Constraints to rare earth supply diversification: Evidence from an industry survey

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Abstract:

Rare earth elements (REEs) are crucial to accomplish renewable energy targets throughout the world, including electrical vehicles and wind energy. Despite the extensive requirements of REEs, current supply chains are mainly fulfilled by the Chinese rare earth (RE) industry. This typically results in price volatility, supply chain uncertainties, and RE trade disputes. 13 different factors were identified as constraints to develop RE supply chains outside China and these constraints were rated by the major RE companies outside China, including RE industry experts. The survey results obtained from RE industry experts have been statistically analysed to ascertain the key factors that affect the development of independent rare earth (RE) supply chains outside China. 4 key factors were identified as statistically important, among them, business uncertainties within the RE industry and the Chinese RE influences on global supply chains being the dominant factors that have inhibited the development of supply chains outside China.

Keywords: Independent Rare Earth Supply Chains; Electric Vehicles (EVs) and Magnets; Rare Earth Elements (REEs); Rare Earth Industry; Renewable Energy; Sustainable Development Goals (SDGs)

Abbreviations:

CAGR	Compound annual growth rate
Ce	Cerium
DOD	Department of Defense
Dy	Dysprosium
Er	Erbium
EU	European Union
Eu	Europium
EV	Electric Vehicle
Gd	Gadolinium
GW	Gigawatts
HEV	Hybrid electric vehicle
HREEs	Heavy rare earth elements
IMC	Innovation Metals Corp.
KMO	Kaiser-Meyer-Olkin
La	Lanthanum
LAMP	Lynas Advance Material Plant
LREEs	Light rare earth elements
Lu	Lutetium
MW	Megawatts
Nd	Neodymium
NdFeB	Neodymium-Iron-Boron
PCA	Principle component analysis
PHEV	Plug-in hybrid electric vehicle
Pr	Praseodymium

R&D	Research and development
RE	Rare earth
REEs	Rare earth elements
REIA	Rare Earth Industry Association
REOs	Rare earth oxides
Sc	Scandium
SDGs	Sustainable development goals
Tb	Terbium
Y	Yttrium

1. Introduction

REEs have been a topic of several recent discussions among researchers, entrepreneurs and politicians. It implies the significance of these elements in the current technological developments, especially in transition to green energy, as REE based permanent magnets are extensively used in wind turbines and EVs (Figure 1). REEs play a vital role also in electrical and electronic equipment such as mobile phones, hard disk drives and fluorescent and LED lamps (Balaram, 2019), defense applications (Mancheri et al., 2013), Catlaysts (Schmid, 2019), high tech (e.g. Haxel et al., 2002) and pharmaceuticals and medicine (Ascenzi et al., 2020). Presence of REEs in living systems and their mobilisation could be used to design niche diagnostic procedures (Ascenzi et al., 2020), though this is still very much in its infancy.

The 15 lanthanides in the periodic table, atomic numbers from 57 (La) to 71 (Lu), plus Sc and Y are known as REEs. These 17 elements are further categorised as LREEs and HREEs. The former consists of La to Eu, while the latter includes Gd to Lu plus Y. Some of the elements experience a high demand than the other due to their critical applications (Dushyantha et al., 2020). For example, Nd and Pr, both are LREEs, are employed in wind turbines and EVs (Ji et al., 2021).

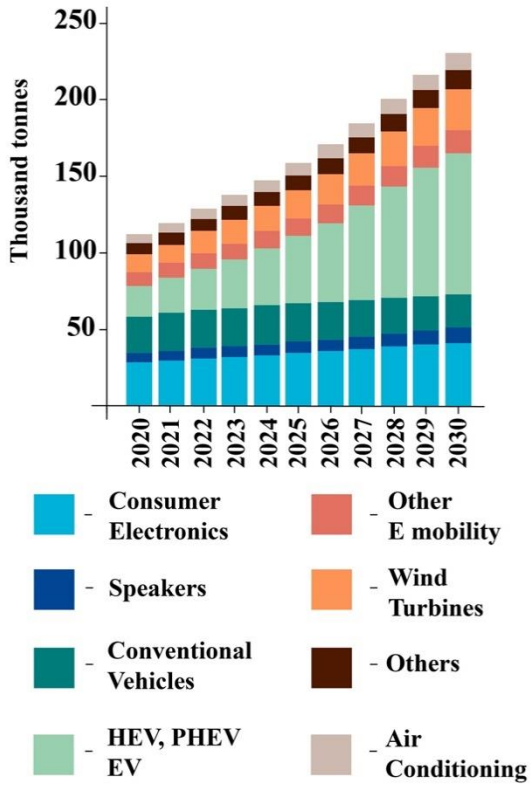


Figure 1: Forecast of NdFeB magnet consumption (Source: Arafura Resource Limited, 2020).

Renewable energy developments are of paramount importance to achieve the United Nations sustainable development goals (SDGs), such as affordable and clean energy (SDG 7), sustainable cities and communities (SDG 11) and responsible consumption and production (SDG 12). In line with this, all major industrialised countries have declared to be carbon neutral by 2050 (e.g. USA - Althaus, 2020) and have set targets to phase out gasoline-based vehicles (Li et al., 2019). Several car manufactures have recently announced their clean energy goals. Car manufacturers, such as Ford (Ford, 2021), Bentley (Jolly, 2020), Volvo (Jolly, 2021), Toyota (Toyota, 2021) and Volkswagen (Volkswagen Newroom, 2021) have declared to produce only EVs by 2030-2050. The global EV sales in 2019 were 4.57 million units, consuming 2624 tonnes of RE magnet materials for traction motors (Adamas Intelligence, 2020). Particularly, about 1.5 kg of Nd is

required for an EV motor (Leotaud, 2018), whereas Toyata's Prius hybrid car motor employed 1 kg of Nd (Horrocks, 2020). The European Commission targets 30 million zero-emission vehicles by 2030 and aims for 60 GW of offshore wind by 2030 and 300 GW by 2050 as it seeks to steer countries away from fossil fuel-based energy and transport (European Commission, 2020). On average, an offshore turbine requires up to 232 kg of NdPr/MW, which means by 2030, the EU excluding the UK would require about 13 thousand tonnes of NdPr, and by 2050, 69.6 thousand tonnes only for wind turbines (REIA, 2020). Figure 1 illustrates the forecasted consumption of Nd based magnets in different sectors until 2030.

Since clean energy transition demands diversified REE applications in a broader spectrum of industries, the global REE market is experiencing a significant growth (Silvestri et al., 2021). It is envisaged that the growth would be 10% per annum over the next 10 years (Jyothi et al., 2020; Kramer, 2021). RE permanent magnets, for example, currently share about 30% of the RE market (Schmid, 2019) as the largest segment of REE applications (Mancheri et al., 2019) and expect to achieve the highest growth by 2030 due to their high demand in EVs and renewable energy. The world's biggest renewable energy companies, such as Enel, Iberdrola, NextEra, and Orsted, have surpassed major oil companies and have been accelerating their renewable energy developments (Eckhouse et al., 2020). Therefore, maintaining a steady and reliable REE supply is required (van Exter et al., 2019) and Fishman and Graedel (2019) addressed future Nd requirementes. In addition, a recent Bloomberg report predicted an estimated investment of 11 trillion dollars in the next 30 years for solar and wind energy (Eckhouse et al., 2020).

China possesses 36% of the global REE reserves or 44 million tonnes (Figure 2a) with mine production share of 62% in 2019 (Figure 2b) (U.S. Geological Survey, 2020). More critically, REE separation and purification is challenging from both an environmental (Packey and Kingsnorth,

2016) and technical perspectives (Ilankoon et al., 2018) and the majority of these operations are restricted to China (Green, 2019). RE concentrates produced in the USA and Myanmar are currently exported to China to carry out the final separation and purification processes. RE production is often expressed as REOs. China accounted for 84% of the total REO production or 132,000 tonnes in 2019 (Figure 2c) (Global Times, 2020). In addition, due to the ever-improving refinery and metallurgical technologies, China still maintain a commanding presence in the REE-related patent portfolio. Since 1983 to October 2018, China filed 25,911 RE related patents (mostly in China), while the USA, Japan and EU filed only 9,810, 13,920 and 7,289 patents, respectively since 1950. China possesses more patents than the sum of the patents owned by the rest of the world each year since 2011 (Figure 2d). It is estimated that China will accumulate more RE patents than the rest of the world combined by 2021.

The Chinese dominance of the RE market has often resulted in supply chain uncertainties (Inoue, 2010). The RE trade war between Japan and China caused the rare earth crisis in 2010 and 2011 (Mogi, 2011) (Figure 3). The USA is almost depended on China for its REE requirements. The USA-China trade disputes in 2019 again resulted in RE supply chain uncertainties (Schmid, 2019). Globally these supply chain uncertainties have been exacerbated by the COVID-19 pandemic and has caused the supply chain disruptions (Figure 4) (Akcil et al., 2020). The Chinese export control law introduced in December 2020 (Yeping, 2020) highlights the goals to produce value-added RE products in China rather than simply exporting REOs (Baruzzi, 2020). These export restrictions are not considered to be a breach of the international trade laws set by the world trade organisation (Hui, 2020). This could also lead to additional RE supply chain uncertinities and the potential for price hikes in the future (e.g. Mancheri, 2015).

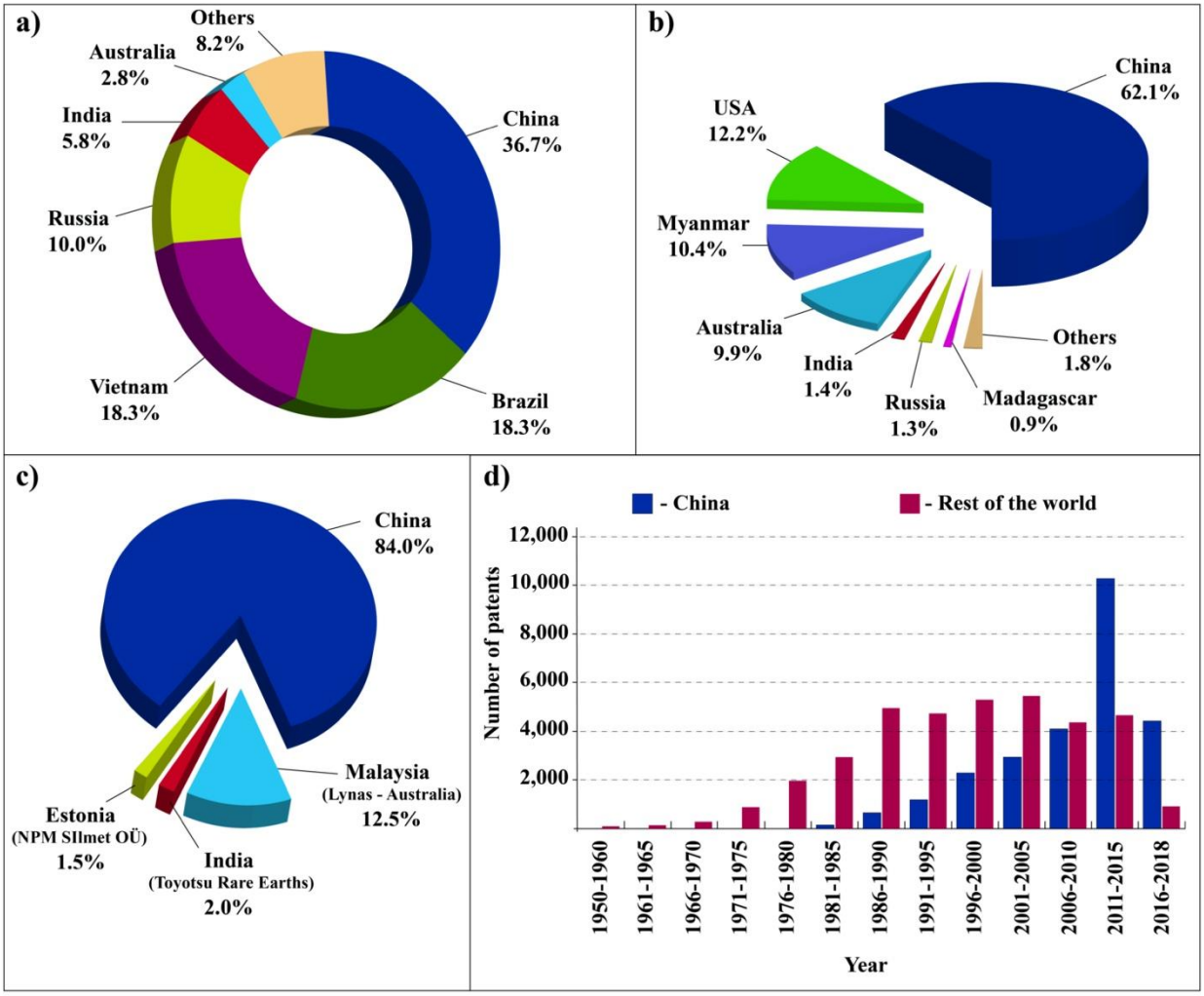


Figure 2: (a) Global RE minerals reserves (Source: U.S. Geological Survey, 2020), (b) Global RE mine production in 2019 by country (Source: U.S. Geological Survey, 2020), (c) Global REOs production (Source: U.S. Geological Survey, 2020), and (d) Global RE patent filings by China and rest of the world (Source: Eric, 2019).

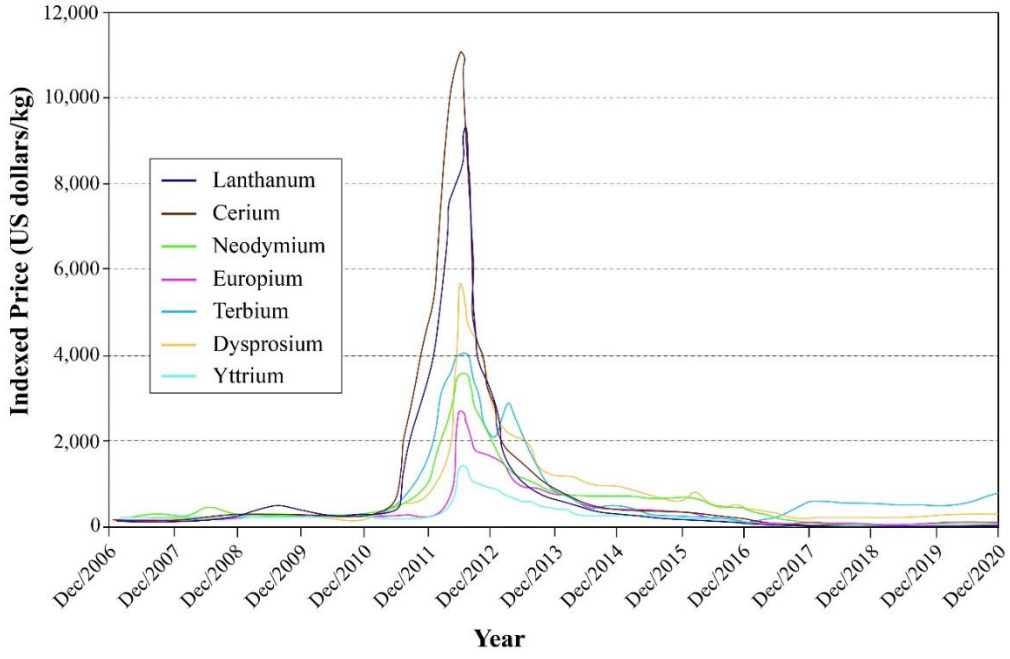


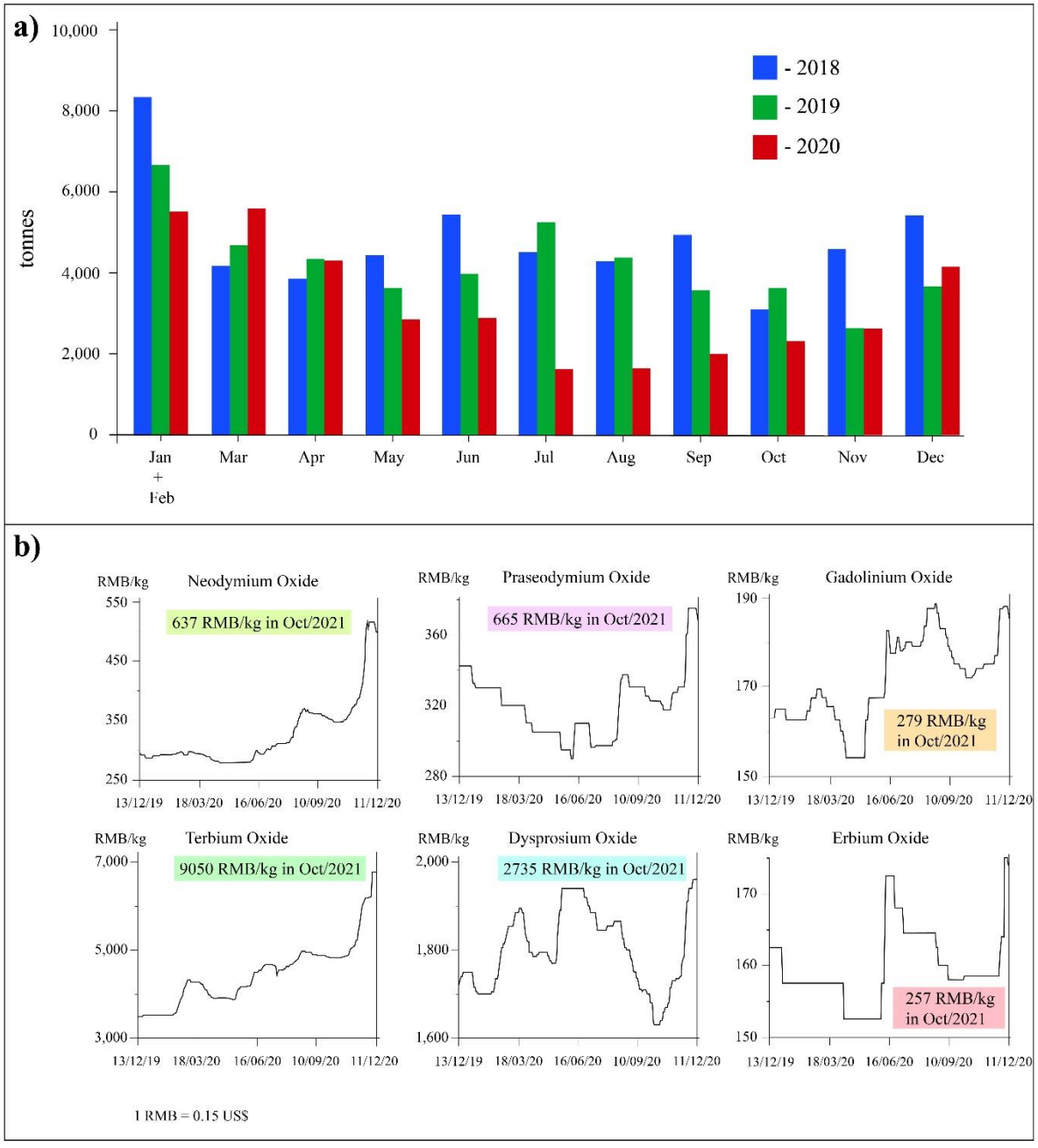
Figure 3: Indexed prices of selected REOs from 2006 to 2020 (Sources: Argus, 2017; Dushyantha et al., 2020; Institute of rare earths elements and strategic metals, 2020a, 2020b; Statista, 2021).

Australia predominantly produces RE ores from Mount Weld deposit and was the second largest RE producer in the world from 2015 to 2020, though the contribution was about 10% in 2019 (Fig. 2b). The Western Australian Mount Weld deposit is known as one of the highest-grade RE deposit in the world. Since 2011, Lynas, a group listed in Australia, processed the RE ore from this deposit in their concentration plant near Laverton in Australia. The shipped concentrates are purified at the LAMP in Malaysia. The LAMP is the world's largest single RE processing plant outside China. REOs production of Lynas during the 2020 financial year is around 14500 tonnes (Smith, 2020).

Given supply chain uncertainties and the likely rapid increase in the demand for REEs, the identification of the main barriers on the development of sustainable RE supply chains outside China is of immense importance in the current global context. Main constraints to develop RE

179 projects outside China are identified in this work based on an indutry survey conducted with major

180 RE companies outside China.



181

182 **Figure 4: a) China's monthly RE exports from 2018 to 2020 (Source: Argus, 2021; Meihan,**

183 **2021) b) price fluctuations of main REOs in China from Dec 2019 to Dec 2020 (Source:**

184 **Shanghai Metals Market, 2020).**

2. Methods

2.1. Methods – Identification of constraints to develop RE projects outside China

There are several key challenges to commission RE projects outside China. Addressing these are of paramount importance to establish RE mines, purification and separation plants, and projects that manufacture rare earth products outside China. A detailed literature survey on REEs and RE industry, the authors identified 13 factors (see below and Figure 5) that hinder RE project developments outside China. RE industry experts subsequently rated these 13 factors (section 2.2).

1) Complexity to establish RE separation and purification plants

REEs separation is typically achieved by both acid and alkaline leaching depending on ore types and purification techniques, such as fractional crystallization, fractional precipitation, solvent extraction and ion exchange are reported in the literature. RE separation and purification methods are often complex and involves a number of intermediate steps (Royen and Fortkamp, 2016). Existing RE separation and purification flowsheets employed by the RE industry are not reported in detail.

It would be relatively easy to produce RE concentrates outside China (e.g. Mountain Pass deposit, USA). However, the RE patent comparison between China and rest of the world (Figure 2d) demonstrates technological lead China possesses on purification and separation technologies. This barrier adds complexity to commission separation and purification plants outside China (McClearn and McGee, 2020). It is supposed that the failure of Mount Pass in 2008 caused partly due to niche, though unreliable technologies. Once the RE prices were high (e.g. during the trade dispute between China and Japan in 2010 and 2011), those would work, if not process economics would not be guaranteed (Green, 2019). Lynas plant is the largest RE purification and separation plant

outside China. This observation also demonstrates the technological challenges to establish RE separation and purification plants, elsewhere in the world. Without those, it would be difficult to alleviate the Chinese RE supply chain disruptions and price fluctuations (Lasley, 2020).

Since China possesses extensive RE purification and separation expertise, China continuously imports RE concentrates from other countries, mainly from the USA and Myanmar, for downstream processes (Argus, 2020). Myanmar primarily supplies ion adsorption clay RE concentrates as mixed RE carbonates, RE oxides and compounds of RE metals. China imported 28893 and 35539 tonnes of RE concentrates from Myanmar in 2019 and 2020, respectively. Myanmar's military seized the power of the country on 1st February 2021 and this would not disrupt long term Chinese RE imports from Myanmar (Yang, 2021). Even if RE purification and separation plants are operational outside China, the strong Chinese RE imports, especially from Myanmar, could reduce the available RE concentrates for these plants (Mancheri et al., 2019). It is expected that this aspect further dampens the investor's interest to commission RE extraction plants outside China.

2) High operational costs of RE separation and purification plants

Complexities of RE purification and separation flowsheets incur relatively high operational costs. It is alleged that the Chinese producers alleviate certain fraction of it due to lenient environmental standards, cheap waste management methodologies, and low wages (Lasley, 2020). Since the same is highly unlikely in a plant outside China, for example in the USA, Canada, Europe and Australia, it is supposed that RE plant operational costs and prices could be high (i.e. less competitive advantage). Lowering RE extraction costs are identified as a critical factor to establish RE supplies in the USA (Tracy, 2020).

3) Lack of large scale R&D to develop niche RE separation and purification techniques

The state owned Chinese rare earth industry is well established due to the significant government investments in R&D (Schmid, 2019). This is clearly evident based on the Chinese production monopoly, including the increased quantities of RE ore imports to be processed in China (Argus, 2021), supply of several RE products and the dominance in intellectual property (Figure 2d). Similar large-scale R&D centres are not yet fully established outside China and this hampers the development of novel, efficient and sustainable RE extraction, purification and separation, and waste management technologies.

4) Lack of RE recycling and challenges associated with RE recycling

Recycling considered to be an important aspect to alleviate RE supply change uncertainties (Binnemans et al. 2013), though it possesses a myriad of challenges (Binnemans et al., 2021). Despite the significant research interests to recycle RE containing materials (e.g. Jowitt et al., 2018) to alleviate the dependence on the Chinese RE imports and significant funding allocated to that sector, industrial plants are not fully developed (Cole, 2019). Very high recycling rates of equipment and components containing REEs will be required to extract a significant fraction of REEs. This could be indeed challenging since circular economic strategies are not widely implemented in most of the countries, especially in developing countries. It is thus expected that recycling alone is not the ideal pathway in the short- to medium-term of securing RE supplies outside China, though it will be a long-term solution. Once high capital-intensive large-scale metal recycling facilities are established, a relatively stable material supply is firstly mandatory. This greatly depends on the life time of RE applications. For example, wind turbines possess a life time of approximately 25 years (van Exter et al., 2019). Since renewable energy sector is not yet

saturated, a stable material supply is highly unlikely. Secondly, waste management in RE recycling could be challenging and requires extensive research studies.

5) Challenges associated with RE substitution technologies

Wind turbine permanent magnets with Nd and Dy are most efficient, though RE substitution was the focus during a RE crisis when the prices were high (Riba et al., 2016). This was the case in 2010 when Nd prices were high. The permanent magnet manufactures adopted strategies to reduce Nd consumption. In certain cases, the drawback would be the suboptimal performance. Even though the substitution of RE metals is appreciated, significant RE substitutions need to be accomplished to alleviate the Chinese RE supply chain pressures. The critical drawback would be substitution only shifts the burden onto another material. The Chinese mining industry supplies several metals, including critical metals, and thus RE substitution through another critical metal imported from China may not be the ideal solution (van Exter et al., 2019). Reduction of REEs through substitution should go hand in hand with RE project developments outside China to minimise the adverse effects of the Chinese RE monopoly.

6) Variability of ore geology compared to the Chinese RE resources

REO percentage is a common indicator to express the grade of a RE deposit. However, this does not necessarily translate to ease of RE extraction. Ores consists of 8% REOs at Mount Pass deposit (i.e. high grade) require extensive and expensive RE purification and separation steps, while the ion adsorption clay deposits having 0.05% REOs (i.e. low grade) in southern China can be easily processed using simple mineral processing techniques (Weng et al., 2015) and Ilankoon et al. (2018) discussed those in detail. Similarly, it was found that some RE ores in Canada are much harder to process (McClearn and McGee, 2020). Despite the presence of ion adsorption clay RE

resources in other parts of the world (e.g. Borst et al., 2020), those have not been developed as industrial RE projects to lower the processing costs of REEs. It would be a niche area of RE research to compete with the Chinese RE prices.

7) **Waste management challenges**

Waste management in RE purification and separation has been a paramount challenge that dampens the establishment of RE extraction plants outside China. Collapse of Mountain Pass mine in 2002 is imputed to RE waste management challenges and significant costs associated with it. Once it is reopened by MP Materials, the produced RE concentrates are exported to China to alleviate waste management challenges in the USA (Green, 2019). Presence of uranium and thorium in RE ores increase the processing costs significantly (McClearn and McGee, 2020). High volumes of toxic waste generation thus deter private sector investments pertaining to RE purification and separation (Citizens for National Security, 2020). Lynas RE purification and separation plant was commissioned in Malaysia despite the public unrest on hazardous waste management (Ismail et al., 2016). In January 2020, Lynas announced their plans to establish a permanent disposal facility in Malaysia for water leach purification residue through a local contractor and it costs USD 98 million until June 2026 (Lynas, 2020). It is alleged that the state-controlled Chinese RE companies accomplished their industry hegemony through lax standards of environmental protection and waste management (e.g. Palmer et al., 2010). Strict environmental protocols for RE extraction facilities outside China will undoubtedly increase RE market prices to yield the RE businesses, which are less price competitive compared to the current Chinese RE market prices.

8) Uncertainty in business due to RE price volatility

The key aspect of RE business would be the establishment of strong supply chains (Green, 2019). Without those, uncertainties would arise that may discourage the investors considering the established and proactive supply chains incorporated with the Chinese RE industry (Hui, 2020). There were several potential new resources and the interests by mining companies to capitalise those in Canada and Australia rejuvenated by the price peaks due to the China-Japan RE trade war in 2010-2011. The RE prices were subsequently dropped that literally wiped out the hype, including some of the RE companies in Canada (e.g. the Strange lake project by Quest Rare Minerals) (McClearn and McGee, 2020). Similarly, in the USA, the reopening of Mount Pass mine by Molycorp in 2010 was futile and the company declared bankruptcy in 2015 (McClearn and McGee, 2020). These show the difficulty of getting competitive advantage for companies outside China over the RE business in China. The USA government considers tax break to establish new supply chains and this is considered to be a positive sign (Horrocks, 2020). Prior to the COVID-19 pandemic, it is envisaged that the RE market grows at a CAGR of 8% until 2024 (2019-2024) (Horrocks, 2020), though the pandemic may cause RE project delays outside China for a significant duration.

9) High capital costs and lack of government support and subsidies

Considering the investment and the uncertainties associated with it, government support is mandatory for RE businesses outside China. It is envisaged that a RE mine development costs an investment of order hundreds of millions of dollars (Kalantzakos, 2020). The Chinese RE business was strongly supported by the Chinese government since the late 1990s (Schmid, 2019), though it was not the case in the USA considering the struggling Mount Pass mine in mid 2010s (Lasley, 2020). Underdevelopment of the Canadian RE resources are also partly due to high capital costs

(Friedman, 2019). Favourable conditions are recently subsequently reported (section 4) and, for instance, USD 9.6 million funding is recently allocated to a company that refines REEs for the defence sector in the USA (Jennings, 2020).

10) Lack of interest from investors

The ministry of land and resources in China recommended RE stockpiling since 2012 to control the global RE industry. The Chinese state reserve bureau initiated RE Stockpiling in late 2014 (Brown and Eggert, 2018). Some of the HREEs, namely, Lu, Tb and Er, are produced in limited quantities. Once the stockpiled fraction is significant with respect to the global annual production, price hikes are expected and those spur investments outside China (e.g. mimics RE price hikes during China-Japan trade war in 2010-2011 that spurred investments outside China, including soaring stocks of Molycorp). Price drops are expected when these stockpiles are released and this results in marginal RE businesses outside China (Mancheri et al., 2019).

11) Supply chain pressures on global RE companies

Relocation of global RE plants to China to secure RE supply chains is considered to be a resultant of restricting the Chinese RE exports (Inoue and Gordon, 2011). Joint ventures with Chinese companies undoubtedly strengthen the Chinese RE business. Japan's position as a dominant NdFeB magnet producer is diminished due the shifting of Japanese companies to China and technology transfer could be a potential factor. Such supply chain pressures on global RE companies jeopardise RE projects outside China (Schmid, 2019). Even though new RE projects are started outside China, this would make serious challenges to establish new supply chains for these new projects.

12) Chinese RE interests outside China

It is supposed that the new RE projects outside China still possess the Chinese influence in terms of investments in active projects. Chinese companies offered investments for the Longonjo project in Angola (Thicknesse, 2020). Mountian Pass project in the USA is currently run by MP Minerals, though a Chinese company, Shenghe Resources, possesses 9.9% share (Horrocks, 2020). The Kvanefjeld REE project (see below for project updates) in Greenland is owned by Greenland Minerals with major investments from Shenghe Resources (Zeuthen, 2017). Pulmoddai heavy mineral beach sand deposit and Eppawala phosphate deposit in Sri Lanka possess significant rare earth extraction potential (Batapola et al., 2020). If a rare earth project is developed, the involvement of strong Chinese state-owned companies is highly likely due to the strong political ties between the two countries. These examples demonstrate the political challenges of initiating independent rare earth projects outside China.

13) Lengthy legislative processes in countries outside China to commission RE projects outside China

Lengthy project approval processes, including environmental impact assessments cause delays in executing RE projects outside China. For an example, lengthy Swedish legal proceedings on Tasman Metals, a subsidiary of Leading Edge Materials, during the development of Norra Karr project in Sweden illustrate this aspect (Leading Edge Materials, 2017). Since this also discourages the potential RE investors, approve prudent policies and expedite project approval processes are considered to be significant. If a RE project approval takes a lengthy duration compared to the same in China, if would simply put China in the commanding position while resulting in too slow progress of the project outside China.

2.2. Methods - RE industry experts survey and statistical analysis

RE industry experts were consulted to rate the each factor (13 factors in total) explained in section 2.1 with score ranging from low importance (score 1) to high importance (score 5) on the development of independent RE supply chains outside China.

30 rare earth industry experts largely representing the RE companies outside China provided their responses for the 13 factors in section 2.1 and this sample size (i.e. 30) is significant as RE industry is relatively a small business. In addition, the KMO was used to measure sampling adequacy, which is a tool to identify the proportion of variance in variables. The KMO measure exceeded the 0.5 cut-off value and this implies that the sample size in this work is adequate.

Geographically, among the respondents 15 industrial experts are located in Europe including the UK. The industrial expert counts for Australia/New Zealand, the USA/Canada and Asia excluding China are 6, 5 and 3, respectively. In addition, the RE industry background of these experts can be categorised as follows based on their main areas of engagement with the RE industry: RE business development (11), RE project development (11), RE related research studies in a university/research centre (5), RE policy development (1) and other RE related fields (1).

2.3. Methods - Statistical analysis of survey data

The authors employed exploratory factor analysis to identify the groups of variables that are highly intercorrelated since the individual analysis of the 13 variables in this study would be difficult. SPSS software was used in this analysis. In addition, this helps to identify the key factors in the development of RE projects outside China. PCA reduced the original components (13) to 4 components based on the Eigen value principle (greater than 1 – Figure 5a). Bartlett's test was also performed and was significant, which indicates that there is a correlation between at least two out

of 13 variables. Communalities were thus calculated. The large values indicate a high proportion of variance of each variable (13 variables) and those can be explained by 4 factors. Since the initial component matrix possesses cross loadings for certain components, and no significant correlations were shown among the 4 factors, variable maximisation or Varimax rotation was employed to yield the rotated component matrix (Figure 5b). Once 4 components were obtained using Varimax rotation (Figure 5c), reliability was tested for all the components. In that case variable 13 (V13) was included in component 1 to improve the reliability even though it possesses the second highest factor loading. In addition, to identify the importance of each component, one way analysis of variance was conducted using the component score coefficients.

3. Results – RE Industry Expert Survey

Based on the RE industry survey, 4 key constraints or components were identified based on the scores of 13 variables for exploratory factor analysis of establishing RE supply chains outside China (Figure 5a).

6 inter-correlated variables resulted in the component 1 (Figure 5b). This primarily addresses two aspects, namely, RE business uncertainties outside China, including high capital costs (variables 8, 9, 10 and 13) and Chinese RE interests outside China (variables 11 and 12). The former aspect seems the dominant one due to high factor loadings assigned to it.

Component 2 (Figure 5b) inter-correlates 4 variables related to RE substitution (variable 5) and recycling (variable 4) challenges, costly waste treatment operations (variable 7) and lengthy legislative hurdles to initiate new RE operations (variable 3). Industrial scale RE recycling is not yet extensively established outside China to generate a significant amount of REEs from secondary RE resources. RE substitution has been applied to a certain extent, though it would not replace the

406 requirement for independent RE supply chains outside China. Waste management challenges,
407 costs and legislative requirements have delayed the development of RE mines and separation and
408 purification plants.

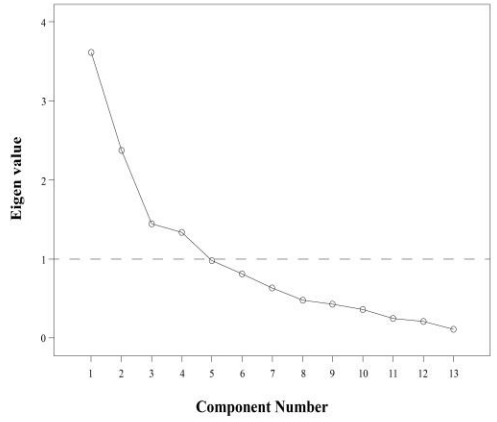
409 2 variables, namely, high operational costs (variable 2) and complexity of RE separation and
410 purification plants (variable 1) resulted in the component 3 (Figure 5b). China attained their RE
411 dominance through developing effective RE separation and purification technologies in the last
412 couple of decades. This paramountcy even leads to significant RE concentrate imports to China to
413 carry out downstream processes. Development of economic RE separation and purification plants
414 outside China would be crucial to address this challenge and establish independent RE supply
415 chains.

416 Component 4 or variable 6 (Figures 5b, 5c) ascertains how ore mineralogy of RE resources affects
417 the development of RE mines and separation and purification plants. The presence of radioactive
418 elements in RE minerals increases the costs of mining and processing. China possesses ion
419 adsorption type RE resources and these are much easier to process compared to other RE resources
420 (Ilankoon et al., 2018; Dushyantha et al., 2020). Despite the potential availability of ion adsorption
421 type RE ores outside China, the projects are not yet initiated except the one developing by Ionic
422 Rare Earths in Uganda.

423 There is a significant difference in mean values. Component 1's mean is clearly different compared
424 to those of other 3 components (Figure 5d). The confidence interval of component 1 is thus disjoint
425 from the confidence intervals of the remaining 3 components, though the confidence intervals for
426 other 3 components have intersections. Component 1, Chinese RE supply chain controls and RE
427 business uncertainties, is thus the single most important factor according to the statistical analysis,
428 that dictate the development of independent RE supply chains outside China. It does not

necessarily imply the other factors are statistically insignificant. Government funding support schemes could alleviate the business uncertainties of developing RE projects outside China. In this context, recent funding approvals by the US DOD for both Lynas and MP Materials (section 4) to develop independent RE supply chains in the USA is a relevant case (US DOD, 2020).

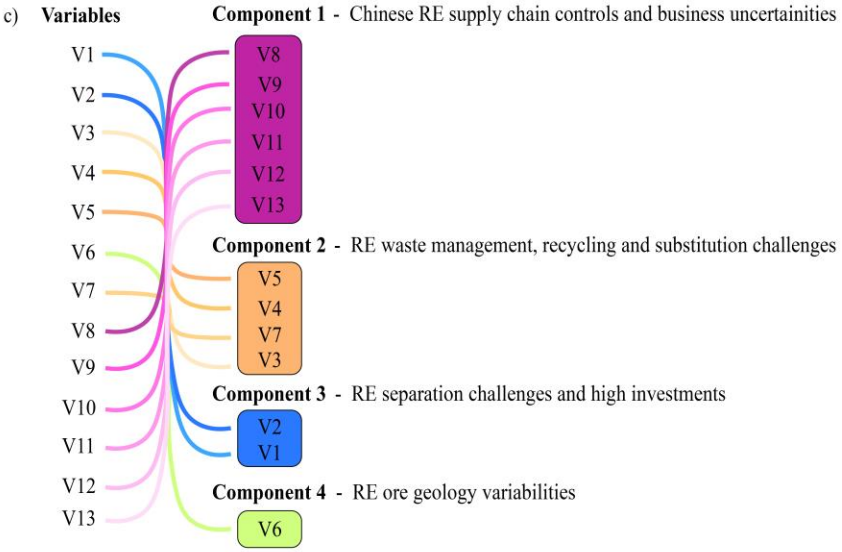
a)



b)

Variables	Variable Names	Components			
		1	2	3	4
V8	Uncertainty in business due to RE price volatility greatly affect commissioning RE projects outside China	0.832			
V9	High capital costs and lack of government support and subsidies for RE projects outside China	0.787			
V10	Lack of interest from investors (interest is mainly shown when RE prices are high)	0.757			
V11	Supply chain pressures on global RE companies (China offers REEs at lower prices and influence of RE investments in China)	0.612			
V12	Chinese RE interests outside China are considered to be political barriers that dampen RE projects outside China	0.456			
V13	Lengthy legislative processes in countries outside China are identified as political hurdles to commission RE projects outside China	0.437		-0.466	
V5	Challenges associated with RE substitution technologies		0.794		
V4	Lack of RE recycling and challenges associated with RE recycling		0.791		
V7	Waste management challenges in the USA, Canada, European Union, Australia and the UK		0.734		
V3	Lack of large-scale research and development (R&D) especially to develop niche RE separation and purification techniques		0.635		
V2	High operational costs of RE separation and purification plants			0.846	
V1	Complexity to establish RE separation and purification plants			0.692	
V6	Variability of ore geology compared to the Chinese RE resources (e.g. ion adsorption ores and resources with less radioactive elements)				0.856

c)



d)

Components	N	Mean	95% confidence interval for mean		Minimum	Maximum
			Lower bound	Upper bound		
1	30	4.65	4.24	5.06	1.55	6.03
2	30	3.43	2.98	3.89	0.97	6.19
3	30	2.36	1.92	2.80	-0.16	4.45
4	30	2.97	2.49	3.45	0.20	5.24

Figure 5: Exploratory factor analysis results: a) Scree plot b) Component matrix after rotation c) the relationship between the original variables and the components, and d) mean values of the components.

4. Current developments outside China

Despite the constraints discussed in this work, there have been several recent developments of rare earth exploration and mining projects outside China, especially in the USA, Australia, Canada and Europe.

In a list of 52 critical mineral commodities susceptible to supply chain disruptions for the manufacturing sector in the USA, 6 of the REEs, namely, Dy, Y, Nd, La, Ce and Pr, were ranked in the top cluster (Nassar et al., 2020). Pursuant to the United States executive order 13817, "a federal strategy to ensure secure and reliable supplies of critical metals", government departments and agencies (US departments of Energy, Defense, State, Commerce Interior, Agriculture, Education and the National Science Foundation) were tasked to achieve the objectives, including the development of RE projects in the USA. The national science and technology council critical metals subcommittee oversees the progress and implements the recommendations (Fortier et al., 2019). The department of interior included REEs as one of the 35 mineral commodities with potential supply chain vulnerabilities (Federal Register, 2017). The USA congress passed 2.3 trillion dollars of R&D funding for RE development on 21st December 2020. The USA department of energy will establish a critical materials consortium and a critical materials supply chain research institution (Althaus, 2020). The US department of commerce urged to boost the dormant RE industry by suggesting both short- and long-term measures, such as stockpiling, explore and develop new RE projects outside China, recycling and replacing of REEs from end of life products and substituting REEs partially or completely by switching to different technologies (Houser, 2020; Schmid, 2019). Several bills have been introduced in the 116th Congress to support RE development in the USA. The bills S. 3694, S. 4537, H.R. 7812 and H.R. 8143 would provide tax intensives for companies who perform local RE extraction and consumption. A federally chartered

cooperative and a federally chartered cooperation will be formed by the bills S. 2093 and H.R. 4410. The former would focus on RE processing into valuable products, while the latter would process hazardous uranium and thorium containing materials from the cooperative. It is supposed that these legislative frameworks support RE mine and extraction plant developments in the USA, especially Mountain Pass, Bokan Mountain, Bear Lodge and Round Top and Elk Creek (Table 1) (Tracy, 2020).

In addition, the USA and Australia joined to initiate RE production using ore resources in the USA. Lynas and Blue Line Cooperation, a Texas chemical company, started this collaboration (Horrocks, 2020). Lynas was funded 30.4 million dollars in February 2021 by the US DOD to design and operate a HREE processing plan in Texas in 2021 (US DOD, 2020). This will be the only HREE processing plant outside China (Mehta, 2019) and it will play a vital role for Lynas' 2025 growth plan (Gross, 2020). Furthermore, MP Materials, who operate Mountain Pass mine was awarded 9.6 million dollars by the US DOD to commission a LREEs separation plant by employing their mixed RE concentrates (US DOD, 2020).

The governments in Canada and the USA also agreed to develop REEs, including other critical metals, in 2019 (Friedman, 2019). The strategy, namely, "The Canada-USA joint action plan on critical minerals collaboration", was subsequently drafted (McClearn and McGee, 2020), though the current developments are not yet reported.

Europe currently receives a foreign supply of critical metals, including REEs despite the availability of resources (e.g. 31000 tonnes of REO potential in Kvanefjeld deposit in Greenland and this deposit is associated with uranium). It is understood that administrative and socio-environmental constraints hinder the development of these resources (van Exter et al., 2019). The result of Greenland's election on 6th April 2021 could halt the development of the Kvanefjeld mine

and this would hamper the development of independent RE supply chains in Europe (Jacob, 2021a). In September 2021, it is reported that Greenland's new government is drafting legislation frameworks to ban uranium mining and it would cease the development of this RE project in the country (Jacob, 2021b).

Hakkar et al. (2021) recently presented enhanced REEs transfer from phosphate rocks to liquid phosphoric acid with additives (fly ash/pure silica) and this would reduce the transfer of REEs to phosphogypsum, which is typically discarded. Considering the phosphate rock reserves in Morocco (50 billion tonnes or about 70% of the reserves) and 577 ppm of total RE content, the reserves could be used to produce 7-15% of the global REO production.

With the support of EIT Raw Materials, a European Commission sponsored organisation, namely, the global REIA was established in June 2019 to support the global efforts in developing a sustainable and transparent RE supply chain. This is the only RE trade association outside China and it is intended to secure RE supply chains. In addition, the action plan on critical raw materials in Europe was launched in September 2020 with consequently the European Commission launching the European Raw Material Alliance with initial focus on REEs (Cole, 2019).

In India, IREL (India) Ltd is the only body that possesses RE mining permits and it was established as a central public sector enterprise under the department of atomic energy, which oversees administrative operations. A plant (OSCOM Odisha) to produce mixed rare earth chlorides was established with 11200 tonnes per annum and individual RE compounds will be produced at Aluwa Kerala, which is the first unit of IREL (IREL, 2020).

Considering the RE potential in the Arctic region, Russia developed "the development strategy of the rare and rare earth metal industry of the Russian Federation for the period up to 2035". Several

deposits were identified in Russia, though the current status of those towards the implementation is not yet reported (Solovyova et al., 2020).

The niche purification and separation techniques would allow to lower the processing costs and mine deposits having lower cut off grades (Fathollahzadeh et al., 2018). Innovation Metals Corp. (IMC) has developed RapidSX, a novel solvent extraction process that combine the conventional solvent extraction and column-based technology, with the funding from the US DOD for the separation of critical and other metals (Tracy, 2020). This process was successfully tested at the pilot scale to separate both LREEs and HREEs. In late 2019, IMC received phase-one funding to commercialise REE separation technology using RapidSX for the RE concentrates from the Hexagon Energy Materials Limited. The technology would reduce the footprint of the plant and the process completion time which will lead to lower the capital and operating costs (Innovation Metals Corp., 2020). As a part of this project, Ucore Rare Metals Inc. acquired 100% of the issued and outstanding shares of IMC via a binding Share Purchase Agreement. Currently, the commercialisation development programme is being conducted at the RapidSX commercialisation and development facility in Canada where Kingston Process Metallurgy Inc. is contracted as the laboratory partner (Innovation Metals Corp., 2020).

The US department of energy formulated the REACT project, “rare earth alternatives in critical technologies”, to ascertain low cost alternatives that result in the same or better performance compared to the products with REEs (REACT, 2020). Governments and relevant bodies should clearly differentiate the policies for both RE substitution and production technologies (Lasley, 2020). If RE substitution is only considered, the dependency on the Chinese RE imports will not be significantly reduced and the RE production outside China will be dormant.

In line with these, the commissioned and potential RE projects outside China are summarised in Table 1. The current status of these key projects, including RE separation and purification plants implies that most of the projects are still in its infancy, except a few. This explicitly demonstrates the challenges of establishing RE processing facilities outside China and the business constraints associated with the RE industry. However, the assessment of project readiness level for each project listed in Table 1 is not the objective of this work.

533 **Table 1: Current developments of rare earth projects outside China.**

Rare earth project/deposit/plant	Country/region	Current Developments	Reference
Norra Karr deposit by Leading Edge Materials	Sweden	Heavy RE mineralisation and only such deposit in the EU Eudialyte (silicate mineral) is the main RE mineral Could produce 5000 REOs per year for 20 years, including 200 tonnes of Dy per year Pre-feasibility study was completed in 2015	Leading Edge Materials, 2021
The Fens field by REE Minerals	Norway	Contains 84 million tonnes of inferred resources at 1.08% REOs Carbonatite RE deposit Initial studies were completed and will be a proven resource in the EU	REE Minerals, 2021
Kvanefjeld deposit by Greenland Minerals	Greenland	Host rock type lujavrite contains REEs, Uranium and zinc Mine, concentrator and refinery will be commissioned and 20-25% RE oxide concentrate will be produced The refinery will produce intermediate RE products and uranium The project development will be delayed due the election's result in April 2021 Greenland's government is drafting legislation to ban uranium mining in September 2021 and this could stop this project	Greenland Minerals Ltd, 2020; Jacob, 2021a, 2021b

Longonjo by Pensana Rare Earths	Angola, Africa (mine)	Feasibility study is not carried out and will be started in the first quarter of 2021 The project may get funding from China Plan to build a separation plant in Europe/England	Hamer, 2020
Songwe Hill by Mkango Resources	Malawi, Africa (mine)	Requires a mining permit from the Malawi government Feasibility study will be carried out in 2021 Has received the support from the EU Plan to build a separation plant in Europe	Hamer, 2020
Gakara project by Rainbow Rare Earths	Burundi, Africa	Managerial change affected commercial production plans Uncertainty of mine operation in Burundi Low levels of radioactive elements is an advantage	Hamer, 2020; NS Energy, 2020
Makutuu project by Ionic Rare Earths (Australia)	Uganda, Africa	78.6 million tonnes of resources at 840 ppm total REO grade Mineralogy is similar to ion adsorption clay deposits in the southern China Heap leaching will be employed followed by membrane technology to upgrade the RE content	Ionic Rare Earths, 2021

Projects by Namibia Critical Metals Inc.	Namibia, Africa	Lofdal project: heavy RE mineralisation of xenotime in carbonatite dykes 2.88 million tonnes of indicated resource at 0.32% total REO grade Preliminary economic assessment has been completed Mining licence application is under review Otjiwarongo project: early stage project, initial survey data indicate an alkaline intrusive complex	Namibia Critical Metals Inc., 2021
Peak Resources, Australia	Tanzania, Africa (mine)	Plan to build a separation plant in Tees Valley, North of England	Hamer, 2020
Phalaborwa rare earth project by Rainbow Rare Earths and Bosveld Phosphates	South Africa	Contains 35 million tonnes of gypsum containing REEs 0.6% total REO grade Pre-feasibility study will be completed soon Low levels of radioactive elements	NS Energy, 2020

Projects by Northern Minerals	Australia	Browns Range project: Heavy RE mineralisation, pilot plant to produce heavy rare earth carbonate was started in late 2018, will be the first significant Dy project outside China Boulder Ridge project: Heavy RE mineralisation, xenotime within quartz veins, test drilling will be continued John Galt project: Heavy RE mineralisation, xenotime deposit, several mineral exploration studies were performed since 2011	Northern Minerals, 2021
Iluka Resources	Australia	The company's RE projects are Eneabba in Western Australia and Wimmera in Western Victoria Monazite concentrate in Eneabba will be used produce REEs	Iluka Resources, 2021
Norlans Project by Arafura Resources	Australia	REE-Phosphate-Uranium-Thorium project 29.5 million tonnes of proved and probable reserves 2.9% total REO grade Design capacity of 300000 tonnes of concentrate production per annum for 33 years Will produce NdPr oxide, mixed middle-heavy rare earth carbonate, Ce hydroxide and phosphoric acid (by-product)	Arafura Resources, 2021

		Could supply about 10% of the NdPr demand in the world Currently procure the required funds	
Projects by Hasting Technology Metals	Australia	Yangibana project: Contains 7.74 million tonnes of probable reserves at 1.13% total REO grade, including significant Nd and Pr contents Definitive feasibility study has been completed, the company signed deals to sell 6000 tonnes of mixed RE carbonate to Chinese companies Brockman project: 41.4 million tonnes of resources at 2100 ppm total REO grade 1800 ppm heavy rare earth oxides Initial drilling and metallurgical test works were carried out	Hastings Technology Metals, 2021
Dubbo project by Australian Strategic Materials	Australia	Polymetallic resource, in central western New South Wales will produce REEs The project is ready for construction, though subjected to financing	Australian Strategic Materials, 2021
Cummins Range by RareX	Australia	Inferred resources of 13 million tonnes at 1.13% total REO grade, including high Nd, Pr Primary RE mineral is monazite Pre-feasibility study will be completed in 2021	RareX, 2021

Dotson Ridge deposit at Bokan Mountain by Ucore Rare Metals	Southeast Alaska	4.8-5.2 million tonnes of indicated resource Establish RE mine and metal separation facility in Ketchikan LREE grade of 0.394% and HREE grade of 0.259% Plan to recover six critical metals additionally Funding in the form of a loan form the Alaska Industrial Development and Export Authority	Lasley, 2020; Tracy, 2020
Ray Mountains deposit by Ucore Rare Metals	Alaska	Placer deposit Initial physical separation yields concentrates with 15-25% of total RE content	Lasley, 2020
Mount Pass deposit by MP Materials	California, USA	Proven and probable resources are 18.4 million tonnes of carbonatite ore in 2019 7.98% average REO using a cutoff grade of 5% REO Produced all the RE production in the USA in 2019, though the RE concentrate is exported to China MP Materials is planning to commission a LREEs processing facility and the US DOD provided funding in November 2020	Tracy, 2020; US DOD, 2020

Round Top project by USA Rare Earth and Texas Mineral Resources	Texas, USA	Combined measured and indicated resources are 364 million tonnes Contains 16 REEs including both LREEs and HREEs, though the main focus would be to extract HREEs 130 year mine life, though the initial mine plan is for 20 years May recover other critical metals, such as lithium, beryllium Preliminary economic assessment was completed in August 2019 Pilot plant was initiated in Colorado in December 2019 Planed to initiate the production in 2023 To support the project, in April 2020 the company acquired the NdFeB permanent magnet manufacturing equipment previously owned by Hitachi Metals America	Horrocks, 2020; Tracy, 2020; Saywell, 2021; USA Rare Earth, 2021
La Paz project by Western Rare Earths	La Paz county, Arizona	10 year old project Present of Sc favours project economics Negligible amounts of radioactive material American Rare Earth Limited will deliver a preliminary economic assessment in 2021	Meridith, 2020; Sharma, 2020

Bear Lodge deposit by Rare Element Resources	Wyoming, USA	18 million tonnes of reserves 3.05% total REO grade Planned to produce RE concentrate at the mine site Planned to commission RE processing plant in Upton, Wyoming	Horrocks, 2020; Tracy, 2020
Elk Creek by NioCorp	Nebraska, USA	Contains Sc and critical metals such as niobium and titanium Estimated mine life is 36 years and planned to perform RE mining and extraction Estimated to produce 95 tonnes of scandium trioxide	Tracy, 2020
ElementUS	Gramercy, Louisiana, USA	Joint venture between DADA Holdings LLC (principal owner of New Day Aluminium) and Enervoxa Extraction of REEs from bauxite residue at New Day's alumina refinery in Louisiana using Enervoxa's technical expertise - Planned to develop a processing plant that handles 1 million tonnes of bauxite residue per year	New Day Aluminium, 2020

Energy Fuels	USA	A key uranium producer in the USA Extraction of REEs from monazite sands is performed and a mixed RE concentrate will be produced Pilot scale tests were completed in November 2020 by employing their existing technology and uranium producing infrastructure	Energy Fuels, 2020
Urban Mining Company	USA	Employ waste magnetic materials to support the company's NdFeB magnet manufacturing process Received 0.86 million dollars funding from the US DOD for RE magnet supply chain studies	US DOD, 2020; Urban Mining Company, 2021
Saskatoon separation plant by the Saskatchewan Research Council (SRC)	Canada	Will be the first North American RE separation plant by the end of 2022 Process monazite hosting REEs at Alces Lake Feasibility study was completed and extended engineering phase of the project is carried out	Drivas, 2020; Treleaven, 2021
RE recycling plant by Geomega Resources	Canada	It would cost 2.5 million dollars RE ore mining project in northern Quebec is considered to be risky	Friedman, 2019

Nechalacho mine by Avalon Advanced Materials	Canada	Initiated RE extraction plans in 2005 Stable RE prices after 2014 made the mine still undeveloped Considered as a failed RE project Lithium, tin and indium projects have been the current focus of the company	McClearn and McGee, 2020
Strange Lake deposit by Torngat Metals	Northern Quebec, Canada	This deposit is previously owned by Quest Rare Minerals Focus on concentrated REEs only Employ a specially designed processing facility in Canada Still raising funds and could take several years for production	McClearn and McGee, 2020
RE extraction plant by Medallion Resources	Canada	Monazite fraction resulting from heavy mineral sands mining will be used to extract REEs Could take several years for production	Friedman, 2019
The Ashram project	Quebec, Canada	Prelimiinary economic assessment was conducted Measured resources of 1.59 million tonnes at 1.77% total REO grade Financial support of Quebec government and pre-feasibility study is ongoing	Commerce Resources, 2021
Foxtrot project by Search Minerals	Labrador, Canada	Contains 4.9 million tonnes of ore grade materials at 0.98% total REEs 14 years mine life could produce 36700 tonnes of total REOs	Search Minerals, 2021

Nechalacho project by Vital Metals	Northwest Territories, Canada	Contains 94.7 million tonnes of measured, indicated and inferred resources at 1.46% RE oxides and targets RE oxide production in 2021 Could produce 5000 tonnes of REOs by 2025	Vital Metals, 2021
Alces Lake and Elliot Lake projects by Appia Energy	Canada	Alces Lake (Saskatchewan) – A deposit of high concentrations of monazite; Monazite is enriched with REEs such as Nd, Pr, and Dy; Several high grade REE zones have been identified Elliot Lake (Ontario) – Uranium-REE mineralisation within quartz-pebble conglomerate; Total RE content in indicated and inferred resources in Teasdale Lake zone would be 21603 and 60328 tonnes, respectively	Appia Energy, 2021a, 2021b
Red Wine Complex by Canada Rare Earth Corporation	Labrador, Canada	The Two Tom deposit possesses inferred mineral resources of 41 million tonnes at 1.18% total REO grade	Canada Rare Earth Corporation, 2021
Bahia state deposits	Brazil	22 million tonnes of reserves containing Nd	Horrocks, 2020
Dong Pao and other deposits in Vietnam	Vietnam	22 million tonnes of reserves Intended to develop the reserves with Japan	Horrocks, 2020; Tracy, 2020

Karnasurt Mountain by Solikamsk Magnesium Works	Kola Peninsula, Russia	Exported about 6000 tonnes of RE compounds in 2017 Processed at the Silmet plant in Estonia	Roskill, 2018; Tracy, 2020
Tomtor deposit by Rostec and the ICT Group	Yakutia, Russia	Niobium-RE project - contains 154 million tonnes ore and 9.5% total REOs grade Ore contains significant radioactive minerals The project was announced in 2018, though the current status is not reported	Roskill, 2018; Solovyova et al., 2020
IREL (India) Limited	India	Expression of interest was announced for setting up a Nd-Iron-Boron permanent magnet manufacturing facility in Kerala, India IREL will provide raw materials for the new magnet making facility	IREL, 2020

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5. Discussion

Since the early 1990s, Chinese RE companies were extensively supported by the Chinese government. Even though initial phases of the businesses incurred losses, the government backing was greatly beneficial to perform their businesses. Six large scale state-owned enterprises, namely, China Minmetals, Chinalco, Baotou Steel, Xiamen Tungsten, Ganzhou Rare Earths, and Guangdong Guangsheng Rare Earths, presently control RE mining, purification and separation in China. It is supposed that this consolidation could alleviate illegal RE mining and environmental pollution (Mancheri et al., 2019). State owned RE business in China thus has been instrumental to accomplish their current RE supremacy.

Understanding of belligerent impacts of RE crisis, huge demand predictions to achieve green energy targets, and supply chain disruptions caused by global pandemics, such as COVID-19 have made proactive discussions, policy developments, government support to initiate RE projects outside China. Considering the existing challenges of RE mining, processing and supply chains, at least a decade is required to build an operational mine (Kalantzakos, 2020). RE business developments outside China, especially in the USA, appear to be a bit scattered, though funding and support frameworks are encouraging. Considering the RE business developments since the RE trade war between China and Japan, the private companies are not really keen to take the risk of their investments. Establishing the companies under a single organisation in a country would be the best way to move forward to commission successful RE ventures. For example, a large joint venture between the USA and Canada would yield better results than the same by several small to medium operations individually. This however requires extensive bilateral discussions and cooperation.

RE recycling and substitution are indeed important, though those should not be the barriers to develop RE mines and extraction facilities outside China. Parallel developments of RE projects and RE recycling and substitution activities need to be performed since the former can only significantly reduce the Chinese RE dependency.

Despite the recent developments to kick-start RE industry outside China, the well-established RE industry in China and their significant influence on RE projects outside China would still help China to dominate the global RE business in the foreseeable future. Significant RE stockpiling and ability to control the prices also place China in the commanding position. RE value added product developments recently initiated by companies, such as IREL (India) indeed strengthen RE downstream activities outside China. These initiatives will have palpable impacts on the Chinese RE monopoly, perhaps after a couple of decades, if new RE mines and their supply chains are connected to such downstream facilities outside China for a sufficiently long time.

6. Conclusions

In order to fulfil modern lifestyles of people all over the world, REEs are indispensable. The global energy giants have been swiftly deploying their resources to initiate renewable energy projects with the green house emission targets set by different countries. China presently holds the global RE industry from mine to value added products. Too much dependency on the Chinese RE supplies results in prices hikes, trade wars, business uncertainties, export controls, including supply disruptions during unprecedented global crisis like COVID-19.

Fulfilment of the United Nations SDGs (SDGs 7, 11 and 12) also considerably depends on the establishment of independent RE supply chains outside China. All the constraints identified in this work are thus crucial to establish efficient RE supply chains outside China. Since the identified

579 constraints cover technical, economical, political and mineralogical challenges associated with RE
580 industry, addressing these challenges effectively with government support schemes would be the
581 best way forward, otherwise it is highly unlikely that the China's RE supremacy is challenged for
582 a foreseeable future. Key challenges and opportunities associated with each constraint are
583 evaluated by the authors and this includes the summary of additional comments provided by RE
584 industry experts.

585 **Constraint 1 – Chinese RE supply chain controls and business uncertainties:** Lack of
586 collaboration between governments and companies, downstream industries outside China, and
587 supportive buyers for downstream RE products, high labour costs and length RE project
588 development are the key challenges that demotivate potential industries. Governments should
589 support the companies, who are ready to develop RE projects and downstream businesses outside
590 China as a risk management strategy (i.e. mimicking state owned RE businesses in China).

591 **Constraint 2 – RE waste management, recycling and substitution challenges:** Since RE waste
592 management and recycling studies are primarily limited to lab studies, with the help of government
593 founding, projects that focus of REEs extraction, purification and refining at industrial scale are
594 recommended.

595 **Constraint 3 – RE separation challenges and high investments:** Lack of funding support and
596 expertise are the key challenges and niche and existing RE separation and purification techniques
597 (e.g. solvent extraction) based projects connected to integrated supply chain should be the way
598 forward.

599 **Constraint 4 – RE ore geology variabilities:** Current RE industry is based on carbonatite rocks
600 and ion adsorption clays and 3 main minerals, such as monazite, bastnaesite, and xenotime. The

reserves are significantly available outside China, though the disclosure of costs due to radioactive waste treatment and manage these with government support are identified as viable options.

The main RE consumers and governments have now understood the adverse impacts and deployed their resources to develop RE projects outside China. These are recognised as encouraging signs to diversify the global RE business, though several challenges need to be addressed to yield a significant impact. If the current initiatives are prolific, independent RE supply chains outside China could be seen in 2030-2050.

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References

Adamas Intelligence, 2020. Rare earth magnet market outlook to 2030. https://www.adamasintel.com/report/rare-earth-magnet-market-outlook-to-2030/ (accessed 3.4.21).

Akcil, A., Sun, Z., Panda, S., 2020. COVID-19 disruptions to tech-metals supply are a wake-up call. Nature 587, 365–367.

Althaus, P., 2020. Congress back moves to bolster rare earth supply chain in US. Asian Financ. https://www.asiatimesfinancial.com/congress-backs-move-to-bolster-rare-earth-supply-in-us (accessed 12.30.21).

Appia Energy, 2021a. Alces Lake. http://www.appiaenergy.ca/projects/athabasca-basin-properties/alces-lake/ (accessed 2.12.21).

Appia Energy, 2021b. Elliot Lake Property. http://www.appiaenergy.ca/projects/elliot-lake-property/overview/ (accessed 2.12.21).

631 Arafura Resource Limited, 2020. Arafura Resource Limited . Rare earth supply demand.
632 https://www.arultd.com/products/supply-and-demand.html (accessed 12.28.20).

633 Arafura Resources, 2021. Nolans . https://www.arultd.com/projects/nolans.html (accessed
634 1.6.21).

635 Argus, 2017. Argus rare earths monthly outlook. https://www.argusmedia.com/-
636 /media/Files/sample-reports/argus-rare-earths-
637 monthly.ashx?la=zh&hash=0A2D56431CB412656828CA6C5BFB74D09892285A
638 (accessed 14.10.21)

639 Argus, 2020. China's October RE imports from US up 81pc: Correction. Arg. Media.com.
640 https://www.argusmedia.com/en/news/2164289-chinas-october-re-imports-from-us-up-
641 81pc-correction#:~:text=Chinese imports of rare earth,according to Chinese customs data.

642 Argus, 2021. China's rare earth exports fall in 2020. Arg. Media.com.
643 https://www.argusmedia.com/en/news/2176856-chinas-rare-earths-exports-fall-in-
644 2020#:~:text=China's total shipments of rare,2018%2C according to customs data (accessed
645 2.3.21).

646 Ascenzi, P., Bettinelli, M., Boffi, A., Botta, M., De Simone, G., Luchinat, C., Marengo, E., Mei,
647 H., Aime, S., 2020. Rare earth elements (REE) in biology and medicine. Rend. Lincei. Sci.
648 Fis. e Nat. 1–13.

649 Australian Strategic Materials, 2021. Dubbo Project - ASM. https://asm-au.com/projects/dubbo-
650 project/ (accessed 8.3.21).

651 Baruzzi, S., 2020. China's Export Control Law Explained. China Brief. https://www.china-
652 briefing.com/news/chinas-export-control-law-explainer-china-briefing-news/ (accessed
653 12.1.20).

654 Batapola, N.M., Dushyantha, N.P., Premasiri, H.M.R., Abeysinghe, A., Rohitha, L.P.S.,
655 Ratnayake, N.P., Dissanayake, D., Ilankoon, I., Dharmaratne, P.G.R., 2020. A comparison
656 of global rare earth element (REE) resources and their mineralogy with REE prospects in
657 Sri Lanka. J. Asian Earth Sci. 200, 104475.

658 Binnemans, K., Jones, P.T., Blanpain, B., Van Gerven, T., Yang, Y., Walton, A., Buchert, M.,
659 2013. Recycling of rare earths: a critical review. Journal of Cleaner Production 51, 1–22

660 Binnemans, K., McGuiness, P., Jones, P.T., 2021. Rare-earth recycling needs market
661 intervention. Nature Reviews Materials 6, 459–461.

662 Borst, A.M., Smith, M.P., Finch, A.A., Estrade, G., Villanova-de-Benavent, C., Nason, P.,
663 Marquis, E., Horsburgh, N.J., Goodenough, K.M., Xu, C., 2020. Adsorption of rare earth
664 elements in regolith-hosted clay deposits. Nat. Commun. 11, 1–15.

665 Brown, M., Eggert, R., 2018. Simulating producer responses to selected chinese rare earth
666 policies. Resour. Policy 55, 31–48.

667 Canada Rare Earth Corporation, 2021. Red Wine Complex, TSX.V:LL .
668 http://www.canadarareearth.com/redwine (accessed 8.3.21).

669 Citizens for National Security, 2020. Rare-Earth Elements: A National Security Crisis. Real
670 Clear Def. https://www.realcleardefense.com/articles/2020/11/17/rare-
671 earth_elements_a_national_security_crisis_649952.html (accessed 12.20.20).

672 Cole, L., 2019. Europe takes on China's global dominance of rare earth metals. EURACTIV.
673 https://www.euractiv.com/section/batteries/news/europe-takes-on-chinas-global-dominance-
674 of-rare-earth-metals/ (accessed 12.1.20).

675 Commerce Resources, 2021. The Ashram rare earth element and fluorspar deposit.
676 https://www.commerceresources.com/en/projects/ashram-rare-earth-element-deposit
677 (accessed 2.12.21).

678 Drivas, A., 2020. Appia Energy Reports on Significant Price Increases in Rare Earth Oxides as
679 China Announces New Export Control Law. Jr. Morning Netw.
680 https://www.juniorminingnetwork.com/junior-miner-news/press-releases/2122-
681 cse/api/88878-appia-reports-on-significant-price-increases-in-rare-earth-oxides-as-china-
682 announces-new-export-control-law.html (accessed 12.12.20).

683 Dushyantha, N., Batapola, N., Ilankoon, I.M.S.K., Rohitha, S., Premasiri, R., Abeysinghe, B.,
684 Ratnayake, N., Dissanayake, K., 2020. The story of rare earth elements (REEs):
685 occurrences, global distribution, genesis, geology, mineralogy and global production. Ore
686 Geol. Rev. 122, 103521.

687 Eckhouse, B., Morison, R., Mathis, W., Wade, W., 2020. The new energy giants are renewable
688 companies. Bloom. Green. https://www.bloomberg.com/graphics/2020-renewable-energy-
689 supermajors/ (accessed 12.25.20).

690 Energy Fuels, 2020. Energy Fuels Produces First Rare Earth Element Concentrate on a Pilot
691 Scale at its White Mesa Mill (Video Link Included) - Nov 3, 2020.
692 https://www.energyfuels.com/2020-11-03-Energy-Fuels-Produces-First-Rare-Earth-
693 Element-Concentrate-on-a-Pilot-Scale-at-its-White-Mesa-Mill-Video-Link-Included
694 (accessed 8.3.21).

695 Eric, N., 2019. China's rare earth producers say they are ready to weaponise their supply
696 stranglehold, pass any tariff as cost to US customers. South China Morning Post.
697 https://www.scmp.com/business/commodities/article/3021947/chinas-rare-earth-producers-
698 say-they-are-ready-weaponise-their (accessed 6.4.20).

699 European Commission, 2020. Sustainable and Smart Mobility Strategy-putting European
700 transport on track for the future {SWD(2020) 331 final}.

701 Fathollahzadeh, H., Becker, T., Eksteen, J.J., Kaksonen, A.H., Watkin, E.L.J., 2018. Microbial
702 contact enhances bioleaching of rare earth elements. Bioresour. Technol. Reports 3, 102–
703 108.

704 Federal Register, 2017. A Federal Strategy To Ensure Secure and Reliable Supplies of Critical
705 Minerals. https://www.federalregister.gov/documents/2017/12/26/2017-27899/a-federal-
706 strategy-to-ensure-secure-and-reliable-supplies-of-critical-minerals (accessed 12.21.20).

707 Fishman, T., Graedel, T.E., 2019. Impact of the establishment of US offshore wind power on
708 neodymium flows. Nat. Sustain. 2, 332–338.

Ford, 2021. The Ford electric vehicle strategy: what you need to know. https://www.sdacford.com.my/ford-stories/electric-vehicle-strategy (accessed 15.10.2021).

Fortier, S.M., Hammarstrom, J.H., Ryker, S.J., Day, W.C., Seal, R.R., 2019. USGS critical minerals review. Min. Eng. 71, 35–47.

Friedman, G., 2019. "You don't control your destiny": Why Canada's rare earth deposits are staying in the ground . Financ. Post. https://financialpost.com/commodities/mining/you-dont-control-your-destiny-why-canadas-rare-earth-deposits-are-staying-in-the-ground (accessed 12.12.20).

Global Times, 2020. China's rare earth still needs an edge up in technology for high-end products. Glob. Times. https://www.globaltimes.cn/content/1203383.shtml (accessed 12.9.20).

Green, J.A., 2019. The collapse of American rare earth mining — and lessons learned. Reagan Def. Forum. https://www.defensenews.com/opinion/commentary/2019/11/12/the-collapse-of-american-rare-earth-mining-and-lessons-learned/ (accessed 12.11.20).

Greenland Minerals Ltd, 2020. Kvanefjeld Project. https://www.ggg.gl/project/ (accessed 12.31.20).

Gross, S., 2020. Lynas to Advance U.S. Rare Earths Plan on Pentagon Funding Deal . Bloomberg. https://www.bloomberg.com/news/articles/2020-07-27/lynas-to-advance-u-s-rare-earths-plan-on-pentagon-funding-deal (accessed 12.19.20).

Hakkar, M., Arhouni, F.E., Mahrou, A., Bilal, E., Bertau, M., Roy, A., Steiner, G., Haneklaus, N., Mazouz, H., Boukhair, A., Benjelloun, M., 2021. Ehnancing rare earth element transfer from phosphate rock to phosphoric acid using an inexpensive fly ash additive. Minerals Engineering 172, 107166.

Hamer, A., 2020. Pensana picks Humber for UK rare earths facility. Investors' Chron. https://www.investorschronicle.co.uk/shares/2020/12/07/pensana-picks-humber-for-uk-rare-earths-facility/ (accessed 12.20.20).

Hastings Technology Metals, 2021. Projects – Hastings Technology Metals Limited. https://hastingstechmetals.com/projects/ (accessed 8.3.21).

Haxel, G.B., Hedrick, J.B., Orris, G.J., Stauffer, P.H., Hendley II, J.W., 2002. Rare earth elements: critical resources for high technology.

Horrocks, J., 2020. Rare Eaths. CdR Capitals. https://cdr-capital.com/articles/views/rare-earths# (accessed 11.02.21).

Houser, D.G., 2020. Rare-earth elements spark resource war. Multi Briefs Exclus. https://exclusive.multibriefs.com/content/rare-earth-elements-spark-resource-war/natural-resources (accessed 12.7.20).

Hui, M., 2021. The US is taking steps towards breaking China's rare earth monopoly. https://qz.com/1969069/the-us-takes-steps-to-break-chinas-rare-earths-monopoly/ (accessed 11.02.21).

Hui, M., 2020. A US rare earths miner is staging a comeback to take on China. QUARTZ. https://qz.com/1931653/us-rare-earths-miner-mp-materials-takes-on-china-dominance/ (accessed 12.12.20).

Ilankoon, I.M.S.K., Tang, Y., Ghorbani, Y., Northey, S., Yellishetty, M., Deng, X., Mcbride, D., 2018. The current state and future directions of percolation leaching in the Chinese mining industry : Challenges and opportunities. Miner. Eng. 125, 206–222.

Iluka Resources, 2021. Rare earth products. https://www.iluka.com/products-markets/rare-earth-products (accessed 8.3.21).

Innovation Metals Corp., 2020. Innovation Metals Corp. Announces RapidSX™ Commercialization and Development Facility; Kingston Process Metallurgy Awarded Contract as RapidSX™ Laboratory Partner. Globe Newswire. https://www.globenewswire.com/news-release/2020/06/23/2052266/0/en/Innovation-Metals-Corp-Announces-RapidSX-Commercialization-and-Development-Facility-Kingston-Process-Metallurgy-Awarded-Contract-as-RapidSX-Laboratory-Partner.html (accessed 12.18.20).

Inoue, Y., 2010. China lifts rare earth export ban to Japan: trader. Reuters (September 29). http//www. reuters. com/article/2010/09/29/us-japan-china-export-idUSTRE68S0BT20100929. Accessed Febr. 11, 2015.

Inoue, Y., Gordon, J., 2011. Analysis: Japanese rare earth consumers set up shop in China. Reuters, August 12.

Institute of rare earths elements and strategic metals, 2020a. Rare earth prices in December 2019. ISE. https://en.institut-seltene-erden.de/preise-fuer-seltene-erden-im-dezember-2019/ (accessed 14.10.21).

Institute of rare earths elements and strategic metals, 2020b. Rare earth prices in December 2020. ISE. https://en.institut-seltene-erden.de/ (accessed 12.10.21).

Ionic Rare Earths, 2021. Project Makutuu, Uganda. https://ionicre.com.au/makuutu-uganda/ (accessed 8.3.21).

IREL, 2020. Indian Rare Earths Limited. https://www.irel.co.in (accessed 12.30.21).

Ismail, T.H.T., Juahir, H., Aris, A.Z., Zain, S.M., Samah, A.A., 2016. Local community acceptance of the rare earth industry: the case of the Lynas Advanced Materials Plant (LAMP) in Malaysia. Environ. Dev. Sustain. 18, 739–762.

Jacob, G.-P., 2021a. Left-wing party wins Greenland election, opposes big mining project. Reuters, https://www.reuters.com/article/us-greenland-election-idUSKBN2BU0V1 (accessed 8.3.21).

Jacob, G.-P., 2021b. Greenland prepares legislation to halt large rare-earth mine. Reuters, https://www.reuters.com/business/environment/greenland-prepares-legislation-halt-large-rare-earth-mine-2021-09-17/ (accessed 15.10.21).

Jennings, S., 2020. The race to secure rare earths: what will higher sustainability standards mean for investors in critical minerals?. Aperio Intell. https://www.aperio-

786 intelligence.com/2020/12/03/the-race-to-secure-rare-earths-what-will-higher-sustainability-
787 standards-mean-for-investors-in-critical-minerals/ (accessed 12.10.20).

788 Ji, B., Li, Q., Huang, Q., Zhang, W., 2021. Enhanced leaching recovery of rare earth elements
789 from a phosphatic waste clay through calcination pretreatment. J. Clean. Prod. 319, 128654.

790 Jolly, J., 2020. Bentley to stop making petrol cars by 2030 and go fully electric. The Guardian.
791 https://www.theguardian.com/business/2020/nov/05/bentley-to-stop-making-petrol-cars-by-
792 2030-and-go-fully-electric (accessed 8.3.21).

793 Jolly, J., 2021. Volvo says it will make only electric cars by 2030. The Guardian.
794 https://www.theguardian.com/business/2021/mar/02/volvo-electric-cars-2030-sell-online
795 (accessed 8.3.21).

796 Jowitt, S.M., Werner, T.T., Weng, Z., Mudd, G.M., 2018. Recycling of the rare earth elements.
797 Curr. Opin. Green Sustain. Chem. 13, 1–7.

798 Jyothi, R.K., Thenepalli, T., Ahn, J.W., Parhi, P.K., Chung, K.W., Lee, J.-Y., 2020. Review of
799 rare earth elements recovery from secondary resources for clean energy technologies: Grand
800 opportunities to create wealth from waste. J. Clean. Prod. 267, 122048.

801 Kalantzakos, S., 2020. The Race for Critical Minerals in an Era of Geopolitical Realignments.
802 Int. Spect. 55, 1–16.

803 Kramer, D., 2021. US government acts to reduce dependence on China for rare-earth magnets.
804 Phys. Today 74, 20–24.

805 Lasley, S., 2020. North to Alaska for rare earth elements. Min. News.
806 https://www.miningnewsnorth.com/story/2020/10/29/critical-minerals-alaska-2020/north-
807 to-alaska-for-rare-earth-elements/6487.html (accessed 12.11.20).

808 Leading Edge Materials, 2021. Norra Karr REE project. https://leadingedgematerials.com/norra-
809 karr/ (accessed 8.3.21).

810 Leading Edge Materials, 2017. Leading Edge Materials Norra Karr Exploration License
811 Reinstated – Leading Edge Materials Corp. https://leadingedgematerials.com/leading-edge-
812 materials-norra-karr-exploration-license-reinstated/ (accessed 8.3.21).

813 Leotaud, V.R., 2018. Importance of rare earth metals mining makes it into COP24. Mining.com.
814 https://www.mining.com/importance-rare-earth-metals-mining-makes-cop24/ (accessed
815 12.12.20).

816 Li, X.-Y., Ge, J.-P., Chen, W.-Q., Wang, P., 2019. Scenarios of rare earth elements demand
817 driven by automotive electrification in China: 2018–2030. Resour. Conserv. Recycl. 145,
818 322–331.

819 Lynas, 2020. 2020 Annual Report. Lynas Corp. Ltd. https://www.lynascorp.com/wp-
820 content/uploads/2020/10/LYC_AR20-30Sep20-LODGE-2122450-1.pdf (accessed
821 12.21.20).

822 Mancheri, N., Sundaresan, L., Chandrashekar, S., 2013. Dominating the world China and the
823 rare earth industry (NIAS Report No. R19-2013).

824 Mancheri, N.A., 2015. World trade in rare earths, Chinese export restrictions, and implications.
825 Resour. Policy 46, 262–271.

826 Mancheri, N.A., Sprecher, B., Bailey, G., Ge, J., Tukker, A., 2019. Effect of Chinese policies on
827 rare earth supply chain resilience. Resour. Conserv. Recycl. 142, 101–112.

828 McClearn, M., McGee, N., 2020. Can the West's economies ever escape China's magnetic pull?
829 The story of rare-earth metals shows how hard it can be. Globe Mail.
830 https://www.theglobeandmail.com/business/article-can-the-wests-economies-ever-escape-
831 chinas-magnetic-pull-the-story/ (accessed 12.10.20).

832 Mehta, A., 2019. To combat China's hold on rare earth minerals, Pentagon looks to Australia.
833 Def. News. https://www.defensenews.com/pentagon/2019/08/27/to-combat-chinas-hold-
834 on-rare-earth-minerals-pentagon-looks-to-australia/ (accessed 8.3.21).

835 Meihan, L., 2021. China's Rare Earth Exports Fall to Over Five-Year Low as Pandemic
836 Devastates Demand. Caixin Glob. https://www.caixinglobal.com/2020-08-26/chinas-rare-
837 earth-exports-fall-to-over-five-year-low-as-pandemic-devastates-demand-101597479.html
838 (accessed 12.10.20).

839 Meridith, D., 2020. Rare Earths Provide Rare Opportunity for Arizona. EIN Press Wire.
840 https://www.einpresswire.com/article/531691185/rare-earths-provide-rare-opportunity-for-
841 arizona (accessed 12.12.20).

842 Mogi, C., 2011. Japan rare earths imports from China jump in Dec. Reuters.
843 https://in.reuters.com/article/japan-rareearth-idUSTOE6BQ02V20110131 (accessed
844 12.18.20).

845 Namibia Critical Metals Inc., 2021. Projects: Namibia Critical Metals.
846 https://www.namibiacriticalmetals.com/project-portfolio (accessed 8.3.21).

847 Nassar, N.T., Brainard, J., Gulley, A., Manley, R., Matos, G., Lederer, G., Bird, L.R., Pineault,
848 D., Alonso, E., Gambogi, J., 2020. Evaluating the mineral commodity supply risk of the US
849 manufacturing sector. Sci. Adv. 6, eaay8647.

850 New Day Aluminium, 2020. DADA Holdings and Enervoxa announce groundbreaking rare earth
851 venture "ElementUS". https://newdayal.com/blog/groundbreaking-rare-earth-venture-
852 elementus (accessed 2.11.21).

853 Northern Minerals, 2021. Projects. https://northernminerals.com.au/projects/ (accessed 1.6.21).

854 NS Energy, 2020. Rainbow, Bosveld to develop Phalaborwa rare earths project in South Africa.
855 NS Energy. https://www.nsenergybusiness.com/news/rainbow-bosveld-phalaborwa-rare-
856 earths-project/ (accessed 12.20.20).

857 Packey, D.J., Kingsnorth, D., 2016. The impact of unregulated ionic clay rare earth mining in
858 China. Resour. Policy 48, 112–116.

859 Palmer, M.A., Bernhardt, E.S., Schlesinger, W.H., Eshleman, K.N., Foufoula-Georgiou, E.,
860 Hendryx, M.S., Lemly, A.D., Likens, G.E., Loucks, O.L., Power, M.E., 2010. Mountaintop
861 mining consequences. Science (80-.). 327, 148–149.

RareX, 2021. RareX Rare Earths | Rare Earths | Cummins Range. https://www.rarex.com.au/projects-cummins-range (accessed 8.3.21).

REACT, 2020. Rare earth alternatives in critical technologies. https://arpa-e.energy.gov/technologies/programs/react (accessed 8.3.21).

REE Minerals, 2021. The Fens field and our project. https://reeminerals.no (accessed 1.6.21).

REIA, 2020. REIA Weekly Newsletter. https://mailchi.mp/c8543c593fb1/reia-weekly-newsletter-4196725 (accessed 8.3.21).

Riba, J.-R., López-Torres, C., Romeral, L., Garcia, A., 2016. Rare-earth-free propulsion motors for electric vehicles: A technology review. Renew. Sustain. Energy Rev. 57, 367–379.

Roskill, 2018. Rare Earths/niobium: Russia puts its weight behind rare earths. Roskill. https://roskill.com/news/rare-earths-niobium-russia-puts-weight-behind-rare-earths/ (accessed 12.11.20).

Royen, H., Fortkamp, U., 2016. Rare earth elements - purification, separation and recycling. IVL Swedish Environmental Research Institute 2016, Report No. C 211, September 2016.

Saywell, T., 2021. USA Rare Earth outlines domestic mine-to-magnet strategy. Nothern Min. https://www.northernminer.com/subscribe-login/?id=1003826738 (accessed 8.3.21).

Schmid, M., 2019. Rare earths in the trade dispute between the US and China: a déjà vu. Intereconomics 54, 378–384.

Search Minerals, 2021. THE FOXTROT RESOURCE DEVELOPMENT PROJECT. http://www.searchminerals.ca/projects/district/foxtrot (accessed 8.3.21).

Shanghai Metals Market, 2020. Latest Update in the China Rare Earth Oxides Market. Shanghai Met. Mark. https://www.metal.com/Rare-Earth-Oxides (accessed 12.20.20).

Sharma, D., 2020. American Rare Earths raises A$2.4 million to drill La Paz project in Arizona. Prot. Investors. https://www.proactiveinvestors.com.au/companies/news/935447/american-rare-earths-raises-a24-million-to-drill-la-paz-project-in-arizona-935447.html (accessed 12.11.20).

Silvestri, L., Forcina, A., Silvestri, C., Traverso, M., 2021. Circularity potential of rare earths for sustainable mobility: Recent developments, challenges and future prospects. J. Clean. Prod. 292, 126089.

Smith, J., 2020. Rare earths on the ASX: New U.S. Minerals bill to bump up Aussie exports. Mark. Her. https://themarketherald.com.au/rare-earths-on-the-asx-new-u-s-minerals-bill-to-bump-up-aussie-exports-2020-09-17/#:~:text=Australia’s biggest rare earths miner,earth mines in the world. (accessed 12.10.20).

Solovyova, V.M., Ilinova, A.A., Cherepovitsyn, A.E., 2020. Strategic forecasting of REE mining projects development in Russian Arctic, In: Advances in Raw Material Industries for Sustainable Development Goals: Proceedings of the Xii Russian-German Raw Materials Conference (Saint-Petersburg, Russia, 27-29 November 2019). CRC Press, p. 456.

Statista, 2021. Prices of selected rare earth oxides in 2018 (in U.S. dollars per kilogram).

Statista.com. https://www.statista.com/statistics/271883/prices-of-selected-rare-earth-oxides/ (accessed 14.10.21).

Thicknesse, E., 2020. Rare earth miner Pensana inks deal with Chinese firm for Angola project. Cityam. https://www.cityam.com/rare-earth-miner-pensana-inks-deal-with-chinese-firm-for-angola-project/ (accessed 12.19.20).

Toyota, 2021. Toyota announces its new BEV series, Toyota bZ, in establishment of a full line-up of electrified vehicles. https://global.toyota/en/newsroom/toyota/35083987.html (accessed 15.10.21).

Tracy, B.S., 2020. An Overview of Rare Earth Elements and Related Issues for Congress. Every CRS Rep. https://www.everycrsreport.com/reports/R46618.html (accessed 12.15.20).

Treleaven, S., 2021. Building the foundations for rare earth elements supply chain. CIM Mag. https://magazine.cim.org/en/projects/building-the-foundations-for-rare-earth-elements-supply-chain-en/ (accessed 8.3.21).

U.S. Geological Survey, 2020. Rare Earth Statistics and Information - USGS. U.S. Geol. Surv. https://pubs.usgs.gov/periodicals/mcs2020/mcs2020-rare-earths.pdf

Urban Mining Company, 2021. A resource breakthrough. https://www.urbanminingco.com/index.php?cat=technology&subcat=technology (accessed 4.26.21).

US DOD, 2020. DOD Announces Rare Earth Element Awards to Strengthen Domestic Industrial Base > U.S. Department of Defense > Release. https://www.defense.gov/Newsroom/Releases/Release/Article/2418542/dod-announces-rare-earth-element-awards-to-strengthen-domestic-industrial-base/ (accessed 8.3.21).

USA Rare Earth, 2021. Round Top Mountain project, Texas. http://usarareearth.com (accessed 1.9.21).

van Exter, P., Bosch, S., Schipper, B., Sprecher, B., Kleijn, R., 2019. Metal demand for renewable electricity generation in the Netherlands. Navigating a complex supply chain.

Vital Metals, 2021. Nechalacho Project, Canada – Vital Metals. https://vitalmetals.com.au/portfolio/nechalacho-project/ (accessed 8.3.21).

Volkswagen Newroom, 2021. Electric vehicles. https://www.volkswagen-newsroom.com/en/electric-vehicles-3646 (accessed 15.10.2021).

Weng, Z., Jowitt, S.M., Mudd, G.M., Haque, N., 2015. A detailed assessment of global rare earth element resources: opportunities and challenges. Econ. Geol. 110, 1925–1952.

Yang, X., 2021. Myanmar crisis poses risks to global rare earth supply chain. Asia Financial. https://www.asiafinancial.com/myanmar-crisis-poses-risks-to-global-rare-earth-supply-chain (accessed 8.3.21).

Yeping, Y., 2020. Concerns about export restrictions drive up rare-earth prices. Global Times. https://www.globaltimes.cn/content/1208106.shtml (accessed 12.16.20).

Zeuthen, J., 2017. Part of the master plan? Chinese investment in rare earth mining in Greenland.

938 Arct. Yearb. 2017.

939