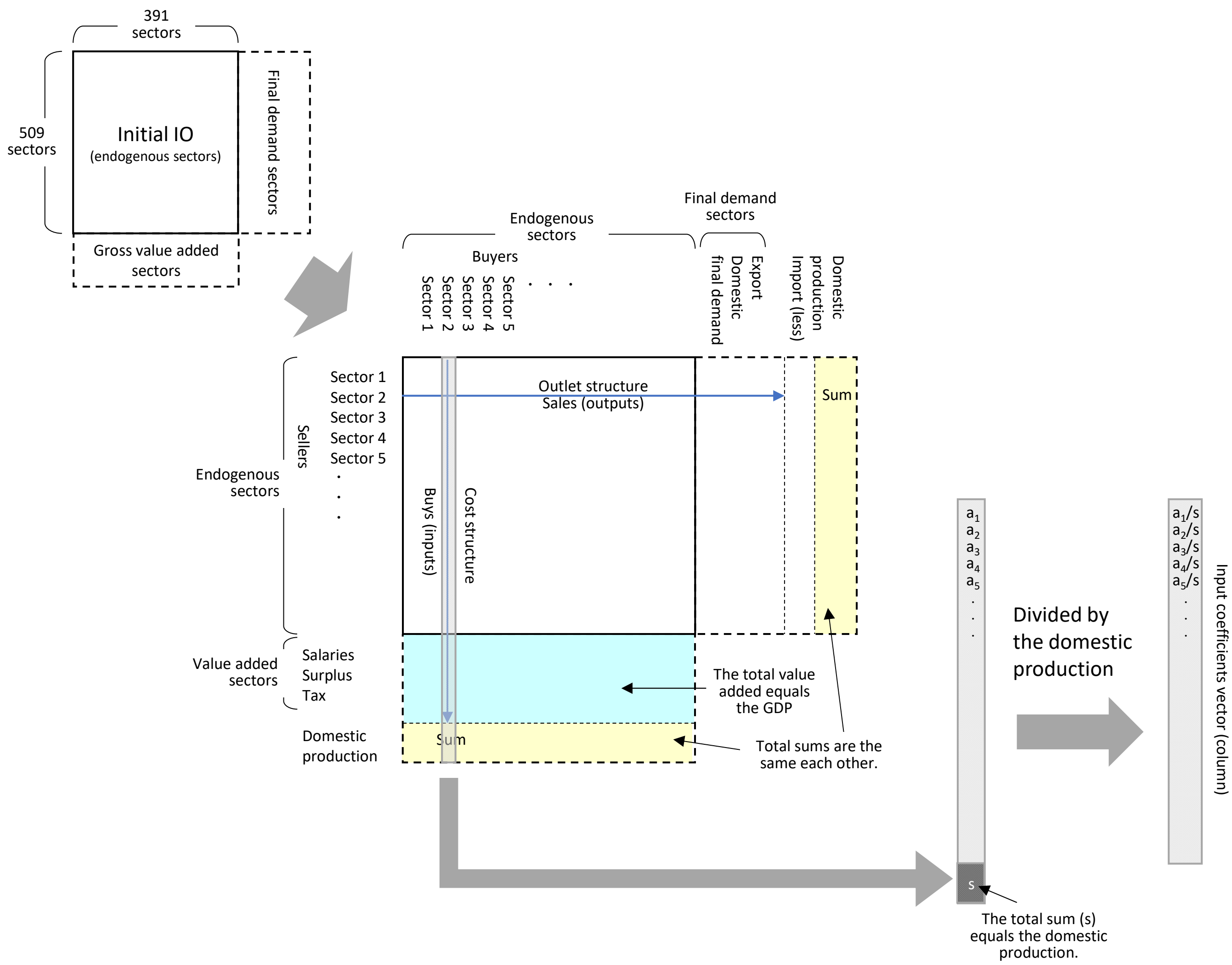

Figure 7 Structure of the input-output (IO) table

3.2. Overview of an input-output approach in this study

This study is based on a uniquely expanded IO table for the estimation of the economic damages of critical minerals and their final destination on an element basis in Japan for 2015. The latest IO table, which is available during this study, is used for analyses. The initial IO table [114], which has a 509 by 391 matrix, is initially converted to a 390 by 390 square matrix. A square matrix is a basis to create an inverse matrix for analysis. The square matrix is subsequently expanded and converted to two hybrid matrices for modeling: a 441 by 441 hybrid square matrix for evaluating economic damages and a 443 by 443 hybrid square matrix for estimating the final destination of critical minerals (Figure 8).

In these hybrid IO matrices, some sectors related to the selected mineral resources (see Chapters 4.2 and 5.2) are converted to described in physical units from monetary units. MATLAB, a programming and numeric computing platform, is used to calculate inverse matrices. This study confirms that all the generated inverse matrices satisfy Hawkins-Simon's condition by calculating the leading principal minor of all orders, which means that all these inverse matrices are under positive definiteness [115], [116].

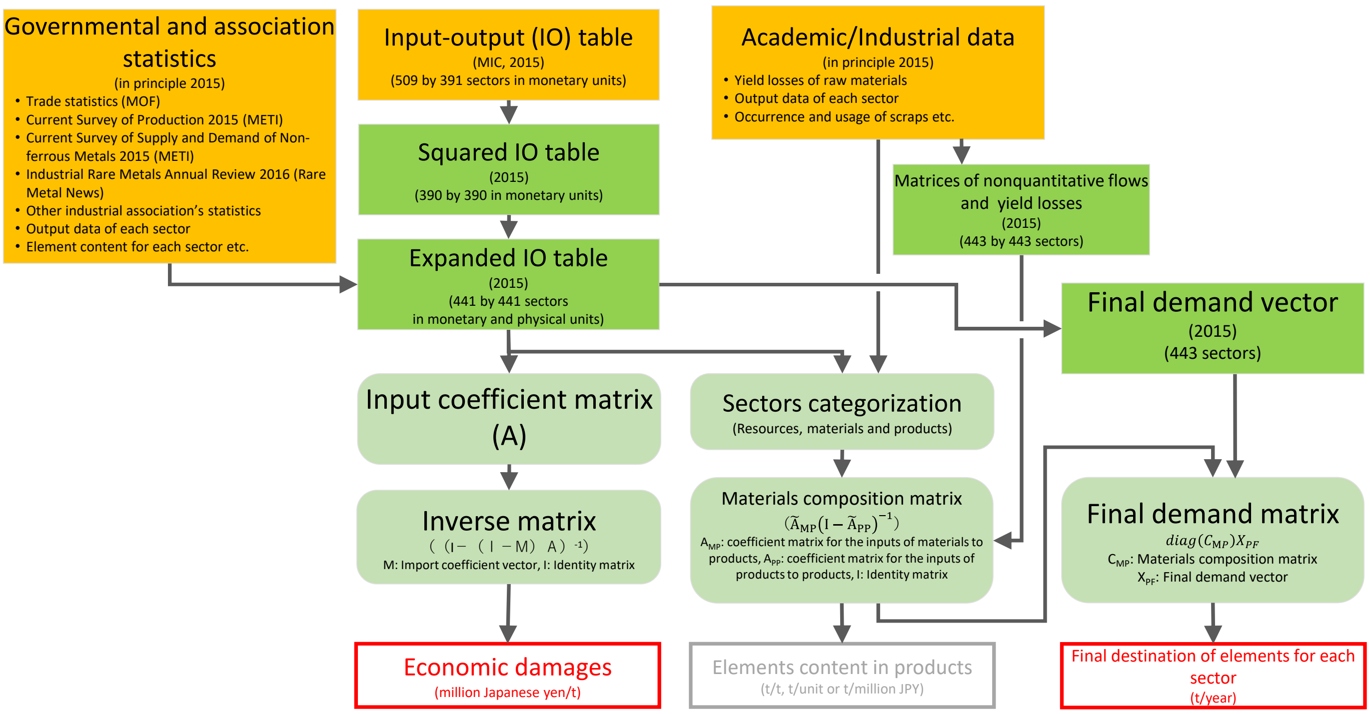

Figure 8 Overview of an input-output (IO) approach in the study

3.3. Expansion of input-output table in this study

3.3.1. Subdividing rows

The domestic production of these segmented sectors is determined based on the physical volume data, as indicated by relevant statistics (Figure 9). These newly defined sectors are specifically linked to the previously mentioned selected mineral resources (elements). Among the 76 segmented sectors, 50 sectors are described in physical units. The physical data of each output row, that is, each sector, primarily relies on governmental statistics and association data. The unit content ratios are established for each sector using data from statistics and specification documents.

Research is conducted to reveal the detailed structure and relationships between raw materials. Based on the results, some existing sectors of the initial IO table are selected to be subdivided (refer from Figure 10 to Figure 19). In the enlarged hybrid IO table, the initial 25 sectors have been further segmented into 76 new sectors, a breakdown derived from various governmental and association statistics. This process is the same as that of Shimizu and Owada (2024) [117]. The detailed categorization is introduced to enhance the resolution of the initial IO table matrix for analytical purposes (refer to Table 3).

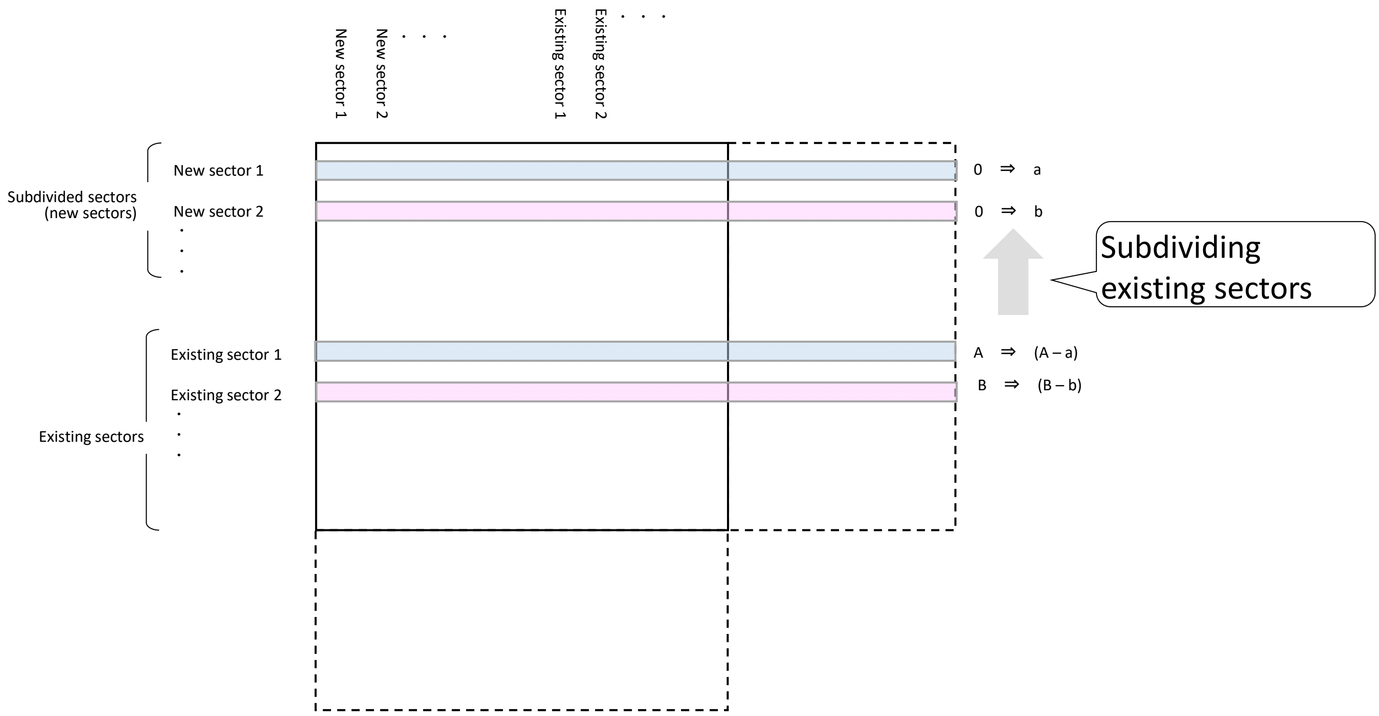

Figure 9 Image of subdividing rows

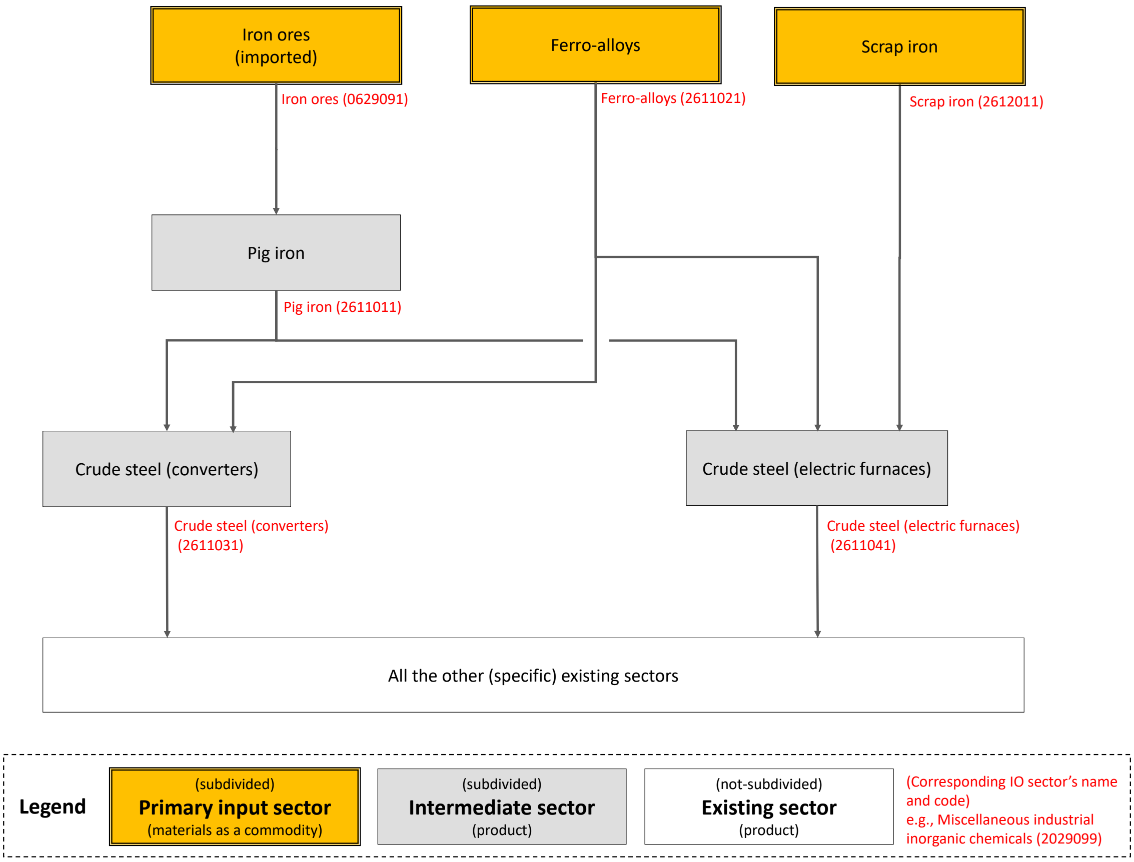

Figure 10 Detailed supply chain of iron (Fe) for the subdivision

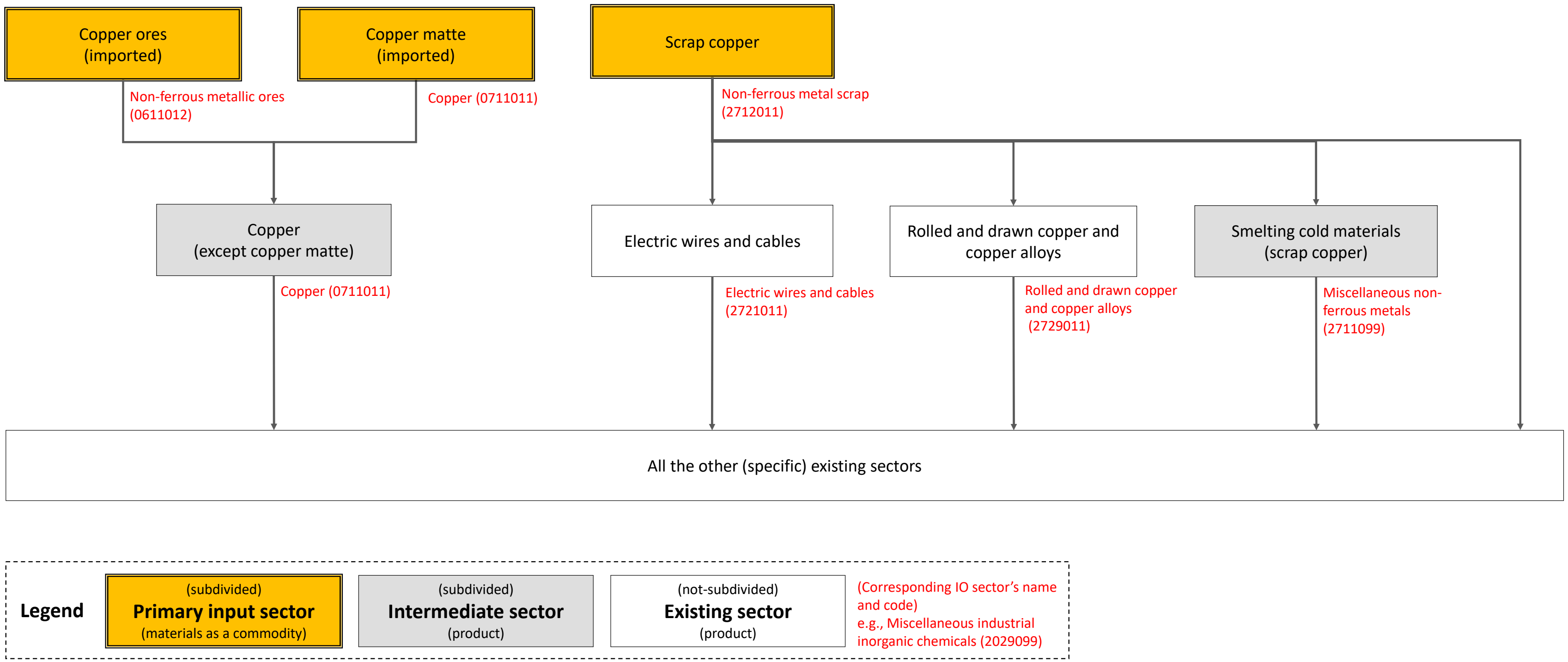

Figure 11 Detailed supply chain of copper (Cu) for the subdivision

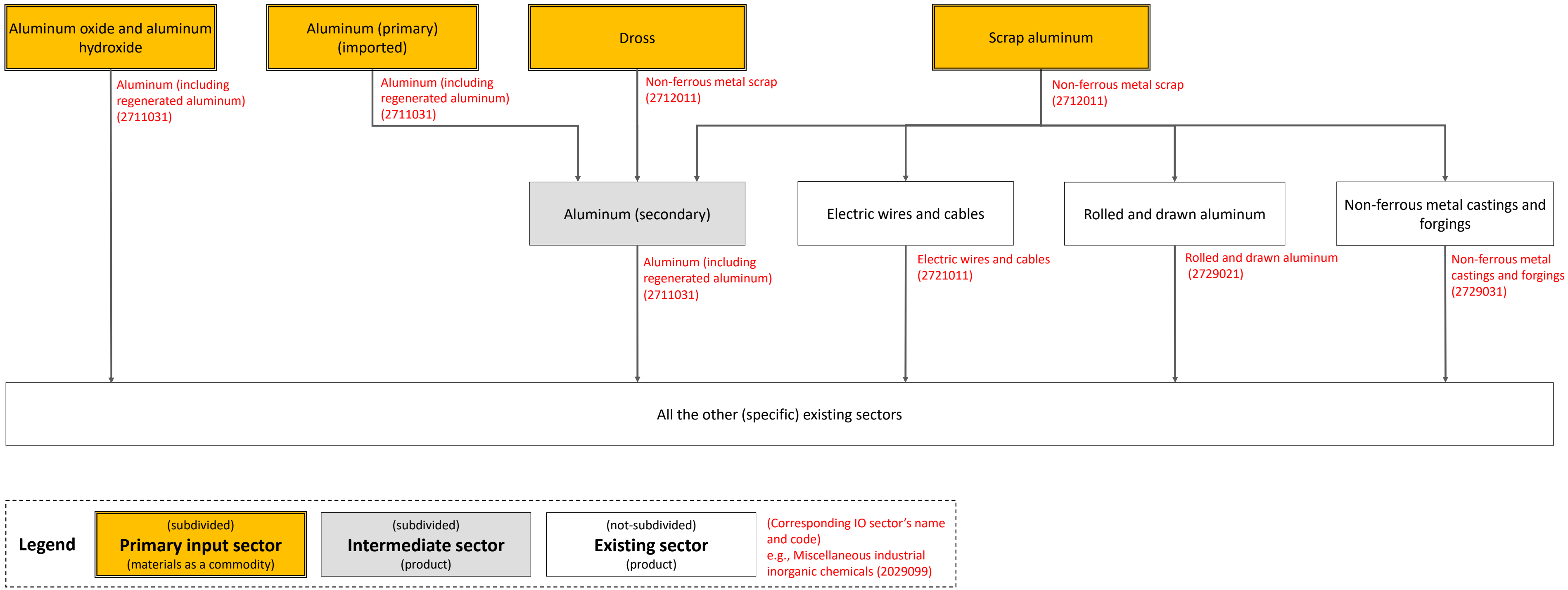

Figure 12 Detailed supply chain of aluminum (Al) for the subdivision

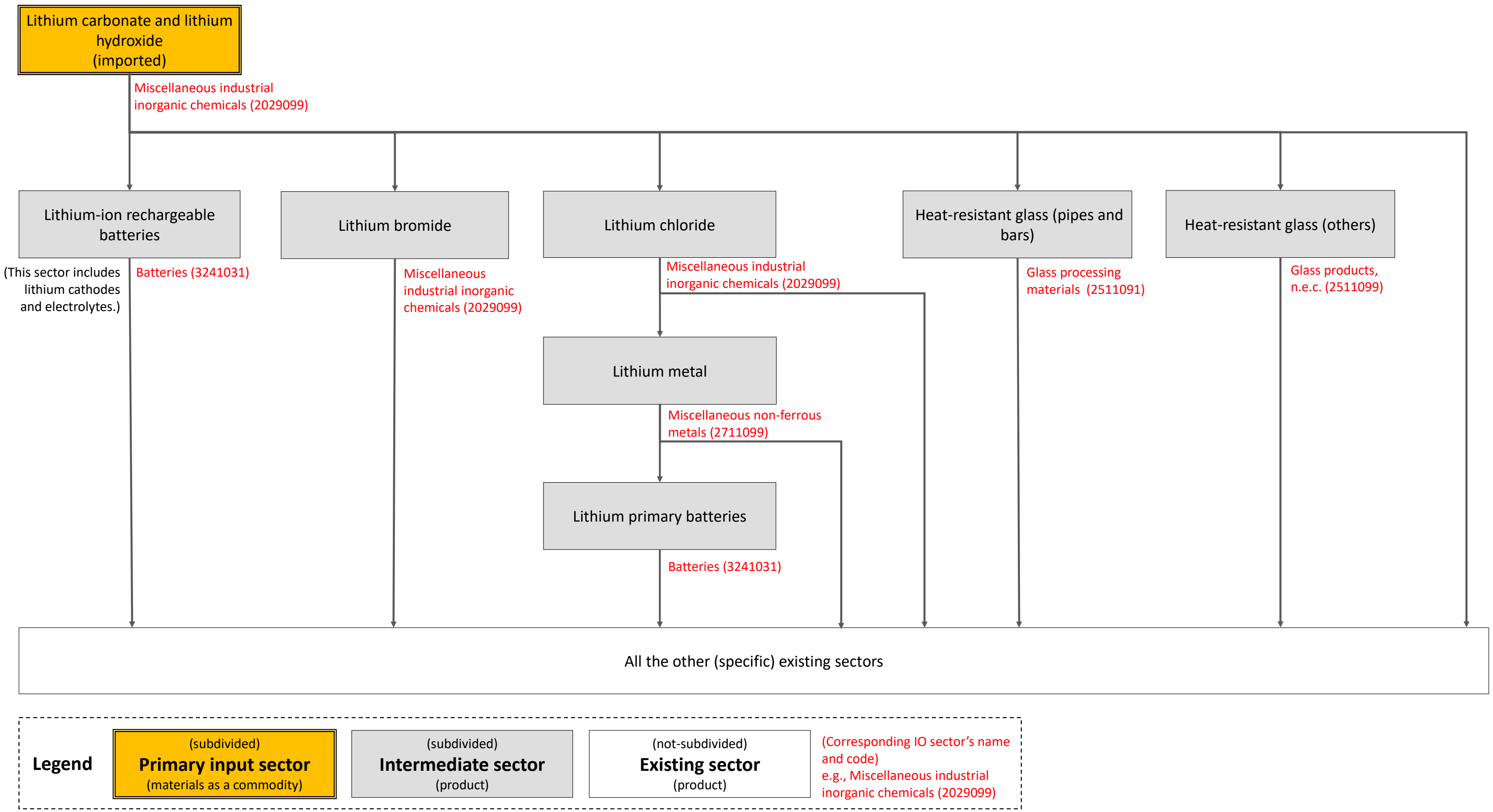

Figure 13 Detailed supply chain of lithium (Li) for the subdivision

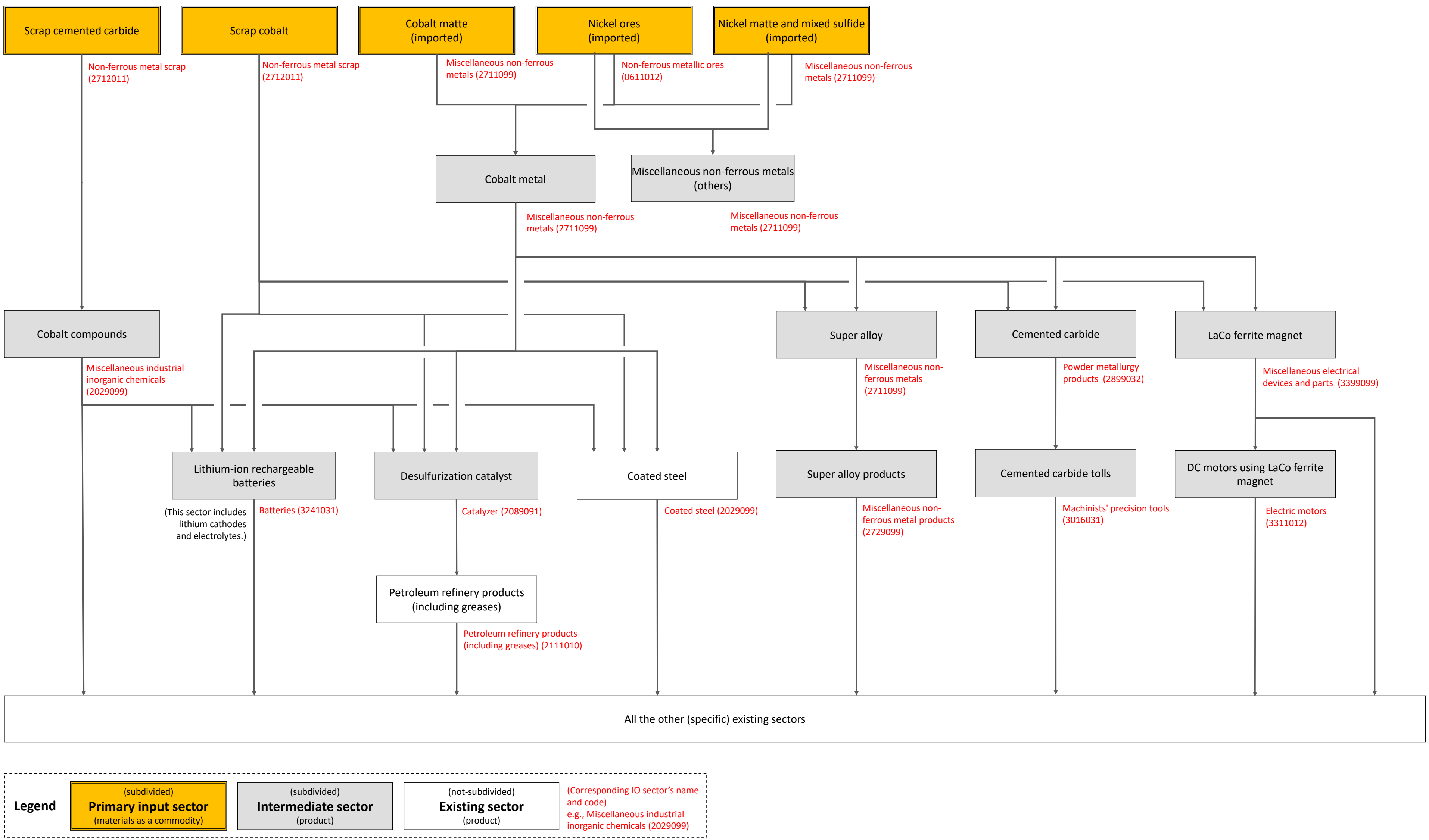

Figure 14 Detailed supply chain of cobalt (Co) for the subdivision

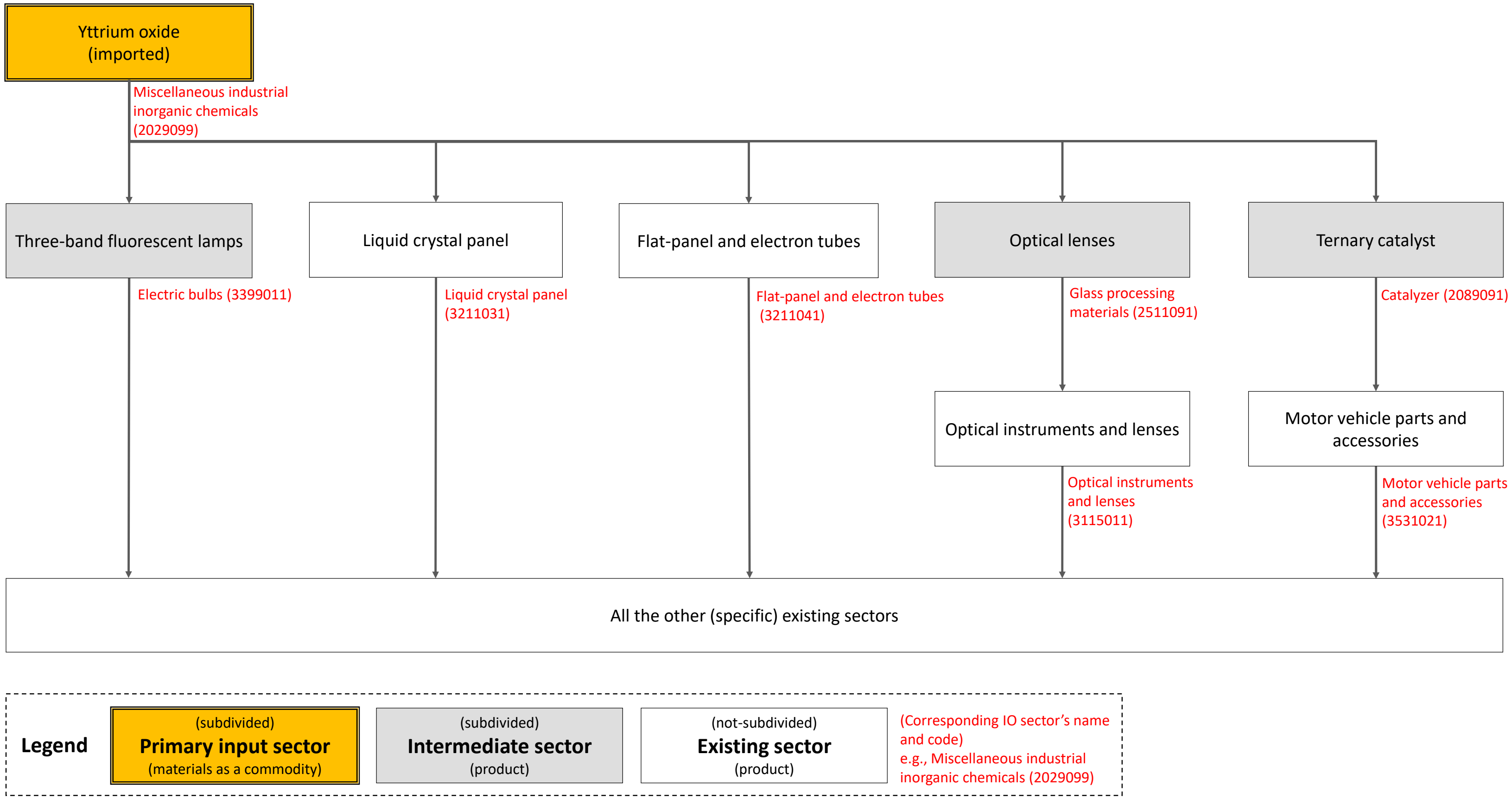

Figure 15 Detailed supply chain of yttrium (Y) for the subdivision

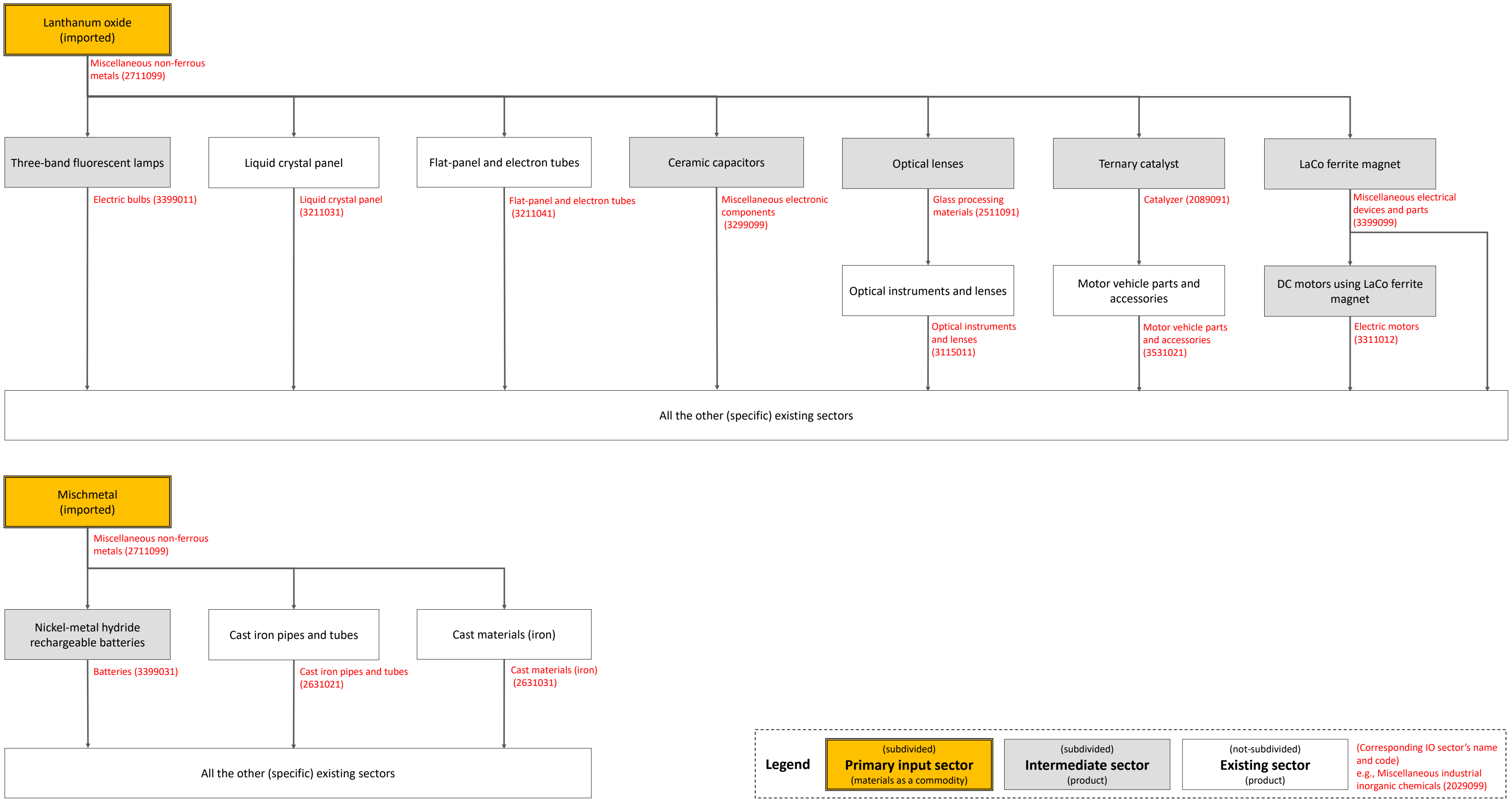

Figure 16 Detailed supply chain of lanthanum (La) for the subdivision

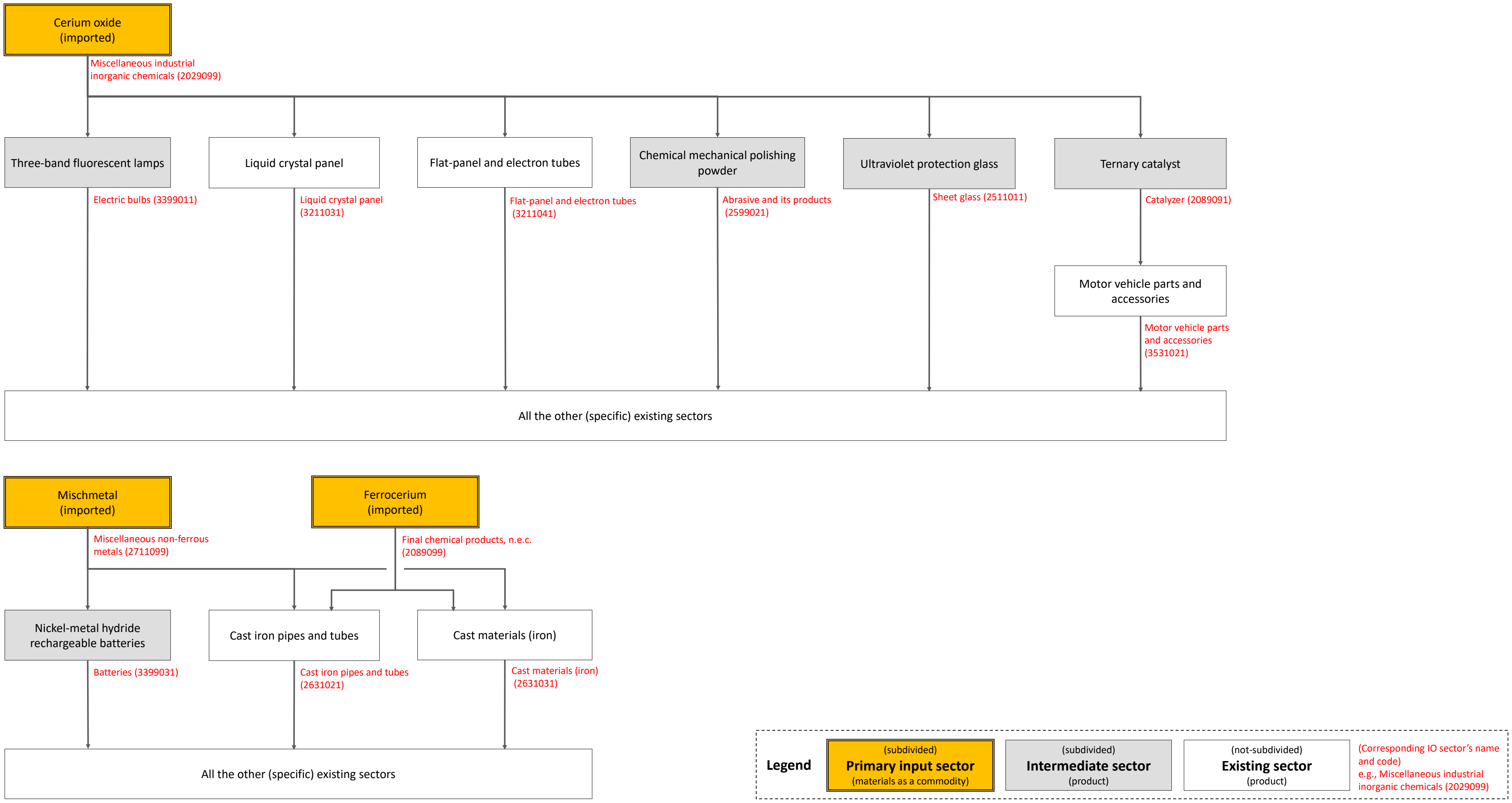

Figure 17 Detailed supply chain of cerium (Ce) for the subdivision

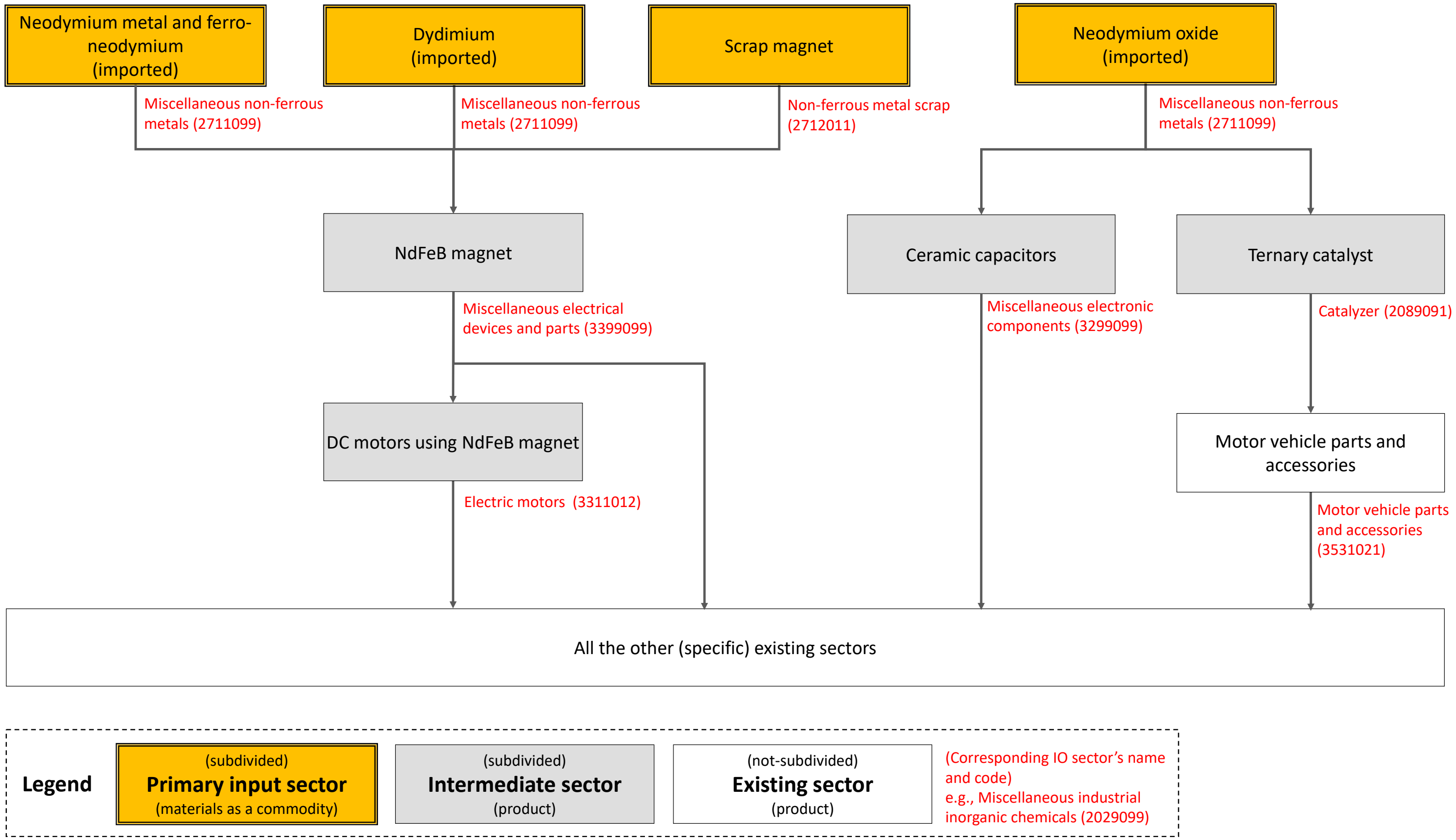

Figure 18 Detailed supply chain of neodymium (Nd) for the subdivision

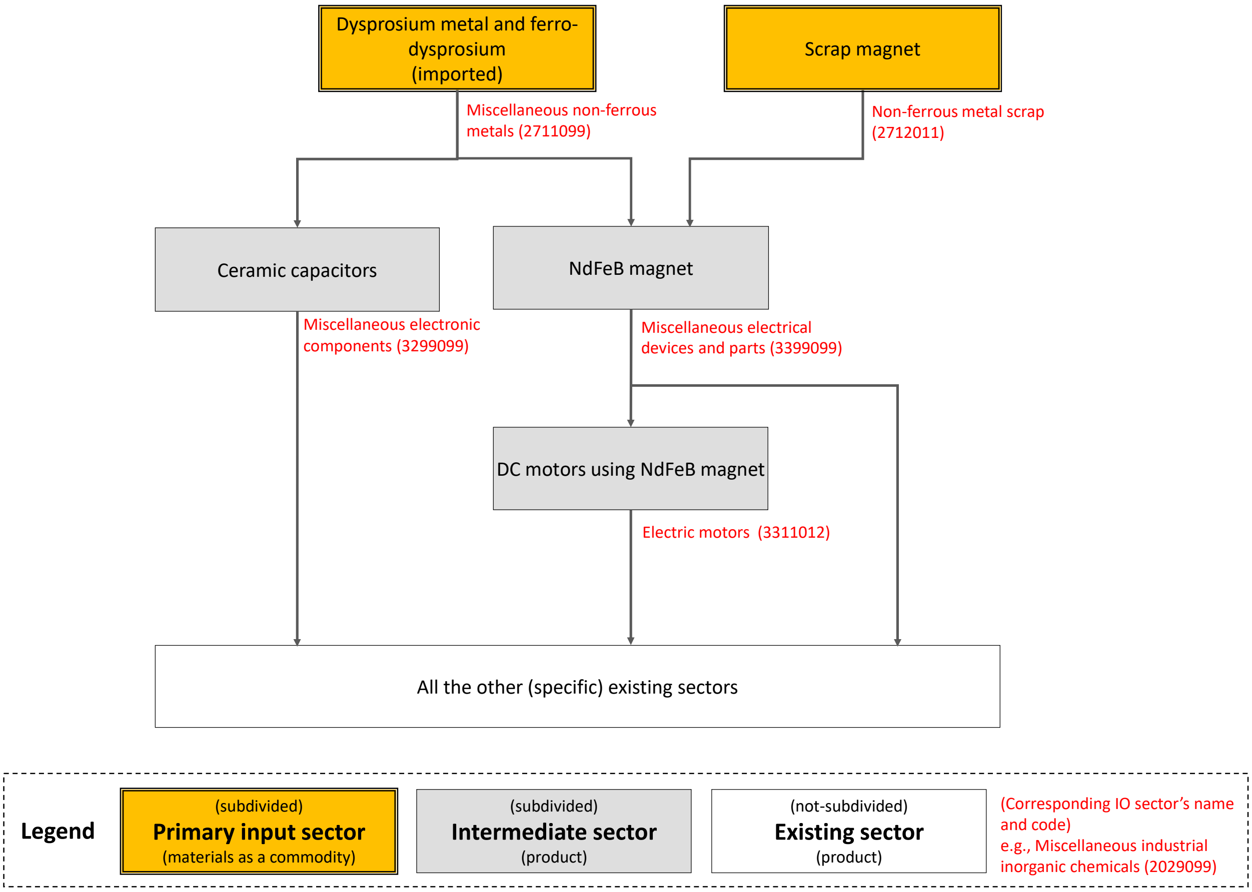

Figure 19 Detailed supply chain of dysprosium (Dy) for the subdivision

Table 3. Domestic production of the original and subdivided sectors [117]

Original sectors and their domestic production		Subdivided sectors and their domestic production (this study)		Evaluated elements
Miscellaneous ores (domestic production only)	160,237 mJPY	- Iron ores (imported)	130,954,875 t [114]	Fe
		- Copper ores (imported)	4,815,914 t [118]	Cu
		- Nickel ores (imported)	4,394,770 t [118]	Co
		- Miscellaneous ores (domestic production and imported others)	367,961 mJPY	-
Miscellaneous industrial inorganic chemicals	925,461 mJPY	- Lithium carbonate and lithium hydroxide (imported)	20,921 t [118]	Li
		- Lithium bromide	2,000 t [119]	Li
		- Lithium chloride	615 t [119]	Li
		- Cobalt compounds	402 t [120]	Co
		- Yttrium oxide (imported)	951 t [118]	Y (REE)
		- Cerium oxide (imported)	12,365 t [118]	Ce (REE)
		- Miscellaneous industrial inorganic chemicals (others)	898,500 mJPY	-
Miscellaneous final chemical products	2,002,522 mJPY	- Desulfurization catalyst	16,496 t [121]	Co
		- Ternary catalyst	9,908 t [121]	Y, La, Ce, Nd (REE)
		- Ferrocerium (imported)	958 t [118]	Ce
		- Miscellaneous final chemical products (others)	1,802,279 mJPY	-
Sheet glass and safety glass	501,284 mJPY	- Ultraviolet protection glass	12,989 t [119]	Ce (REE)
		- Sheet glass and safety glass (others)	488,295 mJPY	-
Miscellaneous glass products	542,317 mJPY	- Heat-resistant glass (pipes and bars)	2,276 t [119]	Li
		- Optical lenses	7,648 t [114]	Y, La, Ce
		- Heat-resistant glass (others)	2,276 t [119]	Li
		- Miscellaneous glass products (others)	469,457 mJPY	-
Abrasive and its products	227,375 mJPY	- Chemical mechanical polishing powder	2,800 t [119]	Ce
		- Abrasive and its products (others)	226,255 mJPY	-
Pig iron	3,033,611 mJPY	- Pig iron	81,010,826 t [114]	Fe
Ferro-alloys	338,026 mJPY	- Ferro-alloys	1,054,265 t [114]	Fe
Crude steel (converters)	4,449,985 mJPY	- Crude steel (converters)	81,081,155 t [114]	Fe
Crude steel (electric furnaces)	1,481,049 mJPY	- Crude steel (electric furnaces)	24,053,223 t [114]	Fe
Scrap iron	394,010 mJPY	- Scrap iron	39,956,970 t [114]	Fe
Copper	1,027,515 mJPY	- Copper matte (imported)	4,924 t [118]	Cu
		- Copper (except copper matte)	1,482,601 t [114]	Cu
Aluminum (including regenerated aluminum)	664,369 mJPY	- Aluminum oxide and aluminum hydroxide	24,796 t [118]	Al
		- Aluminum (imported) (primary)	1,459,036 t [118]	Al
		- Aluminum (secondary)	1,291,211 t [120]	Al
Miscellaneous non-ferrous metals	1,500,558 mJPY	- Smelting cold materials (scrap copper)	207,075 t [120]	Cu
		- Lithium metal	68 t [122]	Li
		- Super alloy	4,679 t [120]	Co
		- Nickel matte and mixed sulfide (imported)	93,957 t [118]	Co
		- Cobalt matte (imported)	0 t [118]	Co
		- Cobalt metal	4,260 t [120]	Co
		- Lanthanum oxide (imported)	2,264 t [118]	La (REE)

		- Mischmetal (imported)	2,409 t [119]	La, Ce (REE)
		- Neodymium oxide (imported)	670 t [119]	Nd (REE)
		- Neodymium metal and ferro-neodymium (imported)	0 t [119]	Nd (REE)
		- Dydimium (imported)	3,463 t [119]	Nd (REE)
		- Dysprosium oxide (imported)	0 t [119]	Dy (REE)
		- Dysprosium metal and ferro-dysprosium (imported)	437 t [119]	Dy (REE)
		- Miscellaneous non-ferrous metals (others)	1,327,729 mJPY	-
Non-ferrous metal scrap	426,784 mJPY	- Dross	79,734 t [123]	Al
		- Scrap aluminum	1,161,769 t [123]	Al
		- Scrap copper	1,178,920 t [124]	Cu
		- Scrap cobalt	1,278 t [118]	Co
		- Scrap cemented carbide	0 t	Co
		- Scrap magnet	0 t	Nd, Dy (REE)
		- Non-ferrous metal scrap (others)	189,496 mJPY	-
Miscellaneous non-ferrous metal products	822,523 mJPY	- Super alloy products	4,679 t [120]	Co
		- Miscellaneous non-ferrous metal products (others)	791,168 mJPY	-
Plumbing accessories, powder metallurgy products and tools	949,085 mJPY	- Cemented carbide	8,128 t [124]	Co
		- Plumbing accessories, powder metall urgy products and tools (others)	695,902 mJPY	-
Machinists' precision tools	882,958 mJPY	- Cemented carbide tolls	8,128 t [124]	Co
		- Machinists' precision tools (others)	629,775 mJPY	
Liquid crystal panel	2,190,471 mJPY	- Liquid crystal panel	496,523,000 units [124]	Y, La, Ce (REE)
Flat-panel and electron tubes	72,693 mJPY	- Flat-panel and electron tubes	1,228,672 units [124]	Y, La, Ce (REE)
Miscellaneous electronic components	5,330,247 mJPY	- Ceramic capacitors	4,118 t [124]	La, Nd, Dy (REE)
		- Miscellaneous electronic components (others)	4,863,518 mJPY	-
Rotating electrical equipment	1,249,851 mJPY	- DC motors using LaCo ferrite magnet	240,383,897 units [124]	Co, La (REE)
		- DC motors using NdFeB magnet	3,210,548 units [124]	Nd, Dy (REE)
		- Rotating electrical equipment (others)	726,857 mJPY	-
Electric bulbs	297,768 mJPY	- Three-band fluorescent lamps	76,523,500 units [124]	Y, La, Ce (REE)
		- Electric bulbs (others)	263,265 mJPY	-
Batteries	1,053,412 mJPY	- Lithium primary batteries	710,161,000 units [124]	Li
		- Lithium-ion rechargeable batteries (This sector includes lithium cathodes and electrolytes.)	983,242,000 units [124]	Li, Co
		- Nickel-metal hydride rechargeable batteries	365,003,000 units [124]	La, Ce (REE)
		- Batteries (others)	537,540 mJPY	-
Miscellaneous electrical devices and parts	750,999 mJPY	- LaCo ferrite magnet	8,668 t [119]	Co, La (REE)
		- NdFeB magnet	11,970 t [119]	Nd, Dy (REE)
		- Miscellaneous electrical devices and	664,598 mJPY	-

parts (others)

Note: "REE" means rare earth elements. "mJPY" means million Japanese yen (1 million Japanese yen was equal to 8,261 USD as an annual average in 2015). The evaluated elements of each product or material are shown in atomic symbols.

After subdividing the rows of the IO table, each newly segmented sector describes the output to the other sectors (Figure 20). This description is made with reference to the supply chain surveys (see Figure 10 to Figure 19) as well as existing statistics (Table 4). If there is no specific output information, the output is allocated according to the original sector's output coefficient. If a specific output destination, such as newly segmented sectors, is based on the supply chain surveys, the output is allocated to the specific sector only. After the output value of the newly subdivided sectors is set, a monetary equivalent of the segmented output value is deducted from the original existing sector. In this case, the original sector remains in monetary units.

Chemical composition formulas and atomic weights are also used to convert from monetary units to physical units to calculate the unit content ratio. Information is obtained through industry sources and hearings for some sectors lacking reliable data. Notably, specific sectors like scrap cemented carbide and scrap magnet are included in the expanded IO table despite having no domestic production, and their domestic production data are not officially or commercially verified. The original IO table employs Stone's method to depict flows of scraps and byproducts. In this method, generated volumes of scraps and byproducts are represented as negative values, while demanded volumes are expressed as positive values in rows. This study transforms the total negative values into positive and interprets them as the domestic production in scrap sectors.

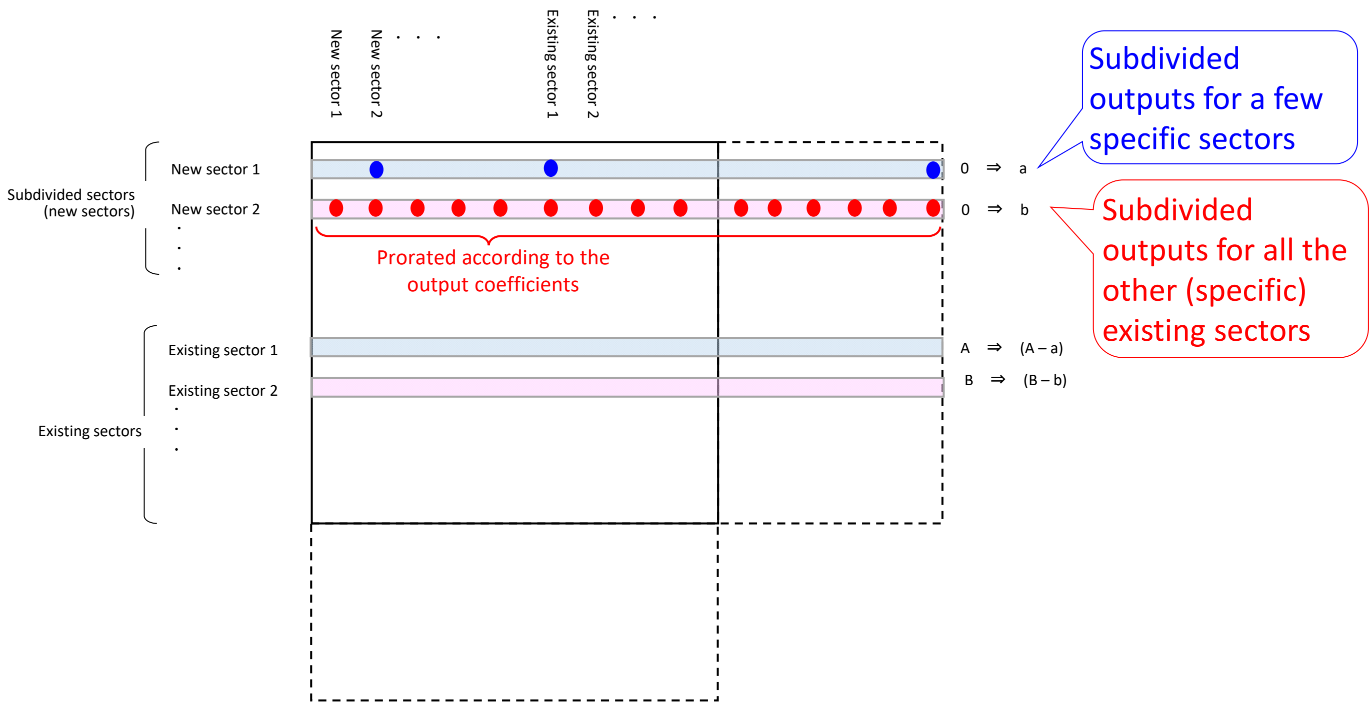

Figure 20 Image of output settings in subdivided rows

Table 4. Output of each subdivided sector

Subdivided sectors in this study	Output sectors: Sectors' name	Output sectors: Sectors' output	Source
- Iron ores (imported)	All endogenous sectors (coinciding with Iron ores)	133,389,751 t	[114]
	TDFD	-2,434,876 t	
	Export	0 t	
	Import	0 t	
- Copper ores (imported)	Copper matte	4,815,914 t	[114], [118], [122]
	TDFD	0 t	
	Export	0 t	
	Import	0 t	
- Nickel ores (imported)	Ferro-alloys	3,719,013 t	[114], [118], [122]
	Cobalt metal	675,656 t	
	TDFD	0 t	
	Export	101 t	
	Import	0 t	
- Lithium carbonate and lithium hydroxide (imported)	Lithium bromide	836 t	[114], [118], [119], [122], [125], [126]
	Lithium chloride	747 t	
	Heat-resistant glass (pipes and bars)	1,105 t	
	Heat-resistant glass (others)	1,105 t	
	Lithium-ion rechargeable batteries (This sector includes lithium cathodes and electrolytes.)	15,097 t	
	Other endogenous sectors (coinciding with Miscellaneous industrial inorganic chemicals)	1,655 t	
	TDFD	0 t	
	Export	376 t	
	Import	0 t	
- Lithium bromide	Miscellaneous metal products	729 t	[114], [119], [122]
	Pumps and compressors	28 t	
	Refrigerators and air conditioning apparatus	38 t	
	Miscellaneous general-purpose machinery	1,153 t	
	Household air-conditioners	53 t	
	TDFD	0 t	
	Export	0 t	
	Import	0 t	
- Lithium chloride	Lithium metal	415 t	[114], [118], [119], [122], [127], [128], [129]
	Miscellaneous metal products	73 t	
	Pumps and compressors	3 t	
	Refrigerators and air conditioning apparatus	4 t	
	Miscellaneous general-purpose machinery	115 t	
	Household air-conditioners	5 t	
	TDFD	0 t	
	Export	0 t	
	Import	0 t	
- Cobalt compounds	Desulfurization catalyst	18 t	[114], [118], [122]
	Lithium-ion rechargeable batteries (This sector includes lithium cathodes and electrolytes.)	788 t	
	Coated steel	58 t	
	TDFD	0 t	

	Export	495 t	
	Import	-956 t	
- Yttrium oxide (imported)	Ternary catalyst	74 t	[114],
	Optical lenses	98 t	[118],
	Liquid crystal panel	521 t	[119],
	Flat-panel and electron tubes	1 t	[122],
	Three-band fluorescent lamps	257 t	[127],
	TDFD	0 t	[128],
	Export	0 t	[129]
	Import	0 t	
- Cerium oxide (imported)	Ternary catalyst	7,876 t	[114],
	Ultraviolet protection glass	1,414 t	[118],
	Chemical mechanical polishing powder	2,908 t	[119],
	Liquid crystal panel	132 t	[122],
	Flat-panel and electron tubes	0 t	[127],
	Three-band fluorescent lamps	35 t	[128], [129]
	TDFD	0 t	
	Export	0 t	
	Import	0 t	
- Desulfurization catalyst	Petroleum refinery products (including greases)	8,452 t	[114], [118],
	FDFD	0 t	[119],
	Export	24,553 t	[121],
	Import	-16,509 t	[130]
- Ternary catalyst	Motor vehicle parts and accessories	7,996 t	[114],
	TDFD	0 t	[118],
	Export	3,041 t	[119], [121],
	Import	-1,129 t	[130]
- Ferrocerium (imported)	Cast iron pipes and tubes	3 t	[114],
	Cast and forged materials (iron)	955 t	[118],
	TDFD	0 t	[119],
	Export	0 t	[122]
	Import	0 t	
- Ultraviolet protection glass	Sheet glass and safety glass (others)	29,843 t	[114],
	Residential construction (wooden)	25,560 t	[118],
	Residential construction (non-wooden)	19,979 t	[119],
	Non-residential construction (wooden)	1,753 t	[122]
	Non-residential construction (non-wooden)	27,124 t	
	Repair of construction	20,208 t	
	TDFD	0 t	
	Export	614 t	
	Import	-17,801 t	
- Heat-resistant glass (pipes and bars)	All endogenous sectors (coinciding with G lass processing materials)	3,007 t	[114], [118],
	TDFD	-98 t	[119],
	Export	118 t	[122]
	Import	-752 t	
- Optical lenses	Optical instruments and lenses	8,374 t	[114],
	TDFD	0 t	[118]
	Export	1,401 t	
	Import	-2,127 t	
- Heat-resistant glass (others)	All endogenous sectors (coinciding with G lass products, n.e.c.)	4,474t	[114], [118],
	TDFD	298 t	[119],

	Export	125 t	[122]
	Import	-2,621 t	
- Chemical mechanical polishing powder	Liquid crystal panel	2,722 t	[114], [118], [119]
	Flat-panel and electron tubes	78 t	
	TDFD	0 t	
	Export	0 t	
	Import	0 t	
- Pig iron	All endogenous sectors (coinciding with P ig iron)	81,336,139 t	[114]
	TDFD	-6,703 t	
	Export	94,026 t	
	Import	-412,637 t	
- Ferro-alloys	All endogenous sectors (coinciding with F erro-alloys)	1,813,059 t	[114]
	TDFD	-3,053 t	
	Export	178,846 t	
	Import	-934,587 t	
- Crude steel (converters)	All endogenous sectors (coinciding with C rude steel (converters))	81,094,656 t	[114]
	TDFD	-13,501 t	
	Export	0 t	
	Import	0 t	
- Crude steel (electric furnaces)	All endogenous sectors (coinciding with C rude steel (electric furnaces))	24,093,776 t	[114]
	TDFD	-6,967t	
	Export	51,970 t	
	Import	-85,556 t	
- Scrap iron	All endogenous sectors (coinciding with p lus-valued sectors of Scrap iron)	32,273,307 t	[114]
	TDFD	0 t	
	Export	7,838,326 t	
	Import	-154,663 t	
- Copper matte (imported)	Copper (except copper matte)	1,624 t	[114], [118], [122]
	TDFD	0 t	
	Export	3,300 t	
	Import	0 t	
- Copper (except copper matte)	All endogenous sectors (coinciding with C opper)	2,228,848 t	[114]
	TDFD	-40,163 t	
	Export	511,117 t	
	Import	-1,217,200 t	
- Aluminum oxide and aluminum hydroxide	Miscellaneous final chemical products (others)	255,624 t	[114], [118], [122]
	Abrasive and its products (others)	250,841 t	
	Pottery, china and earthenware	244,213 t	
	Clay refractories	234,815 t	
	TDFD	201 t	
	Export	152,449 t	
	Import	-1,113,346 t	
- Aluminum (imported) (primary)	Aluminum (secondary)	503,637 t	[114], [118], [122]
	Other endogenous sectors (coinciding with Aluminum (including regenerated alumin um))	950,203 t	
	TDFD	4,192 t	
	Export	1,004 t	
	Import	0 t	

- Aluminum (secondary)	Self-output (Aluminum oxide and aluminum hydroxide, Aluminum (imported) (primary), Aluminum (secondary))	0 t	[114], [118], [122]
	Other endogenous sectors (coinciding with Aluminum (including regenerated aluminum))	2,333,879 t	
	TDFD	10,297 t	
	Export	17,062 t	
	Import	-1,070,027 t	
- Smelting cold materials (scrap copper)	All endogenous sectors (coinciding with Miscellaneous non-ferrous metals)	230,673 t	[114], [120], [122]
	TDFD	0 t	
	Export	0 t	
	Import	-23,598 t	
- Lithium metal	Miscellaneous final chemical products (others)	87 t	[114], [118], [122]
	Lithium primary batteries	71 t	
	TDFD	0 t	
	Export	6 t	
	Import	-96 t	
- Super alloy	Super alloy products	3,415 t	[114], [118], [120]
	TDFD	0 t	
	Export	1,430 t	
	Import	-166 t	
- Nickel matte and mixed sulfide (imported)	Cobalt metal	13,642 t	[114], [118], [120], [122]
	Miscellaneous non-ferrous metals (others)	80,315 t	
	TDFD	0 t	
	Export	0 t	
	Import		
- Cobalt matte (imported)	All endogenous sectors	0 t	[114], [120], [122]
	TDFD	0 t	
	Export	0 t	
	Import	0 t	
- Cobalt metal	Desulfurization catalyst	185 t	[114], [118], [122]
	Super alloy	1,371 t	
	Cemented carbide	602 t	
	Lithium-ion rechargeable batteries (This sector includes lithium cathodes and electrolytes.)	8,190	
	LaCo ferrite magnet	116 t	
	Coated steel	580 t	
	TDFD	0 t	
	Export	2,415	
	Import	-9,200 t	
- Lanthanum oxide (imported)	Ternary catalyst	48 t	[114], [118], [119], [122], [127], [131]
	Optical lenses	315 t	
	Liquid crystal panel	96 t	
	Flat-panel and electron tubes	0 t	
	Ceramic capacitors	99 t	
	Three-band fluorescent lamps	54 t	
	LaCo ferrite magnet	1,652 t	
	TDFD	0 t	
	Export	0 t	
	Import	0 t	
- Mischmetal (imported)	Nickel-metal hydride rechargeable batteries	1,854 t	[114], [118], [119],
	Cast iron pipes and tubes	71 t	

	Cast and forged materials (iron)	479 t	[122],
	TDFD	0 t	[127],
	Export	5 t	[131]
	Import	0 t	
- Neodymium oxide (imported)	Ternary catalyst	130 t	[114],
	Ceramic capacitors	540 t	[118],
	TDFD	0 t	[119],
	Export	0 t	[122],
	Import	0 t	[127], [131]
- Neodymium metal and ferro-neodymium (imported)	All endogenous sectors	0 t	[114],
	TDFD	0 t	[118],
	Export	0 t	[119],
	Import	0 t	[122], [127], [131]
- Dydimium (imported)	NdFeB magnet	3,456 t	[114],
	TDFD	0 t	[118],
	Export	7 t	[119],
	Import	0 t	[122], [127], [131]
- Dysprosium oxide (imported)	All endogenous sectors	0 t	[114],
	TDFD	0 t	[118],
	Export	0 t	[119],
	Import	0 t	[122], [127], [131]
- Dysprosium metal and ferro-dysprosium (imported)	Ceramic capacitors	58 t	[114],
	NdFeB magnet	378	[118],
	TDFD	0 t	[119],
	Export	1 t	[122],
	Import	0 t	[127], [131]
- Dross	Aluminum (secondary)	55,236 t	[114],
	TDFD	0 t	[118],
	Export	40,003 t	[122],
	Import	-15,505 t	[123]
- Scrap aluminum	Aluminum (secondary)	771,003 t	[114],
	Rolled and drawn aluminum	343,527 t	[118],
	Non-ferrous metal castings and forgings	3,490 t	[122],
	TDFD	0 t	[123],
	Export	110,827 t	[132]
	Import	-67,077 t	
- Scrap copper	Smelting cold materials (scrap cop-per)	262,692 t	[114],
	Electric wires and cables	99,834 t	[118],
	Rolled and drawn copper and copper alloys	622,429 t	[120]
	Other endogenous sectors (coinciding with Non-ferrous metal scrap)	0 t	
	TDFD	0 t	
	Export	261,100 t	
	Import	-169,435 t	
- Scrap cobalt	Cobalt compounds	245 t	[114],
	TDFD	0 t	[118],
	Export	1,192 t	[122]
	Import	-158 t	
- Scrap cemented carbide	All endogenous sectors	0 t	[122]

	TDFD	0 t	
	Export	0 t	
	Import	0 t	
- Scrap magnet	All endogenous sectors	0 t	[122]
	TDFD	0 t	
	Export	0 t	
	Import	0 t	
- Super alloy products	All endogenous sectors (coinciding with Miscellaneous non-ferrous metal product)	4,549 t	[114], [118]
	TDFD	-90 t	
	Export	310 t	
	Import	-91 t	
- Cemented carbide	Cemented carbide tolls	8,128 t	[114], [118], [124], [133]
	TDFD	0 t	
	Export	0 t	
	Import	0 t	
- Cemented carbide tolls	All endogenous sectors (coinciding with Machinists' precision tools)	3,539 t	[114], [118], [124], [133]
	TDFD	3,207 t	
	Export	1,938 t	
	Import	-557 t	
- Liquid crystal panel	All endogenous sectors (coinciding with Liquid crystal panel)	408,372,850 units	[114], [118], [124]
	TDFD	4,013,718 units	
	Export	133,067,659 units	
	Import	-48,931,227 units	
- Flat-panel and electron tubes	All endogenous sectors (coinciding with Flat-panel and electron tubes)	1,419,836 units	[114], [118], [124]
	TDFD	9,313 units	
	Export	518,188 units	
	Import	-718,665 units	
- Ceramic capacitors	All endogenous sectors (coinciding with Miscellaneous electronic components)	1,641 t	[114], [118], [124]
	TDFD	59 t	
	Export	3,265 t	
	Import	-847 t	
- DC motors using LaCo ferrite magnet	Machinists' precision tools (others)	1,334,535 units	[114], [118], [124], [134]
	Pumps and compressors	20,809,734 units	
	Conveyors	10,735,538 units	
	Refrigerators and air conditioning apparatus	41,118,129 units	
	Miscellaneous general-purpose machinery	1,980,469 units	
	Machinery for agricultural use	1,201,200 units	
	Machinery and equipment for construction and mining	1,674,687 units	
	Textile machinery	2,627,587 units	
	Daily lives industry machinery	8,816,107 units	
	Chemical machinery	4,404,202 units	
	Casting equipment and plastic processing machinery	5,739,922 units	
	Metal machine tools	12,944,157 units	
	Metal processing machinery	2,557,068 units	
	Semiconductor making equipment	7,976,986 units	
	Vacuum equipment and vacuum component	3,625,526 units	
	Robots	28,117,675 units	
	Miscellaneous production machinery	19,147,492 units	
	Copy machine	2,067,581 units	

	Miscellaneous office machines	1,148,458 units	
	Service industry and amusement machines	9,427,077 units	
	Measuring instruments	4,885,393 units	
	Medical instruments	4,483,610 units	
	Optical instruments and lenses	1,152,607 units	
	Transformers and reactors	112,001 units	
	Relay switches and switchboards	159,409 units	
	Miscellaneous electrical devices and parts	1,047,716 units	
	Household air-conditioners	16,195,160 units	
	Household electric appliances (except air-conditioners)	11,291,989 units	
	Applied electronic equipment	4,310,571 units	
	Electric measuring instruments	1,783,133 units	
	Wired communication equipment	1,460,166 units	
	Mobile phone	106,668 units	
	Radio communication equipment (except mobile phone)	925,048 units	
	Personal Computers	416,005 units	
	Electronic computing equipment (except personal computers)	82,964 units	
	Electronic computing equipment (accessory equipment)	7,612,537 units	
	Motor vehicle parts and accessories	17,599,621 units	
	Steel ships	4,976,060 units	
	Miscellaneous Ships (except steel ships)	21,334 units	
	Repair of ships	210,966 units	
	Rolling stock	1,474,388 units	
	Repair of rolling stock	155,854 units	
	Bicycles	1,844,763 units	
	Miscellaneous transport equipment	416,598 units	
	Toys and games	5,926 units	
	Miscellaneous manufacturing products	26,667 units	
	Public construction of roads	2,963 units	
	Public construction of rivers, drainages and miscellaneous public Construction	576,600 units	
	Agricultural public construction	2,370 units	
	Railway construction	190,225 units	
	Electric power facilities construction	26,667 units	
	Telecommunication facilities construction	1,185 units	
	Miscellaneous civil engineering and construction	130,372 units	
	Motor vehicle maintenance services	962,975 units	
	Machine repair services	27,528,631 units	
	TDFD	114,052,227 units	
	Export	137,508 units	
	Import	-173,439,108 units	
- DC motors using NdFeB magnet	Robots	24,008,743 units	[114], [118], [124], [134]
	Household air-conditioners	13,828,506 units	
	Household electric appliances (except air-conditioners)	9,641,852 units	
	Mobile phone	91,080 units	
	Personal Computers	355,213 units	
	Motor vehicle parts and accessories	15,027,728 units	
	Motor vehicle maintenance services	822,252 units	
	Machine repair services	23,505,778 units	
	TDFD	33,222,645 units	

	Export	93,068 units	
	Import	-117,386,316 units	
- Three-band fluorescent lamps	All endogenous sectors (coinciding with Electric bulbs)	65,356,912 units	[114], [118], [124]
	TDFD	24,806,848 units	
	Export	1,739,448 units	
	Import	-15,379,708 units	
- Lithium primary batteries	All endogenous sectors (coinciding with Batteries)	166,525,985 units	[114], [118], [124]
	TDFD	150,327,028 units	
	Export	533,902,044 units	
	Import	-140,594,057 units	
- Lithium-ion rechargeable batteries (This sector includes lithium cathodes and electrolytes.)	All endogenous sectors (coinciding with Batteries)	37,604,605 units	[114], [118], [124]
	TDFD	33,946,584 units	
	Export	962,330,097 units	
	Import	-50,639,286 units	
- Nickel-metal hydride rechargeable batteries	All endogenous sectors (coinciding with Batteries)	127,092,670 units	[114], [118], [124]
	TDFD	114,729,622 units	
	Export	146,120,172 units	
	Import	-22,939,464 units	
- LaCo ferrite magnet	Miscellaneous electronic components (others)	1,028 t	[114], [118], [124], [134]
	DC motors using LaCo ferrite magnet	5,017 t	
	Wooden fixtures	2 t	
	Machinery and equipment for construction and mining	68 t	
	Measuring instruments	155 t	
	Relay switches and switchboards	430 t	
	Electric measuring instruments	21 t	
	Wired communication equipment	27 t	
	Mobile phone	4 t	
	Radio communication equipment (except mobile phone)	13 t	
	Radio and television sets	4 t	
	Motor vehicle parts and accessories	1 t	
	Toys and games	0 t	
	Watches and clocks	29 t	
	Miscellaneous manufacturing products	74 t	
	TDFD	0 t	
	Export	3,532 t	
	Import	-1,736 t	
- NdFeB magnet	DC motors using NdFeB magnet	6,928 t	[114], [118], [124], [134]
	Medical instruments	580 t	
	Mobile phone	82 t	
	Video equipment and digital camera	550 t	
	Electric audio equipment	1,174 t	
	Personal Computers	159 t	
	Motor vehicle parts and accessories	17 t	
	TDFD	0 t	
	Export	4,877 t	
	Import	-2,398 t	

Note 1: "TDFD" means total domestic final demand.

Note 2: The following equality holds from the structure of the IO table: (All the output of endogenous sectors)+(Total domestic final demand (TDFD))+(Export)-(Import)=(Domestic production)

3.3.2. Subdividing columns

After segmenting the rows of the IO table, columns are subdivided. The domestic production value of the newly segmented column is the same as the domestic production value (in monetary units) of the same row sector (Figure 21). When subdividing the columns, the input allocation is made using the input coefficients of the original sector unless otherwise stated due to the limited statistical information available. A material and monetary balance between the newly segmented and original sectors (column) is considered to keep the original balance described in the initial IO table.

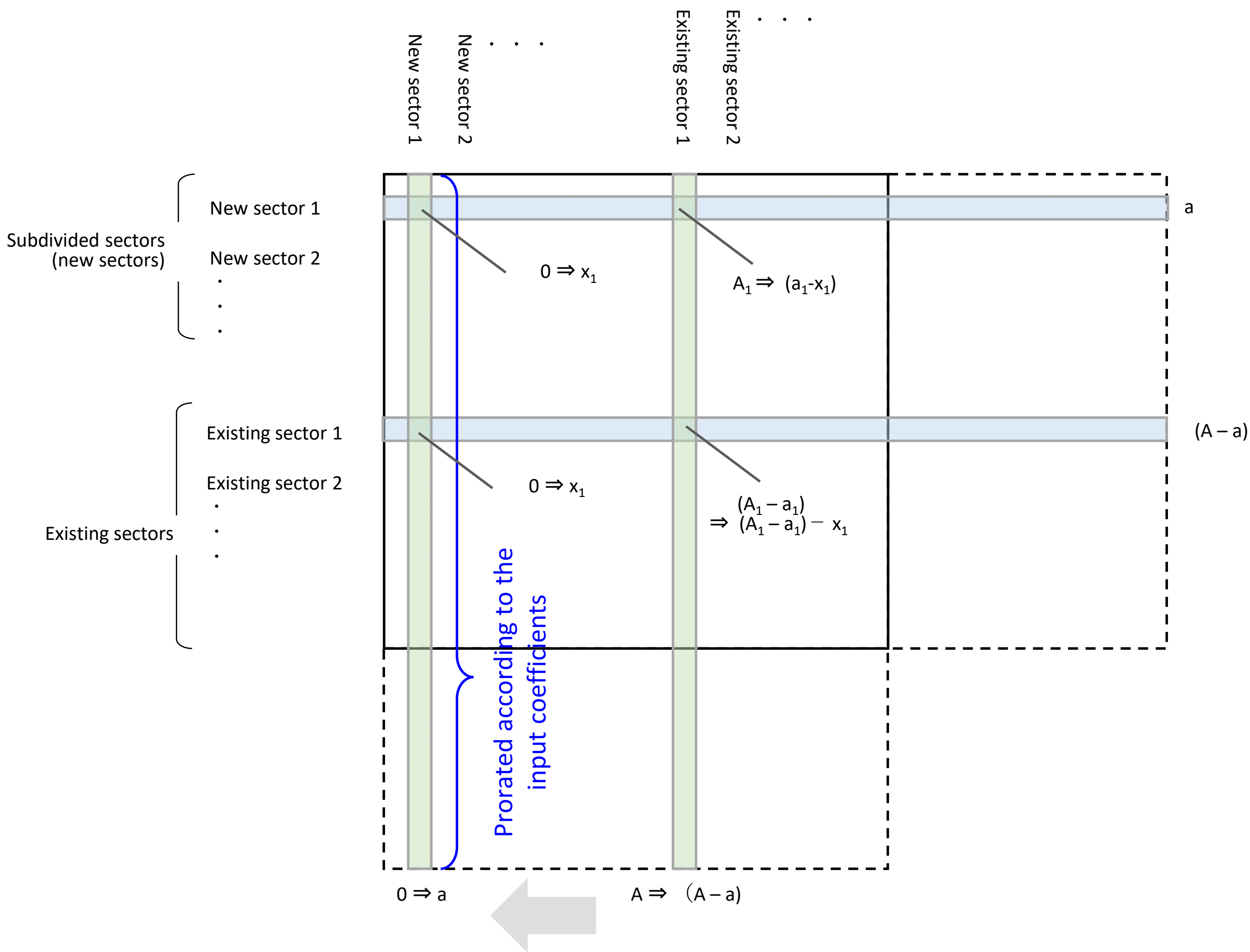

Figure 21 Image of subdividing columns

3.4. Evaluation of economic damages by critical minerals' supply disruption

An economic IO analysis is widely used for calculating supply chain damages or impacts in the disruption or restriction of resources [135], energies [136], [137] and industrial goods [137], [138], [139], [140], [141], [142]. These studies describe the cause-and-effect relationship through IO approaches. We experienced the Chinese government's political embargo of rare earths in 2010 [143], [144], [145]. These years, Resource Nationalisms are considered to cause the possible supply disruption of mineral resources [146]. The IO analysis is useful for discussing the damages and impacts of supply disruption of mineral resources. Assumed impacts, which are calculated as mass value, are helpful in discussing evidence-based policy actions for policymakers.

This study calculates the repercussions effects of the supply disruption of critical minerals using the uniquely expanded high-resolution IO table in the case of Japan as of 2015. In the IO analysis, an induced total sectoral output (x) for a demand change (y) can be calculated with an input coefficients matrix (A) and an identity matrix (I) as follows:

$$x = (I - A)^{-1}y \qquad (1)$$

An inverse matrix $(I - A)^{-1}$ is called Leontiev's inverse matrix in this equation. It represents the series expansion of the input coefficients matrix (A) as follows:

$$(I - A)^{-1}y = y + Ay + A^2y + A^3y + A^4y + \cdot\cdot\cdot\cdot \qquad (2)$$

An induced value-added (v) can be calculated with the induced total sectoral output (x) and a diagonalized matrix for a vector of direct value-added coefficients (V) as follows:

$$v = V(I - A)^{-1}y \qquad (3)$$

Equations (1) and (3) do not distinguish imports from domestic production in their induced outputs (x), value-added (v) and demand changes (y). The following model is usually used for analysis to calculate the domestic effects [114]. In this equation, the input coefficients matrix (A) and a demand change matrix (Y) are multiplied by a self-sufficiency ratio matrix $(I - M)$. The induced domestic value added (V_d) as economic damages by critical minerals' supply disruption is calculated as follows:

$$V_d = V(I - (I - M)A)^{-1}((I - M)Y) \quad (4)$$

where V represents a diagonalized matrix from a vector of direct value-added coefficients, M represents a diagonalized matrix from a vector of import coefficients, A represents a matrix of input coefficients and Y represents a matrix of negative final demands as a critical minerals' supply disruption. The graphic flow image of the calculation process is shown in Figure 22.

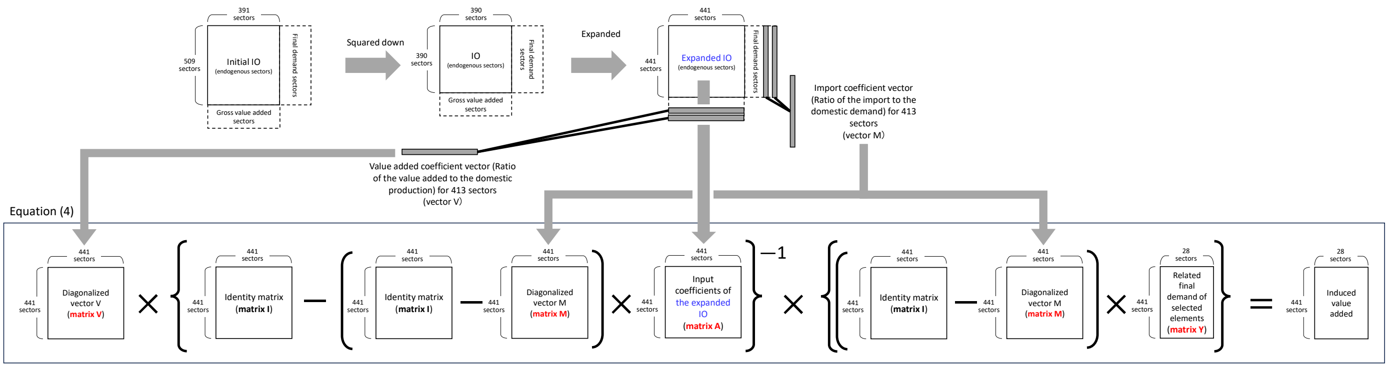

Figure 22 **Calculation flow of economic damages by critical minerals' supply disruption**

3.5. Estimation of critical minerals' final destination

IO analyses derive the final destination, such as domestic final demand and export, as social stocks of each year. The volume and distribution of elements' annual stock and distribution are computed based on the domestic final demand and exports for goods containing them. A detailed process is described in Shimizu and Owada (2024) [117]. A hybrid IO table contributes stock and flow analyses, combining IO flows in monetary and physical units. The WIO-MFA model is known as a pioneer research model in this field [13], [147], [148], [149], [150], [151], [152], [153].

In the model, an input coefficient matrix A undergoes multiplication by two filter matrices, Φ (representing non-quantitative flows) and Γ (representing yield losses). The prime example of the former filter is electricity and services, and the latter filter is scrap generation during production. The filtered input coefficient matrix $\widetilde{A}$ is calculated as shown below:

$$\widetilde{A} = \Gamma \otimes (\Phi \otimes A) \qquad (5)$$

where ⊗ represents an element-wise product (Hadamard product). Filtering aims to adjust the monetary relationships to reflect physical connections.

All the sectors are categorized into three types for estimation: raw materials, materials as a commodity, and products (Table 5). The matrix (C_{MP}) denotes the element (materials) composition per monetary unit (million Japanese yen) of products. Estimating the element composition uses segmented coefficient matrices; $\widetilde{A}_{MP}$ covering from materials as a commodity to products, and ($\widetilde{A}_{PP}$) covering flows between products. Raw materials sectors are excluded from the estimation in the model.

$$C_{MP} = \widetilde{A}_{MP}\left(I - \widetilde{A}_{PP}\right)^{-1} \qquad (6)$$

Table 5. Subdivided sectors categorized into "raw materials" and "materials as a commodity" in the model [117]

Category	Sector's name	Evaluated elements
Raw materials (2 sectors)	- Miscellaneous ores (domestic production and imported others)	-
	- Dysprosium oxide	Dy (REE)
Materials as a commodity ctors) (28 sectors)	- Iron ores (imported)	Fe
	- Copper ores (imported)	Cu
	- Nickel ores (imported)	Co
	- Lithium carbonate and lithium hydroxide (imported)	Li
	- Yttrium oxide (imported)	Y (REE)
	- Cerium oxide (imported)	Ce (REE)
	- Ferrocerium (imported)	Ce
	- Ferro-alloys	Fe
	- Scrap iron	Fe
	- Copper matte (imported)	Cu
	- Aluminum oxide and aluminum hydroxide	Al
	- Aluminum (imported) (primary)	Al
	- Nickel matte and mixed sulfide (imported)	Co
	- Cobalt matte (imported)	Co
	- Lanthanum oxide (imported)	La (REE)
	- Mischmetal (La) (imported)	La (REE)
	- Mischmetal (Ce) (imported)	Ce (REE)
	- Neodymium oxide (imported)	Nd (REE)
	- Neodymium metal and ferro-neodymium (imported)	Nd (REE)
	- Dydimium (imported)	Nd (REE)
	- Dysprosium metal and ferro-dysprosium (imported)	Dy (REE)
	- Dross	Al
	- Scrap aluminum	Al
	- Scrap copper	Cu
	- Scrap cobalt	Co
	- Scrap cemented carbide	Co
	- Scrap magnet (Nd)	Nd (REE)
	- Scrap magnet (Dy)	Dy (REE)
Products (413 sectors)	All the other sectors	-

The final destination (final domestic demand exports) of elements F (vector) is calculated as below:

$$F_{i,k} = \mathrm{diag}(C_{M_i P}) X_{PF,k} \qquad (7)$$

$$(k \in \text{export and domestic final demand})$$

where k denotes a final demand type, such as export and domestic final demand, and i represents an element type. The vector $F_{i,k}$ is obtained by multiplying a diagonalized composition matrix of the element i ($C_{M_i P}$) with a hybrid vector ($X_{PF,k}$) encompassing all sectors' final demand k categorized into products. The graphic flow image of the calculation process is shown in Figure 23.

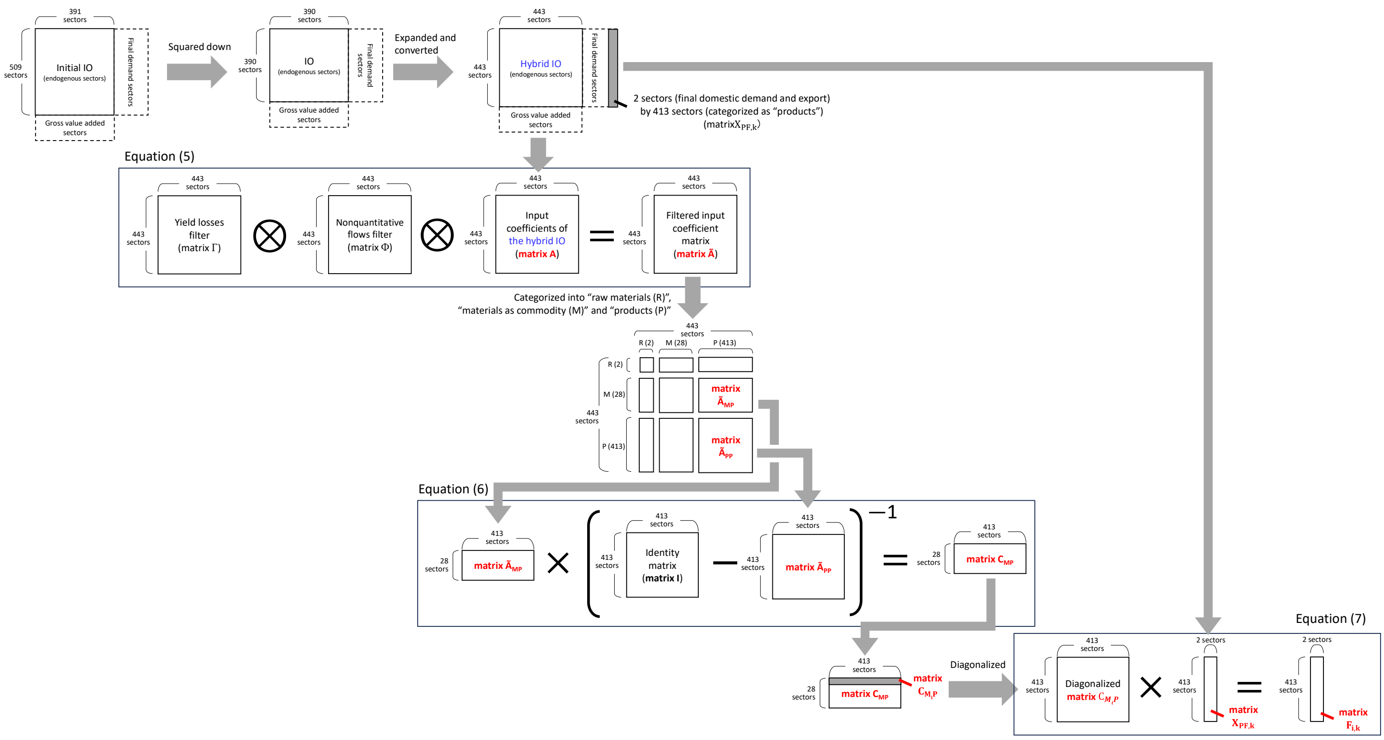

Figure 23. Calculation flow of critical minerals' final destination [117]

Note: Equation numbers are changed from Shimizu and Owada (2024) to coincide with this dissertation.

4 Evaluating the vulnerability of mineral resources' supply disruption as a stress test

4.1. Introduction

After the concept proposal of "critical minerals" by the National Research Council (U.S.) [16], the criticality of mineral resources is generally determined in two dimensions: supply risk and vulnerability. Graedel et al. (2012) expand the concept of a criticality assessment from the above two dimensions to the three, including environmental implications, and from national to global or corporate levels [19]. The combination of the two dimensions, supply risk and vulnerability, is considered to coincide with a classical risk management approach to assess a risk level with the probability of occurrence of a scenario and the potential scale of its damage [81].

After the EU determines their critical minerals with these two dimensions as an actual methodology [17], [101], the criticality of each mineral is generally evaluated by these two dimensions in many cases, which is indicated in some reviews [18], [20], [21], [22]. Indicators for supply risk determination are relatively well developed rather than vulnerability indicators [20], [21], [22]. The most frequently adopted vulnerability indicator is substitutability [20], [22]. This indicator is also used in the determination of supply risks [20], [46]. Economic importance, sometimes the economic size of critical minerals or products using them, determines the vulnerability next to the substitutability [20], [22].

Considering the initial concept of vulnerability determination, the vulnerability indicators are expected to evaluate the impact of supply disruption or restriction [18], [20], [22]. Substitutability is an indicator of the possibility of damage mitigation to the supply disruption, not on damage scales by the supply disruption of mineral resources. Existing economic importance indicators focus on the value-added volume of end-uses weighted by the consumption share of end-uses [19], [46], the induced value added and final use materials of products [154]. Schrijvers et al. (2020) categorize vulnerability indicators into three types: materials usage by systems (e.g., internal demand, sectors using the material, population using the material and apparent consumption), the relative importance of materials (e.g., the price of the material or revenue or GDP impacted by a supply disruption) and others (e.g., substitutability, demand growth, import dependency, trade restrictions, price volatility, stockpiles and resource efficiency) [20]. These vulnerability indicators, however, do not have well-described cause-and-effect mechanisms in their evaluation [20].

For policymakers, the criticality assessment is an essential and rational decision-making tool in the designation of critical minerals. As a stress test, some research pioneer to examinine the impacts of supply disruption on the Japanese economy [78], [103], [129], [155], [156], [157], [158], [159], [160]. The current criticality assessments have a technical issue in not explaining the cause-and-effect mechanisms between assumed risks or events and indicators. This technical issue is a significant challenge for policymakers in the vulnerability evaluation because of less data availability. This study calculates the economic damages of critical minerals' supply disruption with a high-resolution IO approach in the context of cause-and-effect mechanisms. The study aims to improve policymakers' decision flow framework in vulnerability evaluation. For the comparison of methodologies in the IO approach and existing approaches, this study also calculates the economic importance indicators for the same selected mineral resources with the EU methodology [47].

4.2. Materials and methods

The analysis focuses on the following ten elements.

1) Lithium and cobalt: These two elements play significant roles as raw materials in the production of lithium-ion batteries for energy storage
2) Yttrium, lanthanum, cerium, neodymium, dysprosium: Lanthanum, neodymium, and dysprosium are essential for various applications such as electric vehicles, wind turbines, and other generators or motors, contributing to efficient power sources. Yttrium and cerium, categorized as rare earth elements, hold importance alongside the rare earth elements mentioned previously.
3) Iron, copper, and aluminum: These three elements are chosen as reference points due to their widespread use as primary materials.

Calculating the repercussion effects of the selected mineral resources follows the model shown in Equation (4) and Figure 22. The uniquely expanded hybrid IO table (441 by 441 sectors) is used for the analysis. A demand change as the selected elements' supply disruption is input based on the consumption share of each mineral resource as of 2015 in Japan [122] (Table 6). The bulk volume of each mineral resource is calculated from the content ratios (Table 7). For example, the supply disruption of 1.000 t of iron in an element base is input as the supply disruptions of 1.067 t of iron ore, 0.009 t of ferroalloys and 0.325 t of scrap iron simultaneously [122].

Calculating the economic importance of the selected mineral resources is based on the EU (2017) methodology [46]. The share of end-uses and the value-added volume of each mega-sector are based on the related statistics data published by the Japanese Government as of 2015 [122], [161].

Table 6 Critical minerals' supply disruption volume for one element equivalent ton of each element as of 2015 in Japan

Mineral resources	Fe	Cu	Al	Li	Co	Y	La	Ce	Nd	Dy
Iron ores (imported)	1.067									
Copper ores (imported)		1.926								
Nickel ores (imported)					510.6					
Lithium carbonate and lithium hydroxide (imported)				5.613						
Yttrium oxide (imported)						1.266				
Cerium oxide (imported)								1.055		
Ferrocerium (imported)								0.082		
Ferro-alloys	0.009									
Scrap iron	0.325									
Copper matte (imported)		0.002								
Aluminum oxide and aluminum hydroxide			0.009							
Aluminum (imported) (primary)			0.550							
Nickel matte and mixed sulfide (imported)					10.92					
Cobalt matte (imported)					0.000					
Lanthanum oxide (imported)							0.875			
Mischmetal (imported)							0.931	0.206		
Neodymium oxide (imported)									0.211	
Neodymium metal and ferro-neodymium (imported)									0.000	
Dydimium (imported)									1.092	
Dysprosium metal and ferro-dysprosium (imported)										1.005
Dross			0.030							
Scrap aluminum			0.438							
Scrap copper		0.472								
Scrap cobalt					0.148					
Scrap cemented carbide					0.000					
Scrap magnet									0.000	0.000

Note: The column sum equals one element equivalent of each element (metric ton) [122].

Table 7 Basic data of critical minerals related to the selected elements as of 2015

Mineral resources	Selected elements contained	Content ratio (mass fraction)	Unit price (mJPY/t)
Iron ores (imported)	Fe	0.630 [122]	0.009 [114]
Copper ores (imported)	Cu	0.307 [122]	0.196 [118]
Nickel ores (imported)	Co	0.001[162]	0.008 [118]
Lithium carbonate and lithium hydroxide (imported)	Li	0.178 [122]	0.824 [118]
Yttrium oxide (imported)	Y	0.790 [122]	1.369 [118]
Cerium oxide (imported)	Ce	0.814 [122]	0.468 [118]
Ferrocerium (imported)	Ce	0.500 [122]	0.419 [118]
Ferro-alloys	Fe	0.415 [114]	0.321 [114]
Scrap iron	Fe	0.997 *	0.010 [114]
Copper matte (imported)	Cu	0.780 *	0.503 [118]
Aluminum oxide and aluminum hydroxide	Al	0.350 [122]	0.043 [118]
Aluminum (imported) (primary)	Al	1.000 [122]	0.274 [114]
Nickel matte and mixed sulfide (imported)	Co	0.036 [122]	0.948 [118]
Cobalt matte (imported)	Co	0.038 *	-
Lanthanum oxide (imported)	La	0.853 *	0.426 [118]
Mischmetal (imported)	La, Ce	La: 0.272 [163] Ce: 0.487 [163]	0.572[131]
Neodymium oxide (imported)	Nd	0.857 *	4.932 [131]
Neodymium metal and ferro-neodymium (imported)	Nd	0.990 *	6.333 [131]
Dydimium (imported)	Nd	0.750 *	6.393 [131]
Dysprosium metal and ferro-dysprosium (imported)	Dy	0.995 *	35.316 [131]
Dross	Al	0.300 [122]	0.017 [118]
Scrap aluminum	Al	1.000 [122]	0.153[123]
Scrap copper	Cu	0.863 [122]	0.048[120]
Scrap cobalt	Co	1.000 [122]	1.120 [118]
Scrap cemented carbide	Co	0.049 *	-
Scrap magnet	Nd, Dy	Nd: 0.225 * Dy: 0.030 *	-

Note: The value with the symbol "*" is based on the calculation of molecular formula or hearing information about relevant industries. The selected elements contained in mineral resources are shown in atomic symbols. "mJPY" means million Japanese yen (1 million Japanese yen was equal to 8,261 USD as an annual average in 2015).

4.3. Results and discussion

4.3.1. Total economic damage of each mineral resource supply disruption

The model generates the total economic damage of each mineral resource's disruption per one ton (element-equivalent) in the case of Japan as of 2015. The results mean the total economic damages of all the sectors induced by the 1 t of mineral resources (element-equivalent). Large economic damages are induced by the supply disruption of dysprosium (Dy), cobalt (Co), lithium (Li) and neodymium (Nd) (Figure 24). These mineral resources are economically significant in producing and using batteries and other electric devices. Iron, aluminum and copper potentially create relatively small economic damages in their supply disruption (one element-equivalent ton) if compared to the previous rare earth elements (e.g., Nd and Dy) and battery materials (e.g., Li and Co).

Iron, copper and aluminum are called "base metals" or "common metals." These terms probably mean "metals broadly and commonly used as a social base" relative to precious metals, such as gold, silver and platinum. Despite the term's connotations, they do not necessarily have a significant induced value added per unit weight. Rare earth elements are considered critical in many existing mineral resource policy documents (see Chapter 2). The results, however, show that some rare earth elements (e.g., yttrium, lanthanum and cerium) do not have a large negative effect by their supply disruption if compared to neodymium and dysprosium used for magnets.

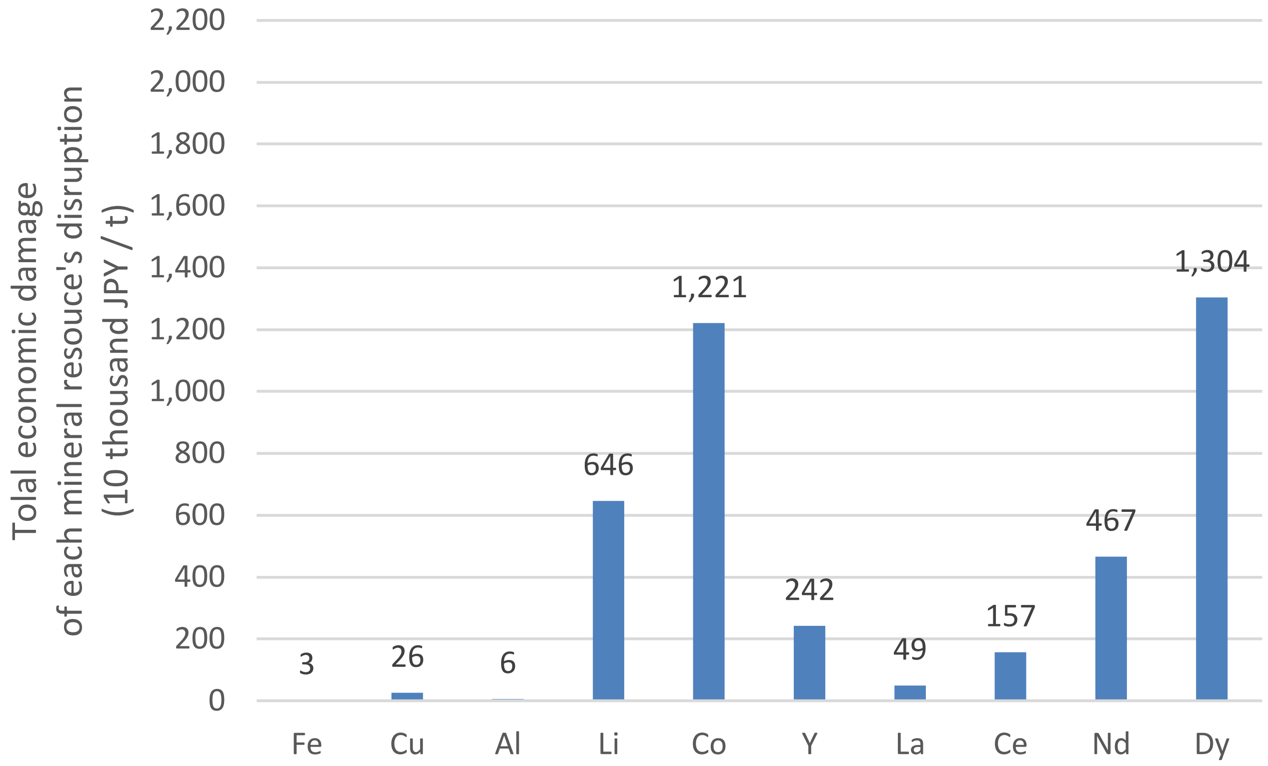

Figure 24 Total economic damage of each mineral resource supply disruption in the case of Japan as of 2015 (per metric ton on an element basis)

The results also show that the import and raw materials manufacturing sectors are the most damaged if some sectors with relatively uncertain direct value-added coefficients are omitted (Table 8). The most economically important sectors have been generally recognized as the end-use sectors, such as automobiles, electric device manufacturers and other related sectors [19], [46], [101]. However, the results indicate that the raw materials and related parts manufacturing and intermediate products sectors are the most damaged in cause-and-effect mechanisms explained by the IO approach. Policymakers are required to change the priority of mineral resources to be considered in the context of mineral resources policy.

Table 8 Top sectors damaged by the supply disruption of each mineral resource

	Top five sectors damaged by the supply disruption of each mineral resource				
	Top (the most damaged sector)	2nd	3rd	4th	5th
Iron (Fe)	Ferro-alloys	Iron ores (imported)	Lithium primary batteries*	Three-band fluorescent lamps*	Pig iron
Copper (Cu)	Copper ores (imported)	Lithium primary batteries*	Three-band fluorescent lamps*	Pig iron	Crude steel (converters)
Aluminum (Al)	Aluminum (imported) (primary)	Lithium primary batteries*	Three-band fluorescent lamps*	Wholesale trade	Road freight transport (except self-transport)
Lithium (Li)	Lithium carbonate and lithium hydroxide (imported)	Lithium primary batteries*	Three-band fluorescent lamps*	Pig iron	Crude steel (converters)
Cobalt (Co)	Nickel matte and mixed sulfide (imported)	Nickel ores (imported)	Lithium primary batteries*	Three-band fluorescent lamps*	Road freight transport (except self-transport)
Yttrium (Y)	Yttrium oxide (imported)	Lithium primary batteries*	Three-band fluorescent lamps*	Pig iron	Crude steel (converters)
Lanthanum (La)	Lanthanum oxide (imported)	Lithium primary batteries*	Three-band fluorescent lamps*	Mischmetal (imported)	Road freight transport (except self-transport)
Cerium (Ce)	Ferrocerium (imported)	Cerium oxide (imported)	Lithium primary batteries*	Three-band fluorescent lamps*	Crude steel (converters)
Neodymium (Nd)	Neodymium oxide (imported)	Dydimium (imported)	Lithium primary batteries*	Three-band fluorescent lamps*	Road freight transport (except self-transport)
Dysprosium (Dy)	Ferro-alloys	Iron ores (imported)	Lithium primary batteries*	Three-band fluorescent lamps*	Crude steel (converters)

Note: (*) represents a sector that may have relatively uncertain direct value-added coefficients due to data shortage.

Each mineral resource's total input (supply disruption) shows a similar trend to the total economic damage of each mineral resource (Figure 25). The total input of each mineral resource represents a monetary value calculated from the critical minerals' supply disruption volume for one element-equivalent ton of each element.

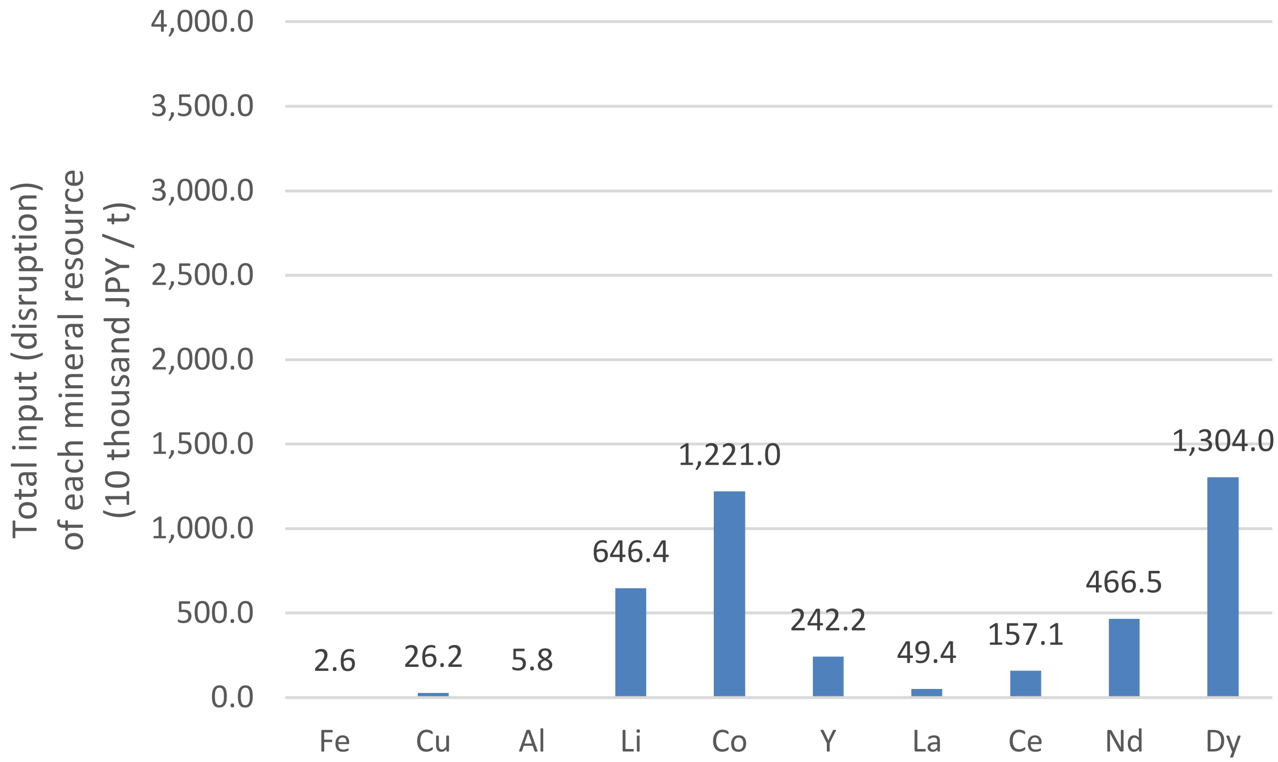

Figure 25 Total input (supply disruption) of each mineral resource

A ratio of the total input (supply disruption) to the total economic damage (amplification effect per unit) is shown in Figure 26. The result indicates that some mineral resources (e.g., iron, lithium, yttrium and cerium) generate more significant amplification effects by the supply disruption per unit. Mineral resources with a high value of this indicator indicate to have a broad and high-value-added sector in their supply chain.

A comparison between the amplification effect and total economic damage per unit is shown in Figure 27. Dysprosium, cobalt and lithium are vulnerable to a national economy if they are evaluated in a small amount per unit. Cerium, iron and yttrium are also vulnerable if they are in a large amount because of their amplification effect. This result suggests that policymakers need to consider the criticality of mineral resources per mass unit and their amplification effects. In other words, the criticality of mineral resources is possibly changed according to the mass volume of mineral resources considered. The amplification effect is expected to decrease relative to higher mineral resource prices per unit weight. This numerical value can be a useful indicator for understanding how supply disruptions of mineral resources affect the national economy per unit value.

In this study, the economic damage of mineral resources' supply disruption is the amount of induced value added per unit weight. The amplification effect is the increased ratio of induced value added per unit value (total input as the supply disruption of mineral resources). The vulnerability evaluation on mineral resources often assesses their economic or strategic importance or substitutability. Many critical minerals are of strategic or functional importance, even in small quantities. A per-unit-weight risk assessment is required to manage the risks of countries, regions, and companies and capture new growth opportunities. Policymakers need to consider a per-unit-weight (or per-unit-value) vulnerability evaluation for critical minerals with a relatively small market.

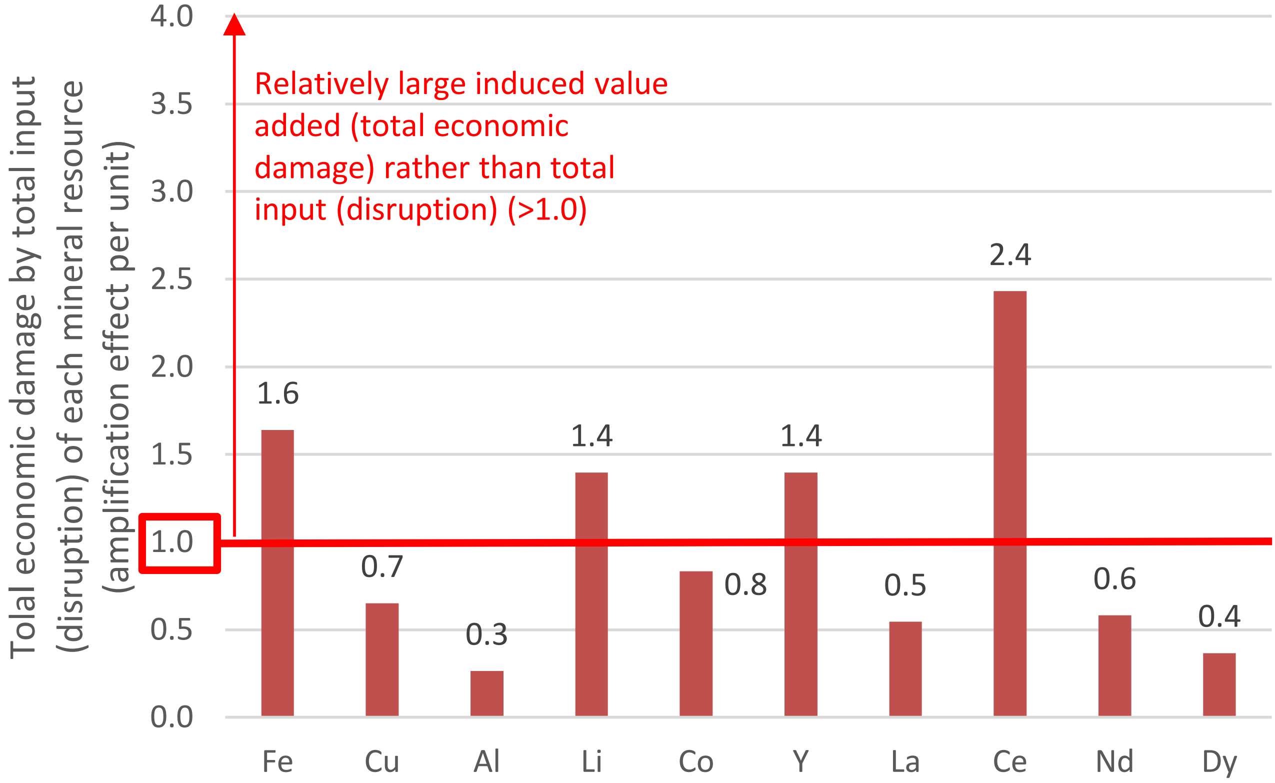

Figure 26 Each mineral resource's amplification effect per unit (total economic damage divided by the total input (supply disruption))

Note: This indicator equals one if the total economic damage is the same as each mineral resource's total input (supply disruption volume in a monetary unit).

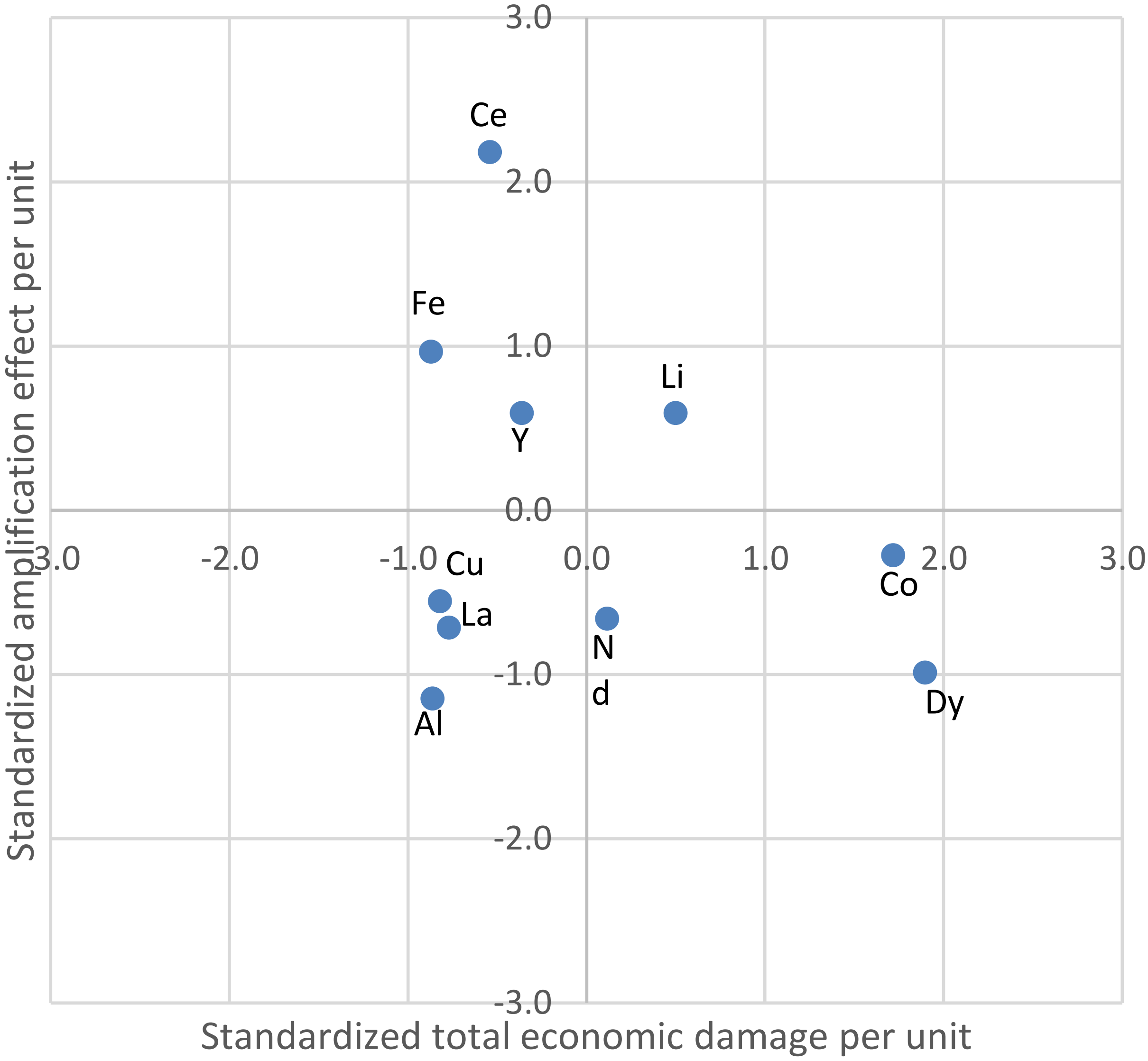

Figure 27 Comparison between amplification effect and total economic damage per unit

For a national economy, the total economic damages can be calculated with the total economic damage per unit weight multiplied by the national consumption volume (weight) of mineral resources (Figure 28). Iron prominently has large economic damage from its supply disruption. However, considering the actual case, sudden and all supply disruption seldom occurs in diversified supply chains, such as for base metals. Policymakers are required to estimate a possible disruption volume (weight) to evaluate the economic damages of critical minerals. Business operators also have a similar case for considering the effects of supply disruptions of mineral resources. The scale of economic damage envisaged will vary with the scale of supply disruption that could actually occur (in terms of volume or value). For this reason, scale-conscious assessments are essential to determine economic damages or importance in line with the actual situation of mineral resources' supply disruption. According to the market scale of mineral resources, assessing the scale of supply disruptions and the possibilities for their occurrence is required for an improved supply risk and vulnerability evaluation per unit weight (or unit value).

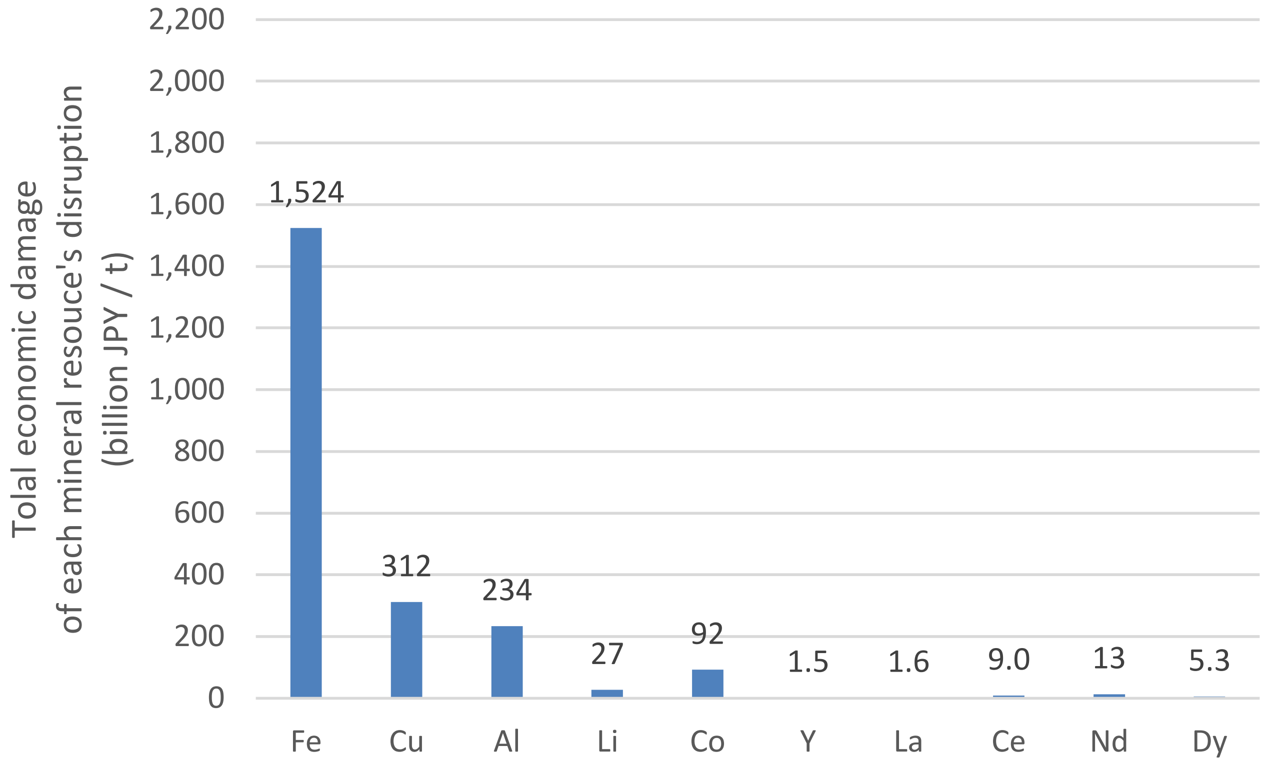

Figure 28 Total economic damage of each mineral resource's supply disruption in the case of Japan as of 2015 (country level)

4.3.2. Comparison between the IO approach and the EU approach

The EU's vulnerability (economic importance) evaluation approach is a major methodology for quantitative determination [33]. In comparing the results of the IO approach (this study) with the EU's approach (evaluation of economic importance), this study aims to discuss the improvements of the EU's approach, which is a major existing evaluation methodology, and the characteristics of the IO approach developed in this study.

The EU's approach is based on the European Commission (2017) [46] (see Figure 5). According to the standard industry classification, the economic importance evaluation requires identifying the end-use of mineral resources and the sectors in which they are used. This study adopts the standard industrial classification used in the National Accounts of Japan by the Japanese Cabinet Office [161] as the closest to the European standard industrial classification (2-digit level classification of NACE Rev.2). The European Commission (2017) methodology also requires the substitution index in evaluation for each end-use of mineral resources. This study follows the European Commission (2017) [46]. The evaluations use data from 2015 in order to compare the results with those of the IO approach. The data used are shown in Table 9 to Table 18. In these tables, "substitute cost performance" is evaluated with the European Commission (2017) [46] criterion (Figure 29);

Table 9 Calculated economic importance of iron (Fe)

End-use applications [122]	Identified sector in the National Accounts [161]	Demand share		GDP at current prices (B) [161]	A*B	Substitution index		
		Amount (kt) [122]	% (A)			SCP	Sub-share	SI
Products for construction	Fabricated metal products	11,095	18.9%	5056	957	0.9	1.00	0.17
General machinery	General-purpose, production and business oriented machinery	2,817	4.8%	15,814	760	0.9	1.00	0.04
Electrical machinery	Electrical machinery, equipment and supplies	1,502	2.6%	6,630	170	0.9	1.00	0.02
Household machinery	Electrical machinery, equipment and supplies	424	0.7%	6,630	48	0.9	1.00	0.01
Steel ships	Transport equipment	4,018	6.9%	15,554	1,066	0.9	1.00	0.06
Automobiles	Transport equipment	12,709	21.7%	15,554	3,372	0.9	1.00	0.20
Trains	Transport equipment	29	0.0%	15,554	8	0.9	1.00	0.00
Other transport equipment	Transport equipment	30	0.1%	15,554	8	0.9	1.00	0.00
Packages	Fabricated metal products	955	1.6%	5,056	82	0.9	1.00	0.01
Others	Others	1,084	1.8%	8,700	161	0.9	0.75	0.01
Products for the following processes	Basic metal	5,352	9.1%	9,804	895	0.9	1.00	0.08
Products for reprocessing	Basic metal	164	0.3%	9,804	27	0.9	0.75	0.00
Products for sales	Others	14,061	24.0%	8,700	2,087	0.9	0.75	0.16
Casting for automobiles	Transport equipment	2,122	3.6%	15,554	563	0.9	1.00	0.03
Casting for electrical machinery	Electrical machinery, equipment and supplies	243	0.4%	6,630	28	0.9	1.00	0.00
Casting for general machinery	General-purpose, production and business oriented machinery	356	0.6%	15,814	96	0.9	1.00	0.01
Casting for construction	Fabricated metal products	1,403	2.4%	5,056	121	0.9	1.00	0.02
Casting for others	Others	258	0.4%	8,700	38	0.9	0.75	0.00
				AQ=A*B=	10,487		Sum (C) =	0.84
							EI=A*B*C=	8,812

Note: SCP: Substitute cost performance (based on the European Commission (2017) [46]); SI: Substitution index; AQ: Share of end-use of a mineral resource in a sector by the sector's value-added; EI: Economic importance index. The calculated AQ excludes duplicated sectors.

Table 10 Calculated economic importance of copper (Cu)

End-use applications [122]	Identified sector in the National Accounts [161]	Demand share		GDP at current prices (B) [161]	A*B	Substitution index		
		Amount (kt) [122]	% (A)			SCP	Sub-share	Amount (kt) [122]
Products for telecommunications (wire)	Information and communication electronics equipment	12	1.0%	3,675	37	0.8	1.00	0.01
Products for electricity (wire)	Electricity supply	59	5.0%	7,038	349	0.8	1.00	0.04
Electrical machinery (wire)	Electrical machinery, equipment and supplies	152	12.8%	6,630	847	0.8	1.00	0.10
Automobiles (wire)	Transport equipment	70	5.9%	15,554	915	0.8	1.00	0.05
Products for construction (wire)	Fabricated metal products	339	28.5%	5,056	1,440	0.8	1.00	0.23
Others (wire)	Others	49	4.1%	8,700	358	0.8	0.75	0.02
Fabricated metal products (alloys)	Fabricated metal products	73	6.1%	5,056	310	0.8	1.00	0.05
Electronic components and devices (alloys)	Electronic components and devices	175	14.7%	5,405	795	0.8	1.00	0.12
Transport equipment (alloys)	Transport equipment	53	4.5%	15,554	693	0.8	1.00	0.04
General machinery (alloys)	General-purpose, production and business oriented machinery	79	6.6%	15,814	1,050	0.8	1.00	0.05
Products for construction (alloys)	Fabricated metal products	6	0.5%	5,056	25	0.8	1.00	0.00
Others (alloys)	Others	123	10.3%	8,700	899	0.8	0.75	0.06
				AQ=A*B=	7,719		Sum (C) =	0.77
							EI=A*B*C=	5,952

Note: SCP: Substitute cost performance (based on the European Commission (2017) [46]); SI: Substitution index; AQ: Share of end-use of a mineral resource in a sector by the sector's value-added; EI: Economic importance index. The calculated AQ excludes duplicated sectors.

Table 11 Calculated economic importance of aluminum (Al)

End-use applications [122]	Identified sector in the National Accounts [161]	Demand share		GDP at current prices (B) [161]	A*B	Substitution index		
		Amount (kt) [122]	% (A)			SCP	Sub-share	Amount (kt) [122]
Packages for foods	Food products and beverages	450	11.1%	13,196	1,470	0.8	1.00	0.09
Fabricated metal products	Fabricated metal products	480	11.9%	5,056	601	0.8	1.00	0.10
General machinery (alloys)	General-purpose, production and business oriented machinery	95	2.4%	15,814	372	0.8	1.00	0.02
Civil engineering machinery	Fabricated metal products	497	12.3%	5,056	622	0.8	1.00	0.10
Products for electricity	Electricity supply	21	0.5%	7,038	37	0.9	1.00	0.00
Products for telecommunications	Information and communication electronics equipment	119	2.9%	3,675	108	0.9	1.00	0.03
Automobiles	Transport equipment	1,633	40.4%	15,554	6,290	0.8	1.00	0.32
Products for chemical industry	Chemicals	5	0.1%	11,249	15	0.8	1.00	0.00
Others	Others	504	12.5%	8,700	1,086	0.8	0.75	0.07
Flocculant and other chemical compounds	Chemicals	173	4.3%	11,249	482	1.0	1.00	0.04
Fine ceramics	Non-metallic mineral products	31	0.8%	3,072	23	1.0	1.00	0.01
Polishing powders and refractory	Non-metallic mineral products	31	0.8%	3,072	23	1.0	1.00	0.01
				AQ=A*B=	11,129		Sum (C) =	0.79
							EI=A*B*C=	8,793

Note: SCP: Substitute cost performance (based on the European Commission (2017) [46]); SI: Substitution index; AQ: Share of end-use of a mineral resource in a sector by the sector's value-added; EI: Economic importance index. The calculated AQ excludes duplicated sectors.

Table 12 Calculated economic importance of lithium (Li)

End-use applications [122]	Identified sector in the National Accounts [161]	Demand share		GDP at current prices (B) [161]	A*B	Substitution index		
		Amount (kt) [122]	% (A)			SCP	Sub-share	Amount (kt) [122]
Cathodes for Lithium-ion rechargeable batteries (lithium carbonate)	Electrical machinery, equipment and supplies	1,551	37.1%	6,630	2,457	1.0	1.00	0.37
Electrolytes for Lithium-ion rechargeable batteries	Electrical machinery, equipment and supplies	56	1.3%	6,630	89	0.9	1.00	0.01
Pottery	Non-metallic mineral products	423	10.1%	3,072	310	1.0	1.00	0.10
Medical products	Chemicals	320	7.6%	11,249	859	1.0	1.00	0.08
Cathodes for Lithium-ion rechargeable batteries (lithium hydroxide)	Electrical machinery, equipment and supplies	1,279	30.6%	6,630	2,026	0.9	1.00	0.28
Greace	Petroleum and coal products	99	2.4%	5,260	124	1.0	1.00	0.02
Others (lithium hydroxide)	Others	107	2.6%	8,700	222	1.0	0.75	0.02
Absorbent for absorption chiller	Electrical machinery, equipment and supplies	160	3.8%	6,630	253	1.0	1.00	0.04
Dehumidifying materials	Electrical machinery, equipment and supplies	33	0.8%	6,630	52	1.0	1.00	0.01
Battery electrodes	Electrical machinery, equipment and supplies	110	2.6%	6,630	174	1.0	1.00	0.03
Absorbent for CO_2	Chemicals	10	0.2%	11,249	27	1.0	1.00	0.00
Polymerization catalyst for rubber	Petroleum and coal products	38	0.9%	5,260	48	1.0	1.00	0.01
				AQ=A*B=	6,643		Sum (C) =	0.96
							EI=A*B*C=	6,388

Note: SCP: Substitute cost performance (based on the European Commission (2017) [46]); SI: Substitution index; AQ: Share of end-use of a mineral resource in a sector by the sector's value-added; EI: Economic importance index. The calculated AQ excludes duplicated sectors.

Table 13 Calculated economic importance of cobalt (Co)

End-use applications [122]	Identified sector in the National Accounts [161]	Demand share		GDP at current prices (B) [161]	A*B	Substitution index		
		Amount (kt) [122]	% (A)			SCP	Sub-share	Amount (kt) [122]
Cathodes for Lithium-ion rechargeable batteries (lithium carbonate)	Electrical machinery, equipment and supplies	5,589	74.0%	6,630	4,910	0.8	1.00	0.59
Special steel	Basic metal	936	12.4%	9,804	1,216	0.9	1.00	0.11
Cemented carbide tools	General-purpose, production and business oriented machinery	396	5.2%	15,814	830	0.9	1.00	0.05
Fabricated metal products	Fabricated metal products	11	0.1%	5,056	7	1.0	1.00	0.00
Magnets	Electronic components and devices	79	1.0%	5,405	57	0.8	1.00	0.01
Catalysts	Petroleum and coal products	126	1.7%	5,260	88	1.0	1.00	0.02
Ohters	Others	411	5.4%	8,700	474	1.0	0.75	0.04
				AQ=A*B=	7,580		Sum (C) =	0.82
							EI=A*B*C=	6,205

Note: SCP: Substitute cost performance (based on the European Commission (2017) [46]); SI: Substitution index; AQ: Share of end-use of a mineral resource in a sector by the sector's value-added; EI: Economic importance index. The calculated AQ excludes duplicated sectors.

Table 14 Calculated economic importance of yttrium (Y)

End-use applications [122]	Identified sector in the National Accounts [161]	Demand share		GDP at current prices (B) [161]	A*B	Substitution index		
		Amount (kt) [122]	% (A)			SCP	Sub-share	Amount (kt) [122]
Ternary catalyst	Transport equipment	24	3.9%	15,554	614	1.0	1.00	0.04
Optical lenses	Electronic components and devices	32	5.3%	5,405	284	0.9	1.00	0.05
Fluorescent powders for a liquid crystal panel	Electrical machinery, equipment and supplies	168	27.6%	6,630	1,831	0.9	1.00	0.25
Fluorescent powders for a lamp	Electrical machinery, equipment and supplies	83	13.6%	6,630	905	0.9	1.00	0.12
Others	Others	301	49.5%	8,700	4,309	1.0	0.75	0.37
				AQ=A*B=	7,943		Sum (C) =	0.83
							EI=A*B*C=	6,590

Note: SCP: Substitute cost performance (based on the European Commission (2017) [46]); SI: Substitution index; AQ: Share of end-use of a mineral resource in a sector by the sector's value-added; EI: Economic importance index. The calculated AQ excludes duplicated sectors.

Table 15 Calculated economic importance of lanthanum (La)

End-use applications [122]	Identified sector in the National Accounts [161]	Demand share		GDP at current prices (B) [161]	A*B	Substitution index		
		Amount (kt) [122]	% (A)			SCP	Sub-share	Amount (kt) [122]
Ternary catalyst	Transport equipment	26	0.8%	15,554	128	1.0	1.00	0.01
Optical lenses	Electronic components and devices	171	5.4%	5,405	293	0.9	1.00	0.05
Fluorescent powders for a liquid crystal panel	Electrical machinery, equipment and supplies	52	1.6%	6,630	109	0.9	1.00	0.01
Ceramic capacitors	Electronic components and devices	54	1.7%	5,405	93	0.8	1.00	0.01
DC motors using LaCo ferrite magnet	Electrical machinery, equipment and supplies	895	28.4%	6,630	1,883	0.8	1.00	0.23
Fluorescent powders for a lamp	Electrical machinery, equipment and supplies	29	0.9%	6,630	61	0.9	1.00	0.01
Nickel-metal hydride rechargeable batteries	Electrical machinery, equipment and supplies	1,925	61.1%	6,630	4,049	1.0	1.00	0.61
				AQ=A*B=	6,617		Sum (C) =	0.93
							EI=A*B*C=	6,165

Note: SCP: Substitute cost performance (based on the European Commission (2017) [46]); SI: Substitution index; AQ: Share of end-use of a mineral resource in a sector by the sector's value-added; EI: Economic importance index. The calculated AQ excludes duplicated sectors.

Table 16 Calculated economic importance of cerium (Ce)

End-use applications [122]	Identified sector in the National Accounts [161]	Demand share		GDP at current prices (B) [161]	A*B	Substitution index		
		Amount (kt) [122]	% (A)			SCP	Sub-share	Amount (kt) [122]
Ternary catalyst	Transport equipment	3,174	55.7%	15,554	8,659	1.0	1.00	0.56
Ultraviolet protection glass	Non-metallic mineral products	570	10.0%	3,072	307	0.9	1.00	0.09
Optical glass	Electronic components and devices	0	0.0%	5,405	0	0.9	1.00	0.00
Polishing powders	Non-metallic mineral products	1,172	20.6%	3,072	632	0.7	1.00	0.14
Fluorescent powders for a liquid crystal panel	Electrical machinery, equipment and supplies	14	0.2%	6,630	16	0.9	1.00	0.00
Nickel-metal hydride rechargeable batteries	Electrical machinery, equipment and supplies	771	13.5%	6,630	897	1.0	1.00	0.14
				AQ=A*B=	10,511		Sum (C) =	0.93
							EI=A*B*C=	9,755

Note: SCP: Substitute cost performance (based on the European Commission (2017) [46]); SI: Substitution index; AQ: Share of end-use of a mineral resource in a sector by the sector's value-added; EI: Economic importance index. The calculated AQ excludes duplicated sectors.

Table 17 Calculated economic importance of neodymium (Nd)

End-use applications [122]	Identified sector in the National Accounts [161]	Demand share		GDP at current prices (B) [161]	A*B	Substitution index		
		Amount (kt) [122]	% (A)			SCP	Sub-share	Amount (kt) [122]
Ternary catalyst	Transport equipment	26	0.9%	15,554	143	1.0	1.00	0.01
Ceramic capacitors	Electronic components and devices	108	3.8%	5,405	206	0.8	1.00	0.03
DC motors using NdFeB magnet	Electrical machinery, equipment and supplies	2,693	95.3%	6,630	6,316	1.0	1.00	0.95
				AQ=A*B=	6,666		Sum (C) =	0.99
							EI=A*B*C=	6,615

Note: SCP: Substitute cost performance (based on the European Commission (2017) [46]); SI: Substitution index; AQ: Share of end-use of a mineral resource in a sector by the sector's value-added; EI: Economic importance index. The calculated AQ excludes duplicated sectors.

Table 18 Calculated economic importance of dysprosium (Dy)

End-use applications [122]	Identified sector in the National Accounts [161]	Demand share: Amount (kt) [122]	Demand share: % (A)	GDP at current prices (B) [161]	A*B	Substitution index: SCP	Substitution index: Sub-share	Substitution index: Amount (kt) [122]
Ceramic capacitors	Electronic components and devices	55	13.6%	5,405	734	0.8	1.00	0.11
DC motors using NdFeB magnet	Electrical machinery, equipment and supplies	350	86.4%	6,630	5,730	0.8	1.00	0.69
				AQ=A*B=	6,464		Sum (C) =	0.80
							EI=A*B*C=	5,171

Note: SCP: Substitute cost performance (based on the European Commission (2017) [46]); SI: Substitution index; AQ: Share of end-use of a mineral resource in a sector by the sector's value-added; EI: Economic importance index. The calculated AQ excludes duplicated sectors.

Substitute material technical performance / *Substitute material cost*	*Similar performance*	*Reduced performance*	*Performance in case of no substitute*
Very high costs (more than 2 times)	*0.9*	*1*	*1*
Slightly higher costs (up to 2 times)	*0.8*	*0.9*	*1*
Similar or lower costs	*0.7*	*0.8*	*1*

Figure 29 Criterionn of Substituion Cost Performance (SCP) [46]

The above results (Table 9 to Table 18) are summarised and compared with the result of the IO approach (Table 19), which includes the economic damages of mineral resources' supply disruption evaluated by the IO approach and the economic importance calculated by the methodology of the European Commission (2017) [46]. The results of the IO approach show that the economic damage for iron is the largest and other base metals (e.g., copper and aluminum) follow it. The results of the EU approach show that the economic importance for cerium, iron and aluminum have larger economic importance. These evaluations are not on a per-unit-weight basis but for the country level and are of the same scope. The IO approach includes the repercussion effect on manufacturing industries, such as raw materials and components manufacturing industries. The EU's approach does not consider the effects on such industries but only evaluates the gross value-added of industrial sectors identified as 'end-use (sector).' The EU approach does not consider the scale of supply disruptions in raw materials (mineral resources) supply chains but the end-use sectors' gross value-added. The EU's approach basically considers no scales of mineral resources' supply disruption. It considers the weighted gross value-added of the end-use sectors, which is weighted according to the share of raw materials (mineral resources) consumed in the country or region.

The industrial structure and their market scales vary with countries and regions. The economic damages and importance of mineral resources' supply disruption vary with the industrial structure and market scales. The IO approach includes the impacts of all the industries, such as intermediate product manufacturing industries. The IO approach is adaptable to any country and region, not depending on their industrial structure and market scales.

Table 19 Comparison between the total economic damage (country level) and the economic importance calculated by the EU methodology (country level)

	Domestic consumption as mineral resources [122]	IO approach (441 sectors) (Figure 28)	EU approach (Table 9 - Table 18)	
			AQ	EI
	(element equivalent-t/y)	(billion JPY/y)		
Iron (Fe)	58,622,000	1,524	10,487	8,812
Copper (Cu)	1,190,000	312	7,719	5,952
Aluminum (Al)	4,038,300	234	11,129	8,793
Lithium (Li)	4,186	27	6,643	6,388
Cobalt (Co)	7,548	92	7,580	6,205
Yttrium (Y)	608	1	7,943	6,590
Lanthanum (La)	3,152	2	6,617	6,165
Cerium (Ce)	5,701	9	10,511	9,755
Neodymium (Nd)	2,827	13	6,666	6,615
Dysprosium (Dy)	405	5	6,464	5,171

Note: AQ represents the share of end-use of mineral resources in a mega-sector (A) by the sector's value added (Q). EI represents the calculated economic importance based on the EU methodology [46] (see Figure 5). 1 million Japanese yen was equal to 8,261 USD as an annual average in 2015.

4.3.3. Testing the IO approach using low-resolution IO tables

Based on the previous discussion, the IO approach can provide the evaluation of economic damages on intermediate manufacturing industries, including actual assumed impacts, and supplement the EU's approach. Many countries, however, do not have high-resolution input-output tables like Japan and others. Those countries and regions may not be able to adopt the IO approach to evaluate the inclusive economic damages of mineral resources' supply disruption. This study tests the availability of the IO approach using low-resolution IO tables.

The Ministry of Internal Affairs and Communications (Japan) (MIC) provides a basic IO table (509 by 391 sectors) [114]. In addition to this basic high-resolution table, other IO tables, 390 by 390 sectors, 187 by 187 sectors, 107 by 107 sectors, 37 by 37 sectors and 13 by 13 sectors tables, are prepared by the MIC [114]. This study calculates the same repercussion effect for each table. The supply disruption of mineral resources is input similarly to the uniquely expanded hybrid high-resolution IO table calculation. The economic damage of mineral resources' supply disruption is calculated as the amount of gross value added induced by a one-ton supply disruption in the supply of mineral resources. Similarly, the gross value added induced by one-ton supply disruption (monetary equivalent) is calculated as the economic damages. All the other IO tables, excluding the uniquely expanded IO table, are described in monetary units. The supply disruption scenario is input in monetary terms for analysis.

The economic damages calculated with the other low-resolution IO tables show varied economic damage in absolute value (Table 20, Table 21) but a similar ranking with the result on the uniquely expanded high-resolution IO table (Figure 30).

Low-resolution IO analyses have been generally considered not to contribute to analyzing the expected real impacts in each industry because of unclear data and information on input-output relationships in supply chains. However, this study shows that even the low-resolution IO analysis can explain the priority of mineral resources to be considered in the contest of mineral resources policy.

Table 20 Comparison calculated economic damages (per unit) between the high and low-resolution IO tables

	Economic damages per unit (Added-value calculated by IO (thousand JPY/t))					
	441 sectors	390 sectors	187 sectors	107 sectors	37 sectors	13 sectors
Iron (Fe)	26.0	1.4	2.1	5.5	4.6	3.9
Copper (Cu)	261.9	15.6	15.6	66.6	21.2	27.0
Aluminum (Al)	57.9	34.5	38.1	52.9	76.4	129.1
Lithium (Li)	6,464.3	2,197.6	2,437.8	2,604.5	2,507.3	2,730.7
Cobalt (Co)	12,209.7	2,373.0	2,777.1	3,211.4	3,814.0	6,350.3
Yttrium (Y)	2,421.5	823.2	913.2	975.7	939.3	1,022.9
Lanthanum (La)	494.5	193.1	228.4	219.3	316.4	534.8
Cerium (Ce)	1,571.0	275.1	306.6	327.6	327.5	381.3
Neodymium (Nd)	4,665.2	1,709.2	2,021.9	1,941.1	2,801.4	4,734.5
Dysprosium (Dy)	13,040.4	7,561.9	8,945.0	8,587.8	12,393.6	20,946.2

Note: 1 million Japanese yen was equal to 8,261 USD as an annual average in 2015.

Table 21 Comparison calculated economic damages (total) between the high and low-resolution IO tables

	Total possible economic damages (Added-value calculated by IO (billion JPY/ year))					
	441 sectors	390 sectors	187 sectors	107 sectors	37 sectors	13 sectors
Iron (Fe)	1,524	80.5	123.6	320.2	272.2	226.2
Copper (Cu)	312	18.6	18.6	79.2	25.2	32.2
Aluminum (Al)	234	139.2	153.9	213.7	308.4	521.1
Lithium (Li)	27	9.2	10.2	10.9	10.5	11.4
Cobalt (Co)	92	17.9	21.0	24.2	28.8	47.9
Yttrium (Y)	1.5	0.5	0.6	0.6	0.6	0.6
Lanthanum (La)	1.6	0.6	0.7	0.7	1.0	1.7
Cerium (Ce)	9.0	1.6	1.7	1.9	1.9	2.2
Neodymium (Nd)	13	4.8	5.7	5.5	7.9	13.4
Dysprosium (Dy)	5.3	3.1	3.6	3.5	5.0	8.5

Note 1: Total annual demand as of 2015; iron: 58,622,000 t(element equivalent)/y; copper: 1,190,000 t(element equivalent)/y; aluminum: 4,038,300 t(element equivalent)/y; lithium: 4,186 t(element equivalent)/y; cobalt: 7,548 t(element equivalent)/y; yttrium: 608 t(element equivalent)/y; lanthanum: 3,152 t(element equivalent)/y; cerium: 5,701 t(element equivalent)/y; neodymium: 2,827 t(element equivalent)/y; dysprosium: 405 t(element equivalent)/y. These data are equal to the total amount of demand shown in Chapter 4.3.2 (from Table 9 to Table 18).

Note 2: 1 million Japanese yen was equal to 8,261 USD as an annual average in 2015.

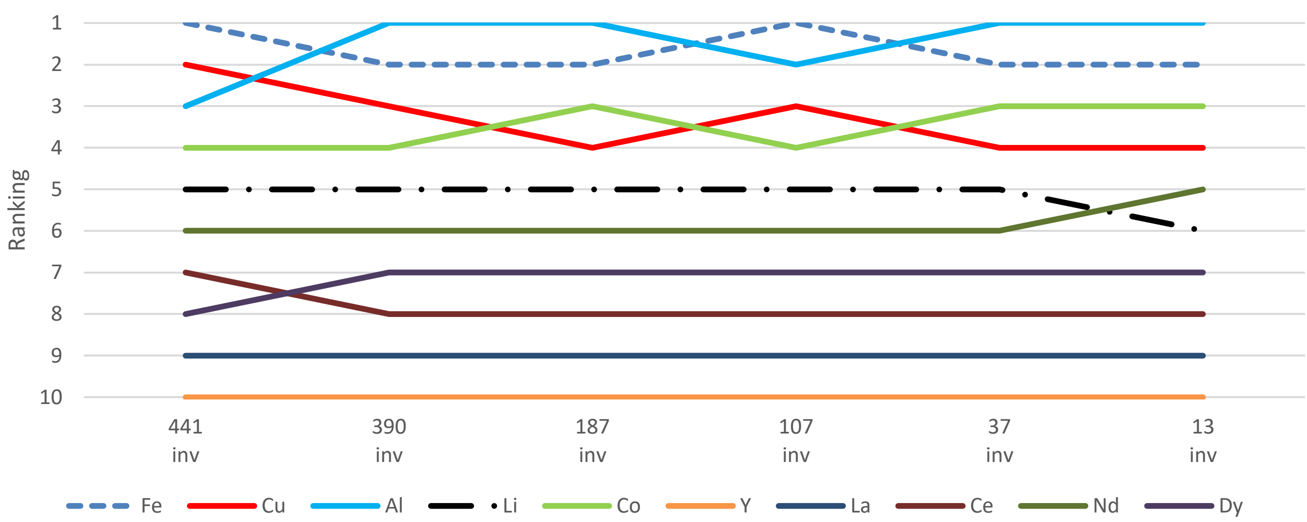

Figure 30 Ranking comparison of total possible economic damages among high-resolution and low-resolution IO approaches

Note: “441 inv” represents ranking results calculated by the inverse matrix (441 by 441 sectors).

In addition to the above, considering Leonchev's inverse matrix is a series expanded sum of the product of the input coefficients matrices as shown in Equation 2 (see Chapter 3.4), direct- and first indirect-induced effects account for the majority of the induced gross value-added (Table 22). The ranking of mineral resources does not change significantly if the economic damage is calculated with the accumulation of direct and a few indirect-induced effects (Figure 31).

Policymakers who do not have a high-resolution IO table may well be able to determine policy priorities for each mineral resource by using the IO approach with low-resolution input-output tables.

Table 22 Comparison calculated economic damages (per unit) between direct-induced and multiplied indirect-induced effects

	Added-value calculated by IO (thousand JPY/ t)				
	Calculated by inverse matrix (Table 20)	Cumulative total from power 0 to each power (accumulated direct and indirect-induced effects)			
		Direct effect (power of 0)	Indirect effects (power of 0-1)	Indirect effects (power of 0-2)	Indirect effects (power of 0-3)
Iron (Fe)	26.0	22.9	23.4	24.3	25.4
Copper (Cu)	261.9	220.0	222.5	234.2	254.2
Aluminum (Al)	57.9	27.0	33.8	42.7	49.6
Lithium (Li)	6,464.3	2,910.6	3,582.9	4,616.5	5,419.0
Cobalt (Co)	12,209.7	8,870.4	9,548.0	10,475.0	11,303.0
Yttrium (Y)	2,421.5	1,090.3	1,342.2	1,729.4	2,030.0
Lanthanum (La)	494.5	242.5	299.1	369.0	422.4
Cerium (Ce)	1,571.0	1,137.4	1,221.7	1,346.4	1,443.0
Neodymium (Nd)	4,665.2	2,434.3	2,935.5	3,554.8	4,027.1
Dysprosium (Dy)	13,040.4	3,170.9	5,388.4	8,127.9	10,217.5

	Added-value calculated by IO (thousand JPY/ t)					
	Cumulative total from power 0 to each power (accumulated direct and indirect-induced effects) (continued)					
	Indirect effects (power of 0-4)	Indirect effects (power of 0-5)	Indirect effects (power of 0-6)	Indirect effects (power of 0-7)	Indirect effects (power of 0-8)	Indirect effects (power of 0-9)
Fe	25.7	25.9	25.9	26.0	26.0	26.0
Cu	258.3	260.0	260.9	261.5	261.7	261.8
Al	54.1	56.0	57.0	57.5	57.7	57.8
Li	5,884.8	6,194.6	6,362.2	6,422.9	6,446.7	6,456.7
Co	11,795.3	12,021.3	12,120.7	12,170.0	12,192.7	12,202.5
Y	2,204.5	2,320.5	2,383.3	2,406.0	2,415.0	2,418.7
La	461.6	479.8	487.6	491.4	493.2	493.9
Ce	1,500.9	1,538.3	1,558.3	1,565.8	1,568.8	1,570.0
Nd	4,374.1	4,535.3	4,604.4	4,638.2	4,653.6	4,660.3
Dy	11,752.5	12,465.9	12,771.7	12,921.3	12,989.5	13,018.7

	Added-value calculated by IO (thousand JPY/ t) (continued)					
	Cumulative total from power 0 to each power (accumulated direct and indirect-induced effects) (continued)					
	Indirect effects (power of 0-10)	Indirect effects (power of 0-11)	Indirect effects (power of 0-12)	Indirect effects (power of 0-13)	Indirect effects (power of 0-14)	Indirect effects (power of 0-15)
Fe	26.0	26.0	26.0	26.0	26.0	26.0
Cu	261.9	261.9	261.9	261.9	261.9	261.9
Al	57.8	57.8	57.8	57.9	57.9	57.9
Li	6,461.0	6,462.8	6,463.6	6,464.0	6,464.1	6,464.2
Co	12,206.6	12,208.4	12,209.1	12,209.5	12,209.6	12,209.7
Y	2,420.3	2,421.0	2,421.3	2,421.4	2,421.5	2,421.5
La	494.2	494.3	494.4	494.4	494.4	494.4
Ce	1,570.6	1,570.8	1,570.9	1,571.0	1,571.0	1,571.0
Nd	4,663.1	4,664.2	4,664.8	4,665.0	4,665.1	4,665.1
Dy	13,031.1	13,036.4	13,038.7	13,039.7	13,040.1	13,040.3

Note 1: "Indirect effect (power of 0-15)" is calculated as $V_d = \sum_{n=0}^{15} V\left((I-M)A\right)^n\left((I-M)Y\right)$. The detailed explanation is described in Chapter 3.4.

Note 2: 1 million Japanese yen was equal to 8,261 USD as an annual average in 2015.

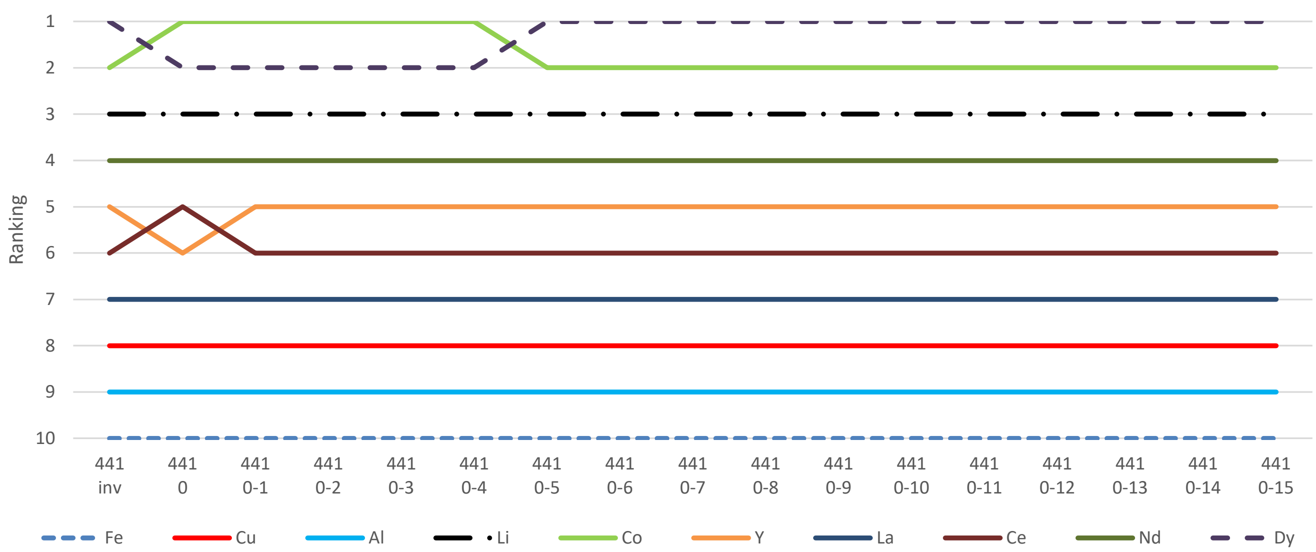

Figure 31 Ranking comparison between direct-induced and multiplied indirect-induced effects

Note: "441 inv" represents ranking results calculated by the inverse matrix (441 by 441 sectors). "441/0-15" represents ranking results in the accumulated induced value-added calculated by the demand changes multiplied by the input coefficients matrix (A) raised to the power from 0 to 15.

4.3.4. Evaluating the economic damages of other critical minerals

In the previous chapter, this study discusses the possibility of the low-resolution IO approach to evaluate the economic damages caused by the disruption of the supply of mineral resources. The ranking of the magnitude of economic damages in the event of supply disruption does not change so much, regardless of the resolution of the IO table. Many countries do not have high-resolution IO tables and may not be able to conduct economic damage assessments using IO approaches similar to those in this study. Therefore, this study tries to evaluate the economic damages of mineral resources supply disruption using a low-resolution IO table for other critical minerals.

In this discussion, the 107 by 107 sector IO table, of which the number of sectors is normal worldwide, is selected for evaluation. As the other critical minerals evaluated, antimony, chromium, fluorite, gallium, germanium, graphite, indium, magnesium, manganese, nickel, niobium, platinum, silicon, tantalum, titanium, tungsten, vanadium and zirconium (eighteen minerals) are selected for evaluation. These minerals are commonly regarded as critical minerals in many countries, as shown in Table 2 (see Chapter 2.4). The supply disruption of these additional critical minerals is set the same as in Table 6, which is one element-equivalent ton of each element as of 2015 in Japan [122]. The calculated results are shown in Table 23.

Table 23 Comparison calculated economic damages (per unit and total) using the 107 sectors IO table

		Total demand amount (t/year)	Added-value calculated by IO			
			Per unit		Total demand	
			Thousand JPY/t	Rank	Billion JPY/year	Rank
	Iron (Fe)	58,622,000	5.5	28	320.2	2
	Copper (Cu)	1,190,000	66.6	24	79.2	6
	Aluminum (Al)	4,038,300	52.9	26	213.7	3
	Lithium (Li)	4,186	2,604.5	9	10.9	14
	Cobalt (Co)	7,548	3,211.4	7	24.2	11
	Yttrium (Y)	608	975.7	14	0.6	28
	Lanthanum (La)	3,152	219.3	18	0.7	27
	Cerium (Ce)	5,701	327.6	16	1.9	25
	Neodymium (Nd)	2,827	1,941.1	11	5.5	17
	Dysprosium (Dy)	405	8,587.8	5	3.5	18
Additionally calculated	Antimony (Sb)	9,362	242.4	17	2.3	24
	Chromium (Cr)	471,200	166.1	21	78.3	7
	Fluorite (F)	190,900	1,939.5	12	370.3	1
	Gallium (Ga)	162	17,358.1	3	2.8	21
	Germanium (Ge)	13	93,859.2	2	1.2	26
	Graphite (Gr)	52,000	58.8	25	3.1	19
	Indium (In)	226	11,622.7	4	2.6	22
	Magnesium (Mg)	37,925	74.5	23	2.8	20
	Manganese (Mn)	844,200	42.9	27	36.2	9
	Nichel (Ni)	289,800	552.7	15	160.2	4
	Niobium (Nb)	5,239	2,647.8	8	13.9	13
	Platinum (Pt)	50	974,592.9	1	49.1	8
	Silicon (Si)	684,037	186.0	20	127.3	5
	Tantalum (Ta)	491	5,242.2	6	2.6	23
	Titanium (Ti)	221,800	121.3	22	26.9	10
	Tungsten (W)	7,444	2,565.2	10	19.1	12
	Vanadium (V)	4,160	1,434.2	13	6.0	16
	Zirconium (Zr)	29,795	203.4	19	6.1	15

Note: 1 million Japanese yen was equal to 8,261 USD as an annual average in 2015.

MURC (2020) discusses the improved methodology for supply risks and economic importance, referring to the EU methodology [157]. This research pioneers a quantitative evaluation of many mineral resources for the Japanese economy. It develops a new comprehensive indicator of supply risks, which is calculated with some basic data, such as the grade down of crude ores, production concentration (country and plant levels), deposit concentration (country and site levels), import concentration (country level), historical price volatility, the percentage change in the number of years of minable years, the percentage of foreign mine offtake volume in domestic demand, domestic recycling ratio and Herfindahl-Hirschman Index (HHI) of import share multiplied by World Bank's Worldwide Governance Indicator (WGI) [157]. This data selection refers to Dewulf et al. (2016) [82]. The economic importance is evaluated in the study referring to the EU methodology [46]. The evaluation concept of economic importance in the study [157] is similar to "AQ," as shown in Table 19 (detailed in Figure 5. See Chapter 2.4). Standardized results of MURC (2020) and this study's total possible economic damages are shown in Table 24.

Table 24 Standardized supply risks and economic importance of MURC (2020) [157] and the total possible economic damages of this study

	MURC (2020) [157]		This study
	Supply risk	Economic importance	Total possible economic damages (Table 23)
Lithium (Li)	0.46	0.74	0.03
Graphite (Gr)	0.29	0.42	0.01
Fluorite (F)	0.60	0.86	1.00
Magnesium (Mg)	0.92	0.72	0.01
Aluminum (Al)	0.60	1.00	0.58
Titanium (Ti)	0.47	0.94	0.07
Vanadium (V)	0.64	0.82	0.01
Chromium (Cr)	0.70	0.75	0.21
Manganese (Mn)	0.33	0.56	0.10
Iron (Fe)	0.36	0.68	0.86
Cobalt (Co)	0.54	0.43	0.06
Nichal (Ni)	0.51	0.41	0.43
Copper (Cu)	0.15	0.80	0.21
Gallium (Ga)	0.85	0.31	0.01
Germanium (Ge)	0.68	0.78	0.00
Yttrium (Y)	1.00	0.00	0.00
Zirconium (Zr)	0.51	0.79	0.01
Niobium (Nb)	0.92	0.73	0.04
Indium (In)	0.55	0.30	0.01
Antimony (Sb)	0.70	0.75	0.00
Lanthanum (La)	0.71	0.48	0.00
Cerium (Ce)	0.71	0.48	0.00
Neodymium (Nd)	0.71	0.48	0.01
Dysprosium (Dy)	0.71	0.48	0.01
Tantalum (Ta)	0.45	0.40	0.01
Tungsten (W)	0.80	0.78	0.05
Platinum (Pt)	0.91	0.75	0.13

Note: Maximum datum is equal to 1.00, minimum datum is equal to 0.00.

The criticality assessment based on MURC (2020) [157] is shown in Figure 32 for the selected 28 mineral resources. The result exchanging the economic importance with total possible economic damages is shown in Figure 33. The results of the criticality assessment, displayed in two dimensions, are variable for many mineral resources. In particular, in the MURC (2020), the majority of mineral resources considered to be of high criticality have moved to the left. When the horizontal axis is replaced by the results of the economic damage evaluated in this study, mineral resources with high unit costs and high demand volume are generally located on the right side (Figure 33).

Conventional vulnerability evaluations have made little distinction between strategic importance and actual economic damage assumed (detailed in Chapter 2.4). The inclusion of actual economic damage assumed in this study has enabled the identification of mineral resources that would cause greater economic damage in actual supply disruption. The results of such an assessment are useful for selecting stockpiled mineral resources for short-term supply disruptions and for determining their stockpile volumes.

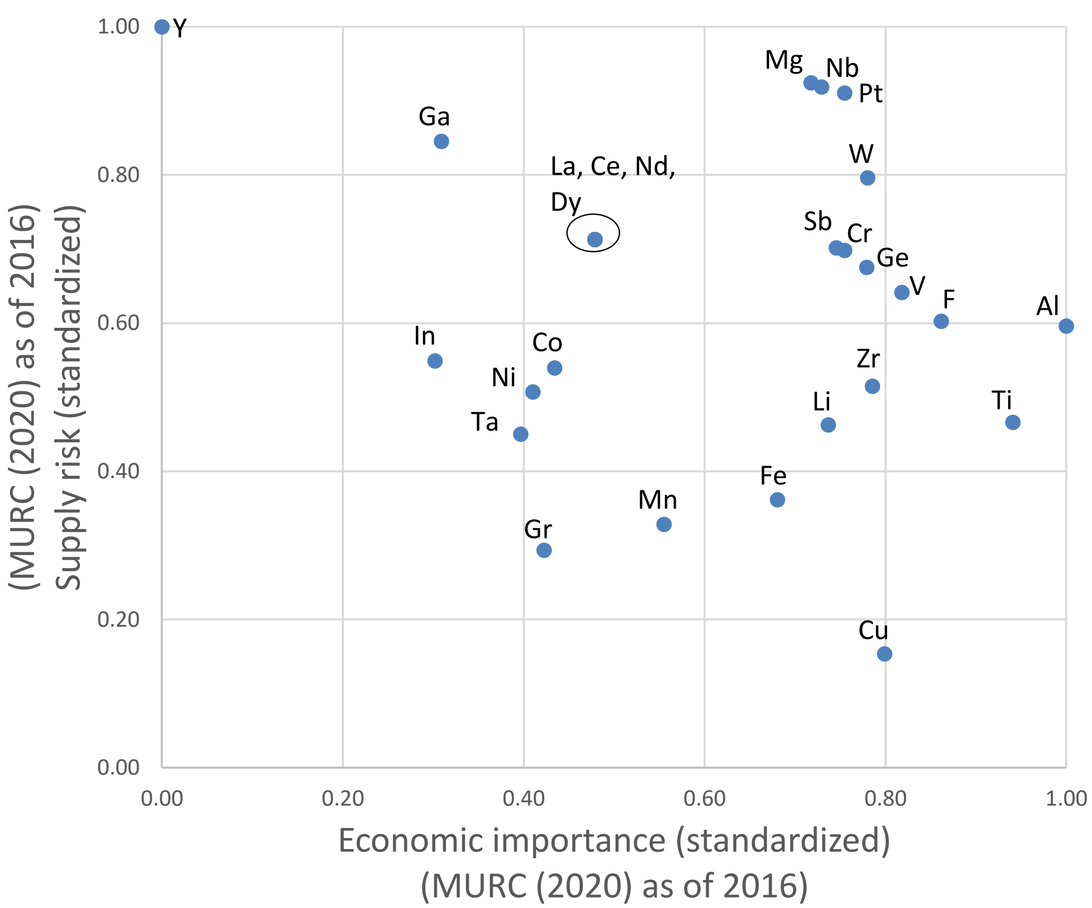

Figure 32 Result of the criticality assessment (Japan as of 2016) [157]

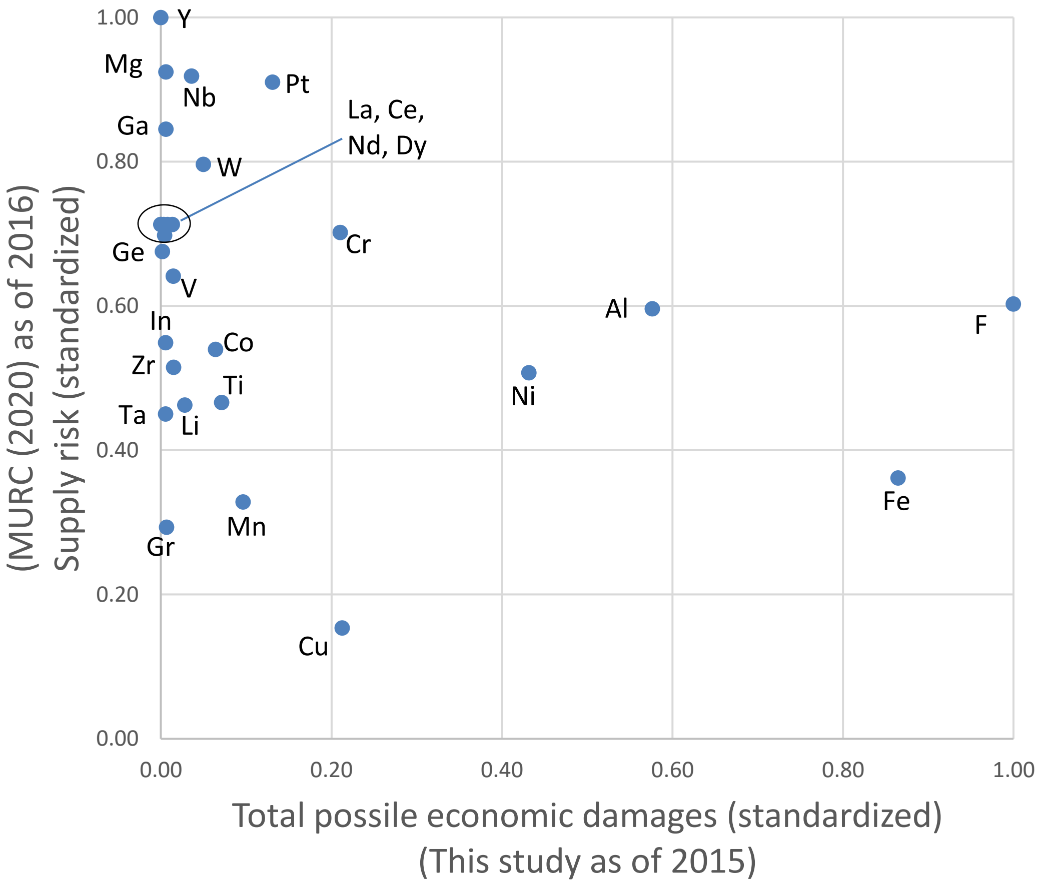

Figure 33 Result of the criticality assessment（Japan as of 2016 for supply risk, as of 2015 [157] for total possible economic damages calculated in this study）

The calculated economic damages represent the total full supply disruption to the national economy. Considering the actual supply disruption situation, such total full disruption barely occurred in the past and will barely occur in the future. With a quantitative estimation of the possibility and volume of supply disruption, policymakers can evaluate the possible economic damages caused by the real supply disruption. Regarding the temporary practical supply disruption of some mineral resources, the actual assumed economic damages can be calculated as shown in Figure 34. This figure assumes 50% supply disruption for fluorite, 10% for aluminum, 100% for cobalt, 10% for iron and 10% for copper. The results show that some highly critical mineral resources, such as iron, aluminum, and copper, shift to lower criticality positions.

Vulnerability evaluation by the IO approach provides policymakers with quantitative and objective decision-making tools, especially in the field of short-term supply disruption, such as mineral resources policy on stockpiling. The developed evaluation method based on the IO approach is broadly adoptable for evaluating the actual possible economic damages, such as political embargo of rare earth and export restriction of nickel by Resource Nationalisms [143], [146], [164], [165], as a stress test for mineral resources' supply disruption.

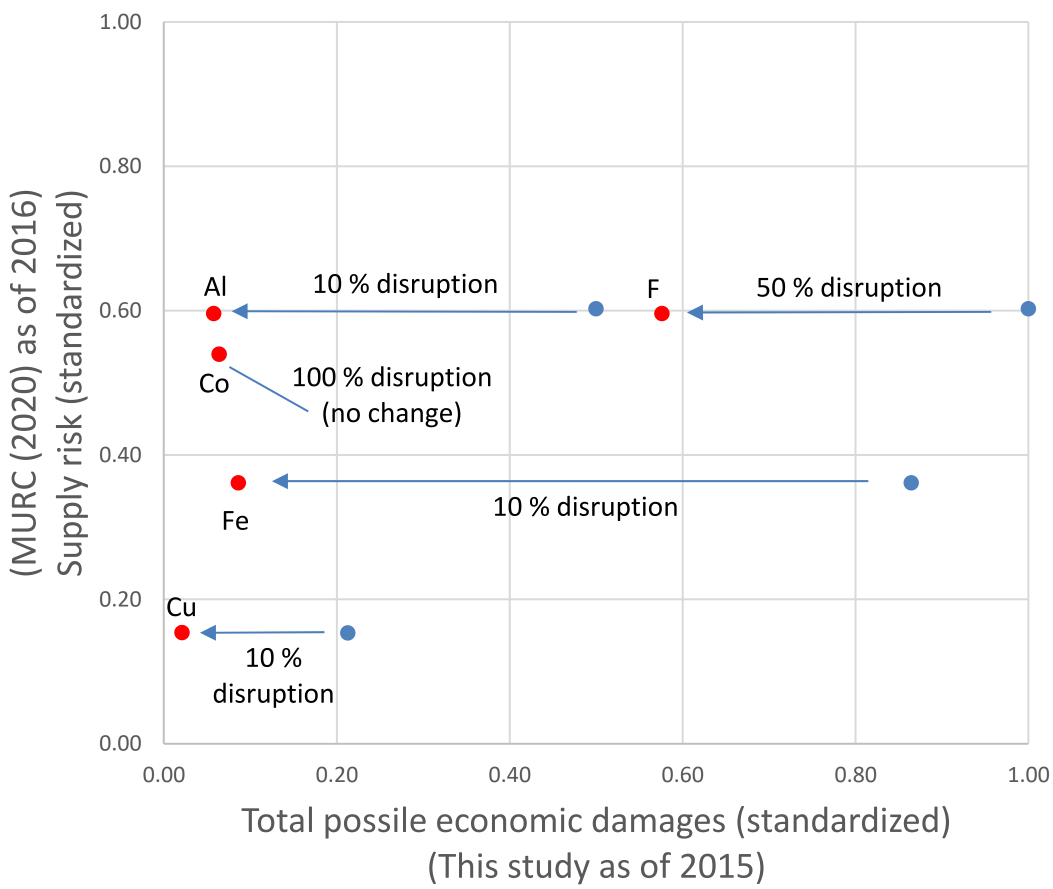

Figure 34 Comparison of economic damages between total-full and partial supply disruption (fluorite, aluminum, cobalt, iron and copper as examples) (Japan as of 2016 for supply risk, as of 2015 [157] for total possible economic damages calculated in this study)

4.4. Conclusion

In summary, this study evaluates the economic damages of the supply disruption of mineral resources with the uniquely expanded high-resolution IO table. Ten elements equivalent to mineral resources, iron, copper, aluminum, lithium, cobalt, yttrium, lanthanum, cerium, neodymium and dysprosium, are selected for analysis. The results show that the IO approach provides a sold methodology to determine the policy priorities in the context of economic damages derived from the disruption of the supply of mineral resources. The results indicate that the raw materials and related parts manufacturing and intermediate products sectors are the most damaged in cause-and-effect mechanisms explained by the IO approach. In addition, the IO approach indicates that scale-conscious assessments are essential to determine economic damages or importance in line with the actual situation of mineral resources' supply disruption. Policymakers need to consider the scale of supply disruptions and the possibilities for their occurrence. This study shows that even the low-resolution IO analysis can analyze the priority of mineral resources to be considered in the contest of mineral resources policy.

Furthermore, a per-unit-weight risk assessment is required to manage the risks of countries, regions, and companies and capture new growth opportunities. Policymakers need to consider a per-unit-weight (or per-unit-value) vulnerability evaluation for critical minerals with a relatively small market. This study suggests that vulnerability evaluation with the IO approach provides significant decision-making tools for policymakers in short-term issues, such as stockpiling, regardless of low or high-resolution IO table. The developed evaluation method is broadly adoptable as a quantitative stress test for evaluating the possible economic damages of mineral resources' supply disruption, such as political export controls and natural disasters.

The IO tables are available every few years, five years in the case of Japan [114]. Dynamic approaches are required in the future to supplement the lack of years during the revision of IO tables. Nakamura and Kondo (2018) examine a dynamic IO approach in modeling [166]. Such dynamic approaches contribute to supplementing missing years. Considering the future industrial structure, the latest IO table does not necessarily reflect the growing demand and related input-output relation between sectors. Scenario analysis is also required to evaluate the strategic importance of mineral resources if adopting the IO approach.

5 Estimating the final destination of critical minerals for their circular flows

5.1. Introduction

Following the practical concept of the circular economy [69], policymakers and researchers extensively covered this approach. Several review papers affirm that recycling is a fundamental component of circular economy strategies [70], [71], [72]. Many countries emphasize the value of recycling in their mineral resources policy documents to generate secondary materials [28], [37], [38], [39], [40], [41], [42]. The major countries consider circular economy implementation in their policy documents (see Table 1 in Chapter 2.3). Circular economy strategies generally include reducing, reusing, repairing, refurbishing, remanufacturing, repurposing, recycling, recovering, and more. Recycling is a circular economy strategy that derives value recovery [73]. Although recycling may not always be prioritized at the top of the hierarchy of circular economy strategies [72], [167], it remains a significant approach alongside others like remanufacturing, refurbishing, repairing, and reusing. In circular economy strategies, the extensive examination of recycling for critical materials is highlighted in a review of 88 studies [99]. In addition, the transportation of post-consumer products and their parts also needs to be highlighted from decarbonization [168].

From a short-term viewpoint, reusing may be prioritized over recycling, as increased emphasis on reusing can potentially reduce recycling. However, all products eventually reach a point where reusing is no longer viable or desirable, making recycling, sometimes including disposal as a bleed-off, a necessary backup system for reusing [169].

End-of-life products using numerous materials have been reevaluated as the deposits of secondary materials, commonly referred to as "urban mining" [170], [171], [172]. The United Nations Environment Programme (UNEP) highlights recycling rates for various metals in post-consumer products and underscores the importance of recycling [44], [173], [174].

Despite many legal systems to promote the collection and recycling of post-consumer products, governments have not necessarily accelerated the recycling of critical minerals. For example, Japan has endorsed the "3Rs (reducing waste generation, reusing, and recycling)" concept in its legal system to facilitate efficient mineral resource use and waste management [175], [176], [177], [178], [179]. Related legal systems have barely improved critical minerals' recovery [125], [180], [181]. Some base metals and precious metals experience high recovery rates alone. A similar status also occurs in the EU [55]. Achieving a recycling business hinges on collecting post-consumer products extensively, particularly those rich in base metals and high-grade valuable metals. Legal systems play a crucial role in supporting widespread collection efforts and advancing recycling technologies, including comminution, separation and sorting.

The EU assesses mineral resources that end up in landfills but falls short of identifying prioritized post-consumer products and their components for collection and recycling [52]. The existing mineral resources policies lack consideration for quantitative evaluation of a secondary materials supply and the prioritization of end-of-life products and their components for collection and recycling. Policymakers need an overarching policy approach to facilitate transitioning from a linear to a circular economy and addressing national security.

This study quantitatively estimates the final destination of the mineral resources selected. The estimated results are evaluated as an annually accumulated volume of mineral resources for future secondary supply. The methodology adopted is described precisely in Shimizu and Owada (2024) [117]. The analysis aims to highlight prioritized end-of-life products to be collected and recycled. The methodology of this study is rooted in the IO approach, utilizing a uniquely expanded IO table and the latest high-resolution IO table for estimation. The application and discussion center on Japan's case for the year 2015.

Notably, existing models using IO approaches focus solely on primary base metals (aluminum, copper, iron, lead, and zinc) and trace materials for electronic devices and special steels (chromium, cobalt, manganese, molybdenum, neodymium, nickel, niobium, platinum, tungsten and vanadium) [148], [149], [150], [152], [153], [182], [183], [184], [185], [186], [187], [188], [189], [190]. Battery materials and various rare earth elements have never been subject to analysis in an IO approach until now. Only dysprosium is examined by the bottom-up approach before [191], [192]. The results support estimating the circular flow of critical minerals. Through the IO approach, this study pioneers the revelation of the element composition, encompassing battery materials and various rare earth elements.

5.2. Materials and methods

As in Chapter 3.5, this estimation focuses on the following ten elements.

1) Lithium and cobalt
2) Yttrium, lanthanum, cerium, neodymium, dysprosium (rare earth elements)
3) Iron, copper, and aluminum

The determination of the ultimate destination of these selected mineral resources adheres to the model outlined in Equation (5), (6), (7), and Figure 23. The uniquely expanded hybrid IO table, comprising 443 by 443 sectors, is employed for estimation.

Shimizu and Owada (2024) test the reliability of the estimated element composition for each product (C_{MP}) and indicate that the estimation strongly correlates with the actual data for some selected elements [117]. The actual data on the content ratio of elements are referred to as reliable existing data [119], [120], [128], [193], [194], [195]. This finding underscores that the actual data provides comprehensive support for the estimated element composition, notwithstanding the detailed differences discussed earlier.

5.3. Results and discussion

5.3.1. Final destination of mineral resources as social stocks

As discussed in Shimizu and Owada (2024), the selected minerals' final destination surpasses the input for copper, aluminum, cobalt, yttrium, lanthanum, neodymium, and dysprosium (Figure 35). Particularly noteworthy is that the final domestic demand exceeds the input for neodymium and dysprosium. The results suggest significant potential for a secondary supply of these rare earth elements from end-of-life products and their components in Japan. The ratio of domestic final demand to the input indicates the supply potential of secondary materials. If this ratio is at a low level, a primary supply source is even now necessary for growing demand.

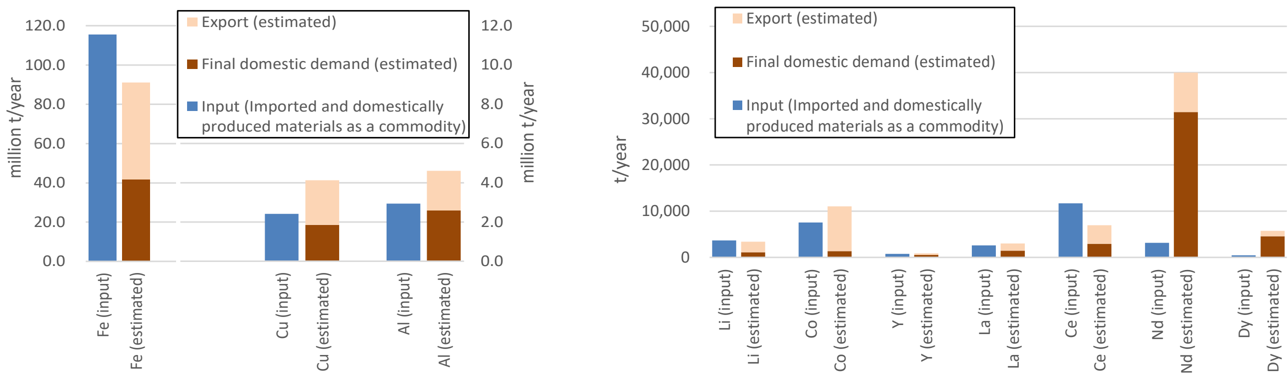

Figure 35. Input and estimated final domestic demand and export in this study (left: base metals. right: selected critical minerals) [117]

Note: "Input" includes imported and domestically produced materials as a commodity for the analysis.

Estimated final destinations for iron indicate that domestic final demand is significant for passenger motor cars and some construction sectors (Figure 36). This result indicates that the social stock of iron will increase in the future. The scrap iron from these sectors (e.g., end-of-life vehicles and construction wastes) can be recovered under a quality-controlled situation if further advanced recycling technologies are used to control impurity elements in scrap iron. Daigo et al. (2017) point out that recycling iron scraps can lead to increased tramp elements in electric furnace steel [196]. Understanding the principles and new optimization criteria is required to research and develop advanced recycling technologies based on understanding thermodynamics [197]. For the quality control of recycled steel products, advanced dismantling, comminution, separation and sorting processes are required at automobile recycling and construction demolition sites to ensure fewer tramp elements in recycled steel. Hot-rolled steel, an intermediate product, is the largest in final demand. Almost all of the hot-rolled steel is exported abroad. An international circular flow of iron can be achieved if it can be imported from abroad and returned as steel scrap.

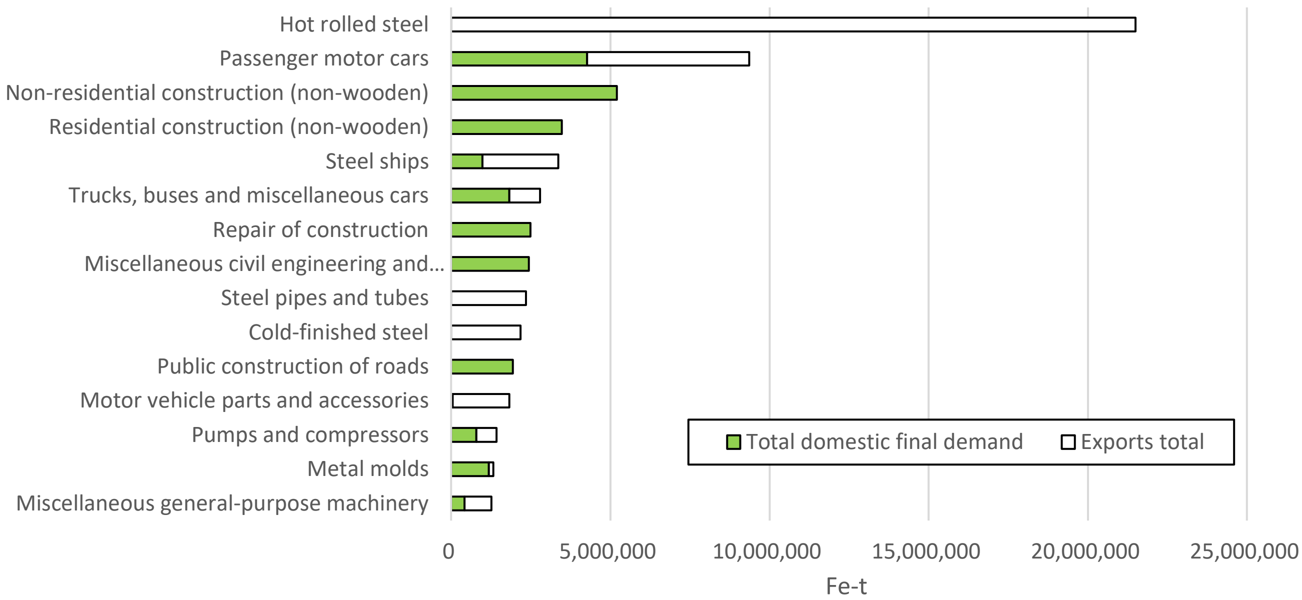

Figure 36. Estimated domestic final demand of iron (Fe) in Japan for 2015.

The largest final destination for copper is exported copper metals, followed by passenger motor cars, rolled and drawn copper alloys, electric wires and cables (Figure 37). Passenger cars are the largest domestic social stock for copper recycling. Other significant stocks are in telecommunications equipment and construction. As with iron's case, there is a large potential for the improved collection and recycling of end-of-life vehicles and construction wastes. In the case of copper, telecommunications equipment, such as mobile phones, is included in the appropriate recycling system.

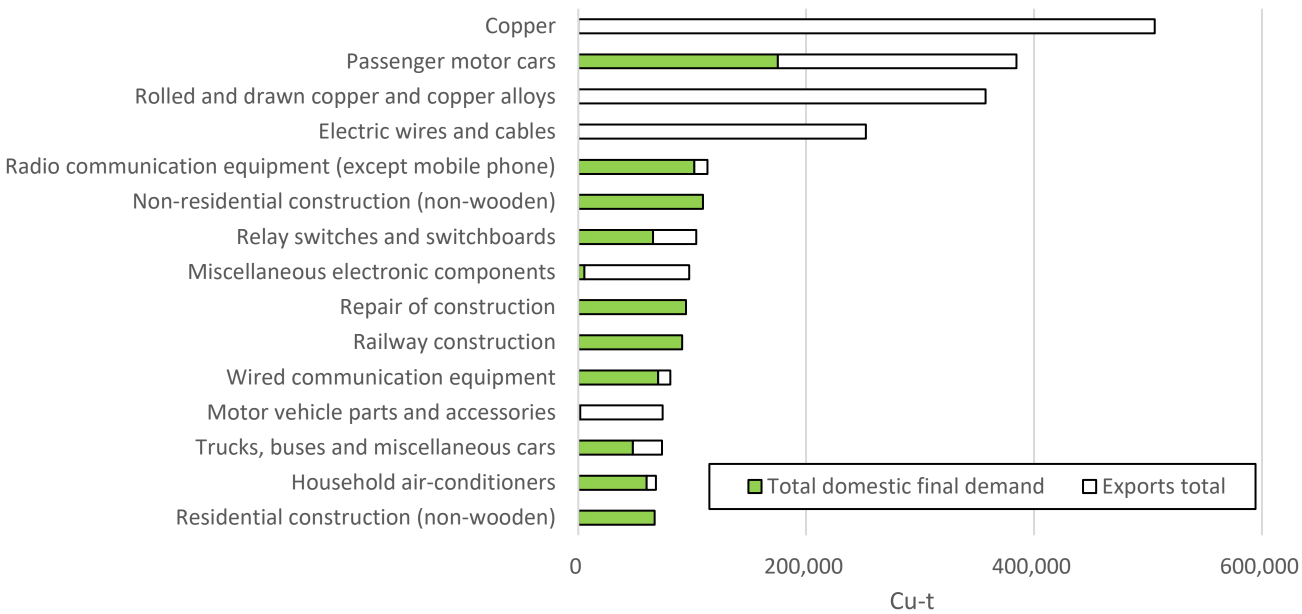

Figure 37. Estimated domestic final demand of copper (Cu) in Japan for 2015.

Aluminum's final destinations are similar in some sectors to those of iron and copper, which are concentrated in passenger motor cars and construction sectors (Figure 38). Aluminum also accumulates in relatively large quantities in household electric appliances. This trend differs from the distribution of iron and copper as social stocks. The recovery of aluminum from end-of-life vehicles, construction wastes and household electric appliances is important to promote the proper recycling of base metals. In Japan, some legal systems already cover collecting and appropriately recycling these post-consumer products and construction wastes [176], [177], [178], [179]. For quality control in the circular flow of these metals, advanced dismantling and comminution processes are required as well as circular design for automobiles, constructions and electric appliances.

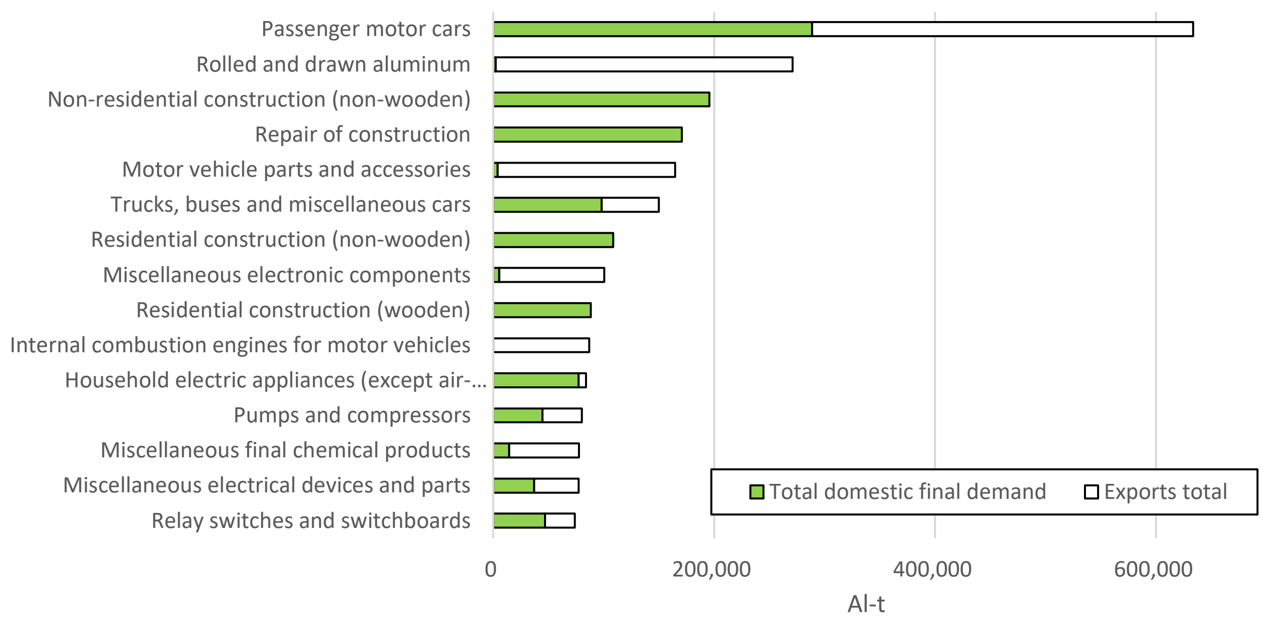

Figure 38. Estimated domestic final demand of aluminum (Al) in Japan for 2015.

Regarding lithium, cobalt and the selected rare earth elements (yttrium, lanthanum, cerium, neodymium and dysprosium), Shimizu and Owada (2024) discuss detailed [117].

As major battery materials, lithium and cobalt find application in lithium-ion rechargeable batteries, encompassing lithium cathodes and electrolytes, with a predominant export orientation toward foreign markets (Figure 39 and Figure 40). This implies that domestic recycling has minimal impact on securing secondary lithium and cobalt for battery manufacturers in Japan. In addition to this aspect, the technological trends in cathodes need to be considered when estimating the future stock of recyclable battery materials. The cathode types of lithium-ion rechargeable batteries vary based on energy and discharged capacities [198], [199]. In the context of a comprehensive mineral resources policy, policymakers require advanced forecasts of technical trends in cathode types and geographically estimated distributions of battery materials. Nansai et al. (2014) and Nakajima et al. (2018) have estimated the global distribution for some critical minerals, such as iron, copper, nickel, cobalt, neodymium, and platinum, using the WIO-MFA model, but lithium has not been addressed [184], [186]. In addition, high-grade natural graphite is primarily found in China [200]. Some countries categorize graphite as one of their critical minerals (see Table 2 in Chapter 2.4). Recycling graphite holds significance for national security.

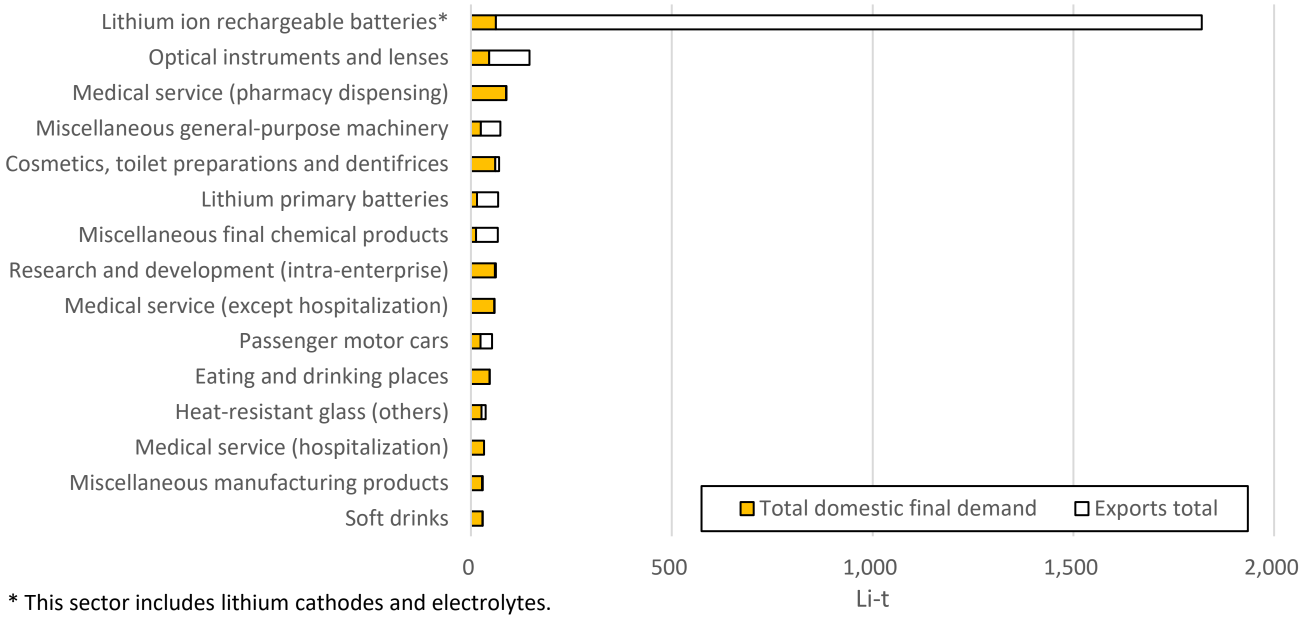

Figure 39. Estimated domestic final demand of lithium (Li) in Japan for 2015 [117].

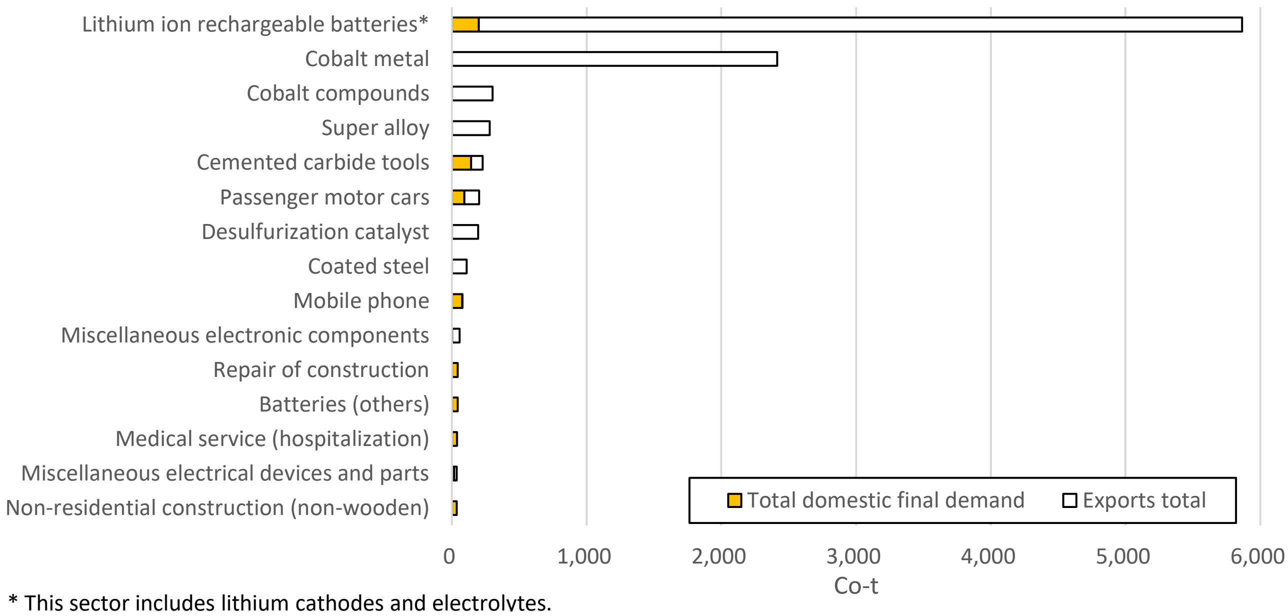

Figure 40. Estimated domestic final demand of cobalt (Co) in Japan for 2015 [117].

The anticipated final destinations for rare earth elements (yttrium, lanthanum, cerium, neodymium, and dysprosium) are contingent on their primary applications (from Figure 41 to Figure 45). A shared characteristic among these selected rare earth elements is the prominence of passenger motor cars as a major application. The most substantial application contributing to increased demand for rare earth elements is the production of permanent magnets [201], encompassing LaCo ferrite magnet and NdFeB magnet. Dysprosium is vital in improving high-temperature performance for some applications, such as power generators and driving motors in hybrid automobiles [202].

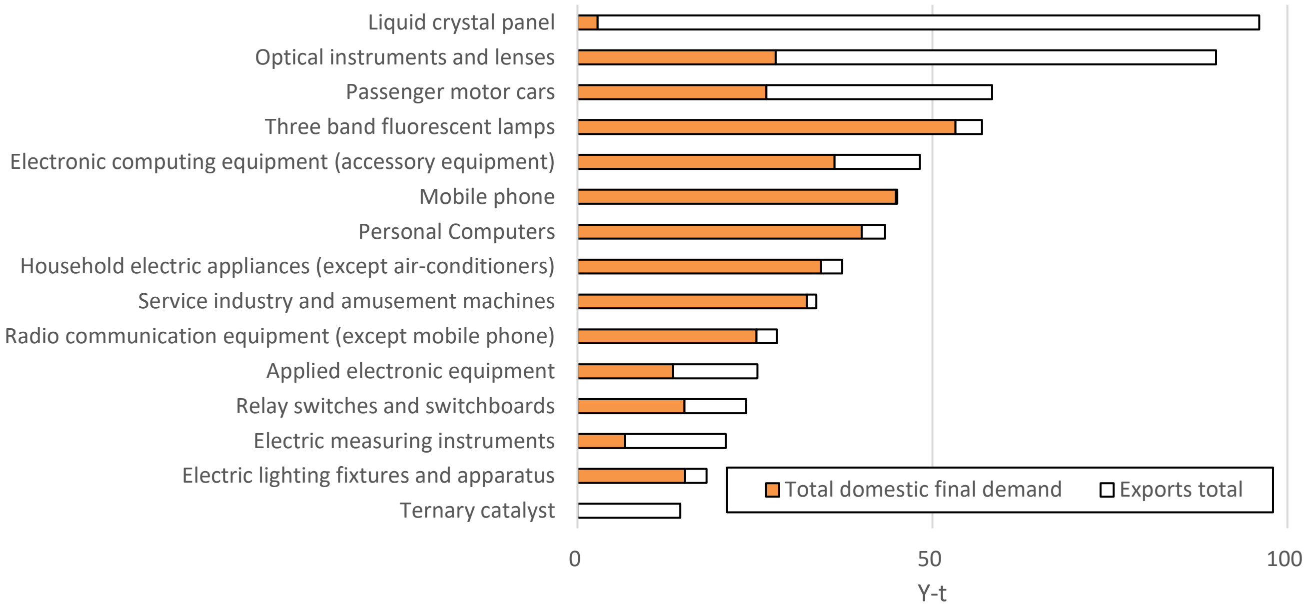

Figure 41. Estimated domestic final demand of yttrium (Y) in Japan for 2015 [117]**.**

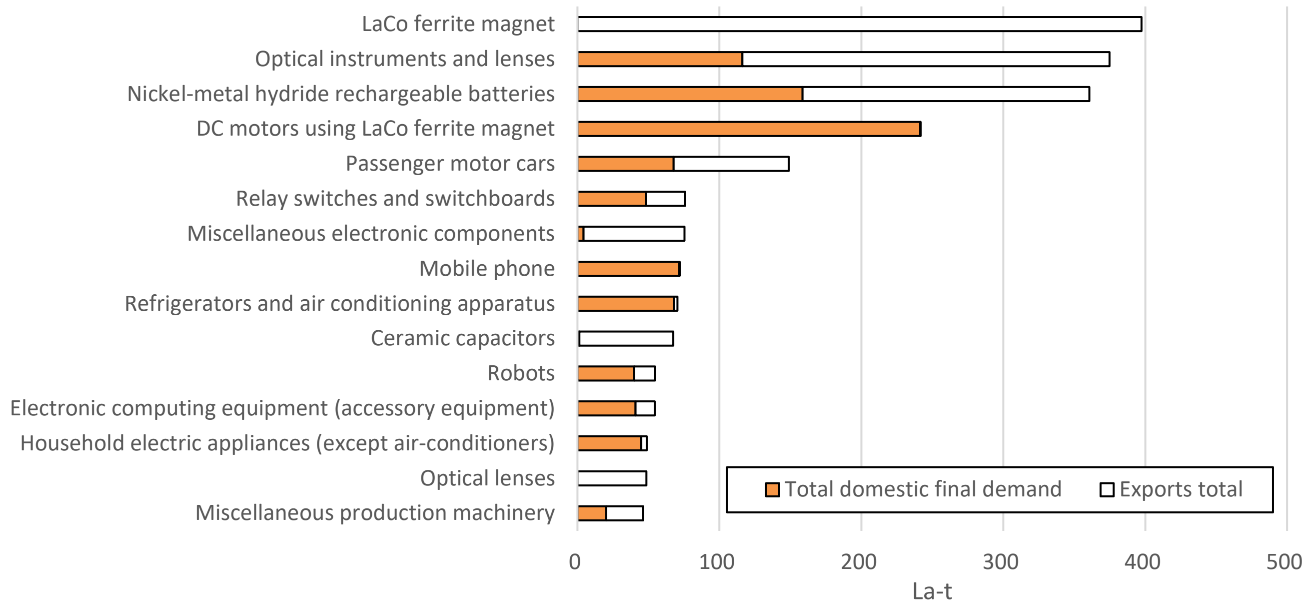

Figure 42. Estimated domestic final demand of lanthanum (La) in Japan for 2015 [117]**.**

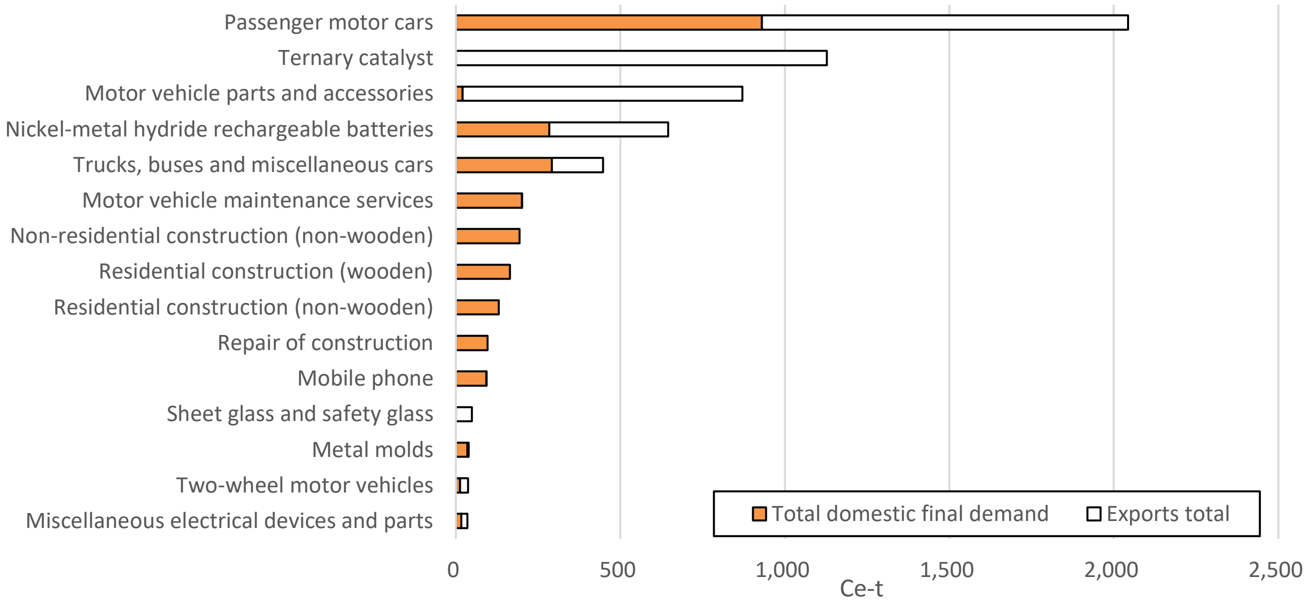

Figure 43. Estimated domestic final demand of cerium (Ce) in Japan for 2015 [117]**.**

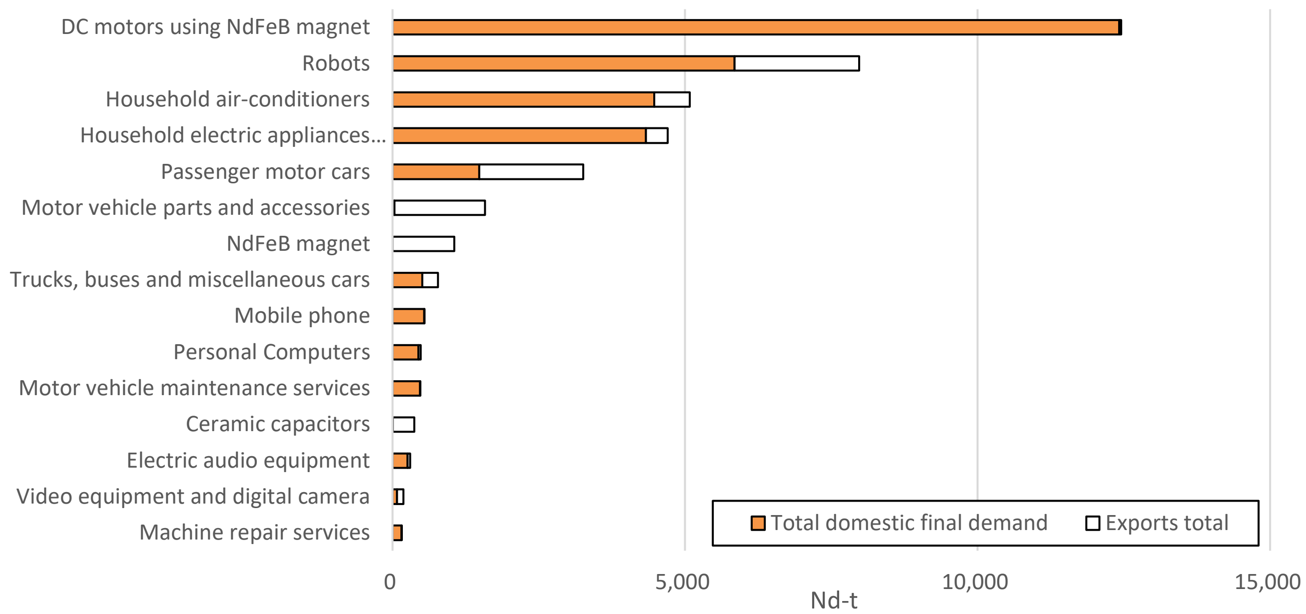

Figure 44. Estimated domestic final demand of neodymium (Nd) in Japan for 2015 [117]**.**

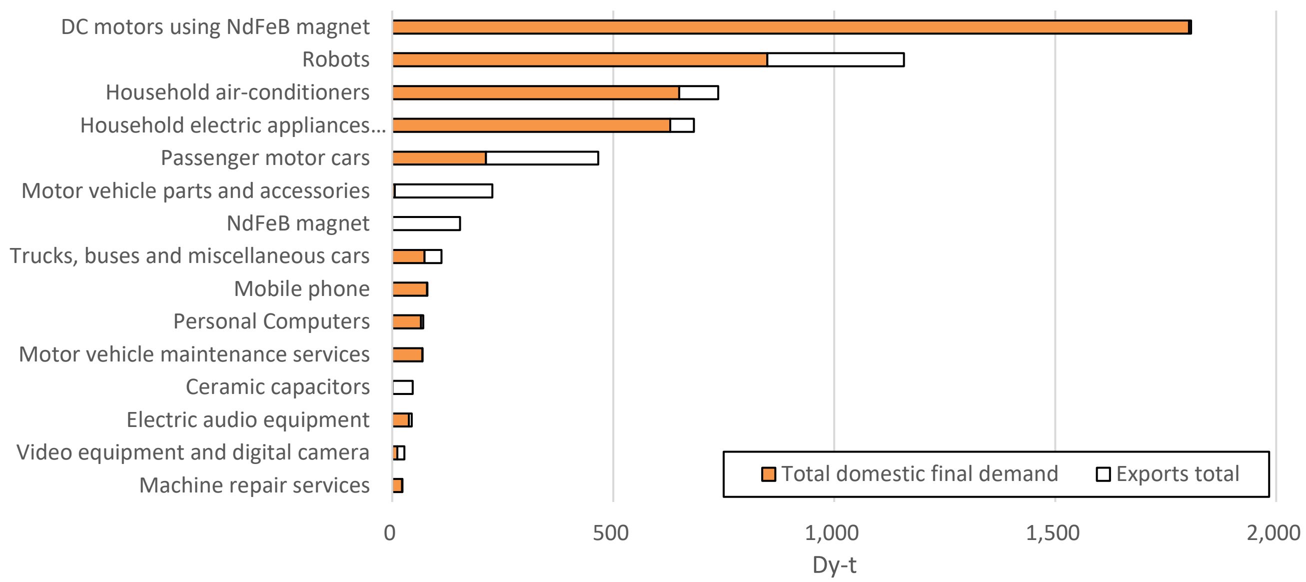

Figure 45. Estimated domestic final demand of dysprosium (Dy) in Japan for 2015 [117]**.**

5.3.2. Policymaking for a domestic and international circular flow of critical minerals

Shimizu and Owada (2024) illustrate a structure of domestic and international circular flows from the perspective of mineral resources policy (Figure 46) [117]. To foster domestic circular flows of critical minerals in final products predominantly demanded within a country (as depicted in Scope 2 in Figure 46), there is a need for additional legal frameworks and policy support. Following the hierarchy of circular economy strategies [72], it is recommended to prioritize the reuse, repair, refurbishment, remanufacture, or repurposing of discarded final products in good condition over recycling. Certain final products and components with a significant export component should be integrated into international circular flows (as shown in Scope 3 in Figure 46). The establishment of a new customs clearance can facilitate the proper trade of well-conditioned parts and scraps in circular economy strategies. If a solid and transparent traceability system between countries is developed, the system can uniquely identify "circular goods" in global trading. This study does not estimate the destination countries. Nansai et al. (2014) estimate the global stock and flow of mineral resources (neodymium, cobalt, platinum) by the IO approach [186]. With trade statistics, global flows of mineral resources can be estimated.

The final destination's estimation contributes to 1) identifying prioritized end-of-life products to be collected and recycled, 2) establishing advanced recycling infrastructure and promoting resource recovery technologies (e.g., dismantling, comminution, separating and sorting processes), 3) fostering circular designs for the recycling of prioritized products (based on the research and development of 2), 4) incentivizing collection and recycling practices (if possible with appropriate legal systems), 5) establishing extended producer responsibility (EPR) and supply chain transparency (if possible for traceability systems), 6) encouraging reuse, remanufacturing and recycling internationally (if possible on establishing international circular flows of mineral resources), 7) rule-making and standardization (as results of 3), 5) and 6)).

Promoting the research and development of recycling technologies varies in countries due to secondary materials or parts market [203]. Each secondary market situation is required to consider the creation of an international circular flow.

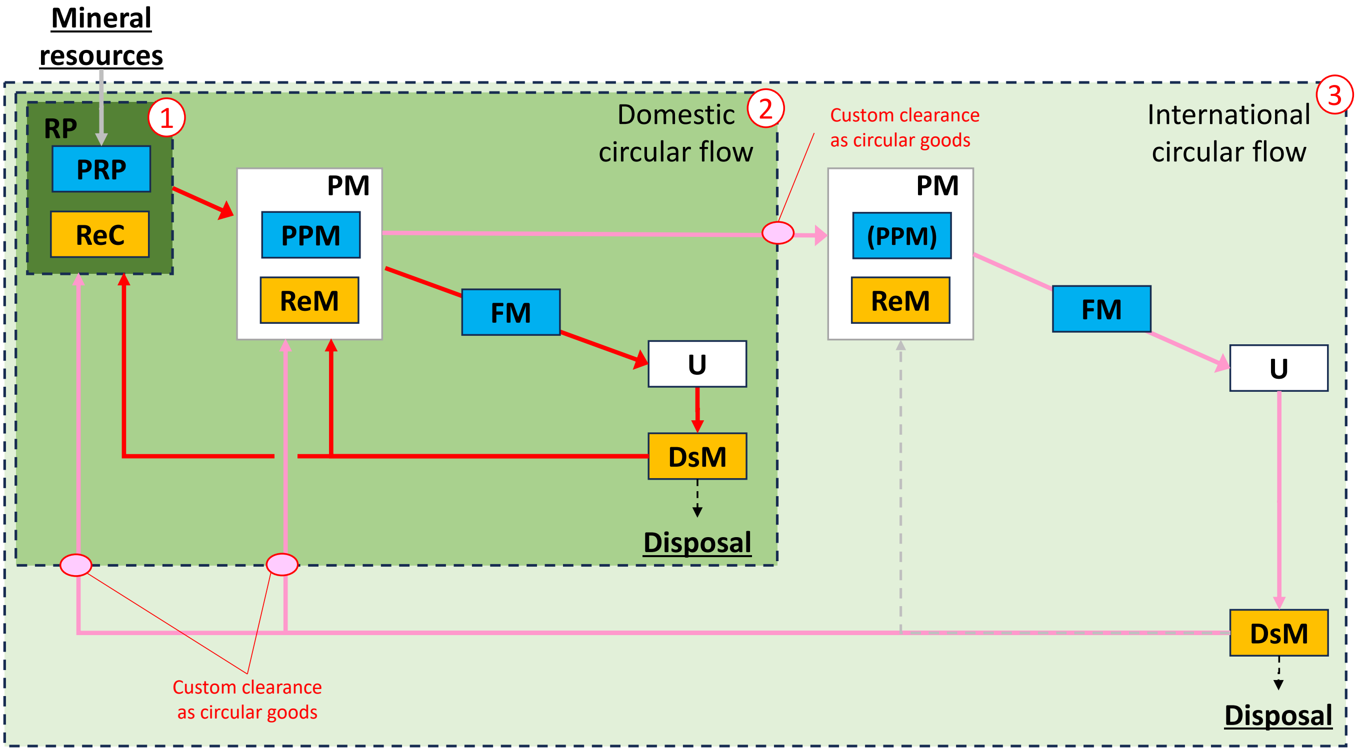

Figure 46. Similarity structure between domestic and international circular flow of critical minerals from mineral resources policy aspect [117]

Note 1: RP: Raw materials production; PRP: Primary raw materials production; ReC: Recycling; PM: Parts manufacturing; PPM: Primary parts manufacturing; ReM: Repurposing, remanufacturing, refurbishing, repairing and reusing; FM: Final products manufacturing; DsM: Dismantling, comminution, separating and sorting; U: Users.

Note 2: Scope 1: Suppliers of mineral resources as raw material producers; Scope 2: Sphere of domestic circular flow; Scope 3: Sphere of international circular flow

5.4. Conclusion

In summary, this study calculates the final destination of some base metals (iron, copper and aluminum) and critical minerals selected (lithium, cobalt, yttrium, lanthanum, cerium, neodymium, and dysprosium). The results highlight disparities between the current policy implementation and anticipated actions for fostering the circular flow of mineral resources for Japan. Utilizing a uniquely expanded high-resolution hybrid IO table for analysis, the study underscores assessing the final destination of critical minerals as potential urban mine deposits. With the precise estimation for the final destination of each mineral resource, policymakers use the results as a decision-making tool to prioritize end-of-life products to be collected and recycled.

The estimation of critical minerals' final destination is an essential aspect of promoting circular economy policy implementation. Understanding where these minerals end up in their life cycle contributes to the development of effective policies that support circularity, resource efficiency, and sustainable mineral management. By estimating the final destination of mineral resources, policymakers can promote some policy implementation, such as building legal systems, researching and developing recycling technologies and circular designs, internationally extending and transparent mineral resource supply chains, and rule-making and standardization. To establish an international circular flow of critical minerals, collaborative efforts on a global scale, including the introduction of new custom clearance systems and international traceability mechanisms, are imperative to facilitate the proper circulation of components and scraps, uniquely labeled as "circular goods."

As concluded in Chapter 4.4, the IO tables are not available every year. Dynamic approaches are required to supplement missing years, as discussed in Nakamura and Kondo (2018) [166]. Additionally, the latest IO table does not necessarily reflect the future industrial structure. Scenario analysis is required to evaluate the strategic importance of mineral resources if the IO approach is adopted.

6 Decision flow framework in future mineral resources policy

Conventional mineral resources policy involves the practical application of policies and regulations to govern the exploration, extraction, processing, and management of mineral resources. Sustainable perspectives change the scheme of mineral resources policy implementation. Current mineral resources policy has two faces: one is the producer's viewpoint, and the other is the consumer's viewpoint. The former perspective encompasses licensing on mining, environmental impact assessments, community engagement, health and safety regulations (labor and residents), sustainable resource management, royalties and revenue sharing, transparency and accountability. The key aspect of the latter is the circular economy, as discussed above, which includes resource efficiency and recycling targets, extended producer responsibility (EPR), design for recycling guidelines, waste reduction and recovery programs, secondary material markets, green public procurement, eco-labeling and certification, sustainable supply chain management, regulatory frameworks for closed-loop systems.

Resource security is the basis of mineral resources policy, often focusing on ensuring a stable and secure supply of critical minerals. Predicting specific mineral resource policy developments requires careful consideration of ongoing trends and emerging global challenges. It is important to note that the future of mineral resources policy will be shaped by a complex interplay of economic, environmental, geopolitical, and technological factors. Ongoing monitoring of global developments and policy changes will provide more accurate insights into the evolving landscape of mineral resources policy.

The relationship between circular economy and mineral resources policy is one of mutual reinforcement. Circular economy principles provide a strategic framework for sustainable resource management, and mineral resources policy can leverage these principles to achieve responsible extraction, reduce waste, and promote a circular flow of critical minerals. The integration of these two frameworks is essential for creating a resilient and sustainable approach to resource utilization on a global scale. Circular economy practices can contribute to resource security by minimizing reliance on primary sources through increased recycling and secondary material utilization. Effective coordination between circular economy policy and mineral resources policy is essential. Governments can create an integrated policy framework that addresses both sustainable resource extraction and circular economy actions to achieve overarching environmental and economic goals.

While the current mineral resources policy predominantly concentrates on criticality for developing modern technologies, it lacks the identification of prioritized post-consumer products and their respective components for collection and recycling to establish circular flows. Previous studies emphasize prioritizing items to be collected and recovered [150], [204], [205]. The introduction of additional legal systems facilitates the extensive collection of end-of-life products containing a large number of critical minerals. Owada et al. (2013) propose "device separation" for an efficient physical separation process with electrical disintegration, contributing to the commercial viability of circular economy strategies [206]. In the story of circular economy strategies, efficient evaluation technologies are needed to prioritize reusing, repairing, refurbishing, remanufacturing, repurposing, or recycling post-consumer products and their components, regardless of their condition. The development of impact evaluation methodologies for policies and legal systems is significant for effective policy implementation. Embracing the concept of evidence-based policymaking is anticipated to offer a solution to this challenge.

Creating indicators for circular design, considering current and expected future technologies in liberation and separation, is vital for policymakers. These indicators contribute to identifying socially and technologically prioritized components and final products for circular economy strategies and guide the selection of technologies that warrant support. With reliable IO data and information on intermediate products, such as electronic parts and devices, the final destination of these components can be estimated by the IO approach adopted in this study, as discussed in Chapter 3.5. The results can explain the number of parts used in final goods and dismantling and comminution possibilities for recycling. This estimation can support policymakers in determining which post-consumer products will be prioritized to be recycled when following the “device separation” concept proposed by Owada et al. (2013) [206].

Promoting recycling and recovery initiatives is crucial for establishing a circular flow of critical minerals, requiring governments to incentivize research and development in recycling technologies, invest in recycling infrastructure, and establish policies that encourage recycling from end-of-life products. Collaboration among governments, academia, and industry is necessary to advance technologies and enhance the sustainability of the entire critical minerals supply chain.

International collaboration involves strategic alliances and partnerships among countries to ensure a stable and diversified supply of critical minerals. Collaborative efforts may include joint exploration projects, technology sharing, and coordinated policies to address global challenges to create the circular flow of critical minerals. International standardization can facilitate smoother cross-border collaboration for environmental protection, worker safety, and product labeling, contributing to a more transparent and sustainable global supply chain.

Critical minerals are recognized as essential items for economic growth. Analyzing the global supply chain dynamics of key minerals is imperative. This involves evaluating the concentration of production in specific countries or regions, assessing geopolitical risks, and identifying potential supply chain bottlenecks. Policymakers are required to consider the strategic importance of minerals for national security and technological advancements. Certain mineral resources may have critical applications in defense, energy, and emerging technologies, requiring policymakers to weigh the strategic implications of supply disruptions when assessing economic damages [207].

Evaluating market dynamics and the feasibility of diversifying mineral sources is important. Assessing the resilience of downstream industries to supply disruptions is necessary, as some industries may have more flexible supply chains and the ability to adapt quickly to changes, while others may face severe disruptions. Policies can be tailored to support the resilience of vulnerable industries. This study shows that the raw materials and related parts manufacturing and intermediate products sectors are the most damaged in cause-and-effect mechanisms explained by the IO approach. In mineral resources policy, economic damages evaluation as a stress test to the supply disruption developed in this study is required to evaluate such vulnerable industries. The developed method is helpful in quantitatively evaluating the possible economic damages of mineral resources’ supply disruption, such as political export controls and natural disasters. In addition, this study shows that even the low-resolution IO approach can contribute to discussing the priority of mineral resources to be considered in the contest of mineral resources policy.

Collaborating with international partners to address supply chain vulnerability collectively is a recommended collaborative strategy. Policymakers can work with other countries to develop common strategies, share information, and implement rule-making and standardization to enhance global supply chain resilience. Developing contingency plans and risk mitigation strategies is vital for every country. Policymakers need to consider potential supply disruptions, establish early warning systems, and implement rules and standards to minimize short-term economic damages in the event of a supply disruption.

By adopting a comprehensive approach considering the interplay of criticality, economic impact, industry dependencies, and global dynamics, policymakers can better distinguish short-term economic damages from the broader strategic importance of mineral resources during supply disruptions. This approach allows for the development of targeted and effective policies to mitigate risks and enhance the overall resilience of the economy.

A comprehensive mineral resources policy is crucial for achieving a sustainable circular flow of critical minerals. Governments, industry stakeholders, and the international community are collaboratively required to address the challenges associated with extracting, processing, and recycling these essential mineral resources. A circular flow of critical minerals can be established through strategic alliances, policy frameworks, and a commitment to innovation, ensuring a resilient and sustainable supply chain for the technologies driving our modern world.

Based on the results and discussion above, this study proposes a decision flow framework specific to multiple critical minerals in mineral resources policy for policymakers, as shown in Figure 47. This framework underscores distinguishing short-term vulnerability (economic damages caused by supply disruption of mineral resources)from long-term vulnerability (strategic importance for sustainability and future economic growth). In addition, the framework provides the priority of circular economy policy implementation in collecting and recovering end-of-life products and their components. Weiser et al. (2020) review existing mineral resources policy and their strategies [207].

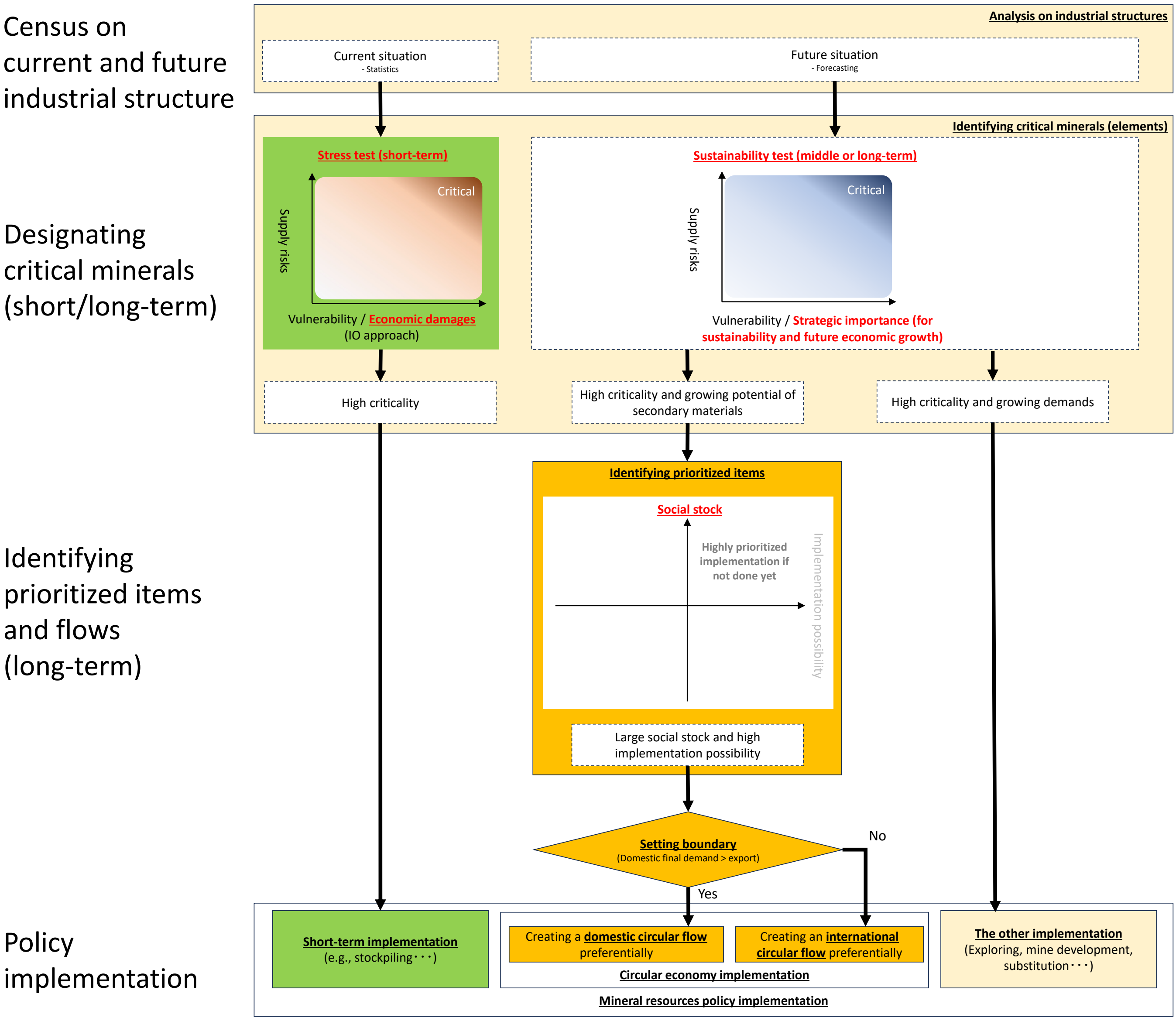

Figure 47 Decision flow framework in future mineral resources policy

Regarding the selected ten elements (detailed in Chapters 4.2 and 5.2), the following policy implementation is required for Japan based on the developed decision flow framework;

- Overarching perspective: revising the priorities of policy implementation based on the developed stress test and the estimation of mineral resources' final destination, reforming mineral types and their volumes for stockpiling, revising mineral types to be recycled domestically, rebuilding the related legal system and research and development for circular economy implementation, creating international standardization between interested countries and organizations for a cross-border circular flow of critical minerals and other related mineral resources, promoting the exploration and development of new mines on some mineral resources having great future demand (e.g., lithium and cobalt), and balancing supply-increasing implementation (e.g., developing new mines, promotion in recycling) and demand-decreasing implementation (e.g., substitution downgraded and not market-needs based for mitigating supply risks);
- Iron's perspective: maintaining the current legal systems for keeping a main circular flow for recycling, controlling the quality of the circular flow of scrap iron (e.g., advanced dismantling and comminution process for impurities (tramp elements) control, category standardization of scrap irons for leveling qualities, and traceability system for registering the origin and quality of scrap irons);
- Copper's perspective: improving the current legal systems for thickening the current circular flow for recycling, research and development of advanced dismantling and comminution process for smart liberation (not contaminate scrap irons);
- Aluminum's perspective: improving the diversity of import parties for mitigating the supply risk, improving the current legal systems for thickening the current circular flow for recycling, research and development of advanced dismantling and comminution process for smart liberation (not contaminate nonferrous scraps for copper smelting process), controlling the quality of the circular flow of scrap aluminum (e.g., advanced dismantling and comminution process for impurities (tramp elements) control, category standardization of scrap aluminum for leveling qualities, and traceability system for registering the origin and quality of scrap aluminum);
- Lithium's perspective: promoting the development and off-taking of lithium brains and hard-rock mines overseas, creating an international circular flow of post-consumer lithium-ion rechargeable batteries and their parts or recycled raw materials (e.g., black mass powder), and category standardization on these post-consumer products and related secondary raw materials;
- Cobalt's perspective: promoting the development and off-taking of base metals' mines overseas (e.g. copper and nickel) to increase cobalt as a byproduct, investing base metals smelting process to increase cobalt as a byproduct, creating an international circular flow of post-consumer lithium-ion rechargeable batteries and their parts or recycled raw materials (e.g., black mass powder), and category standardization on these post-consumer products and related secondary raw materials;
- Yttrium's perspective: research and development of new applications to balance over-supplied yttrium and small demand of current yttrium applications (e.g., fluorescent powders and optical lens), promoting the

development of rare earths mines overseas and process plants (e.g., reaching and separation) other than some dominant producer countries;

- Lanthanum's perspective: promoting the development of rare earths mines overseas and process plants (e.g., reaching and separation) other than some dominant producer countries, improving the current legal systems for keeping a main circular flow of scrap irons for recycling of LaCo magnets, controlling the quality of the circular flow of scrap iron (e.g., advanced dismantling and comminution process for recovering LaCo magnets, category standardization of scrap motors based on magnet types);
- Cerium's perspective: research and development of new applications to balance over-supplied yttrium and small demand of current yttrium applications (e.g., fluorescent powders and optical lens), promoting the development of rare earths mines overseas and process plants (e.g., reaching and separation) other than some dominant producer countries;
- Neodymium's perspective: promoting the development of rare earths mines overseas and process plants (e.g., reaching, separation and smelting (alloy making)) other than some dominant producer countries, improving the current legal systems for keeping a main circular flow of scrap irons for recycling of NdFeB magnets, controlling the quality of the circular flow of scrap iron (e.g., advanced dismantling and comminution process for recovering NdFeB magnets, category standardization of scrap motors based on magnet types);
- Dysprosium's perspective: promoting the development of rare earths mines overseas and process plants (e.g., reaching, separation (including a recovery of a small amount of heavy rare earth elements from the residue of light rare earth elements), smelting (alloy making)) other than some dominant producer countries, improving the current legal systems for keeping a main circular flow of scrap irons for recycling of NdFeB magnets, controlling the quality of the circular flow of scrap iron (e.g., advanced dismantling and comminution process for recovering NdFeB magnets, category standardization of scrap motors based on magnet types)

7 Conclusion and outlook

This study discusses a comprehensive mineral resource policy on critical minerals by conducting a high-resolution input-output (IO) analysis with a uniquely expanded and latest IO table for Japan as of 2015. Mineral resources are essential for people's lives and transitioning to a low-carbon society. Many countries regard these mineral resources as critical minerals. Countries express concern over the vulnerability of their supply chains of critical minerals. A new evaluation method of vulnerability in the event of mineral resources' supply disruptions is developed, which contributes to selecting critical minerals from the perspective of a stress test. With the high-resolution IO table, this study quantitatively estimates the social stock of these critical minerals to identify the prioritized post-consumer products and their components containing these critical minerals to be collected and recovered. In this study, a decision flow framework for comprehensive mineral resources policy is proposed from multiple perspectives, such as national security and circular economy.

Chapter 1 provides the background and objectives as an introduction to this study. This chapter raises the issue of quantitative and objective decision-making on stockpiling policy and the need for a comprehensive mineral resources policy incorporating new policy perspectives such as the circular economy.

Chapter 2 reviews the history of mineral resources policy, focusing on critical minerals after World War II. Before the circular economy concept appeared, most countries emphasized the stable procurement of mineral resources from a national security aspect. Since the 2000s, many countries have encompassed circular economy strategies to produce secondary materials from national security and sustainability perspectives. The NRC (U.S.) proposed the fundamental concept of criticality assessment to designate critical minerals for economies [16]. The methodology relies on the combination of supply risks and vulnerability evaluation. This study indicates the limitations of existing vulnerability evaluation and comprehensive mineral resources policy both for economic and social well-being.

Chapter 3 discusses the function and possibility of the input-output approach in mineral resources policy. This study examines the economic damages of mineral resources' supply disruption and critical minerals' final destination with the uniquely expanded high-resolution IO table. Ten elements equivalent to mineral resources, iron, copper, aluminum, lithium, cobalt, yttrium, lanthanum, cerium, neodymium and dysprosium, are selected for these analyses. For the analyses, the latest IO table on the Japanese economy (as of 2015 [114]) is expanded and converted from a monetary matrix of 509 by 391 to a hybrid matrix of 441 by 441 for evaluating the economic damages of critical minerals' supply disruption, and another hybrid matrix of 443 by 443 for estimating the final destination of critical minerals.

Chapter 4 discusses a new vulnerability evaluation as a stress test for the supply disruption of mineral resources. This study shows that the repercussion effect of the supply disruption of critical minerals impacts intermediate products industries rather than the final goods industries and other service industries using critical minerals. The direct and indirect effects of the supply disruption of critical minerals are examined using an expanded IO table mentioned above. This study concludes that policymakers need to distinguish the impacts of supply disruption from critical minerals' economic or strategic importance. In the context of mineral resources policy, evaluating the impacts of supply disruption is essential for the decision-making of short-term and directly impacted damages, such as the political embargo of natural resources and a supply disruption by natural disasters. The results reveal that a repercussion effect analysis using low-resolution IO tables and a direct impact evaluation of supply disruption are useful for policymakers if they cannot take a high-resolution IO approach. This discussion means that even the low-resolution IO approach can contribute to determining the priority of mineral resources to be considered in the contest of mineral resources policy by validating low-resolution IO analysis with high-resolution IO analysis.

Distinguishing short-term economic damages from the economic importance of mineral resources requires a nuanced understanding of economic, industrial, and geopolitical factors. Policymakers need to consider key aspects to make informed distinctions. A criticality assessment is necessary to identify critical minerals for key industries and technologies, focusing on those with high economic damages and future importance for severe supply disruptions. This assessment evaluates the possibility and level of supply risks of each mineral resource. The developed method is helpful in quantitatively evaluating the possible economic damages of mineral resources' supply disruption, such as political export controls and natural disasters.

Chapter 5 discusses the significance of estimating the mineral resources' final destination for their circular flows. This study emphasizes the usefulness of estimating both the volume and distribution of critical minerals' final destination when deciding to establish a circular flow of critical minerals. Such considerations are essential from the perspectives of national security and the circular economy within mineral resources policy. The results provide a detailed insight into the distribution of critical minerals, offering guidance on prioritized implementations to facilitate the creation and maintenance of both domestic and international circular flows of critical minerals. The circular flow of critical minerals has gained significant attention in recent years due to the growing importance of these minerals in various industrial sectors, including technology, energy, and manufacturing. Establishing effective recycling systems is vital to reduce the environmental footprint and ensure a continuous supply of secondary materials.

Chapter 6 derives findings from evaluating economic damages caused by supply disruption and estimating the final destination of critical minerals. A new decision flow framework aimed at multiple objectives provides policymakers with the ability to identify prioritized mineral resources for stockpiling, prioritized mineral resources and related products, and their components containing them to be collected and recycled. The study underscores the importance for policymakers to take into account not only the strategic importance or intermediate volumes and distributions of critical minerals but also their final destination in order to implement effective measures promoting circular economy implementation. A well-defined mineral resources policy is essential for ensuring a sustainable and efficient circular flow of critical minerals. The developed decision flow framework contributes to effective, comprehensive mineral resources policy implementation from short- to long-term aspects.

Chapter 7 provides a summary of each chapter and the outlook of the study. For further actions, inclusive indicator development is required for policymakers to support the determination of implementation possibilities for effective circular economy policy implementation. This indicator will support the decision-making from social and technological aspects. The developed indicators will explain the possibilities of circular economy implementation, encompassing aspects like evaluating the extensive collection of post-consumer products (social aspect) and the efficient liberation and separation of these materials (technological aspect). Evaluating the indicator can be essential to crystallize the content of new legal systems and technological advancements.

A challenge of the IO approach is the availability of an IO table. Most countries do not publish the IO tables every year. As concluded in Chapter 4.4, dynamic approaches are required to supplement missing years, as discussed in Nakamura and Kondo (2018) [166]. In addition to this aspect, expanding the high-resolution IO table faces the unavailability of data for subdividing rows and columns. Subdividing columns and each input data need more supportive data and information. With support from the industrial sectors in providing actual reliable data, the uncertainty of the expanded IO table is undoubtedly improved. This study is based on Japan's latest IO table as of 2015 [114]; however, scenario analysis is required to determine the strategic importance of mineral resources if the IO approach adopts inclusive evaluation.

This study does not evaluate the foreign stock and flow of mineral resources exported overseas. As Nansai et al. (2014) estimate the global stock and flow of some mineral resources (neodymium, cobalt, platinum) by the IO approach [186], these international stock and flow of mineral resources can be estimated with trade statistics.

In summary, this study has developed a new quantitative and objective evaluation method using a uniquely expanded high-resolution hybrid IO table, while qualitative vulnerability evaluation, such as expert judgment, has been used in mineral resources policy. The methodology provides a practical evaluation that assumes partial supply disruptions that may actually occur, while only supply disruptions of the entire consumption of a country's mineral resources were assumed previously. This study also allows for estimating the final destination of each mineral resource and the volume of those accumulations as a social stock. In addition, a new decision flow framework for policymakers in comprehensive mineral resources policy is proposed in this study. The framework efficiently integrates individual policy implementation, such as stable procurement of critical minerals and promotion of circular economy strategies. Utilizing the results of this study enables the quantitative and objective review of stockpiling policy and other related policies based on the conventional vulnerability evaluation in the event of the supply disruption of mineral resources. The results contribute to redefining circular economy policy implementation, which has traditionally been considered an extension of waste management policy implementation, more comprehensively and consistently from the aspect of mineral resources policy.

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Kotaro Shimizu

17th January 2024 in Tokyo

List of research achievements for application of Doctor of Engineering, Waseda University

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Lectures	○Kotaro Shimizu, “Criticality”, Raw materials for a sustainable future, International Round Table on Materials Criticality (IRTC) conference, Lille, France, 15-17 February 2023
Lectures	○Kotaro Shimizu, “Economic and maritime security in Europe and East Asia”, The Hague Centre for Strategic Studies Webinar, 27 January 2023
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Lectures	○清水孝太郎・迫田瞬・園原惇史，「資源（クリティカルメタル）をめぐる国際ルールの形成動向と循環経済型ビジネス」，資源・素材学会／資源リサイクリング部門委員会総会・講演会（早稲田大学），令和3（2021）年10月18日
Lectures	○清水孝太郎・小川恵司・迫田瞬・園原惇史，「循環経済の実現に向けたルール形成・技術開発ロードマップ」，一般社団法人資源・素材学会包括的資源利用システム部門委員会・令和2年度総会・講演会（循環経済型ビジネスのあり方）（リモート形式），令和3（2021）年1月6日
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List of research achievements for application of Doctor of Engineering, Waseda University

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Lectures	○清水孝太郎，「レアメタルの需給および日米欧中韓のレアメタル関連技術の開発動向」，日本学術振興会産学協力研究委員会／素材プロセシング第69委員会第３分科会（環境関連技術）第12回研究会（千葉工業大学），平成27(2015)年12月16日
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List of research achievements for application of Doctor of Engineering, Waseda University

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Others (oral presentation)	米山基樹・笛木雄大・大和田秀二・清水孝太郎・千賀太喜,「LIBSソーターによる鉄合金類相互分離に関する基礎研究」, 第19回「資源・素材・環境」技術と研究の交流会（オンライン開催）, 一般社団法人資源・素材学会関東支部, 令和4（2022）年8月1日
Others (oral presentation)	○清水孝太郎・迫田瞬,「レアアース（希土類）の需給動向と今後の展開可能性について」, 日本安全保障貿易学会第32回研究大会（リモート）, 令和3（2021）年9月26日
Others (oral presentation)	○清水孝太郎,「循環経済型ビジネスの実現に向けたサプライチェーンの連携と技術開発の方向性」, 資源・素材学会2021年度春季大会（リモート）, 令和3（2021）年3月8日
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Note: A simbol "○" is put in front of each research achievement as a significant contribution to the doctoral thesis.