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Understanding Rare Earth Elements as Critical Raw Materials

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Abstract: The boom in technological advances in recent decades has led to increased demand for rare earth elements (REEs) (also known as rare earth metals) across various industries with wide-ranging industrial applications, including in the clean energy sector, but with some environmental, economic, and social footprint concerns. This paper reviews the complexities of the production, consumption, and reuse or recovery of REEs, presenting current trends in terms of potentials and challenges associated with this. This paper in particular focuses on the supply, demand, and (environmental and economic) sustainability of REEs, as a subset of critical raw materials. It does so via a critical stocktaking of key discussions and debates in the field over the past 15 years up until now, through a thematic analysis of the published and gray (policy) literature with a grounded theory approach. The paper finds that carefully balanced lifecycle sustainability assessments are needed for assessing the respective dimensions of the extraction, processing, and reuse or recovery methods for different types of REE sources and supplies to meet current and future demands. It furthermore diagnoses the need for taking into account some shifts and substitutions among REEs also for reasons of cost and locational supplies for the security of supply. Finally, the paper provides some overall policy recommendations for addressing current problems, with a conceptual framing of the UN Sustainable Development Goals.

Keywords: rare earth elements; critical raw materials; supply; demand; lifecycle sustainability assessment

Citation: Filho, W.L.; Kotter, R.; Özuyar, P.G.; Abubakar, I.R.; Eustachio, J.H.P.P.; Matandirotya, N.R. Understanding Rare Earth Elements as Critical Raw Materials. *Sustainability* **2023**, *15*, 1919. https://doi.org/10.3390/su15031919

Academic Editor: Changhyun Roh

Received: 6 October 2022
Revised: 16 January 2023
Accepted: 17 January 2023
Published: 19 January 2023

1. Introduction: Rare Earth Elements (Rare Earth Metals) and Critical Raw Materials

1.1. Rare Earth Elements

Rare earth elements (REEs) [1], sometimes also referred to as rare earth metals (REMs) [2] as the basis for rare earth materials [3], are critical to producing high technology equipment [4] and for innovative technologies [5], often as alloys [6] or additives thereof [7], to achieve advanced material performance characteristics [8]. However, although some REEs, such as cerium, can be found relatively more often in the earth's crust [9], REEs in general are considered critical raw materials (CRMs) [10], alongside some other strategic mineral resources, such as cobalt, lithium, tellurium, and nickel [11]. These can be listed as follows: scandium (Sc), lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium

(Nd), promethium (Pm), samarium (Sm), europium (Eu), yttrium (Y), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), ytterbium (Yb), lutetium (Lu), and thulium (Tm) [12]. From 2017 onwards, in an increasingly systematic fashion, the European Commission [13,14], for instance, has been developing the availability, accessibility, and criticality assessment of critical raw materials and has included REEs in that context.

There are 17 REEs that are grouped for their similar chemical and physical properties [15], 8 in the light REEs category, and 7 in the heavy REEs category [8]. These materials consist of 15 lanthanides, plus scandium and yttrium. Source [16] notes that the International Union of Pure and Applied Chemistry (IUPAC) considers the elements from La to Eu as light REEs and those from Gd to Lu and Y as heavy ones. In contrast, in Europe, the elements from La to Sm are often grouped as light ones and Eu to Lu plus Y as heavy ones; in China, Sm is considered a heavy REE. The classification of Gd varies between the two groups, according to IUPAC and the United States Geological Survey (USGS) [17]. Furthermore, Sc is also often not described as an REE and is often treated separately as an element [16].

1.2. Relative Geological Abundance of REEs

Notwithstanding the label, REEs are moderately abundant (except for Pm), often more so than critical metals (e.g., copper). REEs are considered rare thanks to the comparatively low quantities of them in locations that support economical mining [17]. REEs are frequently also denominated as "rare earth oxides", currently the predominant way they are traded. Heavy REEs are less common and may be more valued and sought, though this also depends on use forms, material intensity, and substitution cases.

REEs are neither particularly geologically rare or present only in limited deposits. These range from bastnäsite to monozites in quite a few countries and continents, but also, especially for heavy rare earths, apatites, cheralites, eudialytes, loparites, and phosphorites. The latter are sedimentary marine phosphate deposits, which are relatively easily extractable by dissolving them in diluted sulfuric acid to obtain all the REEs in there. REEs are also found in rare earth–bearing (ion-absorption) clays, where REEs can be relatively easily extracted in a trivalent cationic state via surface/mountaintop mining, followed by leaching [18] and then using ion exchangers, secondary monazite, spend uranium solution, and xenotime. REEs typically do not geologically occur as individual elements but instead in differing (and often low) concentrations in ore-accessory minerals. Igneous rocks (alkaline ones and carbonatites) and metamorphic rocks are their classic sources, but there is an increasing interest in sedimentary rocks. Residual deposits from pegmatites and iron oxide copper-gold nickel laterites may also hold interesting concentrates in some cases [19].

1.3. Economically Relevant Geological Deposits of REEs and Accessing Them

Even though there are over 250 minerals that may contain REEs, in principle, economically interesting concentrations for (at least official) profitable mining are found predominantly in carbonatites, alkaline igneous settings, ion-absorption clays, and monazite-xenotime-bearing placer deposits as a result of deep weathering and fluvial processes. REEs are found as solid minerals [20], frequently with radioactive traces of uranium and thorium [17] with both potential yield interests here [21], but also with potentially more challenging handling associated with them because of those traces [22]. Overall, these have also been termed strategic minerals [11].

The primary extraction process of REEs (or primary resources, as opposed to secondary ones from recycling) can vary from open or surface mining, underground mining, or leaching on site, each of which has a different landscape and different environmental, cost, and safety implications, and they will leave byproducts and mine tailings in different ways. Currently, REEs predominantly come from open mining as a byproduct of other mining operations. As REEs are not geologically found in their isolated element form, separation and purification are required. This is typically performed on rare earth oxides through extensive and resource-intensive processing involving mechanical, flotation, chemical, and thermal steps [21]. After mining REEs must undergo several water-, chemical-, and energy-intensive steps for processing, from crushing, milling, cracking, and separation through froth flotation into dissolved concentrates in the first phases. Then purification is necessary, involving several complex chemical reactions to either produce rare earth oxides [21] or to merge those with other elements to produce either metals [22] or alloys [19].

1.4. Notable Supply Chain Risks of REEs

REEs, along with other critical resource materials (CRMs), have high risks associated with their supply chains [23] and have unique properties that are often difficult to replace or duplicate by using modern technology [24] or conventional methods [25]. According to the European Commission [14], CRMs are important for many industries across all their supply chains thanks to their relevance to modern technology (e.g., electric motors, intelligent household applications) and the quality of life based on that and for a clean technology–based future: they are currently irreplaceable, for instance, in solar panels; wind turbines; electric batteries and electric vehicles; automotive catalysts; energy-efficient lighting; liquid-crystal displays for mobile phones, computers, and television sets; glass additives and ceramics; metallurgy; phosphors; and polishing powders.

REEs can become commercially scarce or potentially problematic because of supply restrictions (e.g., for economic production considerations or potential export restrictions by producing countries for domestic national consumption priorities) [26], geopolitical reasons, or substantially increased demand in regional markets [9]. Furthermore, some of the REEs can also cause significant corporate social responsibility headaches for multinational companies because of, in some countries severe, conflict/human rights issues, such as the forced displacement of (what can be indigenous) communities, unsafe labor conditions, and the at times environmentally harmful features of mining/production as well as not yet fully solved waste hierarchy (avoid, reuse, recycle) issues at the production and consumptions ends [21].

Globally, China is still the leading producer of REEs in the world [14], followed a long way behind by the US, Myanmar, Australia, Madagascar, India [27], Russia, Thailand, Vietnam, and Brazil [28], but there are variations in terms of key countries depending on which REEs and CRMs are focused on. There are some further possibilities of producing critical raw materials, including rare earth elements, from primary resource sources in Europe [29].

1.5. Prominent Use Fields of REEs

REEs are used in the production of storage batteries, radar (and radiography) instruments, portable electronics (such as smart phones), advanced television sets, different kinds of electric vehicles (both light and heavy), energy systems, and permanent magnets, among others. Table 1 describes some of the ways they are used. As the problems of climate change and the pressure on sustainability responses grow, REEs are expected to receive more attention for the production of solar panels, electric motors, (hybrid, full battery, and fuel cell) electric vehicles and their batteries, wind turbines and their systems, and other energy systems [7], and they remain important as catalysts and ingredients in many domains (including petroleum refining, specialty steel, the glass and lighting industries, and the aerospace and defense industries) [17].

Table 1. REEs and their usages.

Name	Usage	Reference
	Light REEs	
Scandium (Sc)	As alloy additive in aluminum-based products (such as Al-Mg alloys) for strength. In “super-alloys”, such as in steel. Additionally, in NiMH batteries.	[6,19]

Table 1. *Cont.*

Name	Usage	Reference
Lanthanum (La)	In optics and lighting (e.g., lasers, LEDs, and fluorescent lamps, though these are being phased out), and more specifically in carbon lighting. Capacitors, sensors, and semiconductors. Additionally, in NiMH batteries, and super-alloys, AL-Mg alloys, and steel. Flat display electronics. X-ray imagining. Petroleum refining, automotive catalysts, and diesel additives. Water treatments. Fuel cells. Polishing colorants.	[19,30]
Cerium (Ce)	The catalyst for lighters. In carbon arc lighting. For glass polishing. In NiMH batteries, super-alloys, AL-Mg alloys, and steel. Flat display electronics. X-ray imagining. In capacitors, sensors, and semiconductors. Petroleum refining, automotive catalysts (converters), and diesel additives. Water treatments. Fuel cells. Polishing colorants.	[19,31]
Praseodymium (Pr)	In alloys for aircraft engines. In motors and generators more widely. For NdFeB magnets in lieu of Nd. In NiMH batteries, super-alloys, AL-Mg alloys, and steel. Magnetic resonance imaging (MRI) contrasting agents. In capacitors, sensors, and semiconductors. In flat display electronics. In addition, for X-ray and MRI imagining. In HD drives, microphones, and speakers. For petroleum refining, automotive catalysts, and additives. For water treatments. In fuel cells. For polishing colorants.	[19,26,32]
Neodymium (Nd)	Production of magnets incorporated into electronics, such as computers and cell phones. The basic element for the NdFeB magnets. It is widely used in many vehicle components, such as motors, brakes, speakers, doors, windows, and air conditioners. In NiMH batteries, super-alloys, AL-Mg alloys, and steel. Magnetic resonance imaging (MRI) contrasting agents. Also in HD drives, microphones, and speakers.	[19,26,33,34]
Promethium (Pm)	To produce atomic batteries incorporated into pacemakers and satellites.	[35]
Samarium (Sm)	In optical lasers.	[36]
Europium (Eu)	The most reactive REM and not so widely used. May be used in lasers. Flat display electronics. X-ray imagining. Capacitors, sensors, and semiconductors. In addition, in NiMH batteries, super-alloys, AL-Mg alloys, and steel. Flat display electronics. Petroleum refining, automotive catalysts, and diesel additives. Water treatments. Fuel cells. Polishing colorants. Fluorescent powders are used in lighting equipment, though this is being phased out by LED.	[19,26,37]

Table 1. *Cont.*

Name	Usage	Reference
	Heavy REEs	
Yttrium (Y)	As additive alloys (mostly with aluminum and magnesium) to increase the strength of materials. Can be used to produce YVO_4 europium and Y_2O_3 europium phosphors and gives the red color in color television sets. Flat display electronics. X-ray imagining. Fluorescent powders in lighting equipment, though this is being phased out by LED.	[19,26,38,39]
Gadolinium (Gd)	Not widely used but may be used in alloy production. NiMH batteries, super-alloys, AL-Mg alloys, and steel. Flat display electronics. In HD drives, microphones, and speakers. In capacitors, sensors, and semiconductors. For X-ray and MRI imagine contrasting agents. For petroleum refining, automotive catalysts, and diesel additives. Water treatments. Fuel cells. Polishing colorants.	[19,40]
Terbium (Te)	Calcium fluoride, calcium tungstate, and strontium molybdate are all used in the making of solid-state devices. Flat display electronics. X-ray and MRI imagining contrasting agents. In HD drives, microphones, and speakers.	[19,41]
Dysprosium (Dy)	The basic element in NdFeB magnets for a range of vehicle components. May feature in nuclear reactors. May be combined with other REEs in laser material. For magnetic resonance imaging (MRI) contrasting agents. In HD drives, microphones, and speakers.	[19,26,42]
Holmium (Ho)	In laser production. In capacitors, sensors, and semiconductors. In NiMH batteries, super-alloys, AL-Mg alloys, and steel. Flat display electronics. X-ray imagining. Petroleum refining, automotive catalysts, diesel additives. Water treatments. Fuel cells. Polishing colorants.	[19,43]
Erbium (Er)	During optical fiber production.	[44]
Ytterbium (Yb)	May be used in memory devices and lasers. Furthermore, as an industrial catalyst.	[45]
Lutetium (Lu)	As a catalyst for cracking hydrocarbons in oil refineries and the petroleum industry.	[46]
Thulium (Tm)	The least abundant REM. May be used in X-ray machines. Has the potential as an energy source.	[47]

2. Methodology

For this paper, the authors used a systematic literature review [48], with a number of critical key words (“rare earth elements”, “rare earth metals”, “critical raw resources”, “renewable energy”, “supply”, “demand”, “sustainability”, “markets”, “trade”, “technology”) adopted in a bibliographic search on scientific indexes/web engines of studies [Science Direct, Scopus, Google Scholar]. The abstracts of those papers were first scanned for relevance, and if they appeared to be within the scope of the investigation, the full paper was scrutinized. Because China acted as the then (and still) dominant market player in producing and exporting REEs, in 2010 it imposed some export restrictions [49]. As per the lead-in time of impacts, academic scrutiny, and academic publishing take about three years to be reflected in the peer-reviewed literature debate. Therefore, the authors chose to favor papers from 2013 onwards; they also favored more-recently published papers by authors who have published multiple works on the subject and favored very recently published papers because trends, pressure points, and potential strategies and management options are discussed in them and because of their state-of-the-art and contemporaneous applicability. The framing here stretched from applied geology, resource economics, and political economy to environmental sciences, and some directly pertained to policy fields. The abstracts of papers and the summary descriptions of edited books or monographs were preliminarily assessed for whether they met the inclusion criteria, namely covering REEs at the center of a much wider set of metals, minerals, and critical resources.

In terms of data analysis, a grounded theory approach was employed so as to understand and analyze the data collected from the published literature (articles, book chapters, monographs, reports, and directly pertaining industry analysis media). Although it is a flexible (and iterative) method, it is also a complex one and does not have a rigid framework; it can thus be tailored to a particular research project. The following steps were involved (see Figure 1): the sampling and thematically coding of the data; reviewing the emerging patterns of discussions (agreement and disagreements); familiarization with deeper points made by the respective authors; and clustering them to the point of saturation.

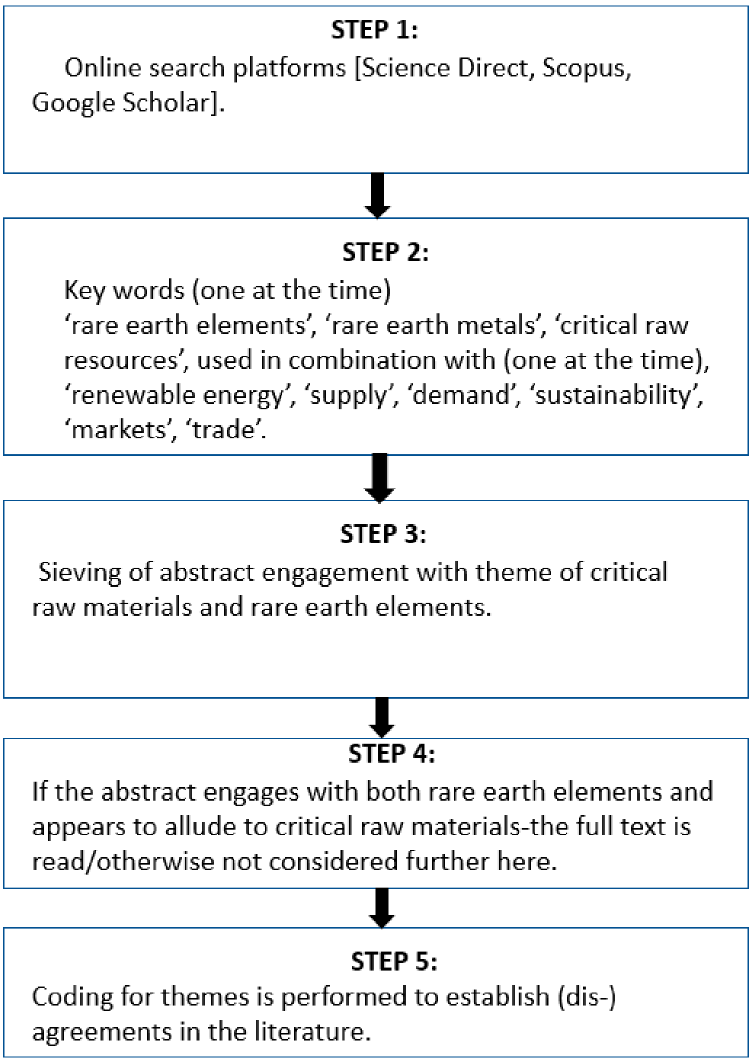

Figure 1. Flowchart of selecting articles/chapters/books coming into the sample frame (source: authors).

3. Results and Discussion: The Problems in Supply and Demand

While there are considerable agreements among the sampled literature (English-language only), there are at the same time diverging assessments and emphases. These concern multiple themes, including market concentration; parts of the production and value chains to be concerned about, as well as national or international perspectives, which forms of and actions within public policy (on balance) ought to be pursued by a range of concerned players (at sometimes local/regional levels but often mostly at the national level, with room or development for the international levels of governance, though the EU level is flagged up here within the external multinational/internal single common market), and finally which different methodological or focused takes on (aspects of) sustainability. The yield from the systematic review is summarized in Table 2.

Table 2. Themes emerging from the (sampled) literature (source: authors).

REEs are not geologically rare	but there are varied legislation/regulatory and financial barriers to accessing them.
Different REEs can be mined/extracted in various forms and by various processes	and these have different environmental/pollution profiles and thus different lifecycle sustainability ones too.
There are active assets and active reserves and those that could be activated,	and there could be further reserves, based on indications from geological explorative indicators.
There is some differential geographical/spatial concentration in REEs, but typically with alternatives in several countries and continents.	The activation and use (domestically and or for export to developing countries/world markets) depends in part on national policy instruments (which may change over time) as well as insertion of REEs suppliers and processors into downstream value chain activities.
The role of the state can be quite critical, including as a (political or commercial) partner for the private sectors (or in some cases through state ownership), as a regulator, and as an actor involved in encouraging benchmarking to standards	but the role of both multinational and national corporations in crucial in investment, processes, technological innovations, and compliance to (perhaps changing) regulations (including environmental) or activities to ensure enhanced corporate social responsibility/environmental, social and governance performance/reporting/accountability/brand image.
Sourcing from secondary sources, i.e., reuse and recycling, can be seen as increasingly promising	but also needs to be seen in the context of efficiency and needs to be subjected to lifecycle sustainability assessments.

The two sections below summarize in more detail the supply and demand problems of REEs.

3.1. Demand-Side Issues

REEs are increasingly needed in industrial ecosystems such as the automotive, renewable energy, high-capacity battery, defense, aerospace [50], and other industries that are putting efforts into developing high-tech devices.

The boom in technological advances in recent decades has led to increased demand for critical raw materials and rare earth elements across various industries, with wide-ranging applications [12] from the high-tech industry [17], defense industry, chemical catalyst, telecommunications (fiber optic cables, cell phones), electric car rechargeable batteries, silicon chips, medical applications, wind turbines, and LED lights [51]. The manufacturing industry's need for REEs (with regard, for instance, to permanent magnets, polishing, and alloy making) with the emergence of green energy is connected to an increase in demand for solar panels [12], chips [17], and smart batteries for alternative energy vehicles [52].

The fourth industrial revolution is also adding more pressure on the demand for REEs as more supercomputers with higher processing capabilities, robots, and other artificial intelligence accessories are needed. In 2019, estimates were that the global cell phone sales stood at USD 400 billion [51], with projections estimating an upward trajectory in demand being driven mostly by the diversification toward green energy and electric vehicles [17]. Furthermore, the REE market is also projected toward growth from USD 5.3 billion (2021) to USD 9.6 billion by 2026 at an anticipated annual growth rate of 12.3% [53]. It is also further projected that there will be significant demand growth for neodymium oxide, which is key in the production of magnets placed in electric vehicles, wind turbines, computer hard drives, and planes [17]. By 2020, the price per metric ton of neodymium oxide was USD 49,763; in 2025, it is expected to reach USD 77,500 per metric ton [17].

The automotive sector will likely need more REEs, as the traditional gasoline- and diesel-powered vehicle production will still require REEs (particularly Nd, Y, Ce, Eu, and Te), while the production of electric vehicles will push the demand for these materials (especially dysprosium and neodymium) because of the importance of neodymium magnets used in electric batteries, especially in the form of the alloy NdFeB. With the addition of Dy, NdFeB can also resist demagnetization at high temperatures. Many electric vehicle batteries also contain Ce and La [21]. Source [26] diagnoses, on the basis of scenario studies for the electrification (hybrid, plugin hybrid, battery and fuel cell electric vehicles) of China's automotive industry, that Nd, Dy, Ce, Pr, and La will increasingly be sought after (with, e.g., Nd and Dy normally in all NdFeB magnets), with the stress of balancing supply and demand for Dy and Pr intensifying. The intensity of this will depend on technological pathways. For instance, La and Ce (the main raw materials of NiMh batteries) optimize hydrogen storage. Source [26] also projects that in addition to the high demand for Ce in hybrid electric vehicles for NiMh batteries, automobile exhaust catalytic converters will increase the demand for it in hybrid and plugin hybrid electric vehicles. They also point to studies by [54] for the increased demand for driving motors and the NiMh battery of hybrid electric vehicles in Japan by 2030 (with significant recovery potentials), as well as [55] in terms of an increased demand for REEs contained in magnets, batteries, and fluorescent powders.

The growing importance of renewable technologies is also among the main factors that are increasing the demand for REEs in the sector, because they are important elements for the wind power industry for the production of turbines using Nd, Pr, and Dy and for the production of solar panels (indium, selenium, and tellurium) [51]. Therefore, the recycling of RE-containing products will have to be explored to ease some of the longer-term supply issues of REEs.

The end form in which REEs are traded (as oxides, metal, and alloys or in powders) depends on the industrial application and has shifted with changing industrial demand over the recent decades, with REE magnets, phosphors, and polishing powders now dominant [21]. For REE magnets, one of the most important application markets, alloys of neodymium and dysprosium are frequently used so as to avoid demagnetization at high temperatures, which is critical for devices such as laptops and tablets, TV screens, mobile phones, portable DVD players, and disc drives, which generate heat. In medical fields, devices such as X-ray and MRI equipment contain REEs, and in the military domain, for instance, fighter jet engines, missile guidance, antimissile defense systems, and space-based satellites and communication systems contain REEs. Steel, aluminum, and glass are other industrial application domains to change their functional properties. The addition of REEs to specialty glasses covers filters, lenses, light-sensitive and photochromic glasses, coloring/decoloring agents, X-ray and gamma-ray absorption properties, luminescence and fluorescence effects, and communication fibers. Innovations such as semiconductor lasers have also been enabled by adding REEs to glasses. REEs are also used as catalysts in many settings, such as La and Ce in the cracking of petroleum to produce gasoline [21]. Source [56] pointed out that permanent magnets with Nd, Sm, Gd, Dy, or Pr has enabled the miniaturization of many electric/electronic components in a range of devices, and it noted that magnetic refrigeration enabled by REEs could become significant. Most wind turbines contain Nd and Dy, but recycling these is only the beginning.

3.2. Supply-Side Issues

Source [57] argued that supply bottlenecks in countries processing and using REEs are a result of market failures. End-user industries across the world were not in tune with the criticality of REEs owing to the normally small share of production costs and did not become involved in keeping mines going. Major mining companies outside China were not focused on REEs as they have other high-volume ores to focus on. REE separation is difficult and specialized and thus handled by smaller companies, which have more difficulties in raising investment, and in any case, there is then a significant time lag. The supply market failures arguably apply to both domestic consumption vs. supply and international trade for REEs. Until 1995, the US was the biggest supplier in the world, and China gained its near monopoly only around 2002 [57]. A Chinese state export-restriction policy in 2010 from a dispute between China (domestically strengthening its technology-led industry and investing in not just mining but also processing capabilities) and Japan (whose advanced product exports often contain REEs) was subsequently settled when China lost a World Trade Organization case brought against it, but it still contributed to a (short-term) rare earths international supply crisis. Prices rose very significantly for many REEs in 2010/2011 more than ten-fold [58]. This in turn meant that a number of countries (Australia, followed by the US, Canada, and, with some delay, Brazil [59], Malaysia, Russia, Thailand, and Vietnam) saw the (re)opening [60] or expansion in established mines [61] and of known and accessible reserves [62]. From the end of 2016, global REE prices significantly rose again [63]. Sources [16,64] explain the "balance/balancing problem" between the economic market demand (through supply chains) of REEs and their natural abundance: avoid the over- or undersupply (production) of REEs because this would stabilize prices, reduce their volatility, and provide more investor security. This would mean to either find new uses for those REEs that are produced beyond current demands or substitute high-demand and limited-supply REEs with another [64] or with a non-REE if at all feasible (achieving the same or at least similar effectiveness) thanks to technological innovations [56]. REEs became the key focus of innovation for geoscientists and process engineers in enterprises, R&D labs, and universities after the price shocks of 2010/2011 to improve our understanding of the sources and geological deposits of future reserves as well as to make primary production and the recycling of secondary sources of REEs more efficient [65]. This was supplemented by material scientists and industrial engineers working on reducing or substituting the REE input in applications and products. Risk–value constructions matter in terms of efforts undertaken to close loops of rare earth elements in global value chains and how this is underpinned by (corporate as well as state) governance [66].

There is a general trend (Oddo–Harkins rule) that elements become geologically scarcer with an increase in atomic number; furthermore, elements with an even atomic number have more deposits than those with an odd atomic number [56]. Accordingly, reserves of the light REEs, Ce or La, are much higher than those for the heavy REEs, Dy, Eu, and Tb, though the heavy REE Y is also more abundant. This is also reflected in supplies and prices. There can be innovation trends that help to address the REE balancing problem and yield net environmental gains, such as using La and Ce as substitutes, where possible, for Pr and Nd in NdFeB magnets. Similarly, rechargeable La-Ni-H are beginning to replace Ni-Cd batteries in electronics and may perhaps eventually replace lead-acid batteries in the (conventional) automotive sector.

The author of [63] is skeptical of how much China can influence, distort, or dictate prices. China's price advantage is argued to be predominantly from lower labor costs and less-stringent (though increased in recent years) environmental standards; if it significantly raised prices, this would stimulate (further) REE production in other countries. However, in particular, the argued fragmentation of China's producers, with many small and diversified producers and exporters, results in disadvantages when negotiating prices with large international importers. The same source [63] points out that China is currently in a "low-end locking dilemma" as far as international trade is concerned, with the majority of its exports being primary materials rather than final products. Although China still has price and regulatory competitive advantages in lower value-added processes, it is lagging behind in the higher value-added processes. The latter is also reflected in industrial patents in key materials (such as REE magnets). The authors of [62], on the other hand, comes to different analytical results concerning the impact of China's state policies. They see global REE prices as largely dependent on China's domestic policies and further consider that international standards, Chinese imports of REEs, and global hoarding by countries and their environmental standards negatively affect REE supply resilience.

Source [49] cautions that we do not know, from the outside, enough about recent trends in consolidation into several large groups of domestic REE companies or enough about the significant Chinese overseas investments into REEs. Furthermore, China, as in the past, could develop different foci, e.g., extracting REEs from recycled materials from products at the end of their lifespan and/or keeping more of this within China with rising demand. By reviewing official Chinese policy documents, they distilled five sequentially linked phases of Chinese REE policies that were shaped by markets and players therein, the progression of the extractive industry, and the shape and state of the Chinese economy. In their analysis, this started from the encouragement and development of upstream value-adding activities in the mid1970s until the early 1990s. Following on from that, China reoriented its focus more on the furthering of downstream processing and products, where REEs are used in manufacturing intermediate and final commodities. From the 2000s onward, China has put additional emphasis on addressing issues to do with environmental impacts stemming from REE mining, processing, and production and on efforts to bring more from all industrial production into the official and legally approved domain.

While China over the past recent decades has had a near monopoly on the production of REEs overall [67], variously put at 85–95% in legal supplies (and hence ignoring the illicit producing and smuggling of REEs), perhaps one-third of the legal production according to [63], after 2010, the Chinese share declined to about 65% of oxide ores containing REEs as REEs have been increasingly produced elsewhere. The majority of REE resources, production, processing, and supply are currently located in Asia-Pacific [22].

Sources [68–71] argue that just now there is a new window of opportunity for non-Chinese processors and productive industries needing REE input, because China's domestic demand exceeds its domestic supply. This means that China would also need to source some REE supplies on global markets and therefore would find it less opportune to internationally control supplies or try to keep prices very high if it can by at times strategically limiting REE flows out of China (which they call "limit pricing"). Now would be the time for more US, federal administration, and other Western governmental financial backers to become more significant REE input producers via viable REE production and processing supply chains. Furthermore, they recommend that efforts focused on long-term solutions "should include stockpiling and recycling, increasing domestic production and refining, and investing in joint ventures with trusted strategic partners. In order to succeed, these ventures will require significant public investments and enduring public support".

According to the United States Geological Survey [6], the worldwide production of REEs was up between 2019 and 2020, including in the US but also Myanmar and Madagascar. US import compounds and metals obtained from Estonia, Japan, and Malaysia stemmed from concentrated minerals and chemical substances sourced from Australia, China, etc., which points to the international supply chains. Source [70] showed that Western green-tech companies sourcing REEs from Chinese suppliers experienced difficulties related to environmental supply credentials with regard to both the structures of the chains and environmental standards–related implementation issues, thus requiring the dynamic capabilities of sensing, alignment, and resilience.

Source [71] considers the imbalance in REEs in terms of supply and demand as primarily a self-imposed phenomenon in countries beyond China, primarily down to regulation barriers because thorium and uranium contain REE minerals accruing in conventional mining in several Western countries. The same source [71] does see a need for additional non-Chinese (or perhaps also Myanmar, etc.) REE resources with a corresponding emphasis on the further integration of REE product value chains. A recent panel regression study [72] has found evidence of especially fierce international competition by advanced economies/countries for REEs for their high-end value chains (Figure 2).

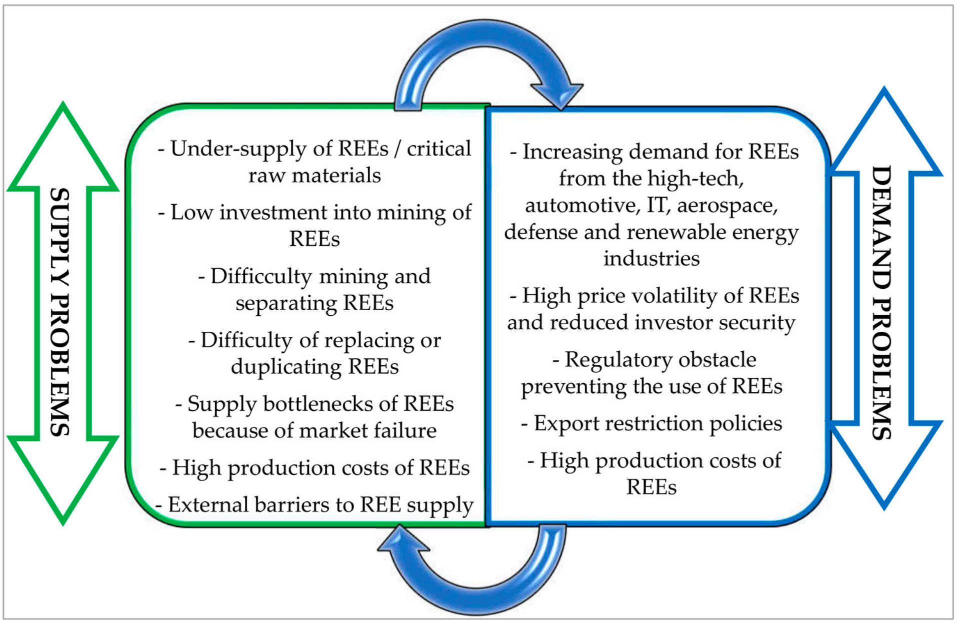

Figure 2. Summary of demand and supply problems of REEs (source: authors).

3.3. Future Pathways

Expert-based scenario analyses for specific REEs may help to better understand the modes and uses of specific REEs in supply chains, such as those performed for indium as a critical metal by [73]. This is likely to be needed, for instance, for metals such as Nd. Source [74] investigated the recycling potential of NdFeB permanent magnets, finding a knowledge gap in the detailed amounts of Nd in wind turbines (depending on type/model/generation, etc.), computer hard disks, and electric cars. Mobile phones are being argued to be not viable for Nd recycling, owing to only minute concentrations in them.

The methodological approach set out by [75] to assess the criticality of metals appears applicable to REEs also across three broad dimensions: supply risk (geological reserves and accessibility, active extraction, and direct and indirect factors influencing this process, such as social, regulatory, geopolitical, technological, and economic indicators). In addition, vulnerability to supply restrictions (e.g., export and import barriers) and environmental implications play roles in the process. A lifecycle sustainability assessment with a multicriteria indicator of REEs can help in this respect, as [76] has set out, based on the three broad dimensions of sustainable development. As the authors of [76] argue, evaluation models ought to be consistent across parameters and have short- vs. long-term stocks (reserves) and backups (including substitutions and recycling/reuse) built in.

It is believed that the recycling of REEs and CRMs [77] can be more economical than extraction from the source in the context of waste electrical and electronic equipment (WEEE) [56] and other secondary resources [78]. This includes end-of-life motors [79] and LED lights [80,81]. It is worth noting that the variety of final application and use forms of REEs presents challenges for their recovery [21] and recycling [82]. However, several rare materials have a high recycling potential, which is economically beneficial. For instance, they can be recovered from wastewater, which has been observed in acid mine drainage that provides an alternative economical method to regular extraction [83]. There are also possibilities from the coal-related material occurrences of REEs [72].

Source [56] notes the difficulties of increasing the recycling efficiency of, e.g., REEs in batteries owing to collection issues as well as techno-economic problems associated with the fact that they are present only in (very) low concentrations in WEEE (thanks to technological innovations in production) [84] and because they play only a small part in the material blend. Recycling routes should thus address both efficiency and environmental impacts [56].

There is now an increased interest from researchers in sustainability issues related to the mining and treatment of REEs. Researchers who work in this field are often concerned with the impacts of REEs on environmental systems and are studying the lifecycle assessment of REEs because they can be a source of contamination in several ecological systems [85] and generate several human-health risks [86].

Another stream that researchers are currently tackling is connected to the circular economy strategies by understanding, for example, how it is possible to adopt the recycling, recovering, or reusing of these elements, generating a reduction in the commercial tensions or the dependency on these elements and teaching how the industries could use the REEs in a more sustainable manner [83,87–90]. This would include recovering REE resources from the industrial production and disposal of waste where techno-economically feasible, with ongoing innovations in this field [19].

In the view of source [19], options for strategies for the more sustainable resource management of REEs include establishing stricter standards and regulations for the industry, reducing administrative barriers for reforms to the system, and cutting out illegal REE mining through more controls.

In addition, other measures to make the use of REEs more sustainable may include developing integrated market pricing and distribution systems for REEs rather than international "free" trade, encouraging investment into environmental improvements in the REE industry footprint, encouraging the participation of countries with a high annual demand in REEs to adopt more-sustainable practices, and promoting REE recycling from enriched wastes, end-of-life products such as consumer electronic devices [91], and other mostly neglected resources.

There are ongoing trends and (dis)agreements with regard to rare earth elements (REEs) (or rare earth metals) as a significant subset of critical minerals and critical raw materials. A more recent trend is a detailed focus on the possibilities and efficacy of the recovery (from byproducts and waste products) of REEs, including by (re)processing and recycling. Some possible substitutions of REEs, and perhaps less so replacement of REEs with the same physical and material performance, with non-REEs can be detected. Likewise, some emerging trends of a more efficient (i.e., volume reducing) use of REEs can be noted. To this, one can add some potential for the synthetic creation of some REEs. However, none of these take away the reality of tradeoff considerations at national or regional (economic and/or security) blocs with regard to supply security and supply chain management with regard to REEs, including supply chain disruptions and risks that may emerge (again) for economic or geopolitical reasons. Some balance of supply and demand (with substitutions trends) issues is likely to persist, and so, there may well have to be steers and signals that go beyond pure trade and commodity pricing on short-term platforms.

If the key players, that is, regional blocs, governments, multinational companies, and regulators (on environmental and public health grounds and accountability), are to be seen as credible and in line with the key targets of the UN Sustainable Development Goals, then a fully-fledged framework of lifecycle sustainability assessments for REEs also needs to be developed and implemented. There is a range of studies on lifecycle assessments (LCAs) for (specific) REEs (and from specific sources and locations) available (see e.g., [92] for a recent systematic overview, and see [93,94]), but these are more narrowly focused on an at times limited set of environmental aspects (and typically also exclude human-health risks connected with toxicity), with differing underlying inventories and thus similar yet different outcomes (even when there are the same process chains). What they do not deliver is a more rounded sustainability assessment, which includes other corporate social responsibility (CSR) or now environmental, social, and governance (ESG) dimensions (which include labor conditions and work safety, for instance), or an economic one with a trend and regulatory context analysis with a view to over- or under-supply and the investment interfaces. This is to be explored more fully in future research. Furthermore, this is arguably not as yet deeply applied or embedded, though discussions and some efforts have clearly started on circular economy models of some REEs [88], which is one link to the United Nation's Sustainable Development Goals (SDGs), though as yet with uncertain economic models underpinning them.

While there has been the development of frameworks on critical raw materials, for instance by the European Commission within and for the European Union, with updating at reasonably regular intervals, what is still needed is a move beyond the notions of lists, classifications, and (mostly industry-sponsored) "round tables" toward a fully-fledged horizon-scanning method and tool that is integrated across the domains listed above, beyond the purvey of (very) expensive applied consultancy market analysis tracking to investors and (stock market share) traders. This is a matter for follow-up research.

Source [21] cautions that the current and forecasted prospective rate of the consumption of REEs raises intergenerational ethical issues that need to be reflected on. Public health and toxicity exposure for workers and nearby residents as well as ecosystems, from potentially unsafe storage and disposal of some materials, including from mine tailings, need to be addressed under a Sustainable Development Goals perspective as well [21]. The (renewable) energy transition clearly does have a material basis in terms of modern technologies [95] as applied in an energy context [96]. Even though rare earth metals are not necessarily very "rare", they do have ecological, spatial, and economic [97] footprints to work through and variable availabilities depending on the strategies and trajectories of mining, production, and consumption [11,98]. This is especially so if we are to enter a post-oil and post-gas phase, with considerable potential for destabilization along that route [99].

As to future trends, there is a need to further explore suitable strategies for making the use of critical raw materials more sustainable [100,101]. The current war in Ukraine and the economic sanctions now imposed on Russia mean that the world's supply of rare earth metals is likely to be reduced, with a cascading effect on various sectors, such as the car industry and aviation, as well as across the electronic goods branch. This shows the need for more environmentally sustainable approaches toward handling REEs [102]. We need to be cognizant of some REEs' toxicity for human health if handled incorrectly [103], and need to develop tools and strategies to encourage more reuse and recycling for these important materials. In the context of sustainable development on the ground for communities close to the extraction processes, critical anthropological/sociological research on the burden and benefits [104] and investigative journalism on research, business/investment, and environmental practices [105] are also of major interest. Source [106], for instance, explores, through a case study in the northeastern borderlands of Myanmar, how Global North "just transition" to clean/decarbonized energy may create sacrifice zones in vulnerable and conflict zones, but nonetheless with a potential for a different supportive local development strategy there.

The issue of the potentials and efficacy of the recycling of REEs [107], as well as secondary sources [108] and production waste [109], will remain on the agenda and will need to be studied for different REEs in different contexts on an ongoing basis. This will be a part of the ongoing attention to the net environmental footprint of REEs and "clean energy" [110]. So will the ongoing development of the lifecycle analyses of REEs [111], including in energy applications [112].

4. Conclusions and Policy Recommendations

This paper has reviewed the current situation regarding critical raw materials, and REEs in particular. There are various concerns about the current use of these materials and in respect of future trends. These straddle extraction, processing, production uses, reuse/recycling/disposal, and the environmental (including carbon, energy and water) footprints of all of these, as well as the economic, geostrategic and security, social (including intergenerational), and spatial aspects of REEs in their industrial and social contexts. The paper points out the need for increased and sustained action in order to address problems related to the reuse and recycling of REEs, so as to make their use as critical raw materials more sustainable.

The results of this present study suggest some policy recommendations that the authors believe they should be deployed to support these efforts. First, the authors believe that legislative initiatives to reduce the quantity of rare earth contained in single-use products should be adopted. Second, there are policy opportunities to provide financial incentives to better improve recovery processes and the reuse of products containing REEs. Finally, the authors believe that research funding programs, which may be used to find suitable alternatives and substitutes for REEs, should be further explored [22]. This is important because they provide an opportunity to explore other options, especially those that may be more sustainable.

This paper has some limitations. First, it examined international trends on REEs without focusing on specific case studies. Second, the study did not include detailed cost–benefit assessments. In addition, the study did not examine future forecasts for exploitation and environmental impacts. Furthermore, this study did not have access to or did not use field explorations on site; nor did it directly process any trading data for REEs on the (legal) international and national markets. No direct expert interviews or surveys were conducted for this study; rather, published literature and grey literature were used. Despite these limitations, the paper is a welcome addition to the literature because it sheds some light on the ways REEs are perceived and are being internationally used.

Author Contributions: Conceptualization, W.L.F., R.K., P.G.Ö. and I.R.A.; methodology, W.L.F., R.K.; formal analysis, W.L.F., R.K., P.G.Ö., I.R.A., N.R.M. and J.H.P.P.E.; investigation, W.L.F., R.K., P.G.Ö., I.R.A., N.R.M. and J.H.P.P.E.; resources, W.L.F., R.K., P.G.Ö., I.R.A., N.R.M. and J.H.P.P.E.; writing—original draft preparation, W.L.F., R.K., P.G.Ö., I.R.A., N.R.M. and J.H.P.P.E.; writing—review and editing, W.L.F., R.K., P.G.Ö., I.R.A., N.R.M. and J.H.P.P.E.; visualization, W.L.F., I.R.A., P.G.Ö., N.R.M. and R.K.; supervision, W.L.F.; project administration, W.L.F. and R.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: There was no Ethical Approval necessary at institutional level for this research, as it drew on secondary and non-sensitive resources only.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: This paper is part of the "100 papers to accelerate the implementation of the UN Sustainable Development Goals" initiative.

Conflicts of Interest: The authors declare no conflict of interest.

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