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A Study Of The Global Rare Earth Industry Transition

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A STUDY OF THE GLOBAL RARE EARTH INDUSTRY TRANSITION

by

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Al Thibeault
2023 December 01

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ABSTRACT

The global rare earth industry is in a period of transition. This transition, led by the Minerals Security Partnership (MSP), aims to ensure supply security for the rare earths needed to meet clean energy transition demands. Supply security requires two goals: first, in the near-term, re-establishing rare earth production and processing in the MSP nations, and second, in the long-term, finding new sources of competitive advantage to create long-term industry stability. Stimulus funding is essential to achieving the short-term goal; however, long-term industry stability requires a strategy to replace stimulus funding with private investment in a profitable industry. Government/industry collaboration to develop new sources of international competitive advantage is necessary to achieve this goal. Long-term industry stability is critically important, as the collapse of a re-established MSP industry would have severe consequences for the clean energy transition. Increasing supply security thus has two key challenges if the MSP is to achieve its aim. This work proposes an interdisciplinary method to study transition strategies that combine elements from systems engineering, technological systems innovation, and international competitive advantage theory. The method uses an exploratory hybrid dynamic simulation model to test various strategy options for meeting the two key challenges for achieving a successful transition. The findings suggest that the method has promise for examining the factors required to achieve a successful rare earth industry transition.

Keywords: rare earth, competitive advantage, hybrid dynamic simulation , clean energy

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GLOSSARY OF TERMS

AB	Agent-Based
CAN	Competitive Advantage of Nations
CAT	Competitive Advantage Theory
CHN	China
DDM	Double Diamond Model
DM	Diamond Model (also known as the theory of international competitive advantage of industries)
HD	Hybrid Dynamics (in this work, a combination of AB and SD)
Kilotonnes (KT)	Metric tonne equal to 1000 kilograms
Magnet metals	The four rare earth elements praseodymium (Pr), neodymium (Nd), terbium (Tb), and dysprosium (Dy)
MSP	Minerals Security Partnership
MSP Nations (alphabetical)	Australia, Canada, European Commission, Finland, France, Germany, India, Italy, Japan, Republic of Korea, Norway, Sweden, United Kingdom, and the United States
RE	rare earths and derivative forms – REE, REM, and REO
REE	rare earth element
REM	rare earth mineral
REO	rare earth oxide
RoW	Rest of the World
SDM	Single Diamond Model (also known as the diamond model)
SD	System Dynamics
TG	Trade Group

AN INTERDISCIPLINARY METHOD FOR THE STUDY OF THE
GLOBAL RARE EARTH INDUSTRY TRANSITION

CHAPTER I:

INTRODUCTION

1.1 The Global Rare Earth Industry

Rare earths, a group of 17 metals with special electrical, magnetic, and optical properties, is a global industry. First discovered in 1788, the commercial beginnings of the rare earth industry began with the invention of gas mantles and flints by Carl Auer von Welsbach in the late 19th century (Klinger, 2015a). Almost 150 years later, the rare earth industry produces hundreds of products used in every facet of today's society, from digital networks and mobile phones to cancer treatments, white goods, industrial robotics, electric vehicles, and wind turbines.

As of 2022 the global rare earth market has grown to approximately US$10 billion (Kruemmer, 2023). Compared to the size of the iron and steel (US$1.7 trillion) or aluminum ($150 billion) markets it is a relatively small industry; however, the market sizes of the five industries[1] most reliant on rare earth permanent magnets[2] totalled US$3.3 trillion. While the most valuable rare earth products, permanent magnets, are essential for the clean energy sector, that is just one example of hundreds of rare earth-based products used by scores of industries. The economic importance of the rare earth industry is not due to the size of industry itself, but to the size and number of global industries that rely on its products.

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[1] Electric vehicles – US$1,900B, white goods – US$697B, defense – US$483B, wind – US$188B, industrial robots – US$17B.

[2] In 2022 the four rare earth elements used in permanent magnets accounted for 94% of rare earth market value.

With industry sources projecting between four-fold (Detry et al., 2023) and six-fold (Tsafos, 2022) rare earth demand growth by 2050, and mostly for magnet metals, the importance of rare earths will become magnified. For this reason, industrial nations have deemed that understanding the challenges facing the industry in meeting this demand is of critical and strategic importance. In this work we will focus on the challenges arising from meeting the rare earth demands of the clean energy sector.

The map in Figure 1 shows the current global footprint of the industry.

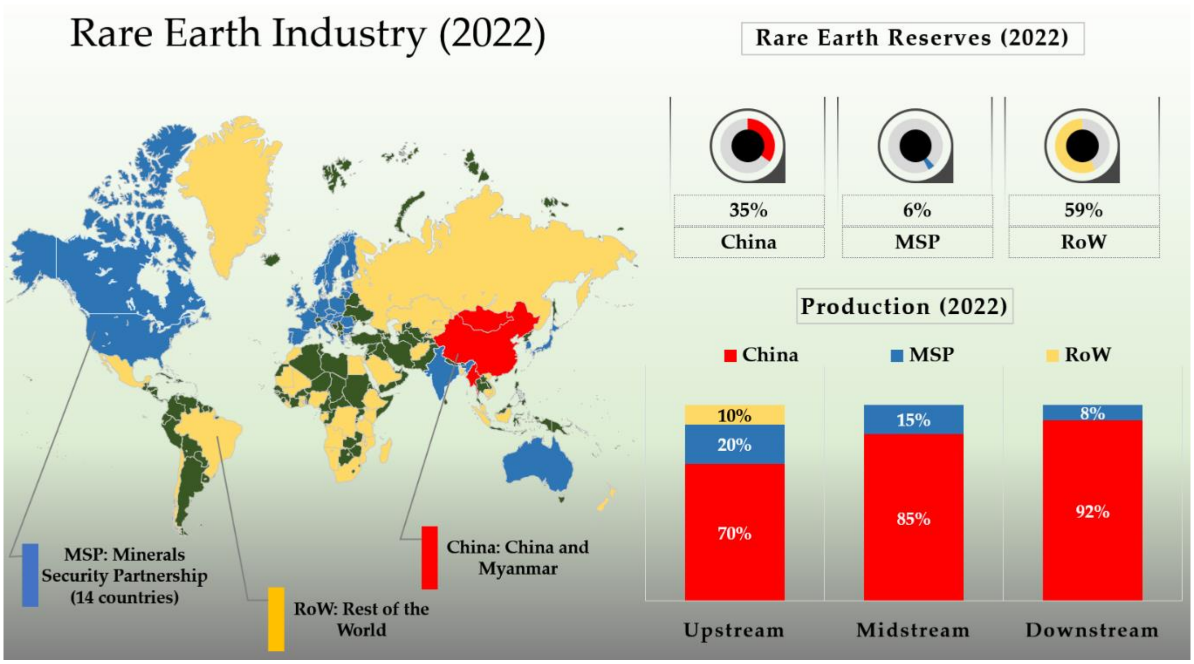

Figure 1. The Global Rare Earth Industry (2022)

Segments of the rare earth industry exist across the globe. Countries coloured red, blue, or yellow, which represent trade groups, have a high level of rare earth activity; the few countries coloured green have relatively little or none. Global production occurs within these three trade groups (TGs). The three TGs are 1) China TG, which includes both

China and Myanmar (formerly Burma), 2) the Minerals Security Partnership TG (MSP)[3] (U.S. Department of State, 2022), and 3) the remainder of the producing nations combined under the collective heading Rest of the World TG (RoW)[4].

As is common with mining and extraction industries, the rare earth industry is generally described as having three stages of production, called streams – upstream (mining), midstream (metallurgical processing), and downstream (refining and fabrication) The map shows the share of each production stream within each TGs (lower right), as well as the share of known rare earth reserves (upper right). China TG has the largest known reserves of any single country, when aggregated to the TG level the RoW TG has a far larger share. As exploration ramps up in the MSP TG and other nations over the next five to ten years to meet increased demand these resource percentages will change.

1.2 The Clean Energy Imperative

The International Energy Agency's report World Energy Outlook 2008 (2008) states that the trends in global energy are environmentally, economically, and socially, "patently unsustainable". Fifteen years later, the Energy Institute 2023 Statistical Review of World Energy (2023) provides a sobering on these trends today. Although renewables (excluding nuclear and hydro) increased their share of primary consumption by 13% in 2022, from 40.0 exajoules (EJ) to 45.2 EJ, global CO_{2e} emissions reached a record level

[3] The original Mineral Security Partnership (MSP) nations: Australia, Canada, Finland, France, Germany, Japan, Republic of Korea, Sweden, United Kingdom, United States, European Commission. Norway joined in September 2022, Italy joined in February 2023, and India joined in June 2023.
[4] Rest of the World (RoW): Primarily Russia, Brazil, Vietnam, and several African nations.

of 39.3 billion tonnes. This is due to energy consumption from fossil fuels (oil, natural gas, and coal) declining by a mere 0.6% from 2021 levels, essentially remaining nearly constant at 82% of total consumption. Energy consumption remains by far the largest source of CO_{2e} emissions, at 87%. As noted in the related report BP Energy Outlook 2023 (2023), “The carbon budget is running out.”

The recently released Intergovernmental Panel on Climate Change (IPCC) Synthesis Report AR6 (Romero et al., 2023) confirms these analyses. AR6 is a ‘stocktaking’ that reports the current state of climate change, its impacts, and risks, and makes recommendations for mitigations and adaptation. Due to increased global surface warming during the period 2011 to 2020 of 1.1°C above that in 1900, the report finds that, globally, significant changes and impacts have occurred. The report also states that the currently agreed national targets for limiting greenhouse gas emissions will likely not be sufficient to limit global warming to less than 1.5°C in this century, and the goal of limiting global warming to less than 2°C is at risk. The report concludes that of the ten key solutions required to return to the 2°C pathway, number one is retiring coal plants and number two is transitioning to clean energy.

The world’s doggedly persistent reliance on fossil energy has deep and complex roots. In Grand Transitions (2021), Smil traces both the pre-modern and post-modern reliance on fossil energy to the complex and interconnected dynamics of energy, population, agriculture and food supply, economies, and the environment. While there is evidence of relatively quick (i.e. – a decade or so) energy decarbonization transition initiatives that have taken place (Sovacool, 2016), the recent BP report reinforces that the clean energy transition has been a protracted process. Figure 2 is a causal loop diagram

(CLD) combining Smil's grand transitions dynamics and the dynamics derived from a recent version of the World3 model (Purvis, 2020; Purvis et al., 2022). World3 was originally developed for the groundbreaking book "The Limits to Growth: a Report for the Club of Rome's Project on the Predicament of Mankind" (Meadows et al., 1972), and is based on the World model originally created by J.W. Forrester (1971).

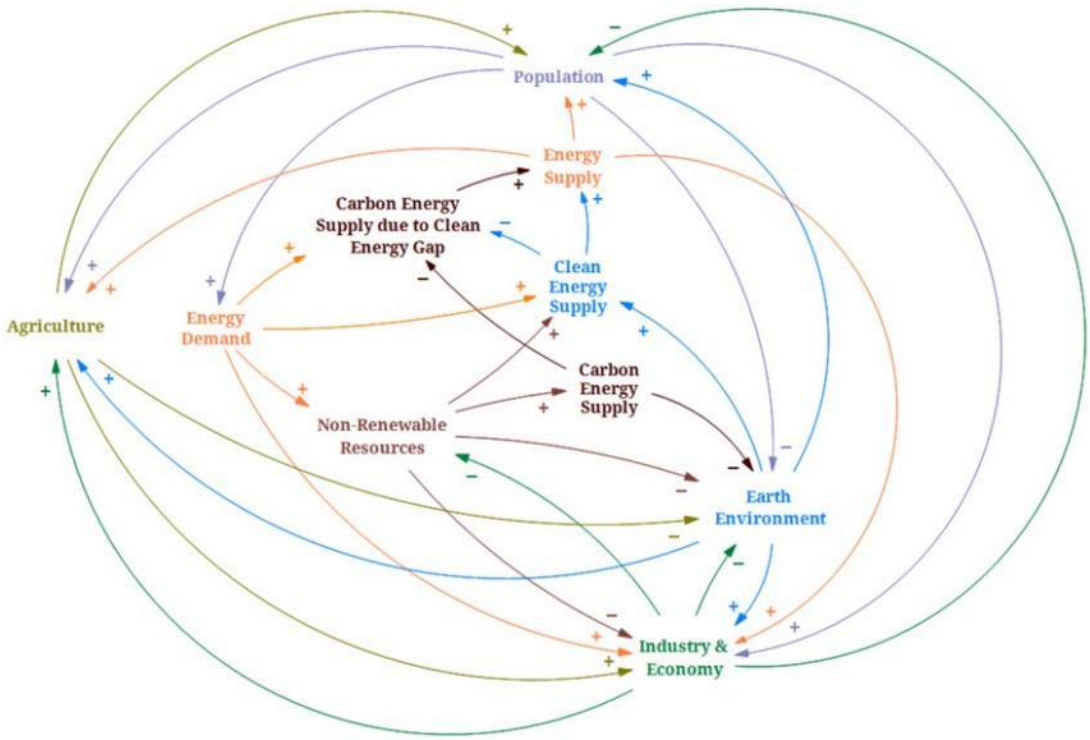

Figure 2. Causal loop diagram of the complex dynamics between energy and resources in the context of a whole world model. (Author's work based on Purvis (2020) and Meadows et al. (1972)).

Within this complex feedback network there are two loops, L1 and L2, that are key to understanding the persistence of carbon energy:

L1: Population $\rightarrow^{+}$ Energy Demand $\rightarrow^{+}$ Carbon Energy Supply due to Clean Energy Gap $\rightarrow^{+}$ Energy Supply $\rightarrow^{+}$ Population

L2: Population $\rightarrow^{+}$ Energy Demand $\rightarrow^{+}$ Clean Energy $\rightarrow^{+}$ Energy Supply $\rightarrow^{+}$ Population

In both loops each feedback link has positive polarity (denoted by the + sign), indicating that both are self-reinforcing loops meaning growth begets growth and decline begets decline. Intuitively this self-reinforcing population/energy causality makes sense. Yet with insufficient growth in clean energy supply the consequence is increased carbon energy consumption and increased CO_{2e} emissions. The resulting negative impacts for the earth environment call into question the persistent delay in reaching the clean energy tipping point.

The BP report suggests three strategies for reducing CO_{2e} emissions from energy: 1) consume less energy, 2) use more efficient CO_2-producing devices to reduce emission intensity, and 3) increase the pace of the clean energy transition. The third strategy – increasing the pace of the clean energy transition – is the focus of this study.

1.3 Coupled Transitions

Recalling the energy-resources CLD of Figure 2 above, the links between energy demand, non-renewable resources and clean energy supply shows a positive causal chain – increased energy demand will lead to increased non-renewable resource production, which is used to increase energy supply. As energy transition policies increasingly take hold the demand for clean energy will shift from non-renewable production from carbon fuels to technology metals (Lifton, n.d.) such as lithium, cobalt, nickel, and rare earths. The increased production of non-renewable rare earth elements is necessary for increased production of wind turbines and electric vehicles, two technologies that are critical and strategic to clean energy (Tsafos, 2022).

In a recent report, the International Energy Agency (IEA) stated that rare earth elements (REE) are essential critical energy transition minerals (2023). The IEA notes in the same report that “there is growing recognition that policy interventions are needed to ensure adequate and sustainable mineral supplies”. The key clean energy technologies, and the minerals required by these technologies, are shown in Table 1.

Technology ⇩ vs Mineral ⇨	Copper	Cobalt	Nickel	Lithium	**REEs**	Chromium	Zinc	PGMs	Alumnium	Wt.Avg	Mineral Intensity Rank
Solar PV	3	1	1	1	1	1	1	1	3	1.44	5
Wind	**3**	**1**	**2**	**1**	**3**	**2**	**3**	**1**	**2**	**2.00**	**2**
Hydro	2	1	1	1	1	2	2	1	2	1.44	5
Concentrating Solar Power	2	1	1	1	1	2	2	1	3	1.56	4
Bioenergy	3	1	1	1	1	1	1	1	2	1.33	9
Geothermal	1	1	3	1	1	3	1	1	1	1.44	5
Nuclear	2	1	2	1	1	2	1	1	1	1.33	9
Electricity networks	3	1	1	1	1	1	1	1	3	1.44	5
EVs and battery storage	**3**	**3**	**3**	**3**	**3**	**1**	**1**	**1**	**3**	**2.33**	**1**
Hydrogen	1	1	3	1	2	1	1	3	2	1.67	3
Wt.Avg	2.30	1.20	1.80	1.20	1.50	1.60	1.40	1.20	2.20		
Mineral Rank	1	7	3	7	**5**	4	6	7	2		

adapted from IEA. (2021). The Role of Critical Minerals in Clean Energy Transitions – Analysis. IEA. https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions

Table 1. Relative importance of minerals for selected clean energy technologies (adapted from IEA (2021))

In the table, minerals (columns) are ranked as essential (3), important (2) or required (1) for the listed clean energy technology (rows). Wind and electric vehicles (EVs) and battery storage have the highest mineral intensities. In this paper our focus will be on wind and EVs, as REEs are not a significant material for battery storage technology. While the relative importance of REEs across all the listed technologies is low, they are essential for both wind and EVs.

The critical need for wind turbines and electric vehicles to decarbonize the energy grid and transportation sectors has been known for several years (Habib & Wenzel, 2014) and continues to researched (Van de Graaf et al., 2023). Rare earth elements (REEs), and by extension the rare earth industry, are thus critical to the global clean energy transition.

The importance of REEs for wind turbines and electric vehicles traces back to the reliance of these technologies on rotating machines, configured as generators or motors respectively, for their operation. The best suited versions of rotating machines for these technologies are those that use rare earth permanent magnets. While more costly, they have superior performance and higher reliability characteristics provide benefits that make them the preferred choice for electric vehicles and offshore wind turbines.

Of the 17 rare earth elements, the four used in permanent magnet manufacturing are of primary concern for clean energy technology. Two are the ‘light’ rare earth elements (LREE) praseodymium (Pr) and neodymium (Nd), and two are the ‘heavy’ rare earth elements (HREE) terbium (Tb) and dysprosium (Tb)[5]. These four elements, known as the ‘magnet metals’, each have unique properties necessary in the making of high-performance permanent magnets. Despite decades of research, the search for substitutes with the equivalent performance characteristics has yielded no results but is ongoing (Bauer et al., 2023). The report “Critical Minerals Market Review 2023” (International Energy Agency, 2023) summarizes the importance of rare earths to the clean energy transition: “Rare earth elements are essential for permanent magnets required by EVs and wind turbines”.

A recent EU JRC study (Carrara et al., 2023) assesses the strategic importance of critical and strategic minerals by examining the number of technologies that would be impacted should supply risks materialize. Figure 3 below graphs the data derived from Table 1 of that study.

Each bubble on the graph represents one of 34 strategic and critical raw materials, plotted on two dimensions – supply risk (horizontal) and strategic importance (vertical). Supply risk is calculated on a scale of 0 (lowest) to 10 (highest), scores ranging from 0.1 to 5.3. Strategic importance is scored from 0 (lowest) to 15 (highest), with scores ranging from 1 to 15. The bubbles are scaled to reflect supply risk.

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[5] The terms light and heavy rare earths are defined in Section 2.1.1.

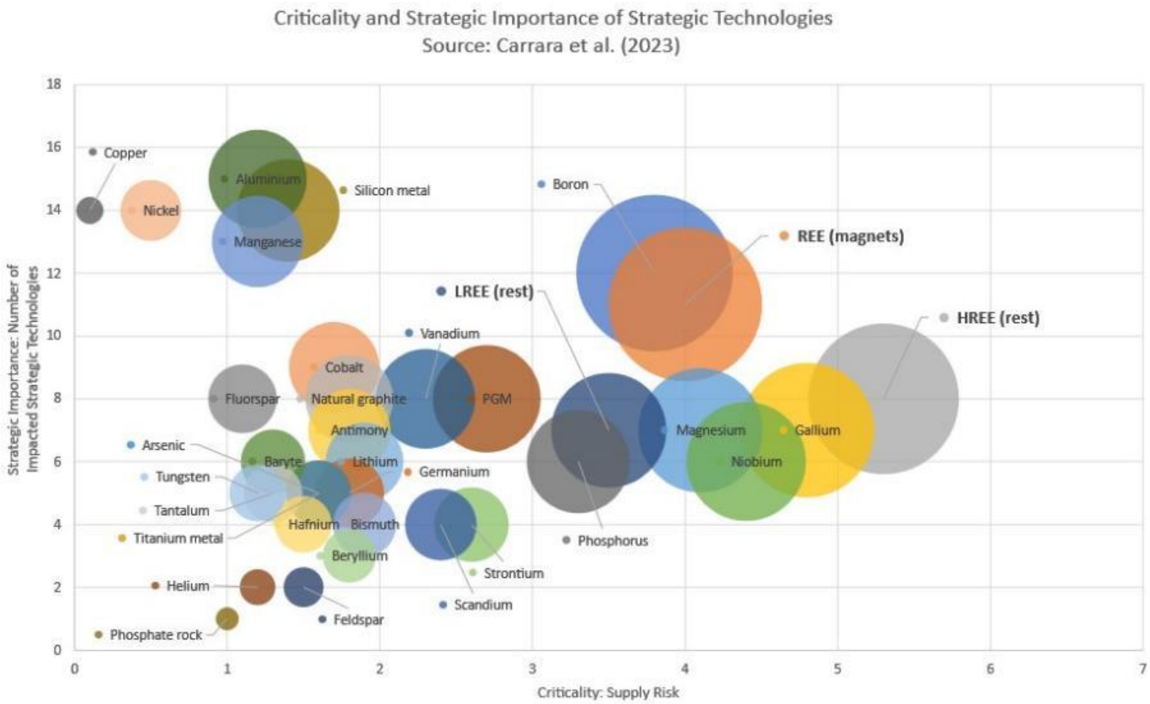


Figure 3. EU critical raw materials assessment (Table 1 from Carrara et al. (2023)). Bubbles are the product of strategic importance and criticality.

Although similar, countries have developed individual methods for calculating supply risk, for example *Methodology for establishing the EU list of critical raw materials : guidelines* (European Commission et al., 2017) and *Methodology and technical input for the 2021 review and revision of the U.S. Critical Minerals List* (Nassar & Fortier, 2021) The EU methodology graphs economic importance versus supply risk, while the U.S. methodology reviews economic vulnerability versus disruption potential.

The methodologies are then applied to prepare the critical minerals list for the country and other studies. For example, *Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU – A foresight study* (Carrara et al., 2023) quantifies the strategic importance of raw materials for 15 strategic technologies. An indication of the critical and strategic importance of rare earths is that they are represented in three separate categories – as REE (magnets), LREE (rest), and HREE (rest) (Figure 3). REE (magnets) is the aggregate score of the four rare earth elements used for permanent magnets, two of which are classified as light rare earths (LREE) and two as heavy rare earths (HREE). Individually, each of the four magnet elements are considered strategic and at supply risk in a larger dataset from which this summary table is derived. LREE (rest) and HREE (rest) are the other two bubbles representing the aggregate scores for the non-magnet elements in those categories.

The important point is that the rare earths, and magnet metals specifically, rank highly for strategic importance and supply risk, as indicated by their bubble size and chart position. It is the need to lower magnet metal supply risk to avoid negative impacts to the strategically important clean energy technologies that is the primary trigger for the rare earth industry transition[6]. The triggers include the supply risk calculation parameters:

- market competitiveness: the rare earth market is highly concentrated in China, which dominates production, processing, and fabrication including approximately 92% of permanent magnet fabrication.
- import reliance: China's market control gives it the ability to establish production and export quotas that restrict supply and increase price, which it has done in the past. As clean energy technology becomes increasingly critical to energy decarbonization the sensitivity to quota restrictions also increases.
- substitution index: R&D efforts to find substitutes for rare earth magnet metals have been underway for decades, with marginal success. Efforts have increased as a means of reducing supply risk.

The U.S. (Bauer et al., 2023) and other countries, agencies, and experts, have made

[6] In this document, we use 'transition' to mean the rare earth industry transition, except where necessary to distinguish it from the clean energy transition.

similar determinations. A report by the International Renewable Energy Agency (IRENA) states "Critical material supply disruptions have minimal impacts on energy security, but outsized impacts on the energy transition." (Van de Graaf et al., 2023). Gaspar Filho & Santos (2022) make a similar connection: "ensuring a stable supply of critical non-fuel minerals at an affordable price is essential for the current energy transition to take place". Based on these assessments we conclude that the clean energy transition and the rare earth industry transition are coupled as shown in Figure 4. This figure uses a systems engineering concept model approach (Vanek et al., 2016), combined with a socio-technical energy transitions (STET) model (Verrier et al., 2022a) to represent the three segments of the rare earth industry transition.

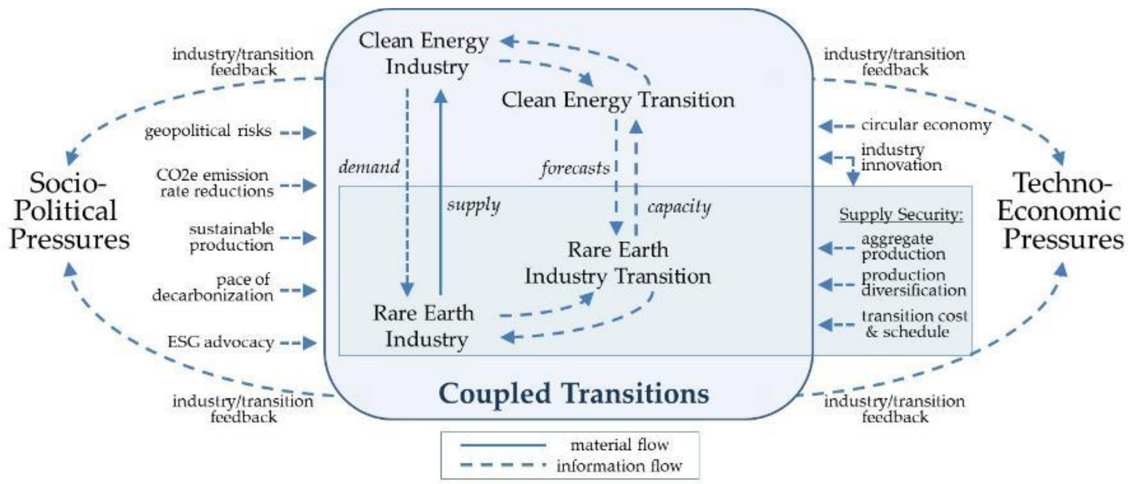


Figure 4. Systems engineering conceptual diagram of the coupled transitions and exogenous pressures. (Author's work, adapted from Vanek et al. (2016) and Verrier et al. (2022))

In the centre are the high-level dynamics of the rare earth industry transition showing the causality of supply and demand at the industry level and forecast demand and capacity growth for the coupled transitions.

On the left and right are the two groups of exogenous pressures – socio-political and techno-economic. These pressures seek to influence the type and pace of both the clean energy and rare earth industry transitions. Similarly, feedback from the industries and industry transition strategies aim to influence these exogenous pressures, iteratively. Not shown are the dynamics that amplify or diminish the exogenous pressures based on perceptions of industry/transition feedback.

This coupled transition approach unites the two main research strands investigating positive tipping points for low-carbon transitions (Geels & Ayoub, 2023). The two strands are techno-economic, which views the tipping point as the inflection point on the low carbon technology diffusion curve, and socio-political, with emerging research focusing on a critical mass of behaviour leading to accelerated adoption. A similar two-strand approach was previously applied to the oil sands industry (Thibeault, Taylor, et al., 2023).

The socio-political and techno-economic pressures listed are broad but not all inclusive. Selected pressures are examined in more detail below.

1.3.1 Socio-Political Pressures

1.3.1.1 Geopolitical Risks

Geopolitical risk factors are the main techno-economic pressure driving the rare earth industry transition. They are at the root of the supply security risks and the drivers for increasing aggregate production and production diversity.

These risks are due to China's dominance of the industry and willingness to manipulate the market for geopolitical gain. These risks have been increasingly evident since the mid-1990s. Figure 5 shows that China's rise to industry dominance started in the mid-1980s, coinciding with their entry into state-sponsored commercial production. (Liu et al., 2023)

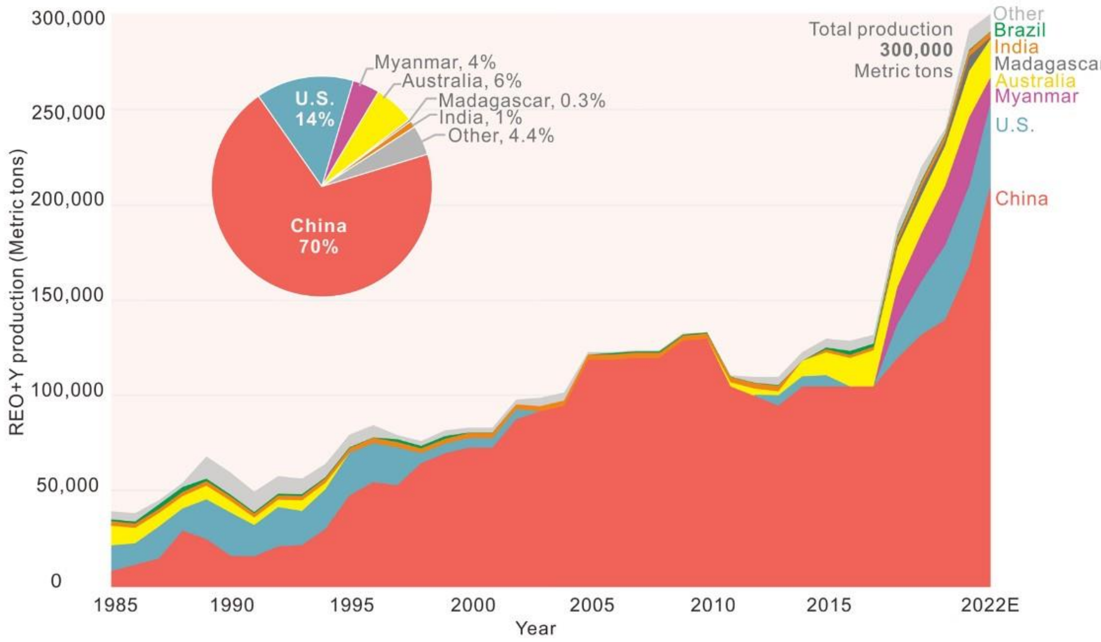


Figure 5. Emergence of China as the dominant rare earth nation. (Source: Liu et al., 2023)

China's production (red area) overtook that of the U.S.(blue area) in the mid-1990s. China's long-term strategy to achieve industry dominance was clearly articulated in 1992 by then leader Xiaoping Deng, with his statement that "the Middle East has oil, but China has rare minerals"(Y. Chen & Zheng, 2019).

Industry observers raised concerns at the time. Knights (1990) wrote "Rare earths have found few new markets for expansion in the past couple of years, sources said, but that has not deterred market activity by China or eased concern as to that country's growing influence in the market"; however, "other facts suggest that the United States is becoming a bigger player in the market". Kingsnorth (1992) noted "China made a concerted effort in the 1980s to become a major rare earth supplier", but continued "China has had to discount prices heavily to obtain its current market share".

The level of concern outside China changed when in 2010 prices rose dramatically and the perceived risk to supply shown previously in Figure 5. Despite the high levels of risk awareness, concrete actions have taken over 10 years to gain traction. During that time, China's dominance has grown.

It is important to understand that the rise of China to dominant player in the rare earth industry is the result of a well-executed, multi-year, state-funded strategy (Duan, 2022). That strategy has gone through iterations – from upstream dominance to downstream dominance, especially in permanent magnets. What is perhaps less well-understood is that a parallel, coordinated, and complimentary strategy was also being enacted. During its period of rise to dominance as a producer, China also became a major consumer of rare earths including for key permanent magnet products. As China's domestic demand for magnet metals grows to meet its clean energy and other demands, the production available for export will come under pressure, putting more onus on the MSP and RoW nations to become self-reliant.

Volumes have been written about the geopolitics of rare earths (Klinger, 2015b), but in in the context of the industry transition other salient factors are:

- China adds a 13% value-add tax (VAT) on nearly all rare earth exports, i.e. – MSP and RoW manufacturers dependent on rare earths from China are at a 13% cost disadvantage to their China counterparts.
- China does not allow the importation of 'used goods', which, by regulation, includes rare earths processed outside of China. Thus, rare earth refiners of magnet metals and fabricators of permanent magnets cannot export those products to China. This restriction has the following implications:

- An MSP downstream refiner or fabricator cannot access the large clean energy demand sectors in China for permanent magnets, most notably wind and electric vehicles.
- MSP downstream refiners and fabricators are competing against the China (non-VAT) material price for magnet metal business outside China. Currently China services nearly 100% of this market. Start-up MSP refiners and fabricators must develop not only new production facilities, they must also develop market share in ex-China demand sectors.
- Until MSP midstream and downstream producers can develop other sources of competitive advantage, they will need to rely on stimulus measures to compete for demand from the MSP clean energy sector.

Thus, the MSP TG requires a holistic, multi-stream strategy to re-establish the industry that relies on innovation to create the new sources of competitive advantage required for long-term industry stability.

1.3.1.2 Environment Factors and Sustainability

CO2e emission reduction and the pace of decarbonization and Environmental, Social, and Governance (ESG) advocacy are separate but related environmental factors that have long been linked to the clean energy agenda but less so at the rare earth industry transition. The ESG advocacy typically associated with the rare earths has been directed at the industry's historically troubled environmental record. Disposal of thorium and uranium, radioactive waste products of rare earth mining must comply with stringent regulations (for example: US EPA, 2015) but continues to be a socio-political stumbling block for licensing of new mines.

Aging carbon-based energy infrastructure will increase sociopolitical pressure to convert to clean energy. Investors have started restricting funds for carbon fuel generation (Creamer, 2023), thus as aging coal plants are taken offline the demand for clean energy capacity will increase. While this will increase the pace of decarbonization, some of these projects will coincide with end-of-life replacement of wind turbines and EVs, potentially accelerating rare earth demand. This pressure will be linked to pressure for recycle permanent magnets.

A recent area of advocacy is related to sustainable production concerns troubling mining practices in countries with lax environmental enforcement, which Klinger labels ‘sacrifice zones’ (Klinger, 2015b). This practice uses the ‘greater good’ rationale to justify mining practices that extensively harm the local environment. While this does occur in some jurisdictions it is not a widespread practice; however, it is adopted by some advocates to rally against all rare earth mining.

Klinger also notes that “empirical evidence that demonstrates that just, secure, and sustainable rare earth production and consumption is possible” (2018), but that those attempting to deliver that message will face “an uphill battle”.

1.3.2 Techno-Economic Pressures

Supply security is essential for both the clean energy and rare earth industries. For clean energy, the need for supply security is driven by the imperative to reach net zero by 2050. Rare earth supply disruptions would interrupt production of EVs and wind turbines, and impact prices. Disruptions typically take the form of supply chain disruptions or production shortfalls if capacity growth does not keep pace with demand. A third disruption type is possible, if stimulus funding to rebuild the MSP TG rare earth industry becomes constrained due to transition cost or schedule exceeding the public mandate for support. In this case, new MSP TG capacity that is not self-sustaining could close and thus limit supply to clean energy industries.

1.3.2.1 Aggregate Production

By some estimates, the forecast exponential growth in EV and wind turbine production is forecast to exceed global production of permanent magnets between 2030 and 2035 (Detry et al., 2023). Rapid expansion of MSP TG capacity is expected to reduce the shortfall, but is hampered by project startup delays, long construction lead times, and a loss of technical expertise since the MSP magnet industry collapsed in the 2000s. Recycling of magnet scrap is another potential source of magnet metals, but new magnet manufacturing is required to process the metals.

1.3.2.2 Production Diversity

The original driver for the MSP transition initiative was the concentration of production, in all three streams, in China. Several new projects are in the development stage, some well advanced and due to be online by 2025. Few of these, however, are heavy rare earth (HREE) projects with the dysprosium and terbium required for high performance magnets. Most of the light rare earth (LREE) projects have low percentages of neodymium and praseodymium that are the primary magnet metals. New projects will shift production capacity away from China but to be economically sustainable will also require magnet producers to make inroads into the large customer base currently served by China.

1.3.2.3 Transition Cost and Schedule

Aggregate production and production diversity objectives will largely determine the cost and schedule of the rare earth industry transition. Numerous peer-reviewed, government, and industry, documents attest to the complexity, and cost of the clean energy and rare earth industry transitions (Andersen & Geels, 2023; *China's Rare Earth Subsidies and Structural Advantages*, 2023; Detry et al., 2023; Guo & You, 2023; Guzzo et al., 2023; Madaleno et al., 2023; Majkut et al., 2023; Nakano, 2023; Potter, 2023; Srivastava, 2023), which are expected to be large. Majkut et al. (2023) cite International Energy Agency estimates that more than US$500 billion for critical mineral mining and processing will be required for the net-zero clean energy transition. The MSP nations are preparing to provide billions of dollars in stimulus funding to rebuild the rare earth industry in their nations, since several factors are causing private investors to be reluctant (Majkut et al., 2023).

While beneficial in the near-term, research shows that long-term stimulus spending is ineffective (Michel, 2020; Ramey, 2019). Large and long-duration stimulus funding thus becomes a transition success risk factor if it is seen as ineffective, potentially leading to curtailment before transition objectives are met.

A stimulus management strategy that spans the 20-plus year expected transition timeframe would assist policymakers and investors develop long-term funding that is in place for the duration of the transition.

1.3.2.4 Circular Economy

Circular economy is considered a techno-economic pressure from the perspective that recycling magnets represents a potentially large supply of magnet metals that do not require additional mining. China currently recycles swarf (waste material from magnet production), but few jurisdictions are close to large-scale recycling of scrap from products.

Significant initiatives exist for recycling scrap containing rare earths, especially permanent magnets. Commercial-scale recovery processes now exist. Kruemmer (2021) reports that new capacity to produce 20,000 t/year of magnet metals is being developed in China. Significant circular efforts are also underway in the EU (Bobba et al., 2023), with recycled magnet metals from EV motors designated as a secondary supply; these are not yet in production.

1.3.2.5 Industry Innovation

Innovation has many dimensions (Eggert et al., 2016) including discovery and management of mineral deposits, process and production efficiency, and developing substitutes with equivalent performance characteristics to reduce rare earth demand.

In the MSP TG, increased innovation will require rebuilding the advanced rare earth knowledge base that was significantly diminished after the shift in production in the 1990s. The benefits of having these specialist resources are not only for developing new innovations, but for widespread deployment throughout the industry on new production projects, potentially reducing project risks and shortening transition schedules.

1.4 Research Description

Having thus established the coupled relationship between the clean energy and rare earth transitions based on the rare earth magnet metals required for permanent magnets, the aim, hypothesis, and scope, of this research are now presented.

1.4.1 Research Aim

The need to address rare earth supply security to mitigate follow-on risks that could threaten the clean energy transition and decarbonization of the energy system.

This research aims to present a method for studying rare earth industry transition strategies that can achieve the twin goals of supply security: first, re-establishing rare earth production and processing in the MSP nations, and second, in the long-term, finding new sources of competitive advantage to create long-term industry stability.

To achieve this aim, the research proceeds as follows:

1. Examine the drivers of the rare earth industry transition. As described above, the exponential demand growth of clean energy transition technology is the key driver, but there are others. We examine forecast demand from the clean energy transition and the impact that has on the rare earth industry transition.
2. Identify quantitative metrics that can measure the success criteria of the MSP TG rare earth industry transition and transition impacts on the other TGs.
3. Construct a method for evaluating viable transition strategies using a hybrid system dynamic simulation model that integrates an adaptation of the international competitive advantage theory diamond model with concepts from systems engineering and technological innovation system (TIS) (Cherp et al., 2018; Jacobsson & Bergek, 2004; Markard et al., 2015)

1.4.2 Research Hypothesis

The research hypothesis is that an interdisciplinary method can identify transition strategies that satisfy the two necessary conditions for transition success: that the post-transition future state results in increased supply security of rare earths for the clean energy industry and long-term stability for the MSP rare earth industry.

This method uses a hybrid dynamic simulation model, a combination of system dynamics and agent-based modeling, to integrate transition approaches drawn from systems engineering, technological innovations systems, and international competitive advantage theory.

A literature review shows that transition studies have focused on either the techno-economic, or socio-political aspects of the transition. This research takes a novel approach in its methodology by constructing a hybrid dynamic simulation model that combines the techno-economic and socio-political approaches to construct an interdisciplinary framework for examining alternative research transition strategies.

1.4.3 Research Questions

From the research hypothesis we derive the following research questions:

- **Research Question 1**: How is increased supply security driving the need for the rare earth industry transition? This question is addressed in Chapter 4 – The Global Rare Earth Industry in Transition.
- **Research Question 2**: What actions are needed to address the supply security transition challenges? This question is addressed in Chapter 5 – Rare Earth Industry Transition Challenges.
- **Research Question 3**: Does the proposed method identify potential strategies for a successful rare earth industry transition for the MSP nations? This question is addressed in Chapter 6 – Transition Pathway Strategies

1.4.4 Research Significance and Novelty

This problem merits study because of the significant investments and stimulus funding planned to re-establish the rare earth industry in the MSP nations. Identifying government policies and industry strategies that result in long-term stability and increased security for the supply of key rare earth elements will not only safeguard those investments but will also support the clean energy transition. Understanding the transition dynamics can to improve the chances of a successful transition and help ensure that stimulus spending achieves its aims.

The research is significant due to the amplified importance climate change has placed on clean energy transition, in which the rare earth magnet metals play an essential role.

This research is novel in the use of an interdisciplinary model to study the transition using an exploratory hybrid dynamic simulation model (Brailsford et al., 2019; Richardson, 2023). Exploratory models focus on simulating industry dynamics to develop and communicate insights about transition strategies for the industry. Exploratory models become the foundation for more complex, data intensive explanatory models that can be validated against industry performance. Hybrid modeling tools are well-suited for this research by allowing the use of heterogeneous entities (e.g. – mines) within a homogeneous entity type (e.g. – mining). This hybrid approach separates model structure from model data to improve model performance and simplify model construction and management.

1.5 Dissertation Structure

This dissertation is organized as follows:

- Chapter I Introduction: an overview of the main elements of the study followed by presentation of the research hypothesis, research questions, and significance of the research.

- Chapter II Literature Review: overview of the published interdisciplinary research on the rare earth industry and the use of simulation models for studying the industry transition.
- Chapter III Methodology: describes the Ventity hybrid dynamic simulation software used and the design of the Rare Earth Industry Transition Dynamics (REITD) model.
- Chapter IV The Global Rare Earth Industry in Transition: describes the driving factors for the industry transition to answer Research Question 1.
- Chapter V Rare Earth Industry Production Challenges: using the REITD model, examine how industry strategy and government policy can affect production diversity and aggregate production to answer Research Question 2.
- Chapter VI Strategies and Policies for Long-Term Industry Stability: using the REITD model, examine how industry strategy and government policy can affect long-term stability of the industry in the MSP nations to answer Research Question 3.
- Chapter VII Findings: discussion of strategy choices for increasing supply security and long-term industry stability.
- Chapter VIII: Conclusions and Future Work

CHAPTER II:

LITERATURE REVIEW

This chapter was originally published as "A Review of Competitive Advantage Theory Applied to the Global Rare Earth Industry Transition" in the journal Resources Policy (Thibeault, Ryder, et al., 2023). Minor changes have been made to reflect industry updates and align with content in other chapters.

The literature review examined relevant, peer reviewed research on the three major topic areas required for this study – rare earths, competitive advantage theory, and hybrid dynamic simulation.

2.1 Introduction

The strategically vital rare earth industry (Lee & Dacass, 2022) is in a period of transition, but not the first. Figure 6 shows it is the third such transition dating back to the 1950s (Zhou et al., 2017).

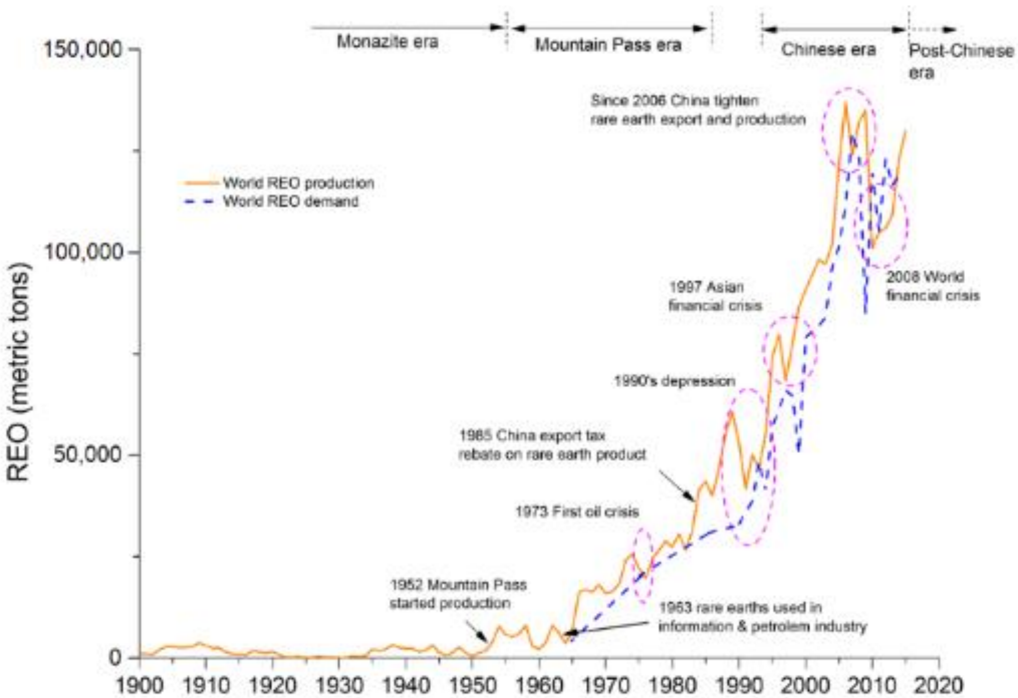


Figure 6. Rare earth industry eras 1920 to 2020, showing transitions. (Zhou et al. 2017)

A lengthy period of discovery preceded the first era, the Monazite era, which lasted from roughly 1920 to 1950. Rare earths were first identified in 1787 but owing to their complex properties the last of the 16 naturally occurring rare earths was not discovered until 1907. The first commercial use of rare earths, the Welsbach gas mantle, occurred in 1889. From that time and up until the end of the first era, small quantities of rare earth were extracted from one of the most important rare earth mineral sources, monazite, mainly for academic study (Haxel et al., 2002).

The transition to the Mountain Pass era occurred in the early 1950's. It was during this period that a rare earth industry appeared, building on improved processing methods discovered during World War II. The eponymous name refers to the large bastnaesite-hosted rare earth deposit at Mountain Pass, California, USA, bastnaesite being another important rare earth mineral source. During the Mountain Pass era that mine was the largest global rare earth producer. China, which had previously discovered rare earth at the much larger bastnaesite deposit at Bayan Obo in Inner Mongolia, started significant rare earth processing in the mid-1960's. By the late-1980's China, using production from Bayan Obo and other mines, became the largest global producer. Owing to several factors discussed later, the transition to the Chinese era occurred over the period from the late-1980's to mid-1990's, with a corresponding decline in production at Mountain Pass. By 2000, China was responsible for approximately 97% of global rare earth production. With an effective monopoly on rare earth, actions by China in 2009 and 2010 led to surges by as much as 4000% for the price of some rare earth metals, on fears of supply constraints.

The current transition, which introduces the post-Chinese era, is a response first to the risks of rare earth production and processing being concentrated in a single nation, and second to the forecast production and processing shortfall due to exponential demand growth. As it is currently conceived, the transition reflects the two short-term policy design goals of production diversification and production capacity growth. Not in evidence is a long-term policy implementation goal that develops a stable and secure rare earth industry.

This paper fills a gap in the literature by bridging policy design and policy implementation following the approach described by Wheat (2010). Current literature focuses on what governments are doing (or not doing) in the short-term to address the rare earth industry transition challenges. Introducing strategic implementation requirements such as those described by Porter in the Competitive Advantage of Nations (Porter, 1998) provides a long-term implementation perspective not previously considered. Policy analysts and industry strategists can benefit by using this work to inform their transition implementation planning.

The brief introduction to rare earth and overview of the rare earth industry that follow provide the context for the research questions at the end of this section.

2.1.1 Rare Earths

The term ‘rare earths’ refers to a group of metals, commonly referred to as the ‘lanthanides’, or more correctly ‘lanthanoids’, found in various minerals in the earth’s crust. The International Union of Pure and Applied Chemists (IUPAC) defines ‘rare earths’ as the 15 elements from Lanthanum (57) to Lutetium (71)), plus two additional elements with similar electrochemical properties – Scandium (21) and Yttrium (39) (Connelly et al., 2005). One of the 17, Promethium (61), is not naturally occurring and is of no practical interest. The periodic table in Figure 7 highlights the rare earth elements.

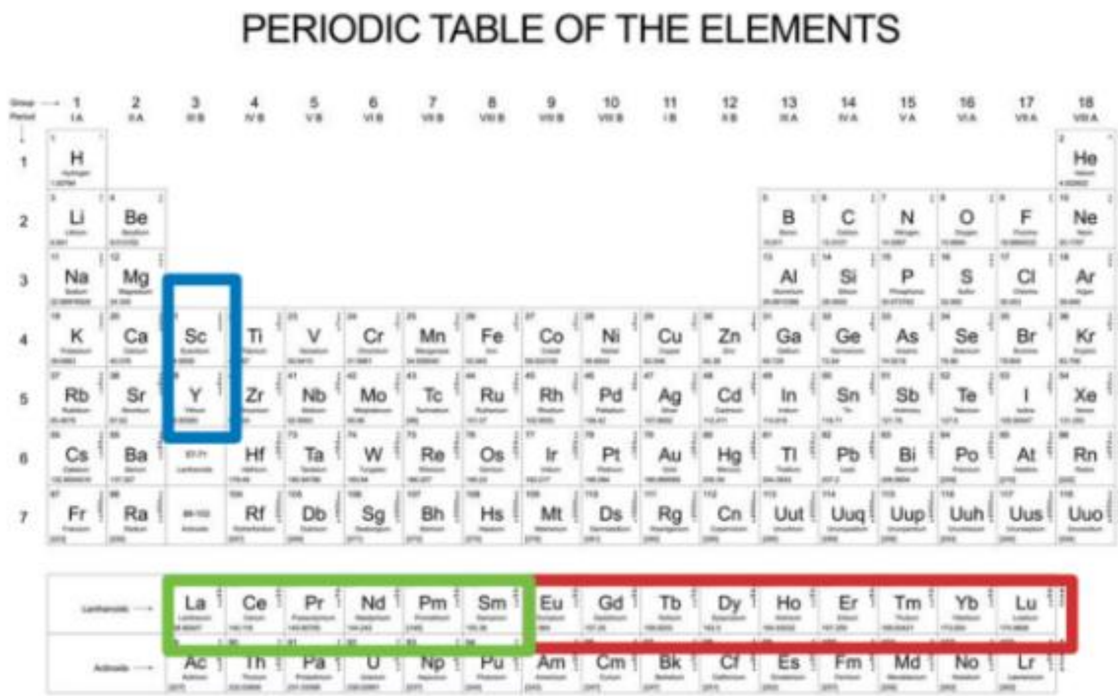


Figure 7. Periodic table showing the Lanthanoids ("like lanthanum") defined by IUPAC Red Book as the rare earths elements.

Four properties of the rare earths are especially noteworthy:

- Rare earths are classified as ‘light’ (LREE, green box) or ‘heavy’ (HREE, red box) according to their atomic weight except Scandium and Yttrium (blue box), which are not so classified. The distinction between LREE and HREE becomes important when discussing host minerology, which in turn impacts processing costs and ultimately economic viability of the mineral reserves. HREE are typically more valuable the LREE, except for Praseodymium (Pr) and Neodymium (Nd) which are two of the four ‘magnet metals’ (the others being Terbium (Tb) and Dysprosium (Dy) used in making permanent magnets.
- Rare earths are highly reactive, forming strong bonds with other host mineral elements and compounds. The electrochemical similarity of the rare earths, coupled with high reactivity, results in the need to separate them individually, in

order of increasing atomic number (with some exceptions). Thus, for example, Nd cannot be separated out before La, Ce, and Pr, again adding cost and impacting economic viability (Gupta & Krishnamurthy, 2005).

- Certain minerals containing rare earths frequently also contain the radioactive elements thorium (Th), Uranium (U), or both. The cost of extracting and containing radioactive waste impacts the economic viability of mines processing these minerals. Monazite and xenotime, two of the three most common rare earth minerals always have some level of Th content.
- The rare earths exhibit a unique property know as the 'lanthanide contraction', referring to the shrinking of the atomic radius with increasing atomic number. This occurs because electrons generally fill the inner core 4f shell, instead of the outer valence 5d shell; see Figure 8 (Gschneidner et al., 2010). The outer shell shields the inner shell, causing the inner shells to be drawn to the electropositive nucleus as electrons are added. This behaviour is key to understanding their magnetic properties (Strange et al., 1999), and also complexities in processing rare earths.

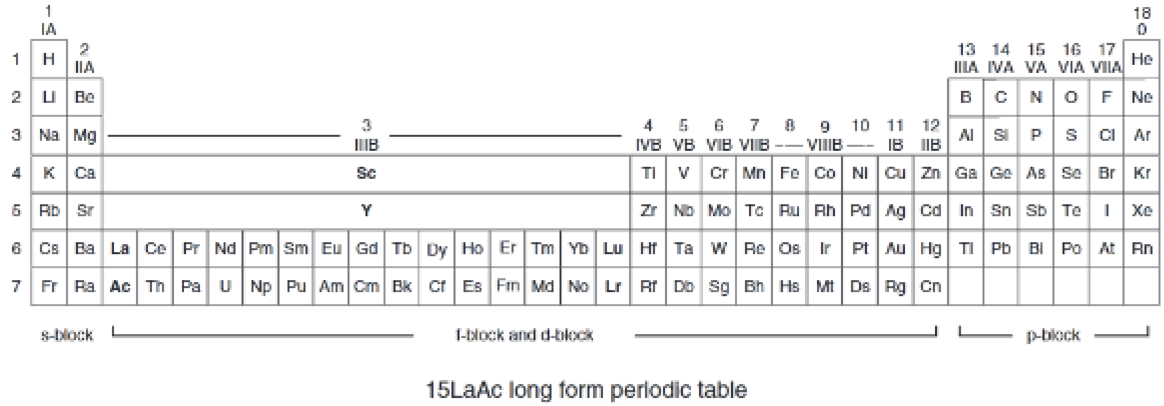


Figure 8. The long form of the periodic table shows the intermingling of the f-block and d-block, which leads to the contraction behaviour of the lanthanide series. (Source: Gschneidner (2010)).

Due to these properties, rare earths, unlike other metals, occur in nature as groups of metal oxides and not in their individual elemental forms. Thus, unlike gold, silver, or iron, there are no seams of lanthanum, lutetium, or yttrium metal. Instead, rare earths are found tightly bound in their oxide forms and in relatively small amounts in minerals bearing the more common metals.

As an example, the largest known rare earth mineral deposits are the Bayan Obo district iron deposits in Inner Mongolia, China. Per 1000 kilograms of ore, the iron content is 510 kilograms, or 51% (Li, 2018), while the associated rare earth content in this deposit are nine oxides totalling 60 kilograms or 6%, of which only 15 kilograms or 1.5% are from the four most valuable rare earths (Dushyantha et al., 2020; Fernandez, 2017).

U.S. Geological Survey data (Orris, Seo, Briggs, Dunlap, et al., 2018) lists over 3,100 known rare earth-bearing mineral deposits in 108 countries, with crustal abundances ranging from roughly 100 times greater than gold to 1,000 times less than iron. Given their crustal abundance, and the large number of known deposits, rare earth cannot be considered rare; however, the ‘rare’ label is still appropriate when considering that of the 3,100 known deposits only approximately 200 are listed as economically viable for production. rare earths can thus be considered rare in the context of economic supply.

2.1.2 The Rare Earth Industry

The rare earth industry is comprised of hundreds of firms, worldwide, involved in the production of the pure, compound, and alloy forms of rare earth. A high-level view of the industry is shown in Figure 9.

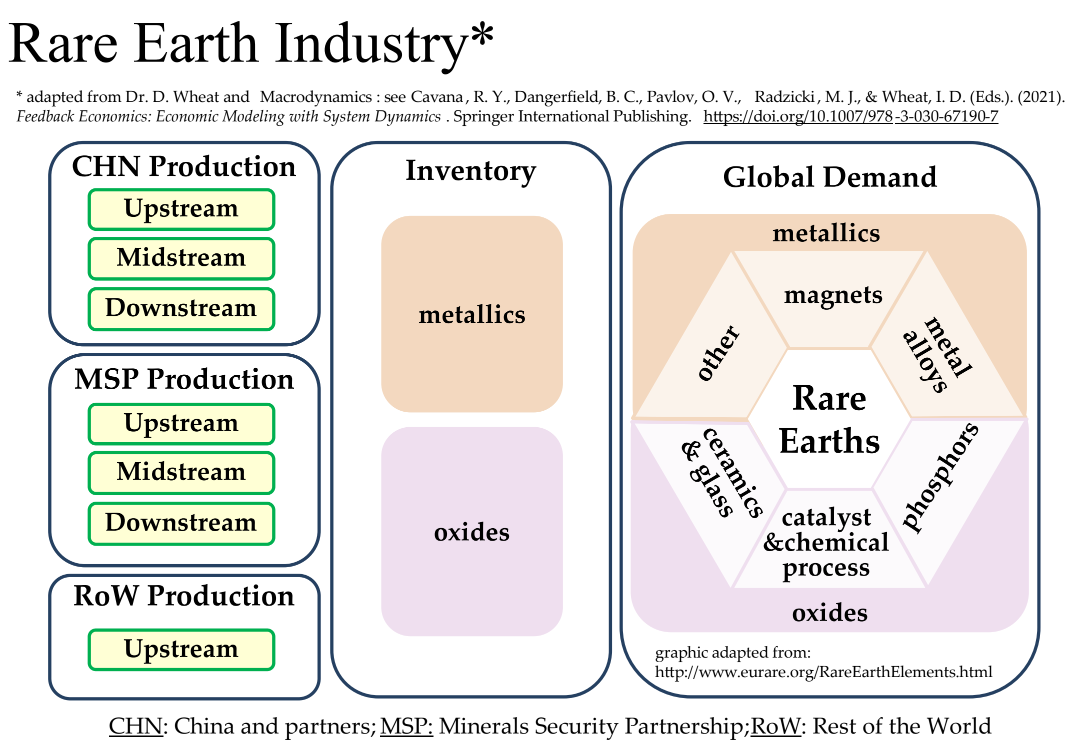


Figure 9. The Rare Earth Industry (Author's work based on various sources)

The industry is comprised of firms engaged in one or more of the three rare earth production streams, grouped within one of three trade groups (TGs) on the left. From their midstream and downstream plants they produce rare earths in the form of oxides (midstream plants) or metallics (upstream), which are pure metals or metal alloys. On the right is a highly aggregated view of the demand sectors. The highest value product, rare earth permanent magnets, are formulated from four elements whose collective value is approximately 94% of the market. The RoW countries currently have upstream production only.

This high-level view of the industry highlights two important features:

- Production is organized into three streams:
    - Upstream – ore extraction and initial mechanical concentration to remove unwanted material (‘gangue’), resulting in a mineral concentrate of ~30 mass% rare earth elements with ~70% rare earth recovery, followed by a secondary concentration using cracking methods to produce a rare earth carbonate precipitate of ~95 mass% rare earth carbonates (dry basis) (Lucas et al., 2015);
    - Midstream – hydrometallurgical processing, typically by solvent extraction of the mixed carbonate precipitate to first create separate individual rare earth solutions, followed by individual rare earth oxide, phosphate, and fluoride precipitates with purities around 99.5 mass%; and lastly
    - Downstream – refining and alloying, to create 99.9 (3 nines, or 3N) or better pure rare earth elements that are sold in individual element form or alloyed with other elements.

China (CHN) dominates the industry in all three production stream as well as in demand (Schlinkert & van den Boogaart, 2015; Tilton et al., 2018). While China has formal critical mineral trade arrangements with several countries under their Belt and Road Initiative, China appears to exert considerable influence over rare earths mining of HREE in the ionic clay deposits in Myanmar. Through various investment vehicles China has board representation on rare earth companies in other trade groups, including the lone U.S. rare earth upstream firm MP Materials.

The Minerals Security Partnership (MSP), formed in 2022 (U.S. Department of State, 2022), has the stated aim of “building robust, responsible critical mineral supply chains to support economic prosperity and climate objectives” as it considers the status quo with a dominant China to be untenable. The RoW nations are a small but growing fraction of industry.

Rare earth production has three stages: upstream, to extract and concentrate (E&C) ore, midstream, to produce separated and purified (S&P) oxides, and downstream, to refine and alloy (R&A) oxides into metals and alloys. In the upstream stage, ore is mined and first mechanically, then chemically, processed to eliminate as much of the non-rare earth material as possible to reduce midstream processing costs. In the mid and downstream stages, concentrate undergoes further processing to produce rare earth in various forms and to varying specifications, to become intermediate and finished goods. Goods produced at the midstream stage tend to be single or two element oxides such as NdPr, while high-purity metals and advanced compounds are produced at the downstream stage. It is the midstream and downstream stages that are the most technically complex and costly, requiring highly skilled resources to design and manage production.

Production data for all three stages for 2020 is shown in Table 2. The 97% share of upstream production from China in 2010 has since declined to 58% in 2020, reflecting China’s focus on the higher value-add stages and strategy to conserve their upstream resources by importing upstream concentrate and carbonate from the MSP and RoW TGs

(Duan, 2022). These figures show the magnitude of the challenge to achieve post-transition production diversification.

Table 2 - Distribution of Production by Nation/Nation Group, 2020 data

Nation/ Nation Group	Upstream Production (1)	Midstream Production (2)	Downstream Production (2)
China	58%	89%	90%
MSP	18%	7%	~1%
RoW	24%	1%	2-3%

Source data: (1) EU JRC (European Commission, 2020), (2) US DOE (Smith et al., 2022))

With variations due to source minerals and technical approach, the three production stages are generally consistent across the industry. There are also non-technical differences, called factor conditions, unique to the industry firms in each nation group based on their home country. Factor conditions include natural resources, infrastructure, mining and environmental regulations, and other conditions. Unique to China is the existence of unregulated, illegal rare earth mining, previously estimated at between 20 to 40 percent of total Chinese production (Y. Chen & Zheng, 2019; Nguyen & Imholte, 2016), although in recent years China has taken steps to constrain this activity (Shuai et al., 2022).

Research in the MSP nations on the importance of rare earth began in earnest over a decade ago (National Research Council, 2008), leading to comprehensive national critical mineral strategies supported by scientific reports (e.g. - Carrara et al., 2023). The EU scientific report prepared by Carrara et al. provides updated findings on the criticality of rare earth for manufacturing in 12 key technologies in five strategic sectors[7]. These five sectors are essential to global efforts "to decarbonize the energy system and deliver the twin transition[8] and ensure security and autonomy in strategic sectors". Equally well-known since the 2000s has been China's dominant position in the industry, and the risks that having a dominant industry supplier entails (Campbell, 2014; Du & Graedel, 2013; Hayes-Labruto et al., 2013; Massari & Ruberti, 2013; Morrison & Tang, 2012; Tse, 2011; Wübbeke, 2013). Klinger (2015a) documents the history of the rare earth industry and China's emergence as the dominant supplier, along with its concomitant environmental and working condition impacts.

The critical importance of rare earth provides the context for the formation of the MSP group and their motivations for initiating the rare earth industry transition, an undertaking expected to require a decade or more to achieve its aim. Their aim is to resolve two pressing challenges: production concentration and aggregate production.

In resolving the first challenge, production concentration, the MSP group seek a path to diversified rare earth production to reduce supply risk. Rare earth production and processing became concentrated in a single country, China, over a period of 15 years from 1985 to 2000. By implementing a low-cost strategy, China developed significant competitive advantage and effectively became a rare earth monopoly. During this period their share of world production increased from approximately 50 to 97 percent while the

[7] The five EU strategic sectors - renewable energy, electromobility, energy-intensive industry, digital, and aerospace/defense.

[8] Twin transition is the combined use of digital information and communication technologies with green technologies to accelerate the achievement of sustainability goals. (https://www.weforum.org/agenda/2022/10/twin-transition-playbook-3-phases-to-accelerate-sustainable-digitization/)

other nations, unable to compete, largely exited the industry. A decade later, the risks of a single dominant producer became clear during the three years 2010 to 2014 when market reaction to China's increased rare earth export controls (Z. Chen et al., 2021) resulted in rare earth prices spiking by as much as 4,000% in July 2011. Prices returned to near pre-2010 levels in 2015 following a World Trade Organization ruling against the use of those export controls (Associated Press, 2015). The extent to which an unusual incident between a Chinese fishing trawler and a Japanese navy vessel in September 2010 (Klossek et al., 2016; Kruemmer, 2020) exacerbated the market instability is unclear; however, that the incident added to international policy concerns is certain (Grasso, 2013).

The market instability from 2010 to 2014 focused international attention on rare earth supply risks. In the years immediately following, governments commissioned critical mineral assessment methodology studies (European Commission et al., 2017; Lusty et al., 2021; Nassar & Fortier, 2021) to quantify the strategic and economic risks of rare earth supply disruption. These studies were then used to prepare critical mineral lists, beginning in 2014 (European Commission, 2016; HM Government, 2022; Natural Resources Canada, 2021; U.S. Geological Survey, 2018, 2022). It is important to note that Japan had published the first such list in 1984 (Nakano, 2021).

Klossek et al. (2016) consider that rare earth criticality is caused by "systemic problems of the rare earth market", noting that the underlying problems are interconnected and that hasty corrective actions could lead to unintended consequences: "Simple solutions for one problem can strengthen other problems through feedback loops, e.g. the consequences of state involvement to other market distortions." This observation established the complex dynamic nature of the transition problem. In testimony before the U.S.-China Economic and Security Review Commission Hearing, Bown (*U.S. Tools to Address Chinese Market Distortions*, 2018) provided an analysis of the perceived supply risks. Bown's analysis was in the context of U.S.-China economic tensions and trade disputes, consistent with the analysis of Duan who noted that "…China's rare earth strategy contains elements of both assertiveness and self-restraint. Beijing is steering a middle course in the crafting of its rare earth strategy, so extreme trade restrictions, such as an embargo, seem highly unlikely because Beijing is quite clear about Chinese advantages and disadvantages in the industry value chain and seeks to balance competing interests and beliefs" (Duan, 2022).

The second industry transition challenge stems from forecasts of exponential growth in key rare earth demand sectors, especially energy transition and electric mobility. These sectors, which require permanent magnets for electric vehicle motors and wind turbine generators for which rare earths are essential, will lead to similarly exponential demand increases for these rare earths (Tsafos, 2022; J. Wang et al., 2020; X. Wang et al., 2017). Addressing this challenge is complex. Recalling that rare earths do not naturally occur as metals, but in oxide form tightly bound with other rare earths, means that producers cannot selectively produce just the one, two, or four high-value rare earth metals needed for permanent magnets. The electrochemical properties that make rare earths so technically important also makes their separation, purification, and refining complex, time-consuming, and costly. The need to separate low-value rare earths first before being able to separate high-value rare earths (Kennedy, 2016) causes an over-supply of the low-value rare earths, resulting in prices lower than their cost of production and thereby driving up the cost of the high-value rare earths. It is also worth noting that in addition to developing new traditional mineral deposits, significant efforts are underway for recovering rare earths from non-traditional sources such as lignite coal (Laudal, 2017), and from mine tailings, and commercial and industrial scrap (Burlakovs et al., 2018) under the umbrella term Circular Economy (Ayres, 2019).

The MSP's bold, post-transition vision of a multi-national production with increased production capacity is being supported by massive government subsidies (Golubova, 2023) and updated national critical minerals strategies (Department of Industry, 2022; European Commission, 2023; HM Government, 2022; Natural Resources Canada, 2022). There remains, however, considerable uncertainty as to whether their response will result in a successful transition, where success means that financially stable firms have formed multinational value streams with sufficient aggregate production capacity to meet global demand over the long-term. If unsuccessful, among the demand sectors at risk are those most vital to achieving our most important societal goals: clean energy for low carbon economic growth, passenger, commercial and industrial electric vehicles for carbon emission reduction, mobile and broadband communications sectors for the information and communications technology infrastructure necessary for digital infrastructure, and the defence systems sector for national security. It is thus imperative that the transition succeed.

For the rare earth industry transition to succeed in the long-term, we hypothesize that a third challenge must also be met, that post-transition, the firms that make up the industry must – in aggregate – be profitable. To become profitable firms must develop and implement competitive advantage strategies while facing formidable competition from the incumbent, China. Unless the firms become profitable, nations will find it necessary to continue providing subsidies and other concessions indefinitely, an unlikely outcome. Without the long-term stability provided by profitable firms, the industry transition is unlikely to succeed resulting in China regaining its industry dominance, perhaps for generations. Thus, for the rare earth industry challenge to succeed all three challenges must be met. We believe including this challenge as a transition requirement is unique to this review, and thus extends the literature.

Given the nature of the rare earth industry, an analysis framework that addresses the three challenges at the level of global competition by multinational corporations is required. Competitive advantage theory ("CAT") appears to provide such a framework. First articulated by Porter in his book Competitive Advantage of Nations ("CAN") (Porter, 1998), CAT seeks to explain how increased national productivity results from its firms, working cooperatively, create and gain sustained competitive advantage in a particular industry . To do that, Porter introduces the diamond model as a system of mutually reinforcing determinants that provide support for a nation's firms competing in international markets.

After the publication of CAN in 1990, scholars identified gaps in the diamond model that are germane to the study of the rare earth industry and proposed diamond model variants to address these gaps, which are discussed in section 3.

With these three transition challenges – production diversification, increased production capacity, and profitable firms – as context, the research questions guiding this literature review are:

- RQ1: Is competitive advantage theory a suitable framework for the study of the rare earth industry transition? and, if so,

- RQ2: Which variant of the diamond model is best suited to the transition study?

The remainder of this review paper is organized as follows: Section 2 Method identifies and reviews the literature on competitive advantage and simulation modeling analysis of the rare earth industry; Section 3 Results and Discussion presents the analysis of the relevant papers, and Section 4 Conclusion summarizes the literature review.

2.2 Method

We reviewed the literature using the stepwise Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) approach as shown in Figure 2. To collect a broad spectrum of publications we selected the Web of Science Core Collection database, Engineering Village Compendex, Inspec and GEOBASE databases, and EBSCOhost Academic Search Ultimate, Business Source Ultimate, and EBSCO MegaFILE databases for the search. Papers previously collected in Zotero from ad hoc searches that met the search criteria were also added to the initial search results.

2.2.1 Search keywords and screening criteria

To retrieve relevant works, we used the search string *("competitive advantage" OR "diamond model") AND industry AND transition* for the initial article collection. The string "rare earth" was not used, as trial searches retrieved few results, as expected. Thus, we opted for a broader search, using the eligibility screening process to identify relevant publications. The substrings "competitive advantage" and "diamond model" were combined using the OR condition as 'competitive advantage theory' and 'diamond model theory' are synonymous. "Industry" is used to retrieve works related to the industry level of analysis, as opposed to the regional, local, or firm level, while "transition" is used to retrieve works related to industries that are restructuring, as opposed to industries defining their competitive advantage strategy for existing industry structures. The literature search was not confined to peer-reviewed journal articles, as government and industry reports, congressional hearing testimony, and reliable news and industry data sources are other important sources of information on this topic. The importance of rare earth to the global economy and decarbonization initiatives must necessarily lead to the inclusion of geo-political references in the critical analysis. Articles that focus on technical processes are too narrow in scope and are excluded; articles discussing research and development with direct relevance to the diamond model are included.

2.2.2 Search result screening and inclusion

The search yielded 841 results for the study period 1990 to 2023 (as of 2023 March 15); 1990 was chosen as it was the publication year of the original edition of CAN. Filtering found 222 duplicates, leaving 619 records for the initial title and abstract review. This screening excluded 187 records, passing 432 through for full-text review. Full-text screening excluded a further 136 records, leaving 51 articles included in the dataset for critical analysis. The results of the four-stage assessment process are shown in Figure 10.

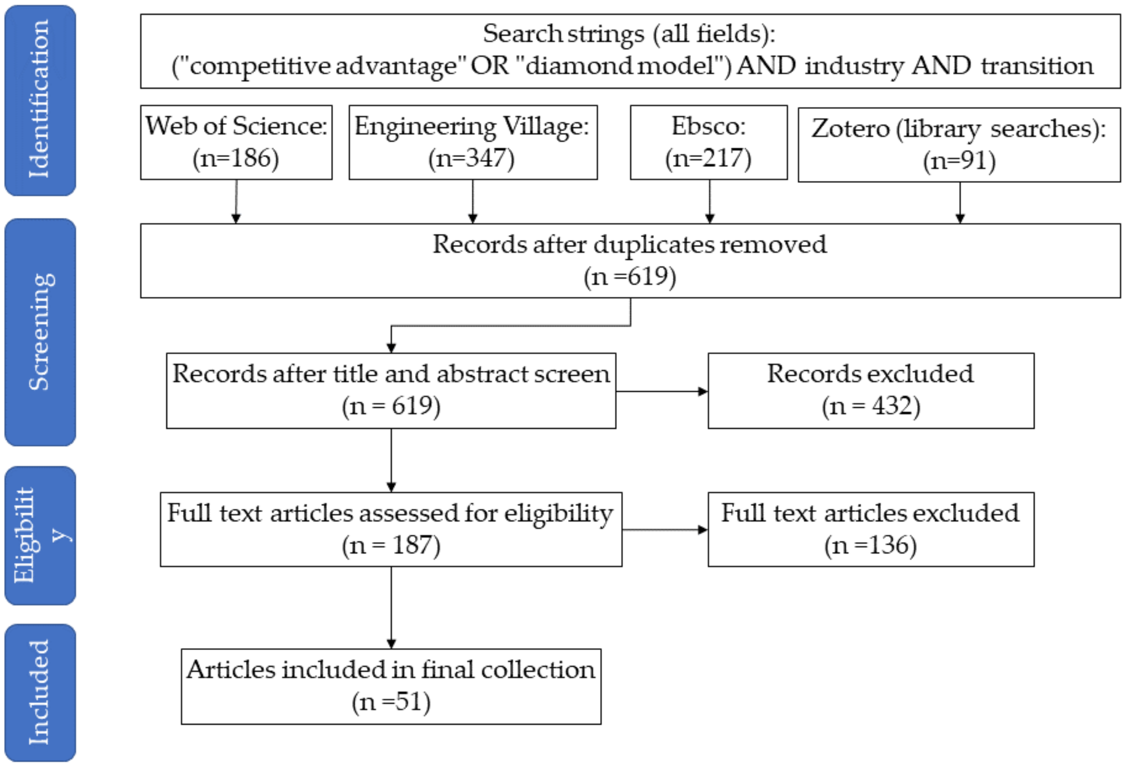


Figure 10. PRISMA four-step article assessment filter.

2.3 Results and Discussion

This section analyzes works using Porter's competitive analysis theory for developing national competitive advantage, and its applicability as an analysis framework for the rare earth industry transition. Following overviews of CAT and the included work, we present our critical analysis of the included research using the category structure of the competitive advantage diamond model.

2.3.1 Overview of Competitive Advantage Theory

The importance of Porter's seminal work *Competitive Advantage of Nations* (Porter, 1998) is evident from the number of citations the work has received – 3,146 for the original Harvard Business Review article (Web of Science) and 136,162 citations for the book (Google Scholar). It has been the subject of several review articles (e.g. - Hanafi et al., 2017; Ketels, 2006) and has been applied to a wide range of industries such as renewable energy (Fang et al., 2018), textiles (Frederick, 2010), information technology (Hayati et al., 2021) and many others including the rare earth industry (Shuai et al., 2022). Sölvell (2015) analyzes the impact of CAN 25 years after its publication, summarizing it as introducing concepts "central to our understanding of how firms build sustainable competitive advantages in global markets."

Porter (1985) introduced the concept of competitive advantage in the book of that title. In this pioneering work competitive advantage is described as a firm's strategy for achieving sustainable, above-average performance. A second new concept – the value chain –describes the way a firm's competitive strategy is implemented. Value chains are frequently confused with supply chains but are quite different (Feller et al., 2006). The relationship between competitive advantage, value chains, and supply chains can be viewed as hierarchical: competitive advantage is a strategy to outperform the competition, based either on cost leadership (low cost) or differentiation (premium price) (Kunc, 2010, p. 1), value chains are the implementation of that strategy, consisting of two groups of activities – primary and supporting – with a subset of the primary activities being roughly equivalent to a firm's supply chain[9].

With CAN, Porter changes the competitive advantage focus from the firm level to that of national industries engaged in multinational competition without losing sight of the fact that industries are comprised of firms ("firms, not nations, compete in international markets"). In the section entitled "Toward a New Theory of National Competitive Advantage" Porter sets the central question for competitive advantage theory as "why do firms based in particular nations achieve international success in distinct

[9] As there is no single definition of supply chain, equivalence cannot be established.

segments and industries?" Porter then splits the question into two components – 1) what strategies must the firm adopt to increase their international competitive advantage in their industry, and 2) what policy goals must their nation set to support that industry.

Porter answers the central question using the diamond model, and in so doing equates competitive advantage theory to diamond theory – the two are synonymous[10]. Porter identifies a second important component of competitiveness - industry clusters – which create competitiveness and innovation, which while acknowledging their importance will be treated as outside the scope of this review.

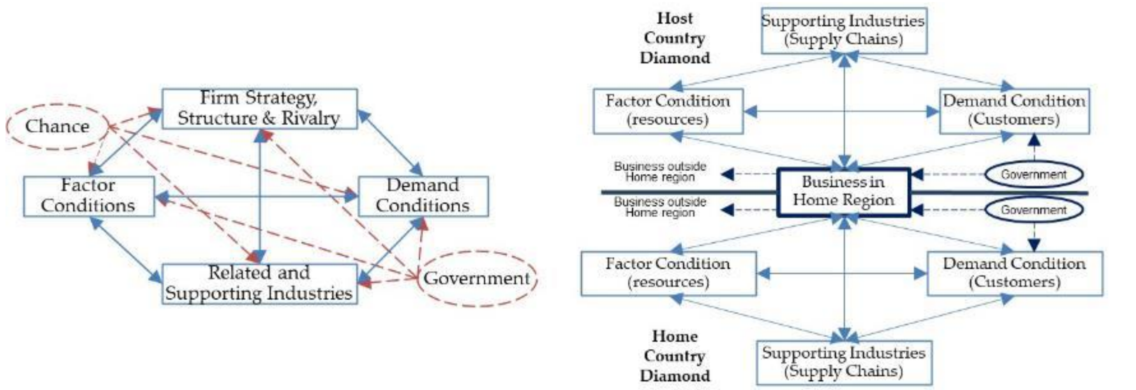
The core diamond model has four key attributes are referred to as 'determinants' – Firm Strategy, Demand Conditions, Supporting Industries, and Factor Conditions. Two additional variables, Government and Chance are included in the full diamond model.

In a review paper Hanafi et al. (2017) summarize several critiques of the diamond model. As some of these critiques proposed variants of Porter's original diamond model, the original is now referred to as the single diamond model or SDM. A well-known variant is the double diamond model (DDM) (Rugman & D'Cruz, 1993), further developed by Chang Moon et al. (1998) and updated by Rugman et al. (2012). Cho et al. (2009) reviewed two other variants, the generalized double diamond (GDD) and the nine-factor model (NFM), before offering their dual double diamond (DDDM) variant. He (2013) offers an "improved diamond model" (IDM) variant specifically for the rare earth industry that disaggregates technical knowledge and skill requirements from other determinants into a new determinant called 'knowledge absorptive capacity". His

[10] The diamond model is also known as the theory of national competitive advantage of industries.

observation regarding the importance of knowledge absorptive capacity offers useful insights for the technical skills that are part of the Factor Conditions determinant.

Figure 11 shows the original single diamond model (Figure 11a) from Porter and the double diamond variant from Rugman et al. (Figure 11b).



11a: Original Diamond Model (Porter, 1990) 11b: Rugman and D'Cruz (1992): Double Diamond Adaption

Figure 11. The Diamond Model - Determinants of National Advantage. 11a (left): Porter's original (single) diamond model (1990). 11b (right): Rugman et al. double diamond adaptation for international competitive advantage by open trading nations (2012).

Criticism of the SDM by Rugman and D'Cruz and Rugman et al. centers on shortcomings in the SDM in explaining competitive advantage in nations that are not home to many large multinational enterprises and yet who still achieve competitive advantage due to their open economies. Canada, Korea, New Zealand, Austria, and Singapore are cited as examples. To overcome the shortcomings, they propose the DDM adaptation, which also a more comprehensive treatment of foreign direct investment (FDI) in host countries. As many of the MSP nations are also open economy nations, the DDM variant fits particularly well with the industry transition vision of the MSP.

In CAN, Porter elaborates on the value chain and the diamond model as a dynamic structure. CAN Chapter 4, The Dynamics of National Advantage, describes how "individual determinants combine to become a dynamic system. Similarly, value chains are described as “an interdependent system or network of activities, connected by linkages” (Porter, 1998). Porter is thus establishing sustainable competitive advantage as the result of dynamic behaviour over time and therefore lending itself to analytical study using dynamic simulation models. Model examples are found in Cavana and Hughes (1995), and Kunc (2010). We comment on the usefulness of dynamic simulation for analyzing rare earth industry transition dynamics in Section 4.

Sölvell (2015) provides an analysis of CAN 25 years after its publication noting that CAN should be viewed as having two eras: 1990 to 2000, when Porter's research focus was advancing the diamond model, and 2000 and beyond when the research focus was on clusters as a means of fostering rivalry to stimulate innovation. These two eras roughly define a focus on competitiveness in the first era, and innovativeness in the second. The first era has the additional characteristics of being nation (home country) focused, having a low cost of production strategy, and with less dynamism in the diamond. In contrast, the second era is characterized as internationally focused, with premium price strategies, intense cluster rivalry, innovativeness, and a dynamic diamond model.

2.3.2 Overview of Included Work

Awareness of the risks associated with a dominant nation in the rare earth industry, and hence the motivation for industry transition by the MSP nations, is reflected in the steady growth in the publications and citations data retrieved using the search string “rare earth” AND “domain*” (dominant, dominance, etc.). Publications increase by approximately 50% immediately after 2012, during the period of rare earth price instability triggered by China’s imposition of export measures; see Figure 12. This result is consistent with the findings of Salim et al. (2022), who reviewed the literature on the related topic of rare earth supply security.

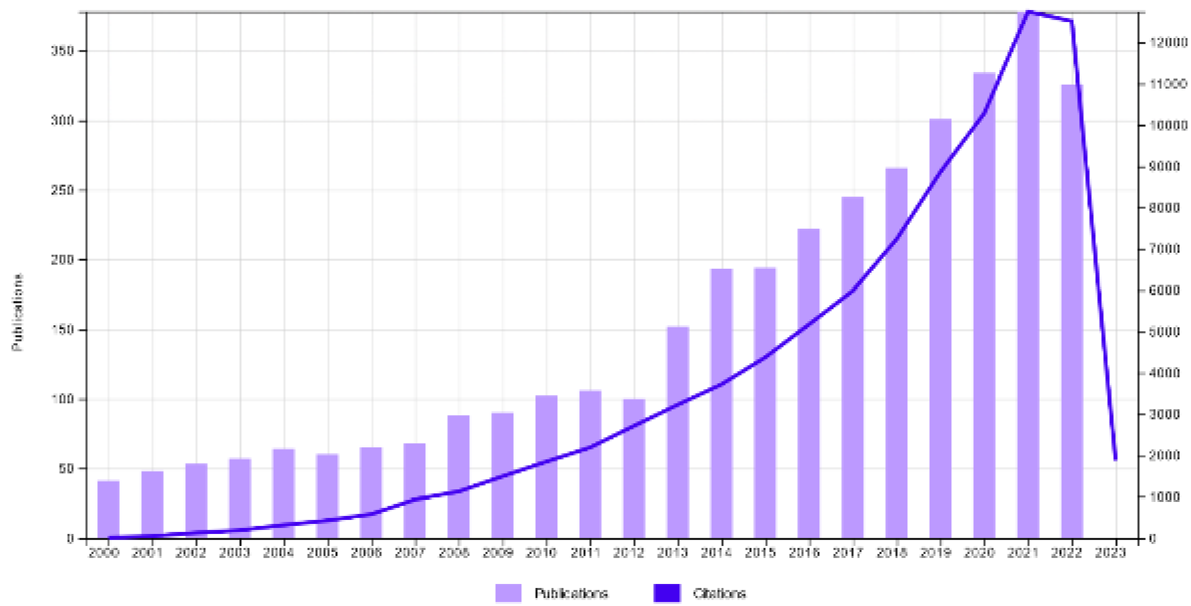


Figure 12 Web of Science publications and citations between 2000 and 2022 for 'rare earth'' AND domin*' (dominant, dominance, etc.).

In the included works dataset, the articles are relatively evenly distributed across the diamond six model variables: Firm Strategy (22%), Demand Conditions (16%), Supporting Industries (16%), Factor Conditions (16%), Government (16%), and Chance (10%).

2.3.3 Critical Analysis

For the critical analysis we use the four core diamond determinants (Firm Strategy, Structure and Rivalry, Factor Conditions, Demand Conditions, Related and Supporting Industries), and the two additional variables (Chance, Government) of the SDM as analysis categories.

2.3.3.1 Firm Strategy

Firm strategy, structure, and rivalry, or more simply ‘firm strategy’, considers “the conditions in the nation governing how companies are created, organized, and managed, and the nature of domestic rivalry" (Porter, 1998).

Papers written immediately following the period of rare earth market instability from 2010 to 2014 continue to provide useful insights for firm strategy today. Campbell's observation that "there is widespread concern internationally about the degree of control that China has over the supply chain of rare earth metals" still applies almost a decade later, and the industry analysis generally applies today (Campbell, 2014). More recent papers such as Fernandez (Fernandez, 2017) provide updated input for firm strategy. An in-depth understanding of the rare earth industry in China is crucial to a successful industry transition. Recent papers such as Wang et al. (2020), Duan (2022), and Mancheri et al. (2019) are informative.

The SDM recognizes, however, the wisdom of the reminder from Antras and Chor (2021) that "we can't lose sight that ultimately it is firms that make up the value chain" and supports the importance of firm profitability. From this perspective, having a detailed and quantitative analysis of competitiveness using methodologies at the firm level such as that developed by Silva et al. (2018) is important.

In transitioning to a new competitive landscape, the industry must take note of Bown's (2018) observations that China's state-owned enterprises (SOEs) will continue to operate ("China's SOEs are not going to disappear anytime soon"), and that "imaginative new approaches and thinking", such as the innovations for achieving competitive advantage suggested by Porter's diamond model. China-based authors Chen and Zheng (2019) and Duan (2022) observe that China, through its SOEs and trade policy, is attempting to follow a "middle course" of providing supply stability while retaining its market power. This suggests a dynamic firm strategy that accommodates endogenous feedback and exogenous (chance) events from trade policy. Trade policy determinants are discussed in the Government sub-section below.

Mining is generally considered a commodity industry with little room for differentiation, making low-cost the obvious strategy choice. That logic may hold for low-value rare earth products; however, high-value rare earths has differentiated demand (Silva et al., 2018). Machacek and Ford (2018) find that the final demand for some rare earth products can be differentiated by specific transaction requirements, such as compliance with ISO technical standards. Thus, the firm strategy determinants for rare earths are more complex than in some mining industries.

Capital investments in developing rare earth deposits are an important aspect of the firm strategy determinant. Riesgo Garcia et al.(2017) address this aspect through their analysis of rare earth mining investments, which as noted earlier are typically multi-product mines – for example, the case of the Bayan Obo mine, which is a metal (iron) mine that also produces rare earths. The authors criticize the multi-product price forecast method traditionally used in mining investment analysis as leading to pessimistic conclusions, when, in the author’s opinion, multi-product rare earth mining investment risks are similar to those of single-product mining projects.

Two papers, Cavana and Hughes (1995) and Kunc (2010) describe using system dynamics to develop decision support models based on CAT. These papers provide powerful insights for a richer model examining rare earth industry transition dynamics.

2.3.3.2 Demand Conditions

The determinant Demand Conditions defines “the nature of home demand for the industry’s product or service”(Porter, 1998) in dynamic combination with the other determinants. In the SDM, firms are best prepared for international competition when they are first able to compete in their home country. With the demand sectors for rare earths concentrated in a small number of countries Rugman and D’Cruz’s DDM (1993), which combines the strengths of the home nation firm with that of its multinational partners, termed host countries, offers a better context for studying demand conditions determinant for the rare earth industry.

Wellmer et al. (2019) point out that “the demand for raw materials is primarily determined by advances in technology”, and this demand changes with the development of new products and technologies that are associated with social progress and industrialization”. Understanding rare earth demand conditions must be done in the context of the complete diamond model. Mancheri et al. (2019) conclude that trade policies, within the government factors, are a greater influence on demand than physical flows. They propose a ‘resilience framework’ that incorporates the factor conditions determinant and innovation research to examine design options including the use of substitution materials in demand management.

Schlinkert and van den Boogaart (2015) use a series of supply and demand models to evaluate market transformation scenarios that align well with this determinant. Severson et al. (2023) modeled future electric vehicle (EV) demand as a means of forecasting demand for cobalt and rare earths integral to EV production, concluding that in some scenarios that demand would exceed forecast supply and requiring non-rare earth substitutions to meet projected demand. Applying this to demand conditions using the DDM would show resource nations building competitive advantage in the upstream stages of the multinational value chain where they are best able to compete, while the larger partners focus on mid- and downstream stages. With this adaptation, the demand condition determinant aligns with the rare earth industry transition requirements. Hanafi et al. (2017) provide a review of CAN based on the determinants of the diamond model, citing 21 papers where demand conditions were part of the diamond model.

2.3.3.3 Supporting Industries

The related and supporting industries determinant, or more simply supporting industries, includes "the presence or absence in the nation of supplier industries and related industries that are internationally competitive" (Porter, 1998).

Ayres (2019) and others (Lopes de Sousa Jabbour et al., 2018; Lu et al., 2022; H. K. Salim et al., 2019) advocate for implementing circular economy infrastructure, a government action implemented in the DDM as a supporting industry. While there are challenges to implementing circular economy processing for rare earths, there are also significant efforts – especially in the EU – to meet these challenges. Circular economy solutions would help solve the "trilemma of security of supply under conditions of economic viability and environmental sustainability" (Wellmer & Hagelüken, 2015). Raspini et al. (2022) studied the challenges of implementing circular economy practices for the rare earth magnet industry in Brazil, concluding that "improvement in competitive advantage" has the highest correlation coefficient among the drivers for adoption.

As reported by Pietrobelli et al. (2018) the mining support and services sector, when linked directly to home country firms, stimulates greater industry engagement from local suppliers; conversely, when production activities are controlled by remote firms their level of engagement is reduced, potentially driving up costs. Rugman et al. (2012) note that "only looking at a sub-component of CSAs (country-specific advantages) will lead to biased results regarding a country's relative competitiveness compared to other countries”. Viz., in multinational value chains nations with strengths in a particular determinant, such as supporting industries, can achieve competitive advantage as a home industry and contribute to the success of the value chain. MSP partners, the EU countries, and Japan rank highly in the DDM in the supporting industries category.

2.3.3.4 Factor Conditions

The strength of a nation’s “factors of production, such as skilled labour or infrastructure” (Porter, 1998) to support not only the firm strategy but also the supporting industries and demand condition determinants make up the factor condition determinants. Rugman et al. ranked MSP partners Canada, the U.S., and the UK highly for factor conditions in their DDM.

Wellmer et al. (2019) also note that “industrialization is a process that transfers the factors of production (material and immaterial resources and services that are required for the production of goods) from primary production (mining, agriculture, forestry, and fisheries) into the industrial sector (processing)”. For rare earth industry competitive advantage, these include R&D, advanced education, capital funding, and infrastructure including information and communications technology (ICT), rail, roads, and utilities.

Porter stresses the importance of innovation as a key contributor to competitive advantage; Kutschke et al. (2016) use the SDM to analyze factors contributing to the performance of innovation networks. When discussing downstream production Wellmer (2022) notes that incremental and breakthrough improvements are due to innovation processes resulting in increased production. Raspini et al. (2022) note the importance of technological innovation in establishing circular economy practices, noted above in the Supporting Industries subsection, in rare earth upstream production.

National policies and multilateral partnerships committed to environmental sustainability and sustainable resource development are factor conditions. The historically poor record for environmental sustainability and the need to address this problem has long been recognized (Dutta et al., 2016). The strong US commitment to environmental protection was a major factor in the second industry transition from the Mountain Pass to the Chinese era. US Environmental Protection Agency regulations introduced in 1984 significantly increased upstream production costs, effectively creating competitive advantage for producers in China who had no such regulations at the time. China is reported to have introduced policies in 2006 to reverse their historically poor environmental record for rare earth mining (Duan, 2022). For the current transition, the MSP charter includes a strong commitment to sustainability through their goal of helping "catalyze investment from governments and the private sector for strategic opportunities —across the full value chain —that adhere to the highest environmental, social, and governance standards" (U.S. Department of State, 2022).

2.3.3.5 Government

Government is an additional variable to the core SDM. Porter's view is that governments must focus their policy goals on industry productivity, a key driver of economic prosperity. Thus, government involvement in factor conditions for industries at the national level are appropriate, but involvements that focus on a single industry or firm, or that cause market distortion, are not. Government policies that promote competition, and that work to eliminate trade barriers, are effectively helping home and partner nations compete and are therefore important.

Governments in the Minerals Security Partnership (MSP) are substantially informed by the critical mineral strategies developed by their countries. Such strategies have recently been developed by Australia, the EU, the UK, Canada, and the U.S. (Department of Industry, 2022; European Commission, 2023; Lusty et al., 2021; Natural Resources Canada, 2022; U.S. Geological Survey, 2022). The aligned efforts of these nations are essential for a successful transition; however, Nakano (2021) warns that national agendas within the MSP group may not be aligned, with the U.S. appearing more attuned to geopolitical issues, while Japan and the EU are concerned with the impact of supply interruptions on industrial competitiveness.

Several publications on criticality risk (Lee & Dacass, 2022; Lusty et al., 2021; Nassar et al., 2020), provide insight into the selection process for the critical minerals lists. Hayes and McCullough (2018) extend the work on transparency by analyzing 32 criticality studies that evaluated 56 elements or element groups, noting that rare earths are one of the three most commonly included on lists published after 2014, supporting the assessment of rare earth supply risks being of global concern.

Korinek (2020) observes that the mining sector in general accounts for a large share of national GDP which is not reflected in mining's impact on employment. This study reports that early-stage global value chain integration typically relies on foreign intermediate inputs, which in the case of rare earths would be especially true as the supply of the processing technology and advanced skills for large-scale process design & operation is currently lacking in the MSP countries. However, as the global value chain matures there is a strategic opportunity to transfer these intermediate inputs to home-nation firms.

Mancheri's study (2019) in light of the 2010 export restrictions, proposes a "resilience framework", a modeling construct providing insight into trade and environmental policy risk. The table of types of system disturbances from previously published SD models by Sprecher et al. (Sprecher et al., 2015, 2017) provides a feedback pattern for the government determinant.

Wübbeke (2013) provides useful insights regarding the exogenous trade events from the 2010 incident, namely that China's export policy should not be judged by single events, an important determinant consideration. Wübbeke's early analysis is consistent with that published more recently by Chen and Zheng (2019) and Duan (2022), as well as by Bown (2018).

2.3.3.6 Chance

Porter (1998) explicitly includes the exogenous variable chance in the diamond model, defining it as "developments outside the control of firms (and usually the nation's government), such as pure inventions, breakthroughs in basic technologies, wars, political developments, and major shifts in foreign market demand".

The industry experienced such exogenous events between 2009 and 2010, when political decisions by China to impose export restriction triggered the 'rare earth crisis' (Y. Chen & Zheng, 2019), a four-year period of rare earth market instability characterized by dramatic price swings (Figure 13). Accordingly, an analysis framework that allows for exogenous shocks is necessary given the history and concern for future similar supply shocks and the corresponding disruptive impact in the rare earth demand sectors. Publications from several scholars including Duan (2022), Chen et al. (2021), Klinger (2018), Keilhacker and Minner (2017) discuss the 2010 market shock period. Their findings support including the first transition challenge, production concentration, as necessary condition for transition success.

Numerous references address the performance of dynamic feedback systems such as the SDM and DDM in the presence of exogenous shocks including (Bland et al., 2022; Glöser-Chahoud et al., 2016; Reboredo & Ugolini, 2020; Song et al., 2020; Stuermer, 2022). Other scholars (Ghadge et al., 2021; Mancheri et al., 2019; Tsolakis et al., 2021) published on the wider topic of examining supply chain resilience using dynamic simulation models, concluding that market conditions are only partly due to Chinese rare earth policies, with global market conditions also contributing to price fluctuations. In the

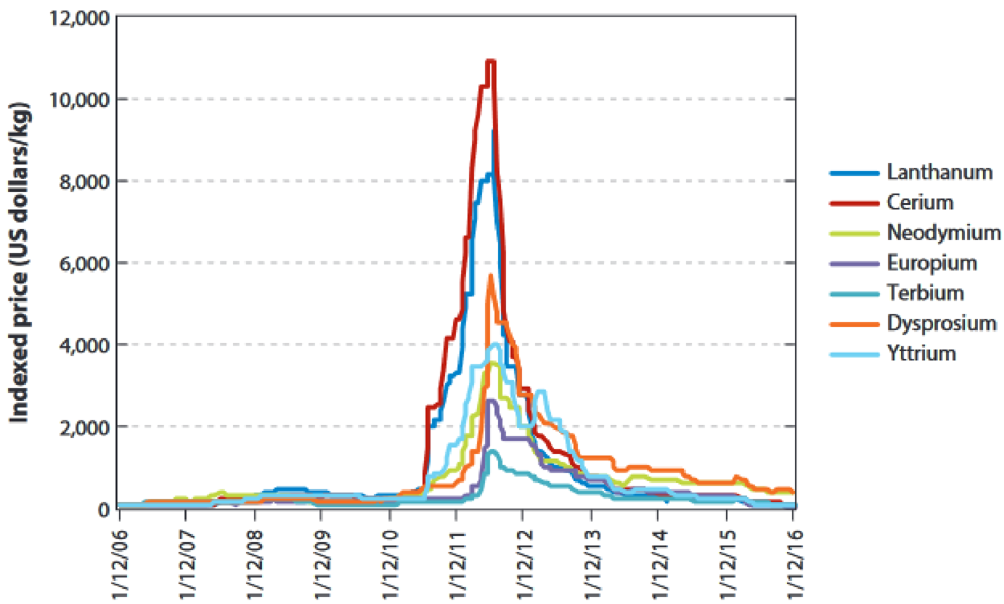


Figure 13. Prices for selected rare earth oxides, 2006 - 2016. Source: Argus Media, from Eggert, R., Wadia, C., Anderson, C., Bauer, D., Fields, F., Meinert, L., & Taylor, P. (2016).

context of CAT, an analysis approach capable of handling complex feedback that includes both exogenous and endogenous factors is therefore required.

An (2014) notes that "exogenous shocks on supply and demand curves, such as regulatory changes, geopolitics, and technological developments could alter the supply and demand dynamics of dysprosium (a rare earth) in unexpected ways, rendering forecasts on shortfalls difficult if not moot." Kunc points out, however, that "the external environment is not completely exogenous but is created in part by managers and their decisions" (Kunc, 2010). This is true in the 2010 case, with increased export restrictions preceding the rapid price rises. In the diamond model, those decision-makers exist in each of the determinants with the feedback effects between the determinants creating complex dynamics.

2.4 Transition Dynamics

We previously noted Porter's emphasis on dynamic feedback as part of the structural foundation of CAT, supporting a finding that dynamic simulation models are appropriate for analyzing both CAT and transition dynamics of the rare earth industry. Before continuing this theme, a brief discussion of simulation models is needed.

Simulation models are computer programs that attempt to produce an outcome that mimics one that would have been produced by the system being modeled. A simple example is using the random function of a spreadsheet (the program) to model a person tossing an unbiased coin (the system). The program generates a random number and then reports that a value less than 0.5 is the outcome 'tails', and greater than 0.5 is 'heads'.

How well a model mimics the system depends on several factors that can be summarized as the performance requirements of the model. If the single performance requirement of this model is that it must always produce an outcome of either heads or tails, then the inevitable case where the outcome is exactly equal to 0.5, causing the model to fail, means the model is assessed as performing poorly. If that performance requirement is relaxed to producing a heads or tails outcome 90% of the time the model can be assessed as performing well.

Simulation models of arbitrary complexity are possible, but in practice models that use dozens to hundreds of variables to focus on a single problem related to the operation of a subset of a system's performance are more common.

All models will fail to mimic the system, or subset of the system, perfectly. The oft-quoted observation of Box (1979), that "all models are wrong, but some are useful", must be kept in mind. Rigorous methods for model validation are known (Barlas, 1996); these are typically used to identify changes required to improve model performance to the point where it becomes useful.

Our interest is the class of models that can use its previous outcomes, automatically and iteratively and recorded as happening at precise intervals, as inputs to the next execution step such that the model mimics the operation of the (sub)system over time. These are referred to as dynamic simulation models. The use of dynamic simulation models for strategic policy models is well established. Forrester (1961), Sterman (2000), and Morecroft (2015) in their authoritative works describe the use of dynamic simulation modeling for the study of strategy implementation. Cavana (1995), and Kunc(2010) went further, using dynamic simulation models for strategy analysis based on competitive advantage theory. Wheat (2010) describes the benefits of and methods for incorporating policy design and policy implementation structure in dynamic simulation models.

Dynamic simulation models, either as system dynamics models, agent-based models, or a hybrid combination of the two, have been used to examine related questions: long-term copper market behaviour (Auping et al., 2014), supply chain resilience (Bland et al., 2022; Kifle et al., 2012; Nguyen & Imholte, 2016), rare earth global markets (M. Riddle et al., 2015).

Constructing dynamic simulation models often begins by preparing a causal loop diagram (CLD). CLDs are qualitative representations of essential feedback structure, used as a method of mapping the dynamic hypothesis of the problem being studied (Sterman, 2000, p. 86). Figure 14 shows the preliminary CLD[11] we have developed showing complex feedback structure of the industry. The shaded background patches show how the SDM determinants can be used to define the sub-model structure.

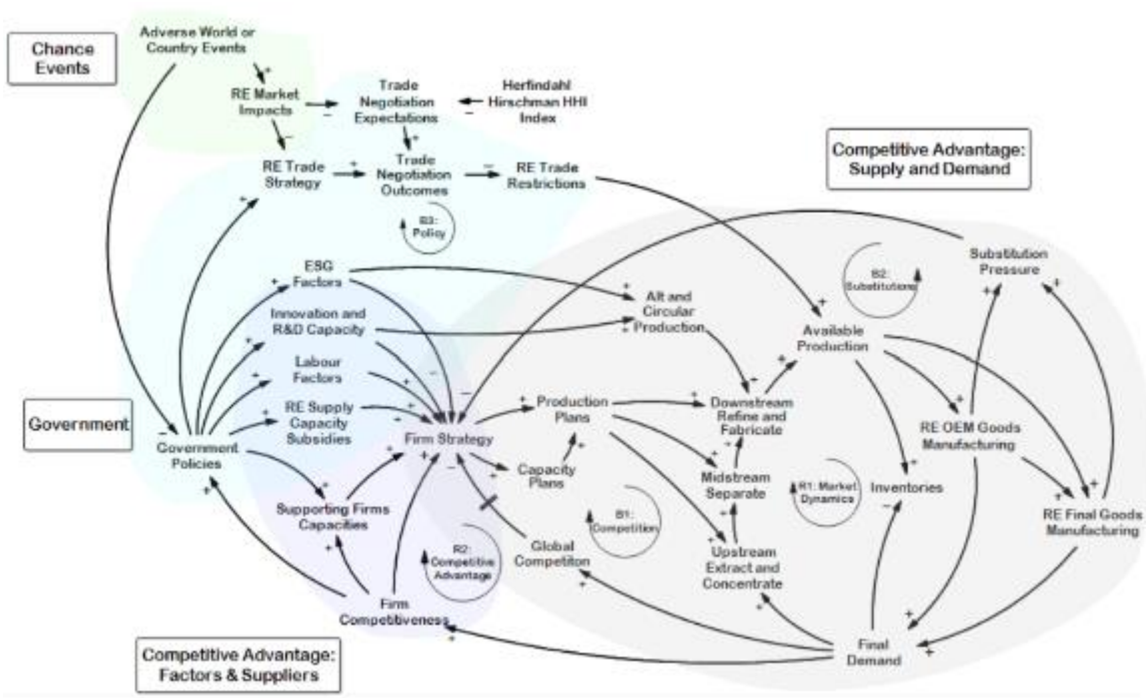


Figure 14. Rare earth industry transition preliminary causal loop diagram (CLD) showing sub-models based on competitive advantage theory. A successful transition sees Firm Competitiveness at a level where industry subsidies are no longer required in the face of global competition, with global production at levels that meet or exceed demand.

As shown, the CLD represents a single-nation view for developing competitive advantage.

Using the CLD as a template, elaborating the structure as a quantitative model using a

[11] A revised CLD is presented in section 3.3.5.

hybrid dynamic model[12] would enable extending the model to become multinational. The hybrid dynamic modeling enables agent-based sub-models for heterogeneous structures such as trade policy and firm production plans to be combined with system dynamics-based sub-models for homogeneous sub-models such as national R&D capacity and national environmental policy. Scenario testing will focus on studying transition dynamics based on key factors suggested by CAN such as firm value chain strategies, national R&D and innovation policies, and international trade policies.

Multi-disciplinary works that examine transition dynamics (Geels et al., 2017; Lachman, 2013; Markard, 2020; Markard et al., 2020; Verrier et al., 2022a) help identify exogenous and endogenous variables useful for identifying sub-model variables and to put the global rare earth industry transition into a multi-generational context.

2.5 Conclusions and Future Directions

In this review, we examined prior work applying competitive advantage theory to the challenges of successfully achieving a transition to long-term stability in the rare earth industry. We used the PRISMA process to select 51 articles for this review of prior work applying competitive advantage theory to the rare earth industry and as an analysis framework for evaluating three transition challenges to achieve long-term stability for the rare earth industry.

In examining the rare earth industry transition challenges – diversified production, increased production capacity, and profitable firms – we conclude that competitive advantage theory is a suitable framework for the transition study. Rugman et al.'s double

[12] Hybrid dynamic simulation models use a combination of individual dynamic modeling approaches, such as system dynamics and agent-based modeling, to obtain the benefits of both approaches in a single model.

diamond (DDM) variant is better suited than Porter's original single diamond model (SDM) to a full industry analysis; however, for the exploratory analysis conducted in this work the simpler SDM will suffice.

The underlying dynamic feedback structure of competitive advantage theory diamond model indicates that dynamic simulation models can be an important tool for analyzing diamond model behaviour. Our preliminary causal loop diagram shows the feedback structure of the rare earth industry using diamond model variables can be used to design the sub-model structure.

Later in this work, we use a revised version of causal loop diagram presented in this chapter to develop the design of a quantitative hybrid dynamic simulation model of the rare earth industry transition. We see this model as being a useful tool for foresight studies of the industry transition for bridging policy design and policy implementation. Collaborative scenario analysis by policy analysts and industry strategists would provide insights into strategies for a successful transition. Future work also includes examining the transition dynamics literature to identify other exogenous and endogenous variables useful for identifying sub-model variables and to put the global rare earth industry transition into a multi-generational context.

The larger body of published literature on the rare earth industry contains relatively little analysis using competitive advantage theory. As the goal of future research is to discover strategies for the long-term stability of the global rare earth industry, the highly regarded competitive advantage theory, having stood the test of time, offers an appropriate analysis framework.

CHAPTER III:

METHODOLOGY

This chapter describes the proposed interdisciplinary method for studying transition strategies that satisfy the two necessary conditions for transition success using a hybrid dynamic simulation model.

3.1 Methodology Overview

This research takes a novel approach by constructing a hybrid dynamic simulation model to implement an interdisciplinary framework for examining rare earth industry transition. The simulation model design is based on an adaption of the diamond model developed by Porter (1998) to explain why industries in some nations succeed in international competition while others do not. The method also incorporates concepts from systems engineering and recent work on socio-political aspects of technological transitions, which influenced the model design.

The simulation model falls into the category called exploratory models (Homer, 1996). An exploratory model is a limited model using synthetic data to examine a class of problems, with the goal of building confidence in the industry insights (Forrester & Senge, 1979), not to attain validation as a model of industry performance. Thus, exploratory models are a foundation, not a finished building.

After the exploratory model, larger explanatory models can follow. Explanatory models are constructed by iteratively improving the dynamic model structure and validity of the datasets with the intent of increasing confidence in the model with each successive iteration.

In taking this exploratory approach, the explanatory model requirement to rigorously fit the model results to ‘hard’ data is relaxed in favour of using a combination of ‘hard’ and ‘soft’ or synthetic data to gain insight into the class of problems. Hard data is verifiable data generated by real systems, while synthetic data is is synthesized from various sources to generate a data set for testing operational or production models (Datagen, 2023). For exploratory models, synthetic data that is based on real-world data is better able to represent data patterns expected from actual operations in an unbiased manner.

Here, we have assembled price, production, and demand data from referenced sources and used industry information to complete the datasets as required to provide data for the entire run time of the model. A base set of data is first identified and collected into an Excel spreadsheet. The data is first assessed for gaps in the model time period of January 2000 to December 2050. Data gaps from 2000 to 2022 are addressed first; if alternative sources are found the data is added using font colours to identify the new data. Forecast data from 2023 to 2050 was difficult to find – in this case published growth projections were applied to complete the dataset, again in different font colour. All data sources are cited in the Info tab of the Excel worksheet. In some cases sparse estimates were available to calibrate the synthetic dataset, as in the case of permanent magnets where U.S. Department of Commerce Bureau of Industry and Security published actual and project demand for 2020, 2030 and 2050. This data and the synthetic data set compared favourably.

Where gaps remained in the time series data the time entries were left blank, with Ventity configured for straight line interpolation to provide the missing data.

Data modeling challenges are discussed further in section 4.3 – Modelling Challenges.

The emphasis for exploratory models is thus to ‘get your arms around the problem’, where insight is favoured over rigour. Accordingly, exploratory models have one or more of the following limitations (Richardson, 2023):

- No obvious problem ‘owner’
- Difficulty modelling the problem boundaries
- Deliberately unrealistic but helpful assumptions
- Emphasis on understandable model structure
- Importance of linking structure to behaviour
- Multifaceted scenario tests

The overall model design is provided by the causal loop diagram (CLD) in Figure 15 below. This expands on the original systems engineering view of Figure 4 to show the high-level design of the hybrid dynamic simulation model developed for this study.

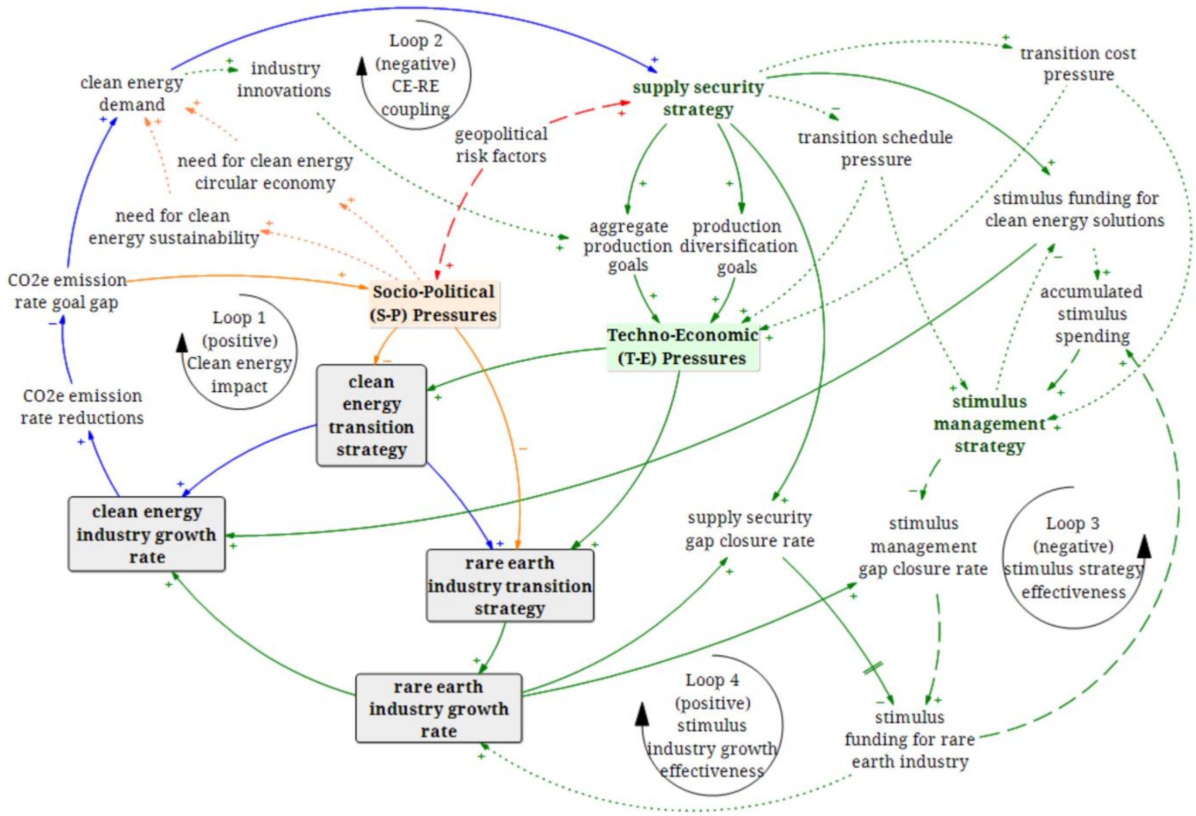


Figure 15. Causal loop diagram of simulation model high-level design

The grey-shaded box shows the four main elements of the coupled transitions using the systems engineering conceptual diagram in Figure 16 (adapted from Vanek (2016) and Verrier (2022b))

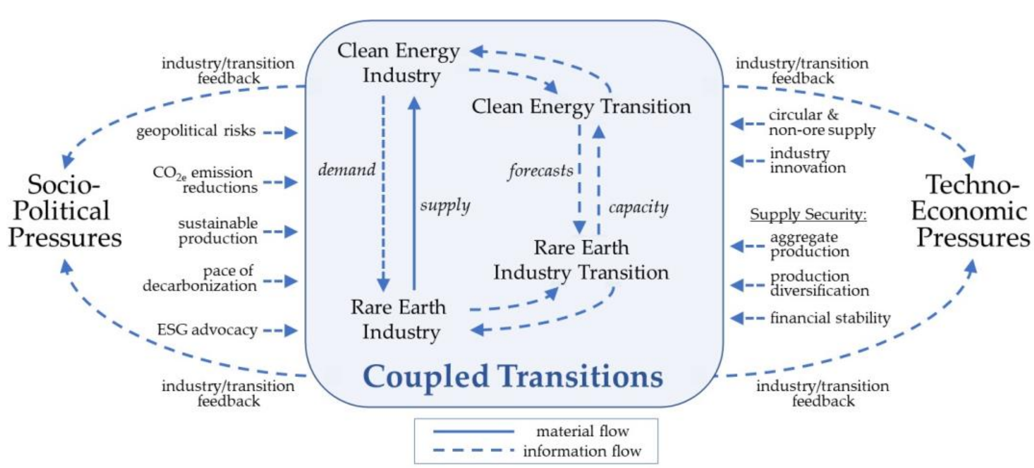


Figure 16. Coupled transitions research framework. (Author's work, adapted from Vanek (2016) and Verrier (2022b)).

The two exogenous variable groups from Figure 4, Socio-Political Pressures and Techno-Economic Pressures, are in the orange and green shaded boxes respectively. The two necessary transition conditions from the research hypothesis – supply security and long-term stability, shown here as stimulus management pressure – are in bolded green font, while the four metrics related to those factors are shown as numbered. The scope of the model are the variables to the right of line intersecting the model; feedback arrows from variables to the left of the line and that cross the line are treated as exogenous inputs. Other variables are shown to present a complete picture of the dynamic behaviour.

There are four main loops that elaborate on research scope:

- Loop 1 (positive or reinforcing). The Clean energy impact loop links the following variables: clean energy industry capacity growth rate → CO_2e emission rate reductions → CO_2e emission rate goal gap → Socio-Political Pressures → clean energy transition strategy → rare earth industry transition strategy → « return». It is a reinforcing loop because reducing the CO_2e emission rate goal gaps will, in the long term, reduce Socio-Political Pressures and increase support for the clean energy transition strategy. This leads to a dichotomy for the causal impacts on the rare earth industry strategy. A reduction in S-P pressures leads to an increase (expansion) in the clean energy transition strategy, which in turn leads to an expansion in the rare earth industry transition strategy because more magnet material is required. At the same time, there is a negative causal link from S-P pressures to rare earth industry transition strategy due to environmental concerns over rare earth mining. Potentially and as part of the rare earth transition strategy there will be actions to reduce the environmental impacts, thereby reducing the negative S-P pressures on the rare earth transition. Elements of that strategy can be seen in the variable rare earth industry S-P gaps closure rate, where sustainable growth in the rare earth industry would lead to a closing of the gap with S-P pressures. This would lead to an increase in rare earth stimulus funding and an increase in the industry growth rate.

- Loop 2 (negative or balancing). The Clean Energy-Rare Earth (CE-RE) coupling loop links the following variables: clean energy industry capacity growth rate → CO_2e emission rate reductions → CO_2e emission rate goal gap → clean energy demand → need for supply security → [aggregate production goals / production diversification goals] → Techno-Economic (T-E) Pressures → rare earth industry transition strategy → rare earth industry growth rate «returns»
  This is a balancing loop because, over the long term, more clean energy will lead to achieving CO_2e rate reduction goals and a leveling off of the growth rates in the rare earth demand. Starting the loop analysis with increasing the need for supply security – a key MSP aim – would result in decreased need for supply security because of the balancing effect.

  Note that supply security bifurcates into two variables [aggregate production goals / production diversification goals] operating in parallel but with the same causality, hence from a causal perspective they can be treated as a single extension of supply security.

- Loop 3 (negative, or balancing). The stimulus strategy effectiveness loop links the following variables: accumulated stimulus spending → stimulus management strategy → stimulus management gap closure rate → stimulus funding for rare earth industry «return». This is a balancing loop because as stimulus spending accumulates over time the gap between industry growth and the stimulus strategy expectations will grow causing the gap closure rate to diminish. This will cause curtailment pressure for additional stimulus funding, leading to a decrease in stimulus spending. Curtailment will result in a slowdown in the rare earth industry growth rate and the clean energy industry growth rate. The shape of this balancing curve will be influenced by the variables transition schedule pressure and transition cost pressure – both of which link to the stimulus management strategy. Compressing the transition schedule and reducing accumulated transition costs will mitigate the stimulus curtailment pressure, leading to stable funding for the duration of the transition.

- Loop 4 (positive, or reinforcing). The stimulus industry growth effectiveness loop links the following variables: stimulus funding for rare earth industry → rare earth industry growth rate → stimulus management gap closure rate «return». Loop 4 acts to counter the effects of loop 3 on stimulus funding. As the rare earth industry uses the stimulus funding to grow it causes the expectation gap to close, leading to more stimulus funding. The positive impact of Loop 4 will diminish over time and shift to the balancing impact of loop 3 curtailment, hence the need for schedule compression and cost management for the transition.

The scope of the research and the dynamic simulation model is the right side of the CLD, as delineated. Variables on the left side are included in the model as exogenous variables, as indicated by the causal links. This structure creates the overall study framework based on the system engineering concept illustrated previously. The chosen hybrid dynamic modelling software, Ventity, allows the variables to be implemented as array objects with heterogeneous attributes, and thus the framework is capable of examining multinational trade groups. The pressures from the systems engineering drawing are also shown on the CLD, with socio-economic inputs included as exogenous variables and techno-economic pressures as a mix of exogenous (influencing clean energy transition strategy) and endogenous (influencing rare earth industry transition strategy). We have chosen international competitive advantage theory to provide the framework of the rare earth industry.

3.2 Diamond Model Design Considerations

Diamond model theory is a strategy framework that seeks to explain why some countries are successful in developing international competitive advantage and others are not. The unit of analysis is the national industry. To compete internationally, industries must first seek competitive advantage in their domestic or home nation. Success in the home nation enables it to expand and be successful internationally.

As the diamond model is inherently a feedback network, it is well suited to study using dynamic feedback models. Porter encouraged the use of dynamic models to ensure logical consistency in the strategy framework, and vice-versa (Porter, 1991). Forrester (1961), Sterman (2000), and Morecroft (2015) and others have described how dynamic simulation models can be applied to the study of strategy modeling. Cavana & Hughes (1995), Kunc (2010), and others have used dynamic simulation models for investigating Porter's strategy framework.

A systems engineering perspective of this theory is the well-known design principle 'loose coupling, maximum cohesion'. This principle says that systems work best when the different functional subsystems interact through a small number of well-defined interfaces. Systems where parts of one component are re-built inside another ‘to improve efficiency’ tend to work less well. In this case, governments attempting to operate inside an industry eventually disrupt its internal cohesion. Thus, the determinants are modeled as independent and operating through defined interfaces.

After its first publication in 1990, scholars identified gaps in the original diamond model and proposed diamond model variants to address these gaps. A frequently cited gap is the treatment of foreign direct investment (FDI) in resource-based nations in developing international competitive advantage (Rugman & D’Cruz, 1993). To address the FDI issue Rugman and D’Cruz developed the double diamond adaptation previously shown in Figure 11. The double diamond adaptation uses a host country diamond to show the partner or subsidiary industry connected to the parent industry in the home country. The host country industry is the recipient of foreign direct investment and returns profits to the home country according to the structure of the connecting Business in Home Region agreement.

A second gap specific to the rare earth industry is the role of government. In the original model government is assigned an ‘influencer’ role, outside the four core determinants. An adaptation to the diamond model is required for the rare earth industry because the main international player, China, has incorporated Government as a core determinant in becoming the dominant nation in the industry. The use of state-owned enterprises (SOEs) and other subsidies and market interventions enabled the Chinese industry to gain near-total market control in the mid-1990s, a position it has not relinquished. Due to China's rise to dominance the rare earth industries in other nations have all but disappeared, resulting not only in a lack of domestic competition for the newly reestablished outside of China, but also the atrophy in the factor conditions and supporting industries necessary to regain the competitive edge.

To overcome the gaps in the original diamond model due to FDI and the much stronger government role from China, we propose an adaptation of the original diamond. This adaptation defines international competition as occurring between the TGs, which we have identified earlier as the China TG, MSP TG, and RoW TG.

In so doing, we effectively collapse the host region/home region boundary proposed in the double diamond variant to a single TG industry that can be represented by the single diamond. This approach recognizes the growing use of trans-border collaboration being established under the terms of inter-trade group agreements. This approach also serves a pragmatic purpose in avoiding the complexities of modeling FDI and the risk of double-counting EU stimulus where EU and EU country policies overlap and differ (Fang et al., 2018).

From a modeling perspective, TGs aggregate national industries at a level between global industry and individual nations. While TGs are not designed or formulated to develop a collective competitive advantage in lieu of that for the individual nations, we will use TGs for this purpose in the model due to the nature of rare earth industry competition from China.

This approach is consistent with recent MSP TG actions. In recent months it has announced joint efforts to "attract public and private investment" in addition to promoting the importance of the socio-political pressures on rare earth industry production through ESG standards. New projects are materializing, such as the Australian company Lynas building a downstream facility in Texas with U.S. financial support.

TG-level aggregation applies less well for the RoW countries, as they have no unifying partnership. For some countries trade accords exist, such as the African Growth and Opportunity Act between the U.S. and sub-Saharan African countries. These do not, however, confer special trade status and are treated only as a trade mechanism between two trade groups, in this case the MSP and RoW(Hendrix, 2023). The rare earth industries in the RoW nations are largely constrained to upstream production, selling their oxide production to China (mostly) and MSP processors (small quantities). They are therefore modeled as an aggregated upstream producer.

In this TG-adapted diamond model, we recognize that governments play a larger role than in traditional international industries. We therefore include Government as a core determinant, especially during the transition period. The larger role that confers will facilitate the government stimulus required initially because the markets for MSP TG firms is too small, relative to the risks, to attract the large amounts of private capital required.

The TG approach also assumes that a broader level of innovation partnership and use of supporting industries will emerge in support of the mutually beneficial aims of the partnership. To simplify the model, supporting industries is not included as a determinant in the TG-adapted model. Supporting industry factors, when required, are included in Factor Conditions. Similarly, Chance is excluded from the TG-adapted model and is included in geopolitical risks as an exogenous variable.

The TG-adapted diamond model is also useful in addressing the fundamental market problem caused not by lack of supply, but lack of demand. As production migrated to China after the mid-1990s, China grew their clean energy industry – the demand side of the equation – by using value-add tax (VAT) rebates for rare earths to domestic manufacturers, especially in the clean energy sector. Such preferential pricing practices have been successful in creating the large Chinese clean energy sector. Since working individually nations have not been successful at building market share in the clean energy sector, the MSP TG must work collectively to accomplish their supply security objective. A TG approach offers a wider range of policy options, but which requires extensive government-level collaboration that supports the inclusion of Government as a determinant in the adapted diamond model.

The TG-adapted diamond model is shown in Figure 17 below.

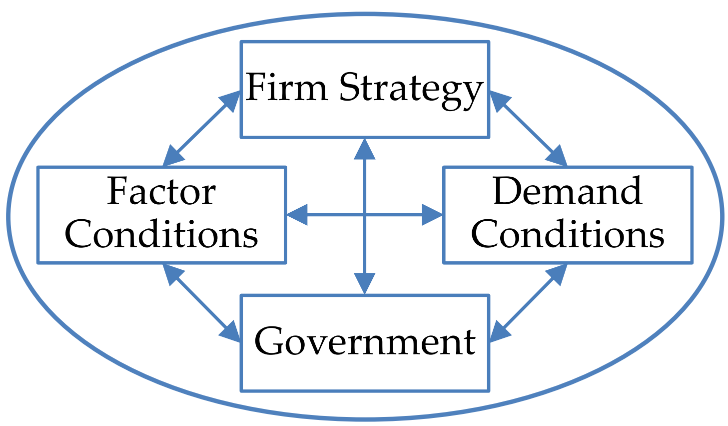


Figure 17. Revised SDM for TGs

Table 3 provides a partial mapping of CLD variables to their diamond model determinants. Only the in-scope variables and the exogenous variables intersecting the scope line are included.

Table 3. Mapping of CLD variables to diamond model determinants.

CLD Variable	Diamond Model Determinant
Supply security strategy	Government
Rare earth transition strategy	Firm Strategy
Aggregate production goals	Firm Strategy
Production diversification goals	Firm Strategy
Stimulus management strategy	Government
Transition schedule pressure	Government
Transition cost pressure	Government
Industry innovations	Factor Conditions
Clean energy demand	Demand Conditions
Geopolitical risk factors	Government

Design requirements for each of the four determinants are given below.

3.2.1 Firm Strategy Requirements

Firm strategy is disaggregated into five entity types that represent the five stages of rare earth mine to magnet production: mining, production, processing, refining, and fabrication. A simple economic analysis for each stage is implemented on the corresponding 'economics' diagram within each entity type. The alphanumeric prefix refers to the main production function of each stage – M1 (mining), C2 (concentration), S3 (separation), R4 (refining), and F5 (fabrication). The model structure of each economics diagram determines the competitiveness of each firm operating a mine or plant in that production stage. In addition to aggregating the economic results, at each time step model logic determines if each firm continues to be viable (bank balance > 0), and, if not, passes information to a deactivation trigger to remove that entity from the industry (the entity is not deleted, and all past data is preserved).

For M1 Mining, firms are aggregated to represent three firms in each TG – LREE, HREE and Circ (circular). The attributes of each firm are the average values for that type of firm for that TG based on the dataset compiled by Liu, (2023).

C2 Production represents the initial mineral concentration that occurs at the mine, therefore the production capacity is set equal to the mine extraction capacity, and all the mine production for that TG/material type is processed by the corresponding C2 entity – i.e. – MSP LREE Mine production is processed by MSP LREE Crush.

S3 Separation is the stage where C2 concentrate is separated into individual element oxides. As noted earlier some applications require rare earths in their oxide form. These are largely based on low value elements such as lanthanum (La) and Cerium (Ce). Separation is a costly and complex process, as many as 1500 steps. The complexity stems from the need to separate rare earths sequentially in periodic table order. Extracting the low numbered metal oxides such as La and Ce, which have market values lower than the cost of separation, requires the losses to be made up by the less plentiful but higher numbered metal oxides. In this exploratory model, S3 feedstock is from the corresponding TG C2 Crush facility. While today this is true only for China and partly true for MSP, such facilities are in the planning stages and will represent valid policy choices within the model timeframe.

R4 Refining consists of one refining plant per TG; however, an allocation mapping is implemented that assigns S3 Processing output to any R4 Refining facility. In the current state China would receive 100% of its own S3 output and 95% of MSP and RoW S3 output. This allocation can be dynamically adjusted by the model.

F5 Fabrication consists of one fabrication plant per TG. The allocation scheme used for refining is also implemented here, as the MSP is currently constructing these facilities. As with refining allocation, fabrication allocation can be adjusted dynamically.

Table 4 below provides the list of the mine to magnet processing entity types. Each of the production entity types reflects a major production stage in the rare earth value chain. The key attribute is a list used create relationships between the entity type entities to link each of the production stages into a mine-to-magnet value chain. For example, a relationship between the key attributes M1 Mining TG and C2 Production TG allows M1 Mining output to be used as feedstock for C2 Production.

Table 4. Firm Strategy model design of production entity types.

Entity Type	Stream	Key Attribute	Entities
M1 Mining	Upstream	M1 Mining TG	RoW - LREE Mine RoW - HREE Mine RoW - Circ Mine MSP - LREE Mine MSP - HREE Mine MSP - Circ Mine China - LREE Mine China - HREE Mine China - Circ Mine
C2 Production	Upstream	C2 Production TG	RoW - LREE Crush RoW - HREE Crush RoW - Circ Crush MSP - LREE Crush MSP - HREE Crush MSP - Circ Crush China - LREE Crush China - HREE Crush China - Circ Crush
S3 Processing	Midstream	S3 Separation TG	RoW - LREE SepCo RoW - HREE SepCo RoW - Circ SepCo MSP - LREE SepCo MSP - HREE SepCo MSP - Circ SepCo China - LREE SepCo China - HREE SepCo China - Circ SepCo

Entity Type	Stream	Key Attribute	Entities
R4 Refining	Downstream	R4 Refining TG	RoW - RefineCo MSP - RefineCo China - RefineCo
F5 Fabrication	Downstream	F5 Fabricating TG	RoW - FabCo MSP - FabCo China - FabCo

The following supply entity types (Table 5) are included in the model (the value chain stage is in parenthesis).

Table 5. Supply Entity Types

Entity Type	Entities	Stream	Feed	Product
Mining (M1)	mines	upstream	resource	ore
Production (C2)	concentration plant	upstream	ore	concentrate
Processing (S3)	separation plant	midstream	concentrate	oxides
Refining (R4)	refining plant	midstream	oxides	metals
Fabricating (F5)	fabrication plant	downstream	metals	magnets

Firm Strategy differs for each TG. China articulated its strategy over 30 years ago – to become the 'Middle East' of the rare earth industry. The MSP firm strategy of supply security emerged after the market disruption in 2010 and increased awareness of supply risks posed by China's strategy to the clean energy transition. The RoW firm strategy of maximizing each nation's economic benefits has only recently emerged, with the prospect of being relegated to ore and concentrate suppliers to others.

The MSP TG firm strategy of supply security is derived from its aim - "realizing the full economic development potential of their mineral resources" (U.S. Department of State, 2022). While realizing supply security satisfies the first criteria of a competitive strategy, namely to identify the desired industry position, it does not address the second criteria of identifying how it intends to sustain supply security over time.

Firm strategy assumptions:

- Maximize production. Treated as a commodity value chain where price before government distortions is homogenous for all firms, therefore revenue is a function only of production. Production increases are funded from revenues prorated over 5 years.
- Maximize innovation. Innovation boosts applies to production only, not operating expenses (no cost reduction innovations)
- Minimize government penalties by meeting ESG spending thresholds. Meeting the threshold is deemed 100% compliance with ESG guidelines. Scenario ESG4 presupposes that China group mines and plants will impose non-compliance penalties. MSP and RoW firms can only access non-China demand for midstream and downstream production due to China import restrictions.
- China allows unlimited upstream concentrate imports and reduces China group mine production to keep concentrate processing at 100% capacity. The model assumes MSP upstream concentrate is sold first to MSP midstream until MSP midstream capacity is reached, and all remaining concentrate is sold to China.

Firms are aggregated by mine type – LREE, HREE, or Circ (recycling). They are created at the start of model time, with capacity increases based on clean energy demand.

3.2.1.1 M1 Mining

The M1 Mining entity type implements the upstream stocks for the resource (ore), ore extraction, and initial mineral concentration.

The mining entities are based on averages for individual mines in the TG jurisdictions based on datasets in papers by Silva et al. (2018) and Liu et al. (2023). As some inconsistencies were noticed in their data it was updated as required. The preferred source for updates was the Qualified Person report (NI 43-101, JORC, or similar) for the mine. For mines in jurisdictions that do not require these documents, the best available source was used. The combined mine data from both studies yielded 65 mines as categorized in Table 6.

Table 6. Aggregate mine profiles for the three trade groups, by mine type.

Entity	Count
China - LREE Mine	3
China - HREE Mine	5
MSP - LREE Mine	10
MSP - HREE Mine	19
RoW - LREE Mine	12
Row - HREE Mine	16
Sum	65

China has fewer mines in their aggregate because they were merged under six, and then four, rare earth mining districts as state-owned enterprises over the last four years.

The initialization data for each entity is given in Table 7, while figures 18 and 19 present the model developed representing mining and is the main mining diagram used for this study.

Table 7. Mining entity initialization summary (REE grades not shown).

TG_Type	Resource [KT] TREO	Grade (wt. %)	HREE %	MagREE %
China_LREE	33524	4.2	1.1	17.3
China_HREE	3190	2.7	26.1	23.7
MSP_LREE	2052	3.0	4.0	22.1
MSP_HREE	293	1.1	28.7	20.7
RoW_LREE	2006	2.4	2.1	20.3
RoW_HREE	3557	2.5	29.6	20.2

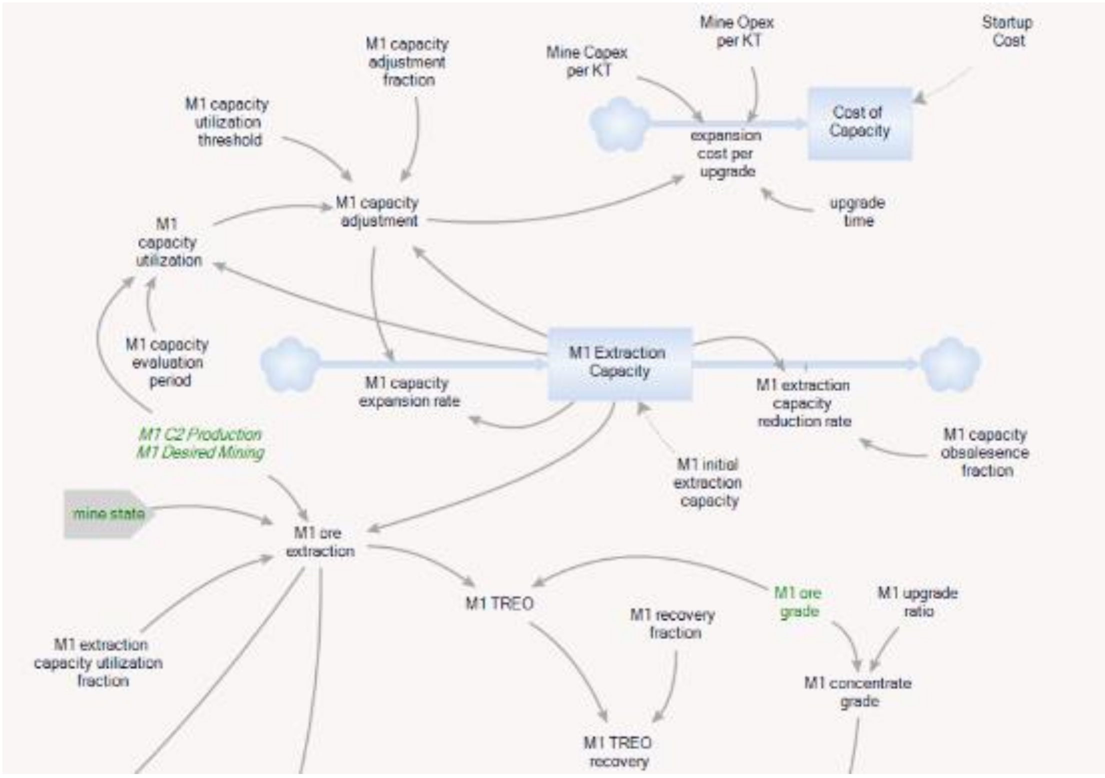


Figure 18. Mining main diagram (1 of 2).

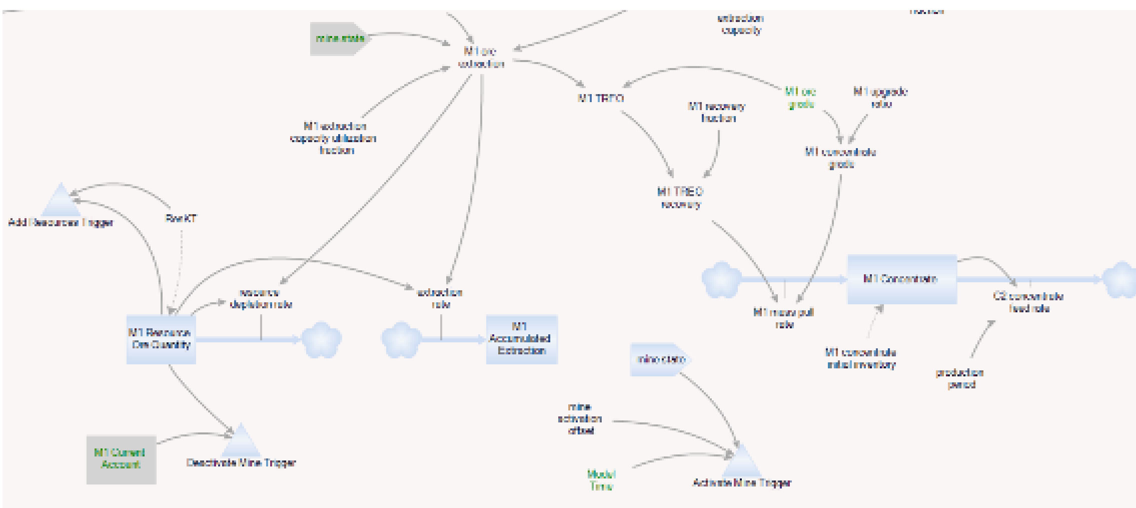


Figure 19. Mining main diagram (2 of 2).

The chart in Figure 21 below shows the results of incremental capacity increases for ore extraction based on ore extraction rate. The dynamics are most clear for the uppermost graphs, which represent China LREE extraction capacity (blue staircase, top) and China

LREE ore extraction rate (blue line, just below). As the extraction rate approaches the extraction capacity, the M1 capacity adjustment variable in Figure 20 adds capacity specified to the mine entities as specified by M1 capacity adjustment fraction.

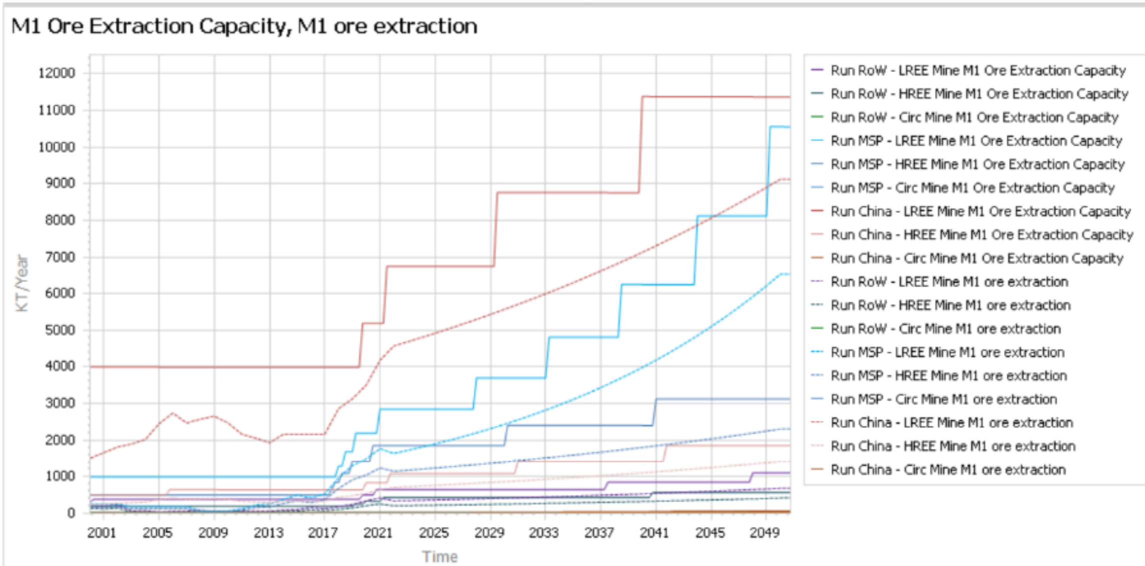


Figure 20. Addition of ore extraction capacity based on ore extraction rate.

The top two curves, which represent China – LREE Mine M1 Ore Extraction Capacity (solid line, staircase shape) and ore extraction (dashed line) are representative of the calculation for adding extraction capacity as the ore extraction reaches the capacity utilization limit. Capacity specified by the variable M1 capacity adjustment fraction is used to specify the capacity adjustment, which is added to the stock M1 Extraction Capacity. The end of each extraction capacity plateau is the point where the growth in ore extraction exceeds the capacity utilization fraction, triggering an expansion project.

The rate variable expansion cost per upgrade (is transferred to the structure in Figure 21 below (middle right, green text)) and connected as an outflow to the stock M1 Current Account. M1 Current Account is the ‘bank account’ for the mining entities that accumulates a gross revenue amount based on the oxide market price per model time step (1/4 year). The current account inflow is the gross revenue from the sale of mineral concentrate minus annual operating costs. If the 'bank balance' for a mine entity exceeds twice the expansion upgrade cost then the upgrade is paid for by the mine entity; if there are insufficient funds the shortfall is offset by government stimulus funding. This logic assumes that the upstream production will be subsidized to ensure the flow of material to the mid and downstream stages.

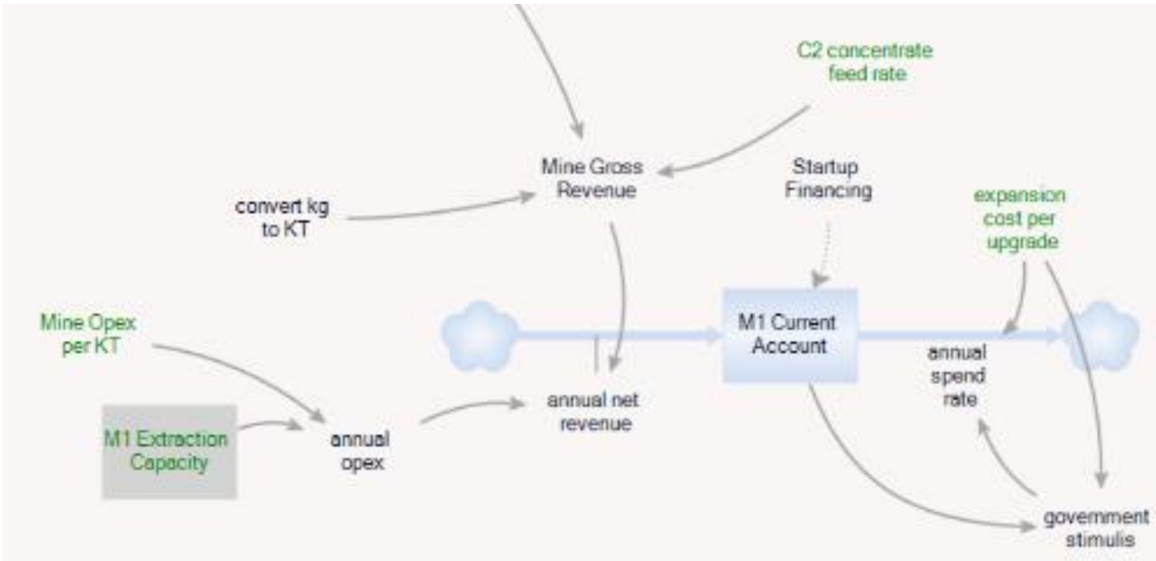


Figure 21. Calculation of the cost to add extraction capacity.

3.2.1.2 C2 Production

The Production entity type converts mineral concentrate to rare earth concentrate, ready for separation. The model approach is that for economic reasons all the mineral concentrate is processed by a production factory from the same TG and for the same mineral type (LREE or HREE). Thus, there is a one-to-one mapping of mines to production facilities as shown in Table 8 below.

Table 8. Production entities.

C2 Production TG	M1 Mining TG
RoW - LREE Crush	RoW - LREE Mine
RoW - HREE Crush	RoW - HREE Mine
MSP - LREE Crush	MSP - LREE Mine
MSP - HREE Crush	MSP - HREE Mine

C2 Production TG	M1 Mining TG
China - LREE Crush	China - LREE Mine
China - HREE Crush	China - HREE Mine

The model structure for C2 Production is shown in Figure 22.

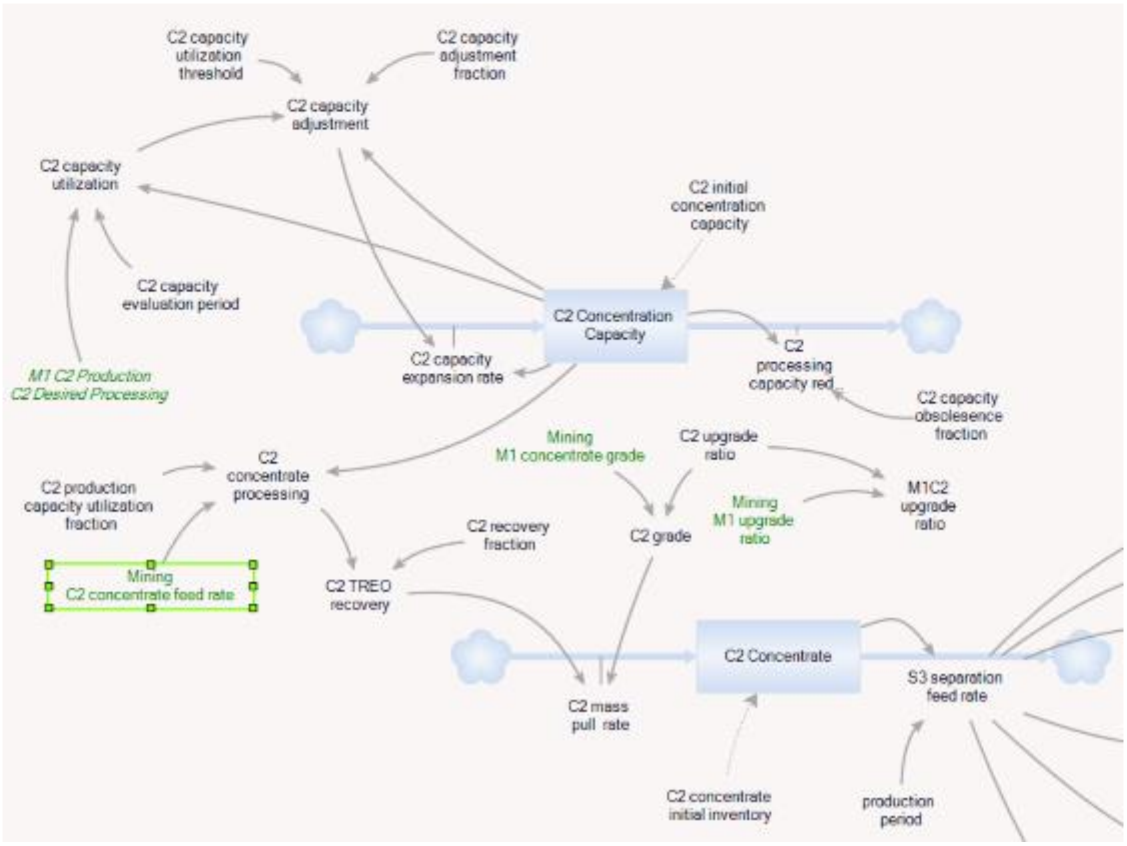


Figure 22. C2 Production entity type.

Mineral concentrate from M1 Mining (green box, lower left) is compared to the level of production capacity and the lesser amount is processed into rare earth concentrate with 60% to 70% TREO depending on the entity parameters in the initialization data. The processing parameters for each production entity are also retrieved from the initialization data so that the concentrate volumes and grades reflect each production entity. For clarity, the concentrate produced after the flotation process in M1 Mining is referred to as mineral concentrate, while the concentrate after the C2 stage is referred to as mixed rare earth carbonate (REC) concentrate or often simply mixed REC. We use the prefixes M1 and C2 to distinguish between the two concentrates.

Figure 23 shows the pronounced growth in separation feed volumes, which reflects the forecasts for clean energy demand. An example of lanthanum (La) volumes for the next separation stage are shown in Figure 24(a) and volumes showing all oxides in Figure 24(b).

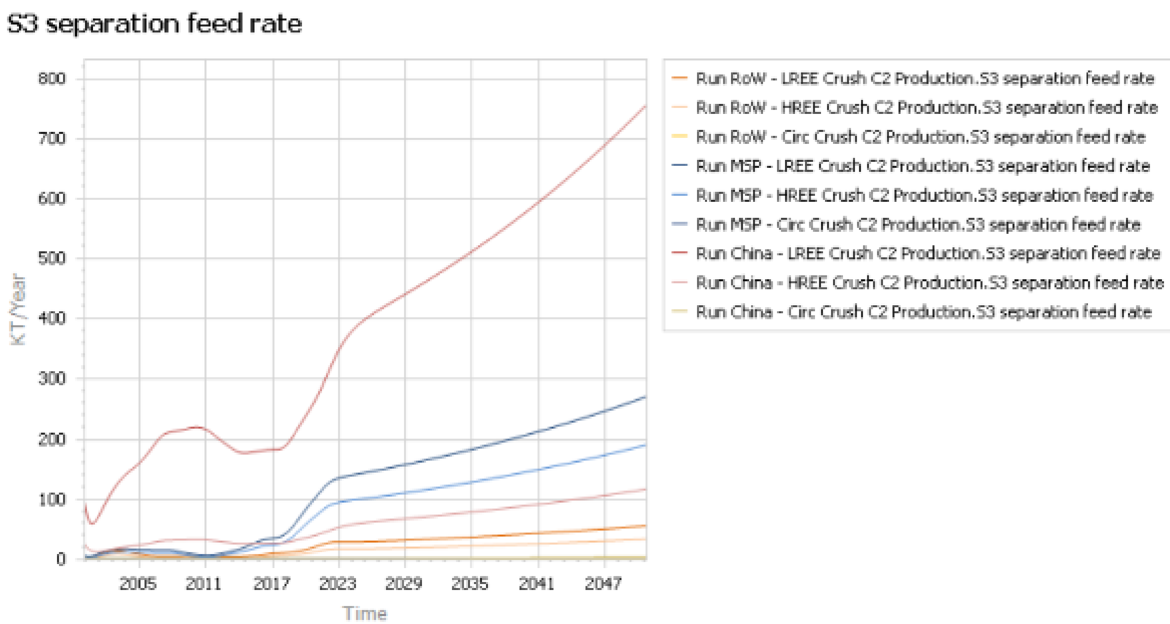
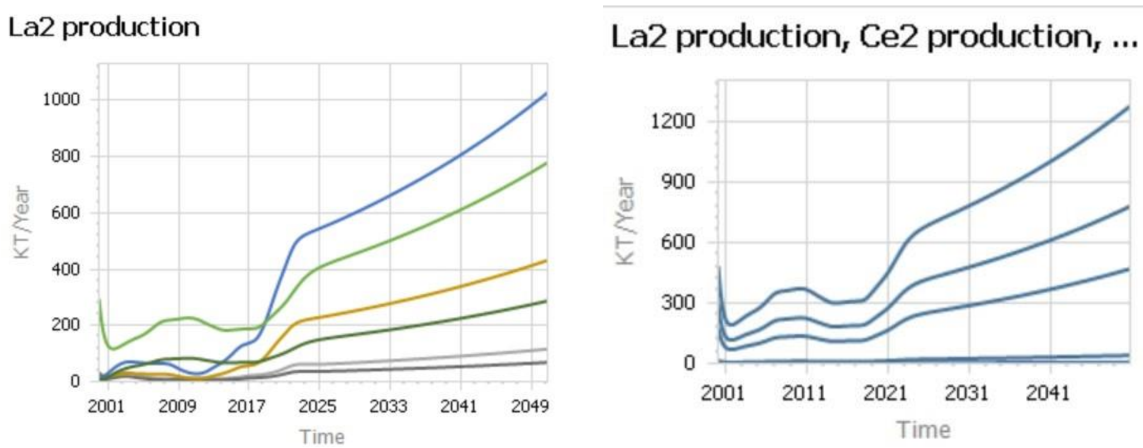


Figure 23. Production S3 separation feed rate output.

The agent capabilities of Ventity to efficiently manage disaggregated entity data can be seen in Figure 23. On the left (a), the chart shows the lanthanum grade for each mine entity, while on the right the chart shows the grade for all six oxides in the China LREE separation feed.



(a) (b)

Figure 24. Rare earth carbonate disaggregation. (a) A single element (lanthanum) for all entities, and (b) all elements for a single mine entity.

3.2.1.3 S3 Processing

S3 Processing is the midstream stage that produces separated rare earth oxides from C2 concentrate. Table 9 shows the list of separation plant entities.

Table 9. Production entities.

S3 Separation TG
RoW - LREE SepCo
RoW - HREE SepCo
MSP - LREE SepCo
MSP - HREE SepCo
China - LREE SepCo
China - HREE SepCo

The S3 Processing contains the separation stage model structure (Figure 25), which is similar to that of the preceding C2 Production stage shown in Figure 22. The separated oxide output flow can be seen on the lower right. Individual element oxides are moved through to the next R4 Refining stage, while the aggregate outflow R4 refining feed rate is used to calculate the required refining capacity per TG.

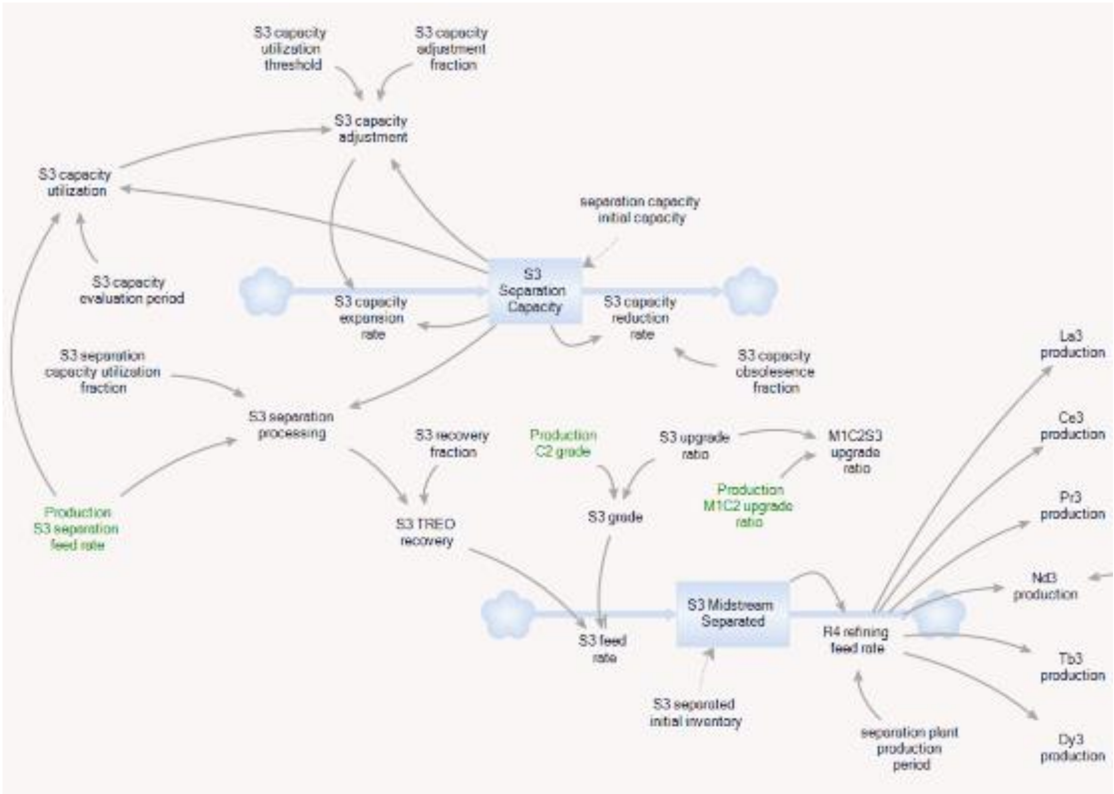


Figure 25. Production stage showing separated oxide output.

Reflecting the current state of refining capacity, in the base case separated oxide output from S3 is no longer sent to the R4 refining plants within the same TG. An allocation table is created in the entity type SepcoRefco to direct separated output to a refinery in the Refining entity type. The allocation mapping is shown in Table 9, while the model structure for distributing the separated material is shown in Figure 26 immediately following. In the base case as in the current state, most refining is done in the China TG.

Table 10. Distribution map for movement of separated oxides to refining.

SepCo	RefCo	R4 initial distribution fraction	SepCo	RefCo	R4 initial distribution fraction
RoW - LREE SepCo	RoW - RefineCo	0.0	MSP - HREE SepCo	RoW - RefineCo	0.0
RoW - LREE SepCo	MSP - RefineCo	0.1	MSP - HREE SepCo	MSP - RefineCo	0.2

SepCo	RefCo	R4 initial distribution fraction	SepCo	RefCo	R4 initial distribution fraction
RoW - LREE SepCo	China - RefineCo	0.9	MSP - HREE SepCo	China - RefineCo	0.8
RoW - HREE SepCo	RoW - RefineCo	0.0	China - LREE SepCo	RoW - RefineCo	0.0
RoW - HREE SepCo	MSP - RefineCo	0.1	China - LREE SepCo	MSP - RefineCo	0.0
RoW - HREE SepCo	China - RefineCo	0.9	China - LREE SepCo	China - RefineCo	1.0
MSP - LREE SepCo	RoW - RefineCo	0.0	China - HREE SepCo	RoW - RefineCo	0.0
MSP - LREE SepCo	MSP - RefineCo	0.2	China - HREE SepCo	MSP - RefineCo	0.0
MSP - LREE SepCo	China - RefineCo	0.8	China - HREE SepCo	China - RefineCo	1.0

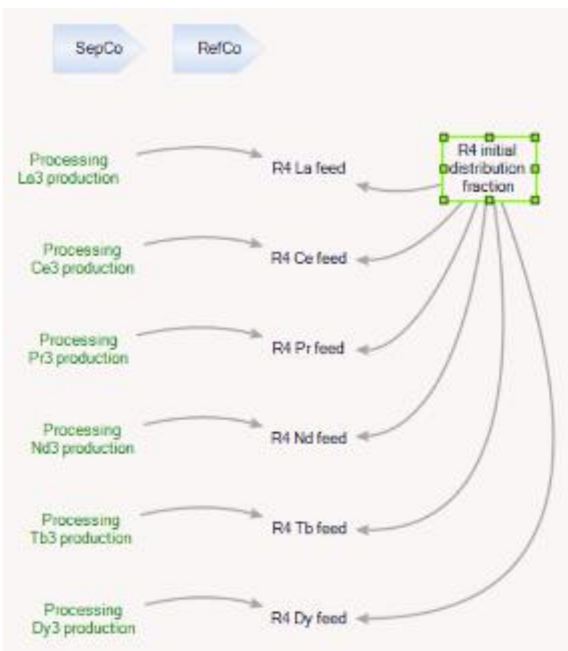


Figure 26. Distribution model structure allocating separted oxides (variables in green text, left) to refining input flow variables (black text, center).

The variable R4 initial distribution fraction (top right) contains data in the columns of the same name in Table 10. The two attributes for the SepcoRefco entity type, SepCo and RefCo, are used to process the oxides from source to destination as per the table. For example, oxides from RoW separation facilities are distributed 0% to RoW refineries (there are none), 10% to MSP refineries (there aren't many, initially) and 90% to China. These allocation percentages can be changed by future model structure as new refining capacity comes online. For this version of REITD concentration is calculated only for downstream fabrication.

3.2.1.4 R4 Refining

The Refining entity type models the conversion of oxides to metals. In practice refining output purity typically ranges from 2N to 3N or 5N; 3N is the initialization value in the model. As shown in Table 21, only three refining entities are defined but as noted above there currently are no RoW refineries and thus have inputs and outputs of zero. Should these facilities be constructed in the future, the model/data separation in Ventity makes it a simple matter to adjust capacity by changing the spreadsheet entries.

The refining entities are shown in Table 11, with the model structure in Figures 27 and 28 immediately following. For REITD, we are only concerned with permanent magnets, thus only four refining paths are required.

Table 11. Refining entities.

R4 Refining TG
RoW - RefineCo
MSP - RefineCo
China - RefineCo

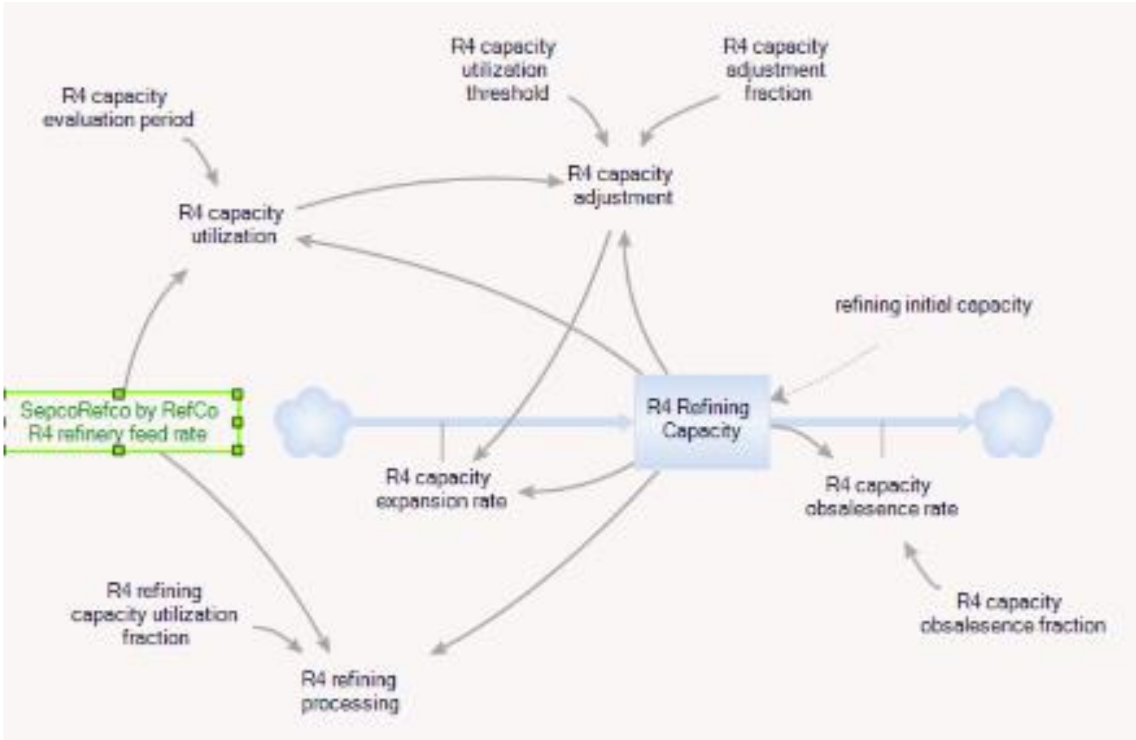


Figure 27. Refining entity type - refining capacity model structure.

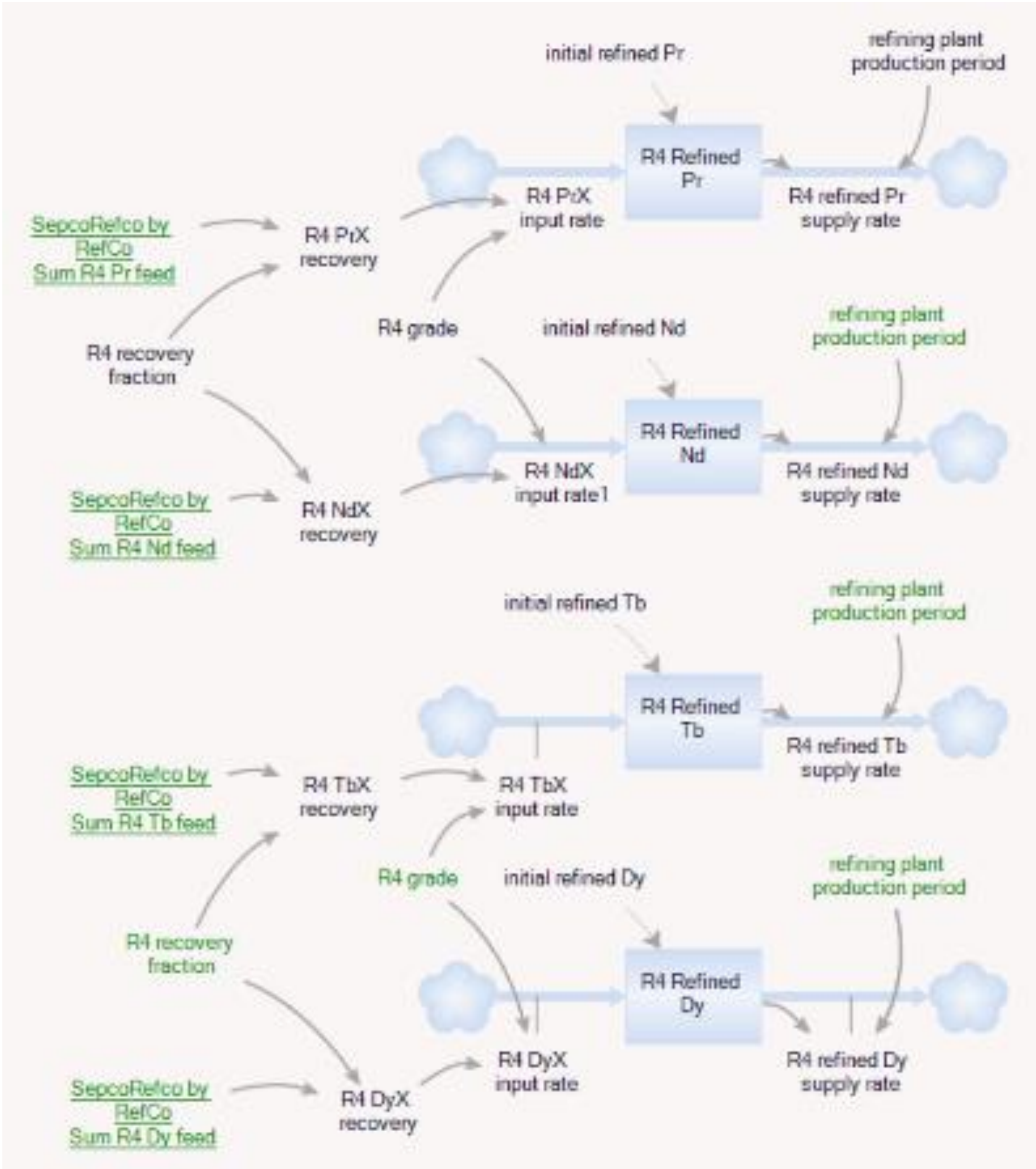


Figure 28. Refining entity type - refining model structure.

As with the SepcoRefco allocation in Table 10 above, a similar RefcoFabco allocation scheme is used to allocate refining output to fabrication facilities, as in Table 12 and Figure 29.

Table 12. Refining to Fabricating allocation table.

RefCo	FabCo	F5 initial distribution fraction
RoW - RefineCo	RoW - FabCo	0.0
MSP - RefineCo	RoW - FabCo	0.0
China - RefineCo	RoW - FabCo	0.0
RoW - RefineCo	MSP - FabCo	0.1
MSP - RefineCo	MSP - FabCo	0.2
China - RefineCo	MSP - FabCo	0.0
RoW - RefineCo	China - FabCo	0.9
MSP - RefineCo	China - FabCo	0.8
China - RefineCo	China - FabCo	1.0

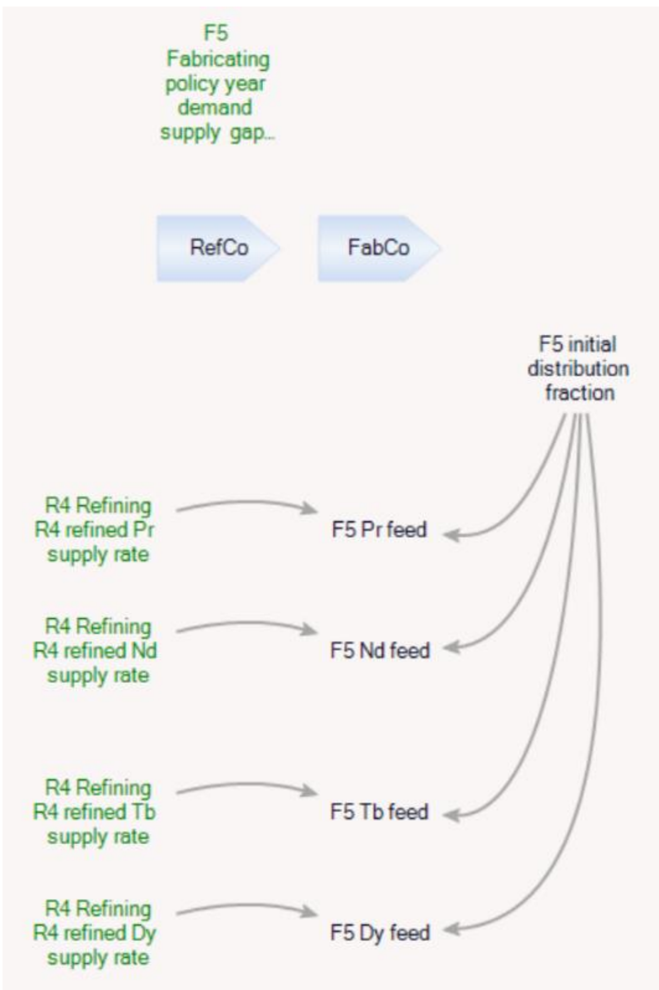


Figure 29. Refco to Fabco allocation.

Only four elements are refined and fabricated, those being the four magnet metals, hence the simpler structure in Figure 28. The allocation variable F5 initial distribution fraction again shows most of fabrication concentrated, in the base case, in China.

3.2.1.5 F5 Fabrication

The final metal processing stage is fabrication. Fabrication takes metal output from refining to produce metal alloys and rare earth products such as permanent magnets, with entities and model structure in Table 13 and Figure 30 below.

Table 13. Fabricating entities.

F5 Fabricating TG
RoW - FabCo
MSP - FabCo
China - FabCo

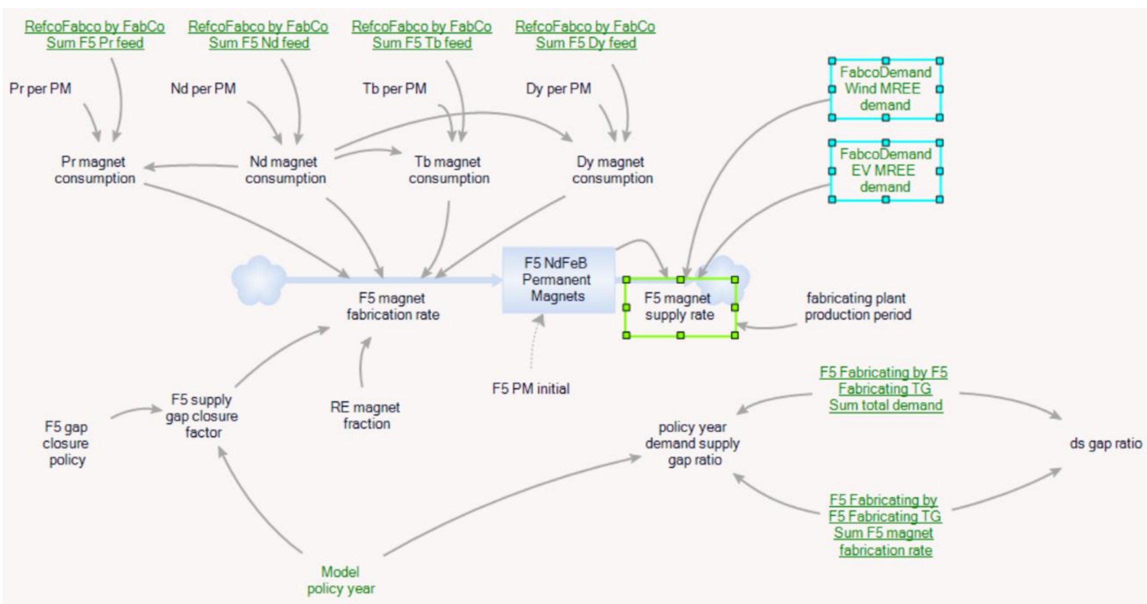


Figure 30. Fabricating model structure, showing permanent magnet production and allocation orders from clean energy demand for wind and electric vehicles (EV).

As before, an entity type FabcoDemand is used to allocate wind and EV permanent magnet demand to TG fabrication plants. The initial allocations used in this work are given in Table 14.

Table 14. Fabricating to Demand allocation.

Demand	F5 Fabricating TG	F5 initial distribution fraction
RoW TG	RoW - FabCo	0.0
RoW TG	MSP - FabCo	0.0
RoW TG	China - FabCo	1.0
MSP TG	RoW - FabCo	0.0
MSP TG	MSP - FabCo	0.1
MSP TG	China - FabCo	0.9
China TG	RoW - FabCo	0.0
China TG	MSP - FabCo	0.0
China TG	China - FabCo	1.0

Initialization data reflects the concentration of fabrication in China and absence of capacity in the RoW TG. Note that 100% of China demand is allocated to China FabCo.

3.2.2 Demand Conditions Requirements

The demand conditions determinant is simplified to one product – permanent magnets – for two clean energy sectors – wind and EV. For wind, only a small percentage of onshore wind turbines use the permanent magnet direct drive design. Offshore turbines, with higher reliability and performance specifications due to the cost of maintenance, heavily favour permanent magnet direct drive generators. One entity type sub-dividing model structure across three diagrams is used to implement rare earth industry demand from the clean energy sector (Figure 31). In addition to adjusting capacity in the production stages, demand information is used to dynamically calculate production minus demand, by trade group, to determine if aggregate production is meeting demand. This data is used to the evaluate aggregate production performance metric.

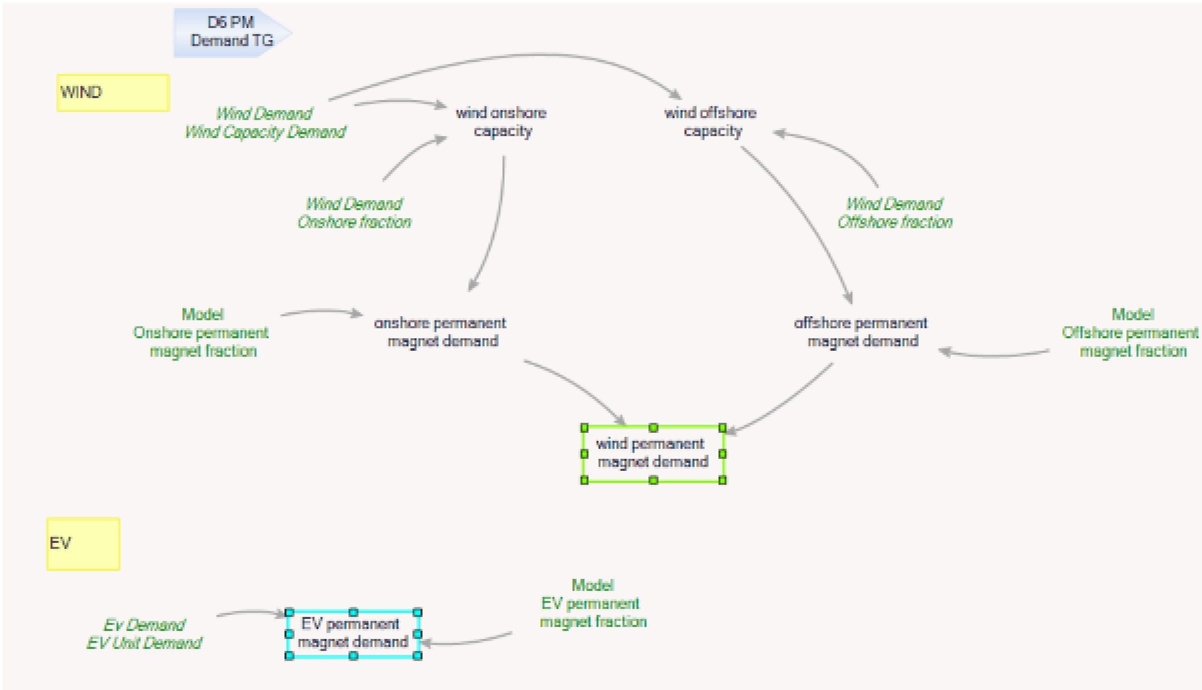


Figure 31. Demand model structure. Demand data is loaded from the Production .xlsx file.

Wind and EV demand is fed back to Fabricating both to adjust supply and allow the supply/demand gap to be calculated.

3.2.3 Factor Conditions

Factor Conditions is not included as an entity type; however, factor condition variables are added within the entity types of the mine to magnet model structure. The importance of other factor conditions such as process innovations, industry R&D, advanced skills training, and transportation and utilities infrastructure are noted for inclusion in a future version.

3.2.4 Government

Government is used as a determinant in this framework due to the importance of providing stimulus funding and addressing geopolitical risks to reestablish the MSP TG industry. As with Supporting Industries it is not included as a separate entity type, but as variables within the mine to magnet model structure. Government is used as a scenario in Chapter 6.

3.3 REITD – Rare Earth Industry Transition Dynamics Model

The simulation model developed for this study is designated as REITD – 'Rare Earth Industry Transition Dynamics'. The model was developed using Ventity version 5.0 (beta 2) (Ventana Systems, 2021). The model datasets were created from a combination of imported referenced datasets and synthesized using industry parameters. The model datasets were managed using Excel MSO 365 Version 2307. REITD contains 550 model components within 12 entity types, eight data entity types three time series data files, and three entity initialization files. The complete model definition is provided in Appendix A; a high-level summary will be presented in Section 3.6

The model takes a high-level macrodynamic approach (Wheat et al., 2021) instead of a supply chain approach (Guo & You, 2023) to focus on comparing production and demand instead of the simulating the supply chain complexities to satisfying market demand from production inventories. REITD is not a macrodynamic model but is influenced by its feedback-rich, stock-and-flow design principles.

3.3.1 Model Objectives, Scope, Constraints and Assumptions

The aim of this research is to present a method for studying rare earth industry transition strategies that can achieve the twin objectives of supply security and long-term stability. This method uses the diamond model theory as the transition analysis framework of the rare earth industry using a hybrid dynamic simulation model.

Model Objective

The objective of this simulation model is to determine if the proposed method can determine viable strategies for the MSP TG transition. A viable strategy addresses the twin challenges of supply security and long-term industry stability.

To do this, we model the main value chain stages – upstream (mining and concentrating), midstream (separation), and downstream (refining and fabrication). Clean energy demand for EVs and wind is treated as an exogenous input.

Model Scope

The model scope was outlined in the CLD of Figure 15, repeated here as Figure 32. The variables to the right of the scope line are included as endogenous variables in the model. Variables on the left are treated as exogenous if their feedback arrow intersects the scope line and are treated as out of scope for these modelling efforts.

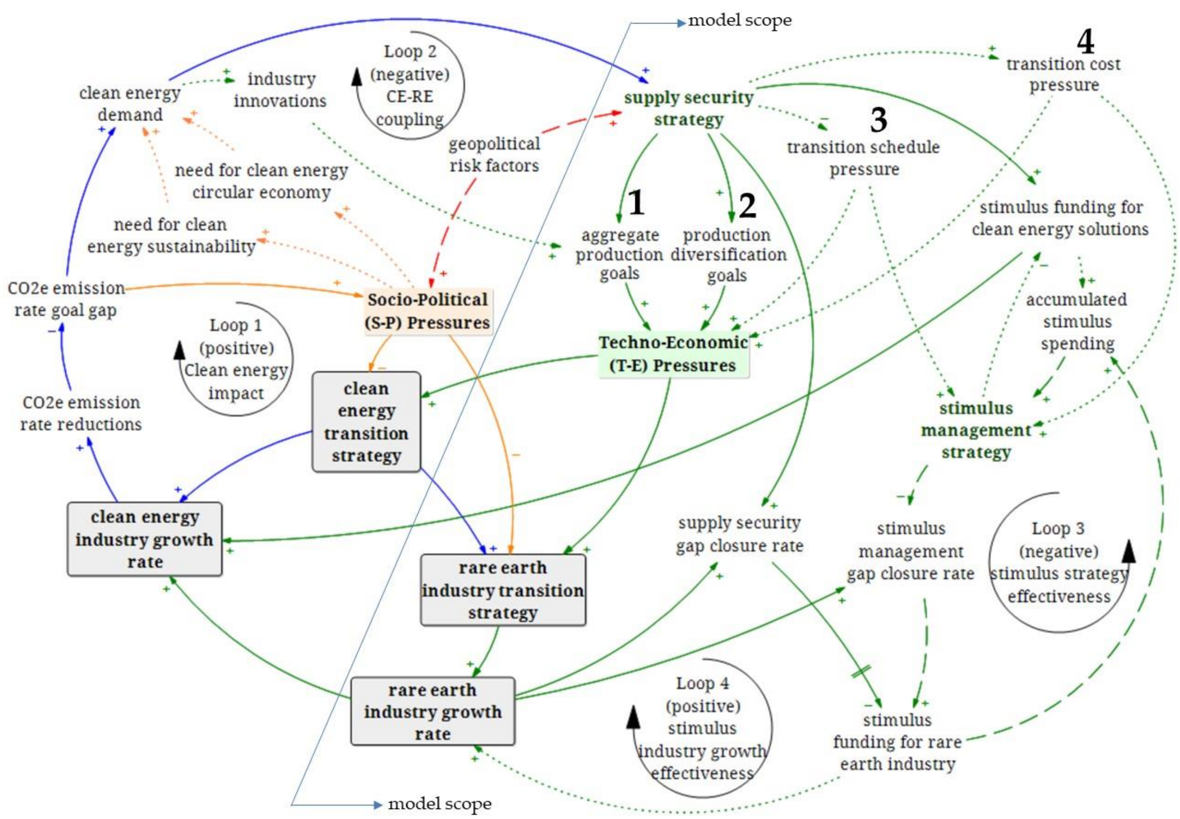


Figure 32. Model CLD showing the model scope line (Reprise of Figure 15).

Model Constraints

Historical time series data for price, production and demand from single sources was not available, requiring combining data from multiple sources and use of interpolation to create a synthetic time series dataset. As a result, validation of the model to industry performance was not possible; however, the datasets are sufficient for the purposes of this exploratory model.

Model Assumptions

Supply chain logistics are not required to implement the exploratory model.

3.3.2 Model Setup

The values entered in the Run Control table establish the runtime parameters for the model. The key parameters are:

- Model time: calendar-based time, 40 years from 2000/01/01 to 2050/12/31
- Unit of Time: Year
- Time step: 0.25 years (204 time steps)

The model time was selected to capture the ten-year period before the rare earth market price shock of 2010 and extend to the limit of available energy demand forecast data to 2050. During validation testing the time step (0.25 year) will be decreased to check for stability. These runtime parameters will apply to all scenarios. The runtime parameters are summarized in Table 15.

Table 15. Model run control parameters.

Name	Initial Calendar Time	Final Calendar Time	Time Step	Unit Of Time	Save Time Step	Initial Save Calendar Time	Final Save Calendar Time
Base	01/01/2000	12/31/2050	0.25	Year	0.25 (204 total)	01/01/2000	012/31/2050

3.4 Dynamic Simulation Modeling

The previous sections (3.1-3.3) show the development of the CLD and the integration of the various factors that need to be considering when modelling the complexity of the transition of the rare earth industry. Here we introduce Ventity, the primary software that is used to reduce the previously developed models into practice.

Dangerfield (1991) suggests the role of dynamic simulation models is to provide computer-based scenarios that "offer improved understanding and insight" in the assessment of strategic policy.

3.4.1 System Dynamics Modeling

Using computer-based dynamic simulation models to study complex management problems has its origins in the work of J.W. Forrester at MIT in the 1950s and the development of system dynamics (SD). First applied to the manufacturing industry, the use of SD quickly expanded into social and economic policy. Today SD is used in dozens of fields, and notably by health policy strategists during the recent COVID-19 pandemic.

Forrester based SD on two main principals – that the system under study be modeled as variables interconnected by feedback loops, and that the behaviour of the system over time was determined by the system's structure. In this way, a validated model could be used to rapidly provide insights into the system's behaviour by changing the variables in the model.

The SD models are comprised of four elements – stocks, flows, variables, and arrows. Stocks and flows are types of variables that capture the state of the system and its rate change, while arrows are used to construct feedback loops. Using these four elements enables the modeler to construct dynamic feedback models of arbitrary complexity.

Stocks are generally homogeneous variables but can be disaggregated using subscripted arrays. While adding functionality, internally the array processing can lead to operations on large sparse arrays that can impact the performance of large models.

SD has been successfully applied to various rare earth problems (Elmasry & Größler, 2018; Kifle et al., 2012; Severson et al., 2023; Speller et al., 2007; Sprecher et al., 2015, 2017; X. Wang et al., 2017).

3.4.2 Agent-Based Modeling

The origins of AB date back to the creative efforts of leading mathematicians in the 1940's, notably Von Neumann, Ulam, and Conway. With the advent of the powerful computers of the 1990s the development of AB accelerated. Models of the complex social interactions of large population groups were developed. More recently AB has been applied to scientific fields, including rare earths (Brailsford et al., 2019; Cao et al., 2021; Hansen et al., 2019; M. E. Riddle et al., 2021; Sanchez-Segura et al., 2018).

Unlike SD, which uses stocks and flows to create an aggregate representation of the system, agent-based (AB) models consist of networks of agents and accumulate disaggregated data from the behaviour of individual agents over time. Using agents as the level of granularity makes agent-based highly suitable for heterogeneous models, in comparison to the homogeneous stock-based focus of systems dynamics.

Agent behaviour is modeled as independent and adaptive, but compliant with a set of system rules. Model complexity is achieved through the aggregate action of multiple agents. The availability of disaggregated model data is built into the model, albeit at the cost of higher model construction effort than for SD.

A literature review on the use of AB models for the energy transition by Hansen et al. (2019) examined 62 papers, noting the effectiveness of the AB models for policy and planning decision-making. AB has been applied to critical mineral supply problems by Riddle et al. (2015, 2020; 2021) and Knoeri et al. (2013).

3.4.3 Hybrid Modeling

Hybrid dynamic (HD) simulation modeling emerged from the desire to combine the strengths, and overcome the weaknesses, of the individual SD and AB modeling approaches in a single model. While hybrid can be inclusive of other modeling approaches such as discrete event simulation (DES), in this study we consider only the combination of SD and AB.

Research by Łatuszyńska (Łatuszyńska, 2020) suggests that the hybrid approach can offer more detailed insights into problems in the fields of economics and business. Following Swinerd and McNaught (2012) and Langarudi et al. (2021), we examined the case for the HD approach and how it can be applied to the complex problem of resource management, as summarized below.

Hybrid dynamics (HD) is considered as a modeling option when the problem consists of both homogenous and heterogeneous structures. Sanchez-Segura et al.(2018, p. 300) provides a detailed comparison of modeling effort for two commercial simulation applications – Vensim (SD application) and NetLogo (AB application). The authors provide a detailed analysis of the effort required using eight modeling criteria. Łatuszyńska (2020) provides a comparison of SD AB, and hybrid approaches, while also providing three categories of HD approaches – interfaced, sequential, and integrated, and three options for implementing the integrated category. The paper also observes that the use of the HD approach is growing.

Sterman (2000) in his reference text on system dynamics notes advantages for using AB over SD such as when firms, groups, or other cohorts can be modeled explicitly rather than as a single homogeneous entity, allowing the cohort members to be modeled heterogeneously with specific attributes and actions. Martín García (2021a) summarizes the choice of AB versus SD thusly: “An AB model is used when we have a system composed of elements that, although similar, have characteristics that make them unique and critical to understand the system as a whole to decide policies that must be applied to manage it and achieve the proposed objective”.

Langarudi et al. provides a useful classification framework of four hybrid AB-SD integration approaches. extending the work of Swinerd and McNaught. Brailsford e al. (2019) also provides a comparison of three modeling methods applicable to hybrid simulation – AB, SD and Discrete Event Simulation (DES).

Applying this research to our requirements, we have determined that hybrid simulation using AB and SD is the best modeling approach. For the REITD model, mineral production and processing is modeled heterogeneously. For production, we want to know the quantity of rare earth material produced at by each trade group at each of the production stages. For demand, we aggregate the permanent magnet demand from the wind and EV clean energy sectors calculate the upstream, midstream, and downstream demand for magnet metals (Nd, Dy, Pr, and Tb). In this version of REITD we are not concerned if permanent magnet demand is from wind turbines, electric vehicles, industrial robots, or other sources. Thus, with a modeling requirement for homogeneous demand and heterogeneous production, a software package that combines the hybrid AB/SD approaches will require the least modeling effort to produce the level of disaggregated data required for analysis.

3.5 Ventity

Ventity (Ventana Systems, 2021) was chosen as the hybrid AB/SD software package for this model as it meets the requirement of combining both the system dynamics and the agent-based approaches.

The original Ventity product description (Yeager et al., 2014) provides an overview of Ventity modeling capabilities; a recent video provides a current overview of its capabilities (Ventana Systems, 2022).

Key modeling concepts unique to Ventity (adapted from Martín García, 2021a, 2021b) include:

- Data / model separation: data is loaded during model initiation from Excel worksheets, avoiding the need to adjust model structure when initialization and time series data changes.
- Modular: major model structures are created as Entity Types, with References used to link the Entity Types to integrate the model. Modular structure simplifies model design and construction.
- Dynamic creation of structure – actions and triggers: Actions to add (Create) and delete (Delete) entities (individual agents) or change model values (Command) allow the model to be adjusted based on the logic embedded in the Triggers. For example, Mining (group of all mines) is defined as an Entity Type and individual mines are entities. If the trigger logic applied to Mining determines

that a particular mine is no longer profitable (Revenue-Expenses < 0), the trigger will invoke the Delete Mine action (the mine data is not deleted, it is just made inactive in the model. Model data for the mine entity up to the action event is preserved).

- Disaggregation: using HD to create the disaggregated model structure of Entities (mines) within an Entity Type (Mining), thereby allowing decision makers to see a deeper level of detail, requires less modelling effort with HD software than with pure SD or AB software.

3.5.2 Using Ventity

Models are constructed in Ventity using the features described below.

3.5.2.1 Entity Types

Entity types are the central feature of a Ventity model. They contain the dynamic structure of the model. An entity type contains one or more entities – a useful analogy is entity types are tables containing rows, which are entities, and columns, which are the attributes and other data that uniquely define each entity. Entity types are homogeneous, i.e. – they contain entities that are related, such as mines, factories, etc. Continuing the analogy, the table (entity type) Mines contains rows representing a specific entity (mine). The columns in the table could include the mine name, size (kilotonnes of rare earth mineral), total rare earth oxide (TREO) content (sum of the element grades), cost of the mine, and annual operating cost.

The level of entity disaggregation is determined by the attributes defined for the entity type. For example, mine entities (rows) in the Mines entity type (table) could be assigned an attribute value (column entry) of LREE or HREE. References and collections, described below, use attributes to link tables or for selecting a subset of table values (all LREE).

Most entity types are defined by the modeler but one entity type, the Model entity type is defined by Ventity when a model is created. The Model entity type is unique in that it contains global variables that can be readily used by all other entity types. Frequently used global variables are Time, Time Step, Initial Time, and Noise Seed – used by random functions.

3.5.2.2 Diagrams

Model structure is built by placing model elements on diagrams; they are the drawing pages that will hold the various parts of the model. Each entity type is created with a Main diagram; more can be added. Examples are given in sections 3.5.2.3 to 3.5.2.6.

3.5.2.3 Entities

Entities are the individual items within an entity type and can act as agents in the model. Each mine has a heterogeneous state by storing attribute data specific for each mine, the model equations can operate at an individual mine level of detail. An attribute is an alphanumeric variable that applies to one or more entities. For example, a mine attribute can be the type of ore produced by the mine, the country, etc. Attributes can then be used to make sub-groups (collections and sub-collections) for further analysis.

3.5.2.4 References

References define the relationship between two entities based on common key attributes. Marking an entity type as a singleton makes the variables in that entity type available as global variables. References are not required for singleton entity types such as the Model entity type. References allow the entity values in one entity type to be used in another entity type, such as mine production in the Mine entity type being used as feed stock to concentrate production in the Production entity type.

3.5.2.5 Collections

Collections are subsets of the entities in an entity type to enable aggregate processing. The subsets can be the proper subset (all entities), or a selection of entities. The selection criteria are entity values in an entity type. Thus, for the Mines entity type with an attribute Mine Type with values LREE and HREE, collections of all mines, LREE mines, or HREE mines are possible.

An aggregate is a set of actions performed on a collection or sub-collection. Frequently used aggregate functions are sum, average, max or min, and standard deviation. Thus, if all Brazilian mines is a collection, the total production of all Brazilian mines is an aggregate sum of Brazilian mines.

3.5.2.6 Actions/Triggers

Actions can dynamically change certain model elements based on the logic in the trigger. Actions can add (Create action) or delete (Delete action) entities within an entity type or can change attribute values (Command action) based on the logic embedded in the associated Triggers.

3.5.3 Data Entity Types

A key feature of Ventity is data/model separation. Model structure is stored in the *.vmdl file in the main folder created for each model, while model data is stored separately in Excel spreadsheets or built-in data structures in subfolders that are separate from model structure.

There are two types of data:

- Entity initialization data: data that initializes certain variables at the beginning of a simulation run. Initialization data can be used to set constants, stocks, and attributes.
- Time series data: Time series data is loaded when the model is opened and read at each time step over the model run period. Time series data is not modified by the model; however, missing data can be interpolated when loaded by the model. Interpolation options are straight, hold backwards, or look forward.

Details of the model data structure is provided in the following section.

3.6 Model Design

REITD contains over 550 model elements including 12 entity types, 8 data entity types from 3 time series data files, and 3 entity initialization files. The complete model definition is provided in Appendix A; a high-level summary is in Table 15.

Table 15. REITD high level model summary mapped to the diamond model elements.

Entity Types	Attributes*	Actions/Triggers
M1 Mining • Ore extraction • Produce mixed concentrate (crush & flotation)	M1 Mining TG (PK) C2 Production TG mineral type mine state	Activate M1 Mine Production Add M1 Resources Deactivate M1 Mine Production
C2 Production • Produce mixed rare earth carbonate (leaching)	C2 Production TG (PK) M1 Mining TG S3 Separation TG	
S3 Processing • Produce separated rare earth oxides (solvent extraction)	S3 Separation TG (PK) C2 Production TG R4 Refining TG	
R4 Refining • Produce refined 99.5% pure rare earth magnet metals (Nd, Dy, Pr, Tb)	R4 Refining TG (PK)	

Entity Types	Attributes*	Actions/Triggers
Fabricating [F5] • Produce NdBFe permanent magnets as 35% rare earths, Nd = 77%, Dy = 17%, Dy = 5.5%, Tb = 0.5% • High temperature PM magnet	F5 Fabricating TG (PK)	
Demand	D6 PM Demand TG (PK)	

* Attributes designated (PK) are the primary key for entities of that entity type. If there are two primary keys for an entity type they form a compound key.

3.6.1 Model Structure

The high-level model map is produced by Ventity to provide an overview of how the main model elements are structured (Figure 33):

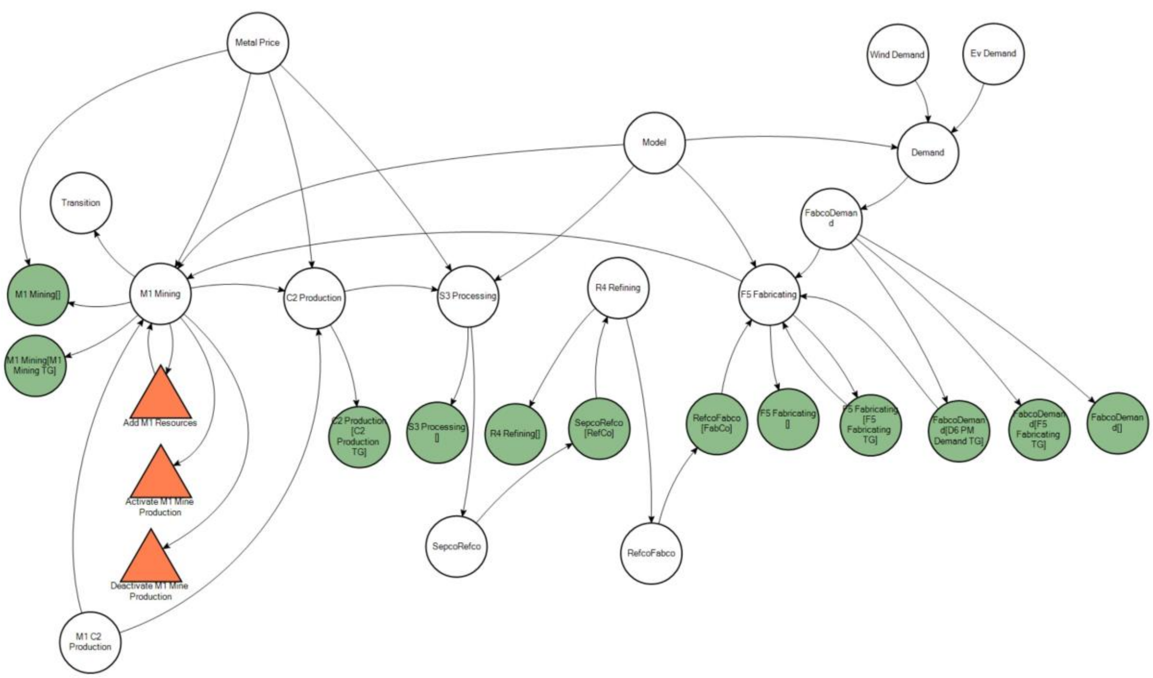


Figure 33. Model map of REITD. Legend: White circles – entity types, Green circles – collections, Orange triangles – action/triggers.

Figures 34 to 39 in the sub-sections below show main sections of model structure. Note that describing the production chain in five stages follows a value chain approach and is not necessarily representative of the physical implementation. The value chain approach allows for calculation of revenue from the output at any stage. Examples of sales from any stage can be found in current industry practice.

3.6.1.1 M1 Mining

The mine to magnet process starts with mining. Figure 34 shows the Main diagram for this entity type; The M1 Concentrate stock (bottom right) tracks current inventory of mineral concentrate after the initial communition (crushing) and bubble froth stage.

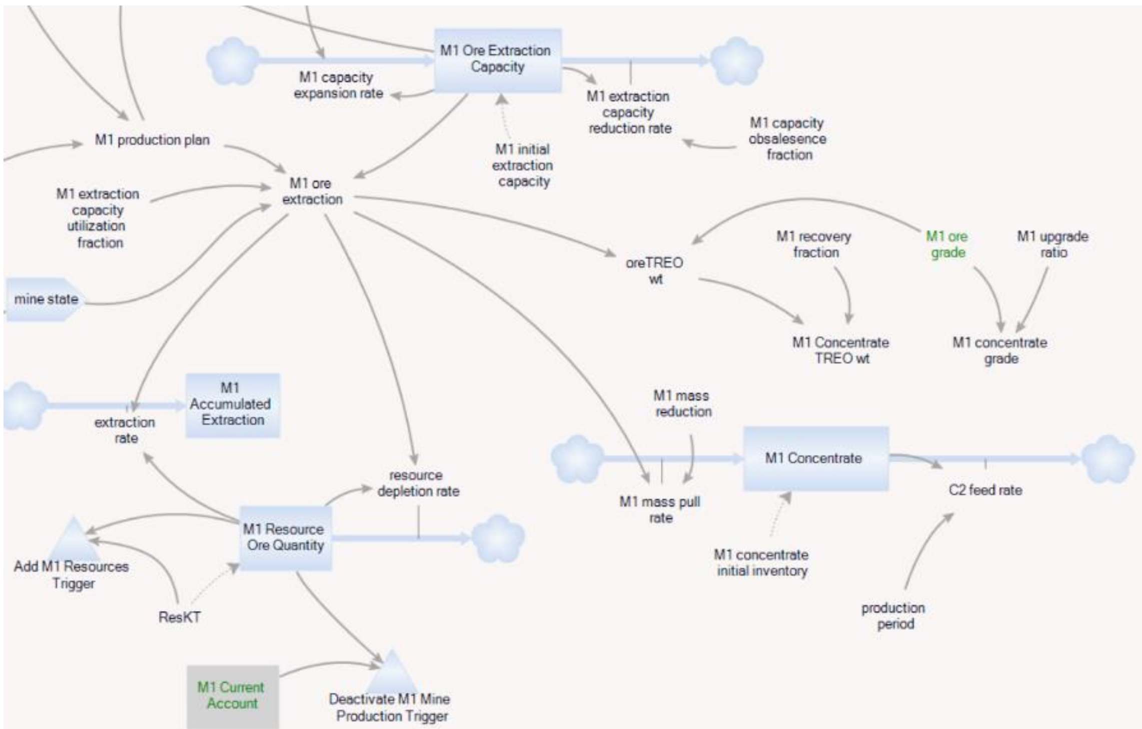


Figure 34. M1 Mining model structure

The mine to magnet process starts with mining. Figure 34 shows the Main diagram for this entity type; The M1 Concentrate stock (bottom right) tracks current inventory of mineral concentrate after the initial communition (crushing) and bubble froth stage. The calculations for mass reduction, mineral upgrade, and metal recovery are based on average grades for the mines selected for the TG mine dataset and industry standards provided by Sykes (Sykes, 2013a, 2013b).

Also shown are two triggers, denoted by triangles, in the lower left. The Add M1 Resources Trigger causes mine resources to be added when the remaining ore quantity falls below 25% of the original resource. This logic assumes that at the TG level that sufficient resources have been identified and can be brought into production. Given the level of resource development taking place due to growth forecasts this is not an unreasonable assumption. The added resource will be for the mine entity that has been depleted below the threshold, i.e. – if an MSP HREE resource has been depleted new resources will be added either by expanding the existing resource or opening a new resource with equal or better Tb and Dy grades than the existing resource.

The Deactivate M1 Mine Production Trigger will cause the TG mine state attribute to change from “active” to “inactive” if the ore resource quantity falls to zero or the financial state of the mine entity, represented by M1 Current Account, falls below the insolvency threshold. In this exploratory model neither of these conditions will trigger; the logic was added as a placeholder for future model development.

Figure 35 below shows the M1 Economics diagram from the M1 Mining entity type that contains the calculation for gross revenue and the cost of required mine expansions per TG to keep pace with upstream demand. The M1 Current Account stock is used to indicate the mine entity financial status. In addition to being used by the Deactivate trigger, it is used in the calculation of the stimulus funding required to support mine expansion.

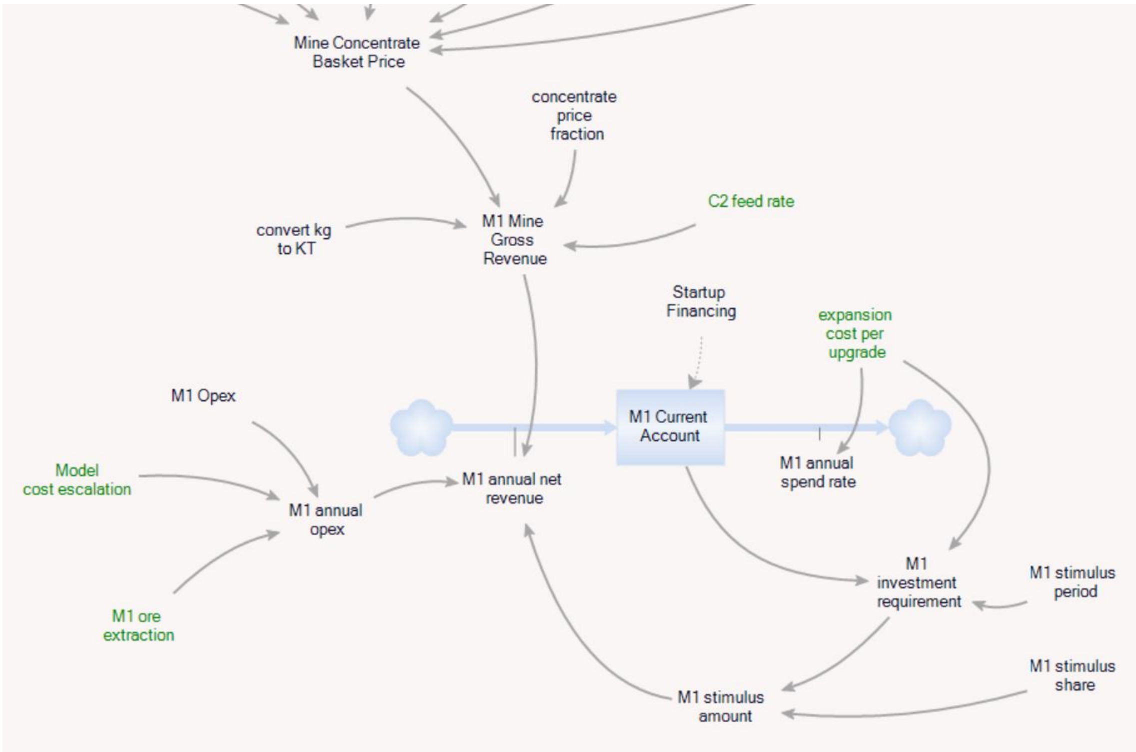


Figure 35. Calculation of stimulus amounts to fund M1 Mining capacity growth.

3.6.1.2 C2 Production

Figure 36 shows the main diagram for producing mixed rare earth carbonate from the M1 mineral concentrate. This stage uses various hydrometallurgical treatments to reduce the unwanted minerals and increase the grade of the desired minerals before the next separation stage to reduce the separation stage costs (McNulty et al., 2022).

Production processes frequently consist of baking and/or acid digestion to “crack” or release the rare earth minerals from the unwanted material, followed by leaching to improve the carbonate grade.

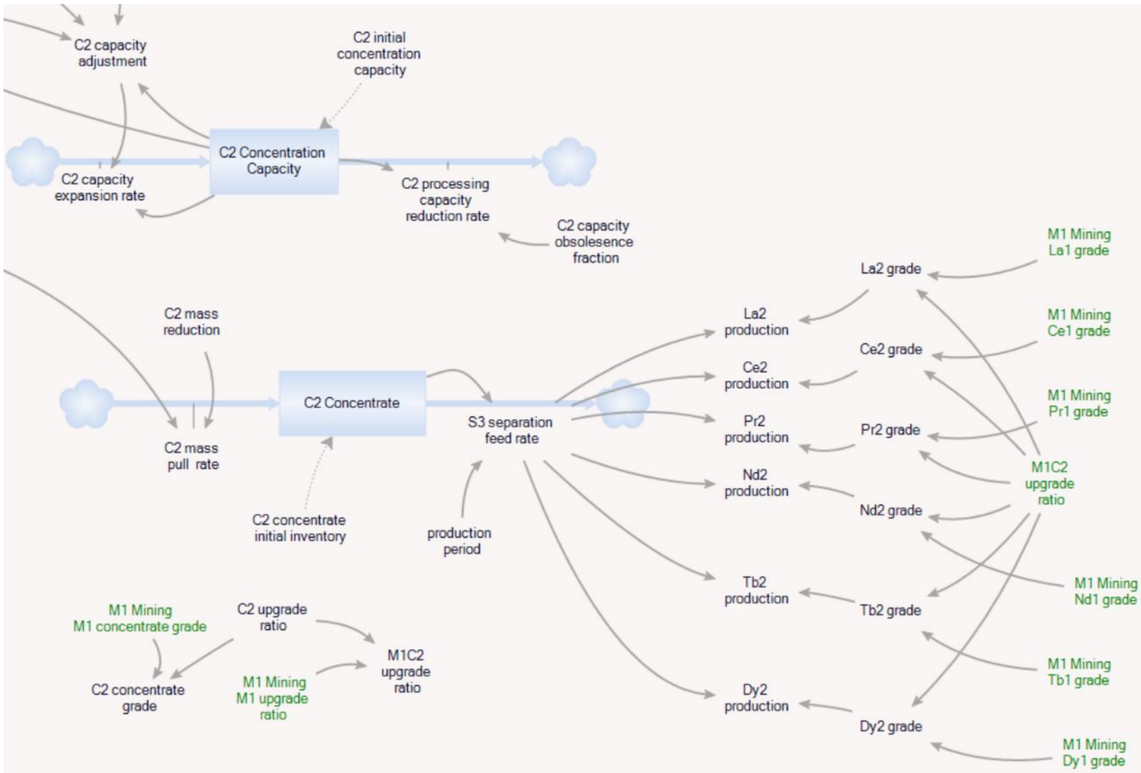


Figure 36. C2 Production model structure

3.6.1.3 S3 Separation

Next shown in Figure 37 is the separation process model structure. It summarizes the results of the complex solvent extraction stages to produce the individual rare earth elements as oxides. As the study is focused on the magnet metals only six oxides results are calculated – lanthanum and cerium as the most common oxides and the four magnet metals. S3 Midstream Separated is the stock of separated oxides per TG mine, with the outflow R4 refining feed rate (bottom center, in green box) being the disaggregated flow of separated oxides. The variables La3 to Dy3 represent the quantity of oxide produced from each TG mine. As the ocus of this model is magnet metals for wind and EV demand, only the oxides of the four magnet metals are carried forward to the refining stage.

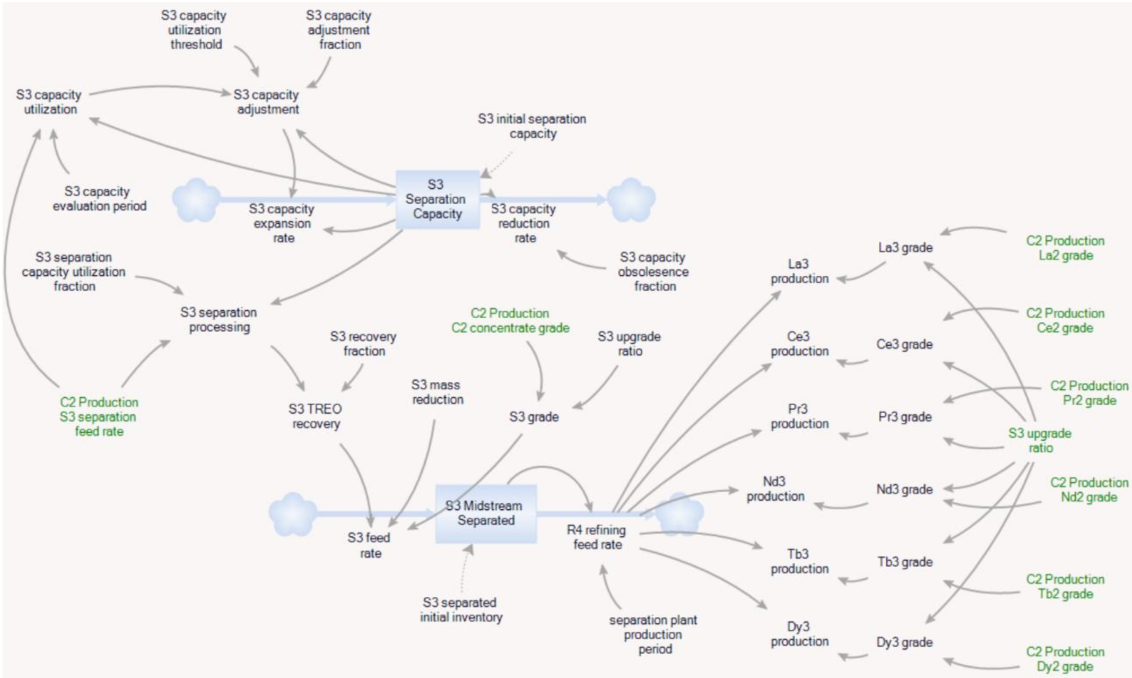


Figure 37. S3 Processing model structure.

This structure presumes using solvent extraction as the separation process. Solvent extraction, or SX, became the industry standard in the 1960s (McNulty et al., 2022). Many of the patents and intellectual property related to SX are now controlled by China, prompting new research for alternative methods. A brief survey of recent announcements is below.

- Opare et al. (2021) recently published a survey article of emerging separation techniques including bioabsorption (Costa et al., 2020) as well as polymer adsorbents for wastewater feedstocks (Pereao et al., 2018) and techniques for separating non-ore feedstocks (Meshram & Abhilash, 2020)
- Micro-biology: early-stage research is being funded by DARPA to separate Lanthanide series elements using bacteria. Lab-scale results are planned for 2026 (Dance, 2023). Researchers from the University of North Dakota supported

lab testing of biosorption methods for recovery of rare earths from lignite coal, with promising results (Park et al., 2020a).

- A new membrane solvent extraction technique for HREE extraction has been patented by Oak Ridge National Laboratories and has been licensed by the developer of the Pea Ridge, Missouri mine.

3.6.1.4 R4 Refining

The R4 Refining model structure is shown in Figure 38. Technically complex but straightforward for this model, the magnet metal oxides from S3 Processing are refined to pure metals. We have chosen a single level of purity of 99.9% ('3 nines') for the mass reduction and upgrading calculations.

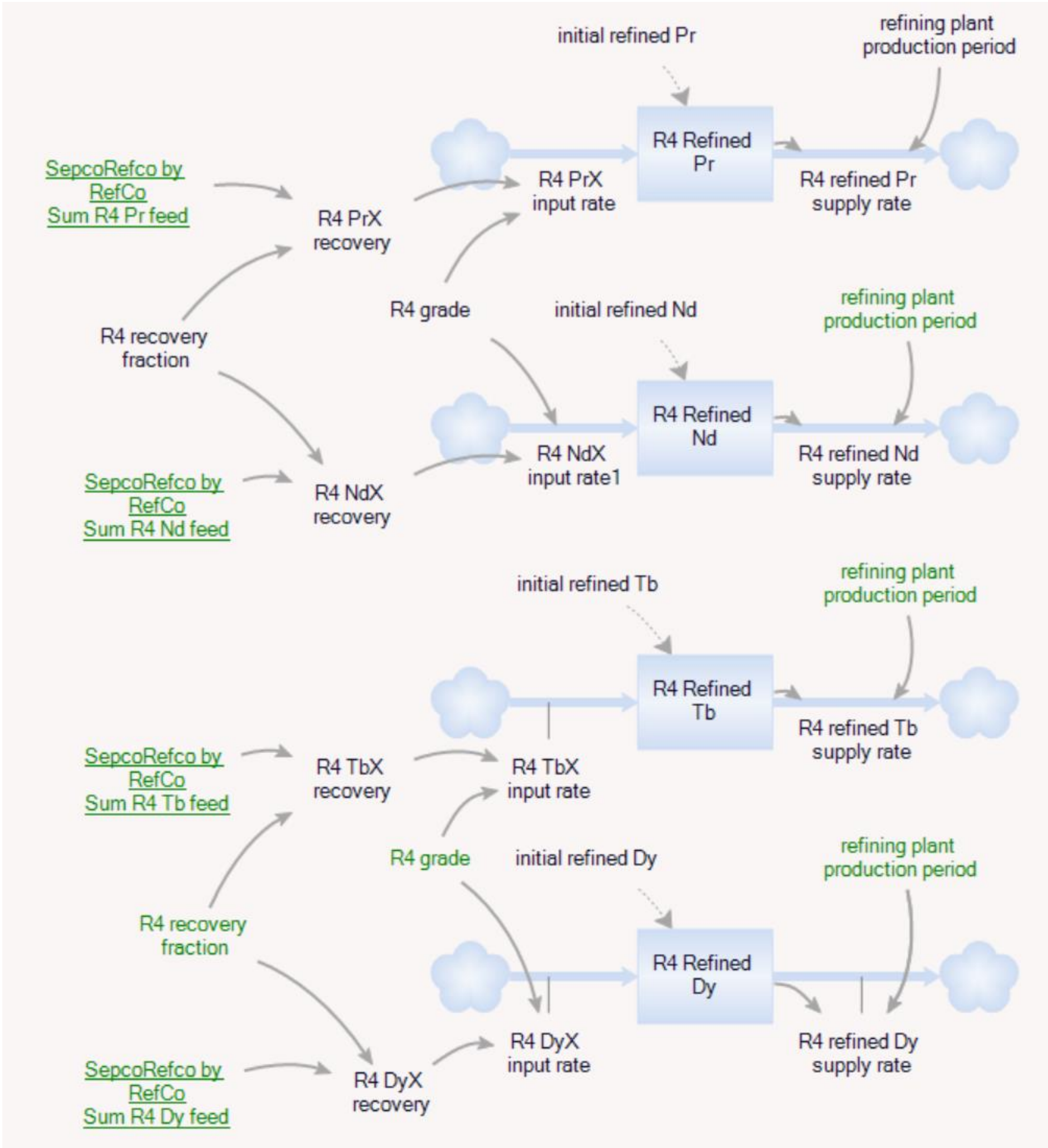


Figure 38. R4 Refining model structure

3.6.1.5 F5 Fabrication

Finally, Figure 39 shows the F5 Fabrication structure that calculates the kilotonnes of permanent magnets that are manufactured based on the feed rate of the individual magnet metals from R4 Refining. For this exploratory model a single magnet formulation is used consisting of 32.5% rare earths in the proportion of 0.02 Pr, 0.25 Nd, 0.005 Tb, and 0.05 Dy.

In addition to clean energy permanent magnet demand the structure to include other permanent magnet demand is shown. The lookup table is used to implement the inverse nonlinear relationship between clean energy demand and other demand. Other demand declines, nonlinearly, from 90% in 2000 to a projected 28% in 2050.

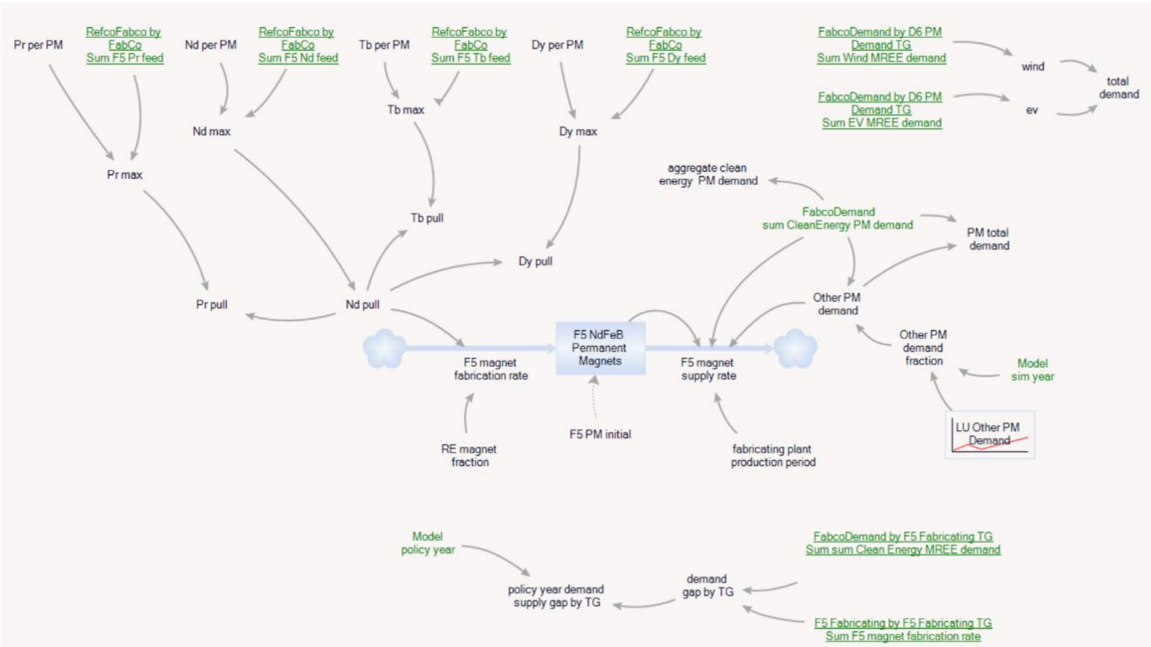


Figure 39. F5 Fabricating model structure.

3.6.1.6 Demand

The Demand model structure (Figure 40) consists of data for wind demand (MW/Year) and EV demand (units/Year) loaded from the time series Excel files. By convention imported data is shown in green italics. The data is used derive the permanent magnets production (KT/Year) required to meet each demand. Only offshore wind demand is calculated as onshore wind turbines are typically constructed with cheaper induction motors.

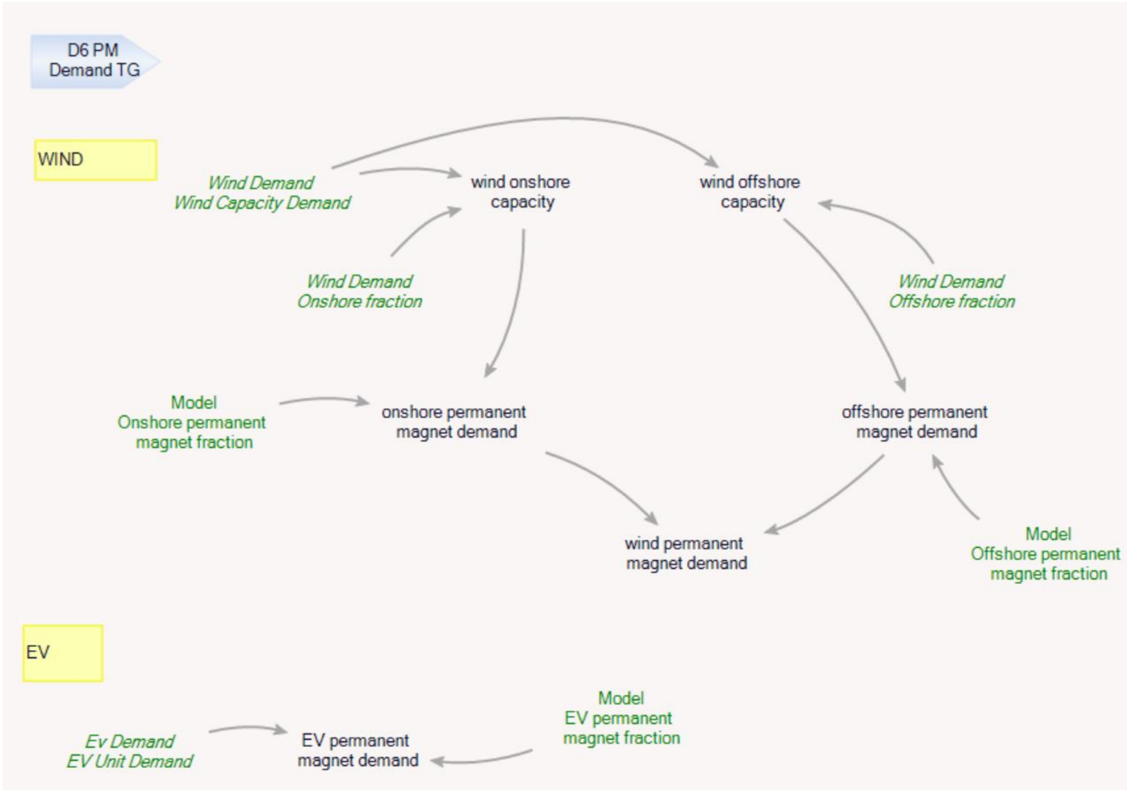


Figure 40. Demand model structure.

3.6.2 Model Data

Ventity models defines two types of external data – entity initialization and times series, as described below. Data for these data types can be stored either in an internal data structure called Builtin data or stored externally in Excel files. Excel files are stored separately from the model structure in the Data sub-folder of the model file folder. The model structure is stored in a .vmdl file in the model folder.

Internal data such as model constants that do not vary with the scenarios, are entered directly into entity type variables.

External time series data also uses a sub-folder called DataSourceMappings, which maps the data variables in the Excel file to a model data entity variable.

Before describing the types of data, we provide an overview of the sources of model data.

3.6.2.1 Sources of Model Data

Data for the model was retrieved from several sources. The data sources are cited in each Excel spreadsheet. The primary sources were:

- Peer-reviewed papers – Liu et al. (2023) and Silva et al. (2018) published extensive datasets on active mines that included detailed information on grades and metal distribution (total rare earth oxides (TREO). These are the primary data sources for the M1 (upstream) entity type. Corrections to these datasets were made based on updated data in industry filings (see below).
- Government sources – United States Geological Survey (USGS), Joint Research Council (European Union), Austrian Federal Ministry of Finance (World Mining Data report), Congressional Reference Service (U.S.) publish reliable, referenceable data in annual or ad hoc reports.
- Industry standard sources – British Petroleum (BP)[13], International Energy Agency (IEA), International Renewable Energy Agency (IRENA), and various sources either directly from their websites or through Statista (a statistical data service). As Statista is a secondary source, both Statista and the original source are cited when used.
- Industry filings – Rare earth companies intending to raise investment funds from public solicitations must file the prescribed report with the investment regulator. These reports have a set format and require the company to disclose both technical and financial data regarding the mine project. These filings have various names depending on the jurisdiction; NI 43-101 (Canada and

[13] In 2023 BP transferred stewardship of their annual energy statistical review report to the Energy Institute (UK)

U.S.) and JORC (Australia) are most common. As these reports are legal documents prepared by an independent third party legally accountable for their contents, they are considered reliable and used to correct other data sources.

- Online and other sources – Various companies, consultancies, and industry trade publications specializing in critical minerals publish limited publicly available data to promote their commercial data offerings. Occasionally the publicly available data is helpful, especially in creating synthetic data for long-term forecasts.

3.6.2.2 Entity Initialization Data

Entity initialization data is, as the name suggests, used to initialize constants used in the model. If the constant is created with a default value, the value in the initialization file overrides the default value.

As noted above, initialization data can be entered into an internal Builtin data structure or stored in an external Excel file.

A key benefit of the way Ventity manages initialization data is that the different versions of the initialization file can be applied to different scenario runs by putting the files into model folders with the scenario name. Thus, a version of the constant values for a base case can be stored in the base_case.xlsx file and named as the initialization source for the BaseCase scenario; the file name in the scenario folder is not a replica of the file but simply a pointer to the file. If the same file is used in several scenarios, changes in one scenario are applied to all instances.

Similarly, the set of minimum and maximum constant values can be stored in min.xlsx and max.xlsx for the MinScenario and MaxScenario. Using the Ventity Run control all three scenarios can be run consecutively using the Run command, with model results for each scenario stored individually in the Results manager.

From a data management perspective, changes to several constants can be done quickly by editing the Excel file, rather than singly by opening each constant in the model.

Figure 41 is a subset of the initialization data for the M1 Mining entity type from the base case file PM_BD.xlsx. Within the single M1 Mining entity type there are nine different mine entities – three for each of the three TGs. Note that each mine has its own attributes, making each mine entity unique.

CalendarTime	M1 Mining TG	C2 Production TG	mineral type	mine state	M1 mining activation offset	M1 initial extraction capacity	M1 concentrate initial inventory	La1 grade	Ce1 grade	Pr1 grade	M1 ore grade
01/01/2000	RoW - LREE Mine	RoW - LREE Crush	LREE	active	0	400	0	0.00688	0.01140	0.00102	0.02590
01/01/2000	RoW - HREE Mine	RoW - HREE Crush	HREE	active	0	200	0	0.00445	0.00623	0.00093	0.02581
01/01/2000	RoW - Circ Mine	RoW - Circ Crush	Alt	active	35	50	0	0.00027	0.00080	0.00011	0.00252
01/01/2000	MSP - LREE Mine	MSP - LREE Crush	LREE	active	0	500	0	0.00760	0.01371	0.00147	0.02964
01/01/2000	MSP - HREE Mine	MSP - HREE Crush	HREE	active	0	250	0	0.00183	0.00372	0.00040	0.01051
01/01/2000	MSP - Circ Mine	MSP - Circ Crush	Alt	active	25	50	0	0.00027	0.00080	0.00011	0.00252
01/01/2000	China - LREE Mine	China - LREE Crush	LREE	active	0	3000	0	0.01359	0.02026	0.00196	0.04200
01/01/2000	China - HREE Mine	China - HREE Crush	HREE	active	0	9600	0	0.00381	0.00736	0.00119	0.02664
01/01/2000	China - Circ Mine	China - Circ Crush	Alt	active	25	100	0	0.00027	0.00080	0.00011	0.00252

Figure 41. Entity Initialization File

As previously mentioned, different versions of this file can be created by altering one or more data columns. For example, the column M1 mining activation offset is a constant that is added to the initial model year (in our case, 2000) to indicate the startup year for that mine. The three values shown indicate that circular processing of recovered rare earths will begin in 2035, 2025, and 2025 for the RoW, MSP, and China facilities respectively. Optimistic and pessimistic dates can be entered in versions of this file.

3.6.2.3 Time Series Data

Time series data provides variable data for each model time period as defined in the model setup.

For each of the three time series files used in this model, historical data from 2000 to 2021 is used, except for energy demand which is from 2010 to 2021.

Growth forecasts are computed outside the model based on referenced research and stored in the relevant time series data file for the years 2021 to 2050.

Time series data is loaded into the model by defining data source files. Each data source file is an Excel spreadsheet with separate worksheets (tabs) for each time series. For each data source file, a mapping file is created to map the spreadsheet columns with model elements. Once the Mapping table is completed Ventity creates data type entities that operate in much the same way as model entity types.

The REITD time series data is contained in the Market_Data.xlsx, Energy_Demand.xlsx, and Production.xlsx spreadsheets.

Figure 42 shows a truncated list of the EV demand data from the Energy_Demand.xlsx timeseries data file, showing values from 2000 to 2050 (2019 to 2040 are excluded from this example for space reasons). As the model setup is for 204 time steps (4 time steps per year x 51 years), the quarterly values are generated by Ventity using straight line interpolation (this is a configurable option). As mentioned above, references are cited in the info tab.

DateTime	D6 EV Demand	EV Unit Demand
01-01-2000	China	0
01-01-2001	China	0
01-01-2002	China	0
01-01-2003	China	0
01-01-2004	China	0
01-01-2005	China	0
01-01-2006	China	0
01-01-2007	China	0
01-01-2008	China	0
01-01-2009	China	0
01-01-2010	China	31991
01-01-2011	China	31593
01-01-2012	China	86145
01-01-2013	China	158837
01-01-2014	China	96518
01-01-2015	China	176782
01-01-2016	China	201048
01-01-2017	China	315717
01-01-2018	China	376847
01-01-2041	China	7357206
01-01-2042	China	7044804
01-01-2043	China	6727657
01-01-2044	China	6336347
01-01-2045	China	5894712
01-01-2046	China	5622311
01-01-2047	China	5243791
01-01-2048	China	4989517
01-01-2049	China	4720509
01-01-2050	China	4518305

info | Wind Demand | EV Demand

Figure 42. Energy_Demand.xlsx time series data

3.6.2.3.1 Market Data

This data is in the spreadsheet Market_Data.xlsx and contains price data. As there is no single source of publicly available price data that covers the model time period, three sources were used: USGS Mineral Commodity Summaries, Statista/Stormcrow, and TREO.

3.6.2.3.2 Energy Demand Data

This data is in the spreadsheet Energy_Demand.xlsx and contains Wind and EV demand data. The source dataset is the JRC – The Role of Rare Earth Elements in Wind Energy and Electric Mobility – Database published by the European Union Joint Research Centre.

3.6.2.3.3 Production Data

This data is in the spreadsheet Production.xlsx and contains desired production goals for M1 Mining production and C2 Production processing. The data was collected from the annual USGS Mineral Commodities Summaries from 2000 to 2022. Data for 2023 to 2050 was extrapolated based on forecast demand.

3.6.2.4 Constants

Model constants such the weight of magnet metals per MW of offshore wind turbine capacity that do not change with the transition scenarios are entered directly into entity type variable. The list of constants is included in the model documentation in Appendix A. Constants such as the weight of magnet metals are cited in the documentation; simple constants such as the number of kilograms in a kiloton, are not.

3.7 Modeling Challenges

"It is better to be roughly right than precisely wrong." – John Maynard Keynes.

Keynes was referring to economic forecasts, but the sentiment applies equally well to modeling the rare earth industry.

At the core of the modeling challenge is that a large part of the rare earth industry system structure is a black box. As noted previously, China dominates both sides of the industry – both supply and demand, and therefore price. Since China's decision-making responsible for market dynamics is not transparent, the mechanics of supply and demand for the magnet metals needed to meet clean energy technology are unknown. Clarity on midstream and downstream production dynamics is of primary concern.

The lack of understanding of industry dynamics by MSP policy makers is described in the recent industry article “IRA Subsidies Might Create Energy Minerals Supply Shortages” (Blackmon, 2023). The article notes that Inflation Reduction Act (IRA) tax incentives for clean energy solutions are fueling increased demand for clean energy solutions. While laudable, 97% of the permanent magnet supply for clean energy solutions today comes from China, which is trying to keep up with its own increased demand for permanent magnets. Thus, as the article points out, the unintended consequence of a policy that doesn’t comprehend the lack of transparency into the industry dynamics is that the stimulus measures are making the demand-supply gap bigger. Figure 43 is a stock-flow representation of the policy problem.

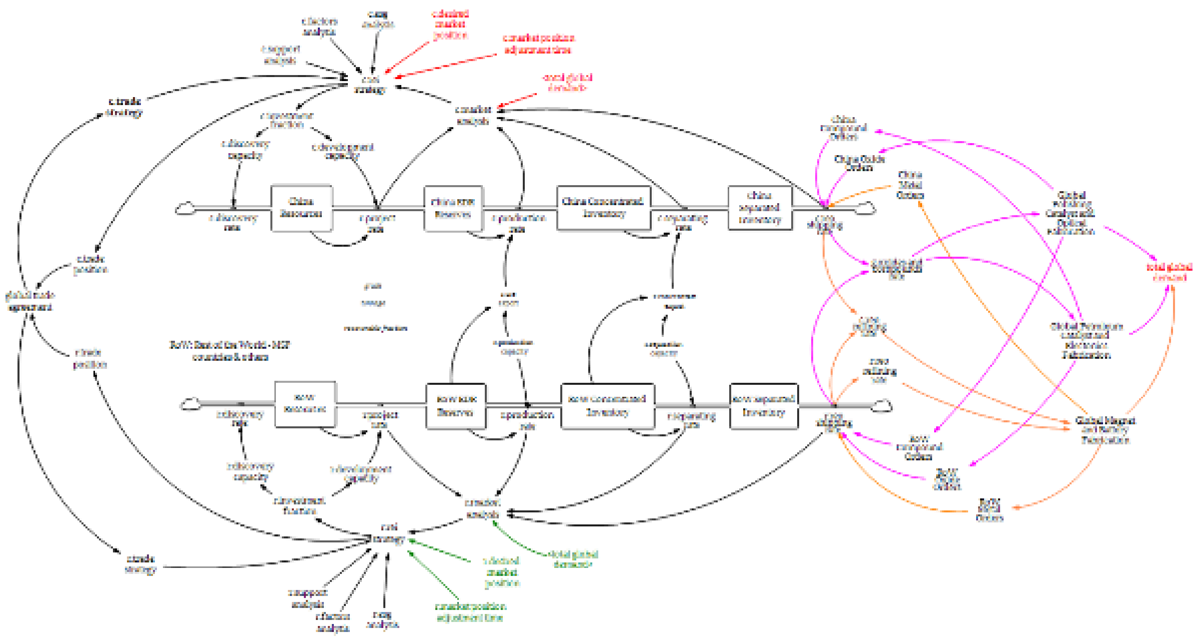


Figure 43. CLD Loop 5: Demand-supply stimulus coordination between the clean energy and rare earth industry transitions.

This busy diagram essentially has two sections – the China rare earth industry on top, and the MSP and other countries (labelled here as RoW) on the bottom. Note that there are links showing the movement of rare earth products from the RoW to China, but not the reverse. This is because China encourages imports of low-value, early-stage production to reduce domestic mining and conserve domestic reserves. China has the mid- and down-stream capacity to process these imports into finished rare earth goods such as permanent magnets, while currently the RoW does not. The point that Blackmon is making is that using IRA funding to increase will increasingly stretch Chinese producers attempting to supply their own domestic clean energy industry at the same time as increased demand from the RoW clean energy industry. This is what Petavratzi and Gunn (Petavratzi & Gunn, 2023) refer to when policy makers focus only on tier 1 (finished goods such as EVs or wind turbines) without considering tier 4 (raw materials such as rare earths) production required before the tier 3 (metal alloys and compounds) and tier 2 (electric motors) suppliers can produce the tier 1 assemblies.

The ‘black box’ modeling problem is the lack of transparency into, and hence limited understanding of, China’s behaviour regarding rare earth supply and demand. Without this understanding the ability to accurately model the dynamics of supply security is limited.

Related to the black box issue is the lack of publicly available, consistent, longitudinal data for the rare earth industry. Chen et al. (2023) cite the unavailability of data for material flow analysis of dysprosium and thus needing to rely on secondary sources for their study. Publicly available data such as the well-known Mineral Commodities Summary (MCS) reports and other datasets are published by the United States Geological Survey (USGS). These do yeoman’s service; however, the accompanying notes describe caveats that limit the usefulness of the data. A small number of industry data service providers will provide quality data for considerable fees. Given the state of the industry, the service providers expend considerable time and resources collecting and collating data, which, when portions of which are obtainable, is of high quality. In contrast to oil however, there is no West Texas Intermediate or Brent public data source that tracks price and volume of a standard commodity unit over a period of decades. Instead, rare earths data relies on the ubiquitous ‘rare earth oxide equivalent’ that implies knowledge of the grade and purity of the weight of material being traded to be useful.

CHAPTER IV:

THE GLOBAL RARE EARTH INDUSTRY IN TRANSITION

This chapter addresses Research Question 1 – How are increased supply security and long-term industry stability driving the need for the rare earth industry transition?

We examine this question from the perspective of the three multi-national trade groups (TGs) as defined in the Introduction, noting the different driving factors for each TG. A common driving factor for all TGs is clean energy, specifically achieving de-carbonized energy targets to achieve their Nationally Determined Contribution commitments to the global climate change targets of the Paris Agreement (United Nations Climate Change, 2023).

This chapter begins by describing what is meant by a system transition, and then reviews the industry current state followed by a detailed discussion of the transition drivers.

4.1 System Transitions Overview

Before discussing the transition drivers, we first review the general topic of system transitions. There is a growing body of research on this subject under the heading technological innovation systems (TIS) (Cherp et al., 2018; Rahmani et al., 2022; Zou et al., 2017) based on pioneering work by Jacobssen and Bergek (2004). Further research led by Markard (2020; 2015; 2008) and Geels (2023; 2002, 2014; 2017; 2023) have extended the research to energy transitions. Verrier et al. (2022a) extend the work by examining socio-technical scenarios related to energy transitions.

Fazey and Leicester (2022) provide a detailed analysis of system transitions, including energy transitions. They define a system transition, intentionally broadly, as "a fundamental change (system) occurring over time (transition)". Here we define the system as the rare earth industry and the transition as establishing the secure supply of magnet metals for the clean energy industry from a global rare earth industry with long-term stability.

Fazey and Leicester define four archetypes, or patterns, of system transitions using the "Three Horizons" heuristic. An overview of Three Horizons is given below using the "smooth transition" archetype, which depicts an idealistic transition, as shown in Figure 44.

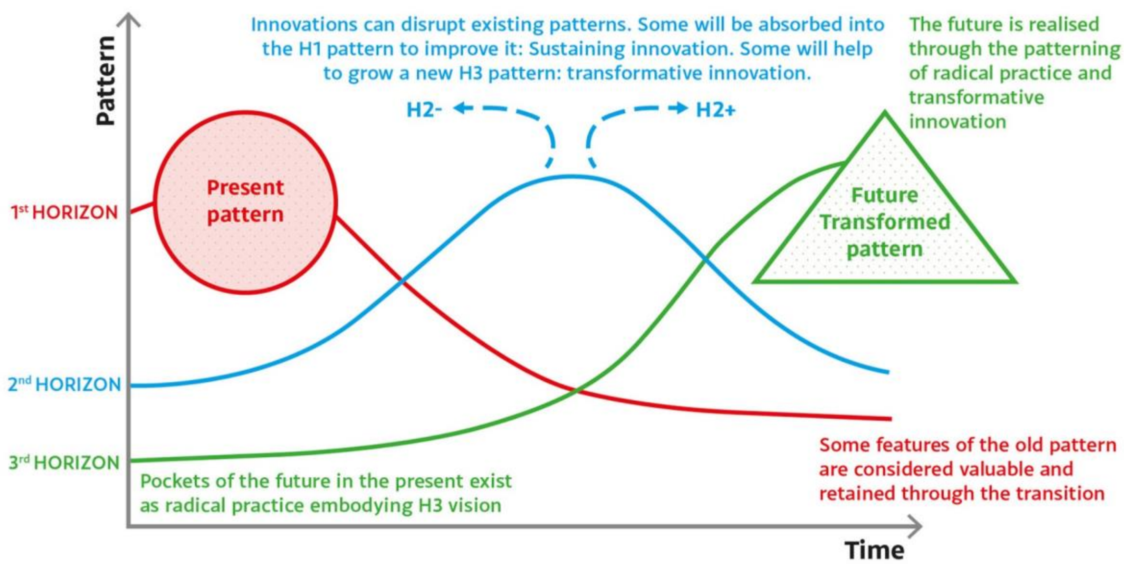


Figure 44. Smooth Transition Archetype (Fazey & Leicester (2022)).

The 'three horizons' refers to the behaviour projections of the current system (H1 or present pattern), the future system (H3 or transformed future system pattern), and the transformation drivers projection (H2 or disruption/innovation pattern).

The H2 pattern has three transformation dynamics. The primary dynamic is that H2 represents emerging disruptive and innovative practices, processes and technologies that are not present in the current system that are adopted to form the future H3 system.

Alternatively, the H1 system can appropriate H2 transformational elements intended for the H3 future system (H2- arrow) thereby extending the life of the current H1system. Similarly, H1 elements can be appropriated as transformational adaptations by H2, causing elements of the current system to be retained in the future system (H2+ arrow) and accelerating the transition to the future H3 system. All three patterns continue to co-exist as long as each system stays above the time axis; a system ceases to exist when its pattern intersects the time axis. A successful transition occurs when at some time in the future the H3 future system becomes sustainably dominant, thus becoming the current H1 system, and the cycle repeats.

All four archetypes are shown in Figure 45.

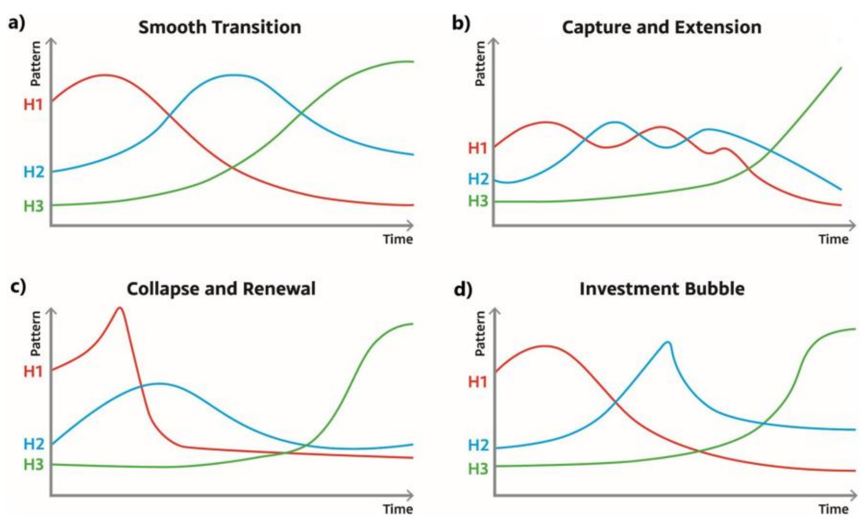


Figure 45. The four Three Horizons archetypes (Fazey & Leicester (2022))

The Smooth Transition archetype is shown again as 18a. The other three are:

- Capture and Extension (b) – H2 transition drivers emerge at signs of stress on H1, but the H3 transition is delayed due to the strength of H1 using the H2 drivers (H2- behaviour) to extend its pattern. Eventually H1 gives way to H3, and a future state is achieved.

- Collapse and Renewal (c) – H2 is delayed due to significant investments to prolong the current system H1, until the impetus for transition is too strong and H2 transition drivers are deployed and take effect, leading to a delayed but rapidly emerging future system H3. Note there is little adoption of the H1 system by the H3 system in this archetype.
- Investment Bubble (d) – the current system H1 begins to decline causing a rapid and large influx of resources for the H2 transition drivers, accompanied by inflated expectations. When the H2 goals are not achieved quickly, the investments and resources are withdrawn just as rapidly – hence the name 'investment bubble'. Eventually the current system must change, new resources for the H2 transition drivers are found and the new future system H3 appears.

Fazey and Leicester point out that "all four archetypes are likely to be in play at the same time for different parts of a complex system transition", as is the case with the rare earth industry transition.

Using systems thinking terminology, the reference mode is a graphic depiction of the problem behaviour over time (Sterman, 2000). This reference mode diagram is illustrative and intentionally not quantified to bring focus to the shape and relative position of the curves, not precise values. The reference mode for the rare earth industry from 2000 to 2020 is an adaptation of the Capture and Extension archetype shown in Figure 46:

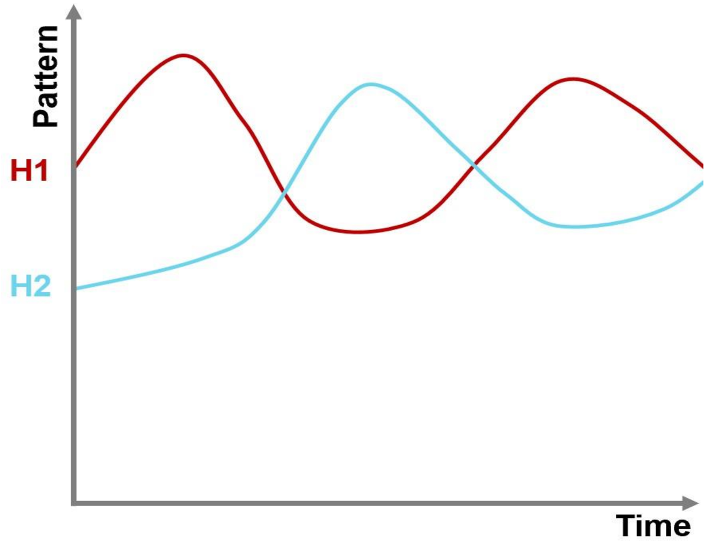


Figure 46. REIT Reference Mode (Fazey & Leicester (2022))

The current state of the industry (H1) is such that a single producer, China has most of the global upstream production and effective control of midstream and downstream production. Most of the recent investment (H2) by the MSP and RoW nations to divest production control from China has been in upstream production which has had some success; however, since there has been little mid or downstream investment most of the new upstream production is sold to China for further processing. China has effectively captured the MSP and RoW upstream H2 investment, allowing them to preserve their domestic mineral reserves while gaining the sales of the high value-add products from downstream processing. Slight oscillations in the curves as shown have appeared where MSP and RoW nations have gained market share, as is the case with upstream production in the past two years. China has recently indicated it is making additional investments to retain its strategic advantage in the market, likely leading to another oscillation cycle in the transition pattern.

To understand the origins of the reference mode we examine the current system in the next section.

4.2 Critical and Strategic Minerals

Rare earth pioneer Karl Gschneidner ascribed the transitions between early rare earth eras to improvements in “the availability and purity of the metals”, with successive improvements leading to new commercial applications (Gschneidner, 1984). Gschneidner went on to predict nearly forty years ago that the future of the industry will be about “its science, its technology and its commercial utilization”.

This prediction has come true. The importance of the current rare earth industry is well documented (International Energy Agency, 2022). There are hundreds of products in daily use that would not exist in their present form, quantity, quality, or price, without rare earth minerals. Gasoline, catalytic converters, factory robots, lasers, cellular phones, and medical diagnostics are but a few. Figure 47 (Tracy, 2020) shows global and U.S. demand for products containing rare earth minerals.

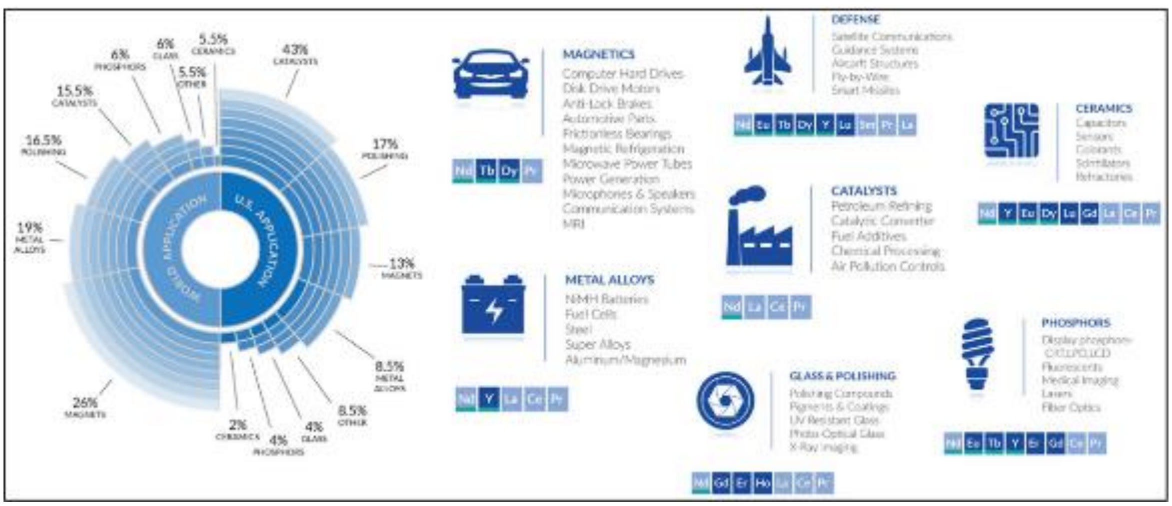


Figure 47. Global Demand and U.S. Domestic Consumption of REE (Source: Tracy (2020)

Table 16 combines global and U.S. data from Figure 46 with data published for China (Figure S2. Dai et al., 2023) to extend the consumption analysis.

Table 16. Global rare earth consumption (2020).

Application	U.S. [%]	China [%]	RoW [%]	Global [kt]
Magnets	13%	38%	24%	66kt
Catalysts	43%	14%	23%	45kt
Glass & Glass Polishing	21%	23%	11%	36kt
Metallurgy/Batteries	9%	17%	16%	37kt
Phosphors	4%	1%	10%	14kt
Ceramics	2%	2%	3%	6kt
Other	8%	5%	13%	21kt
	8kt	92kt	125kt	225kt

Reinforcing the importance of rare earths, several MSP nations have published critical mineral lists, which evaluate mineral supply on two dimensions – importance to economic and national security, and risk of supply disruption. The U.S. Department of Energy publishes a similar list (Bauer et al., 2023), termed a critical materials list, that considers critical minerals and other materials for energy-specific needs. In every case, rare earths are included in the list.

Having previously established that rare earths are essential for the clean energy transition, it follows that risks to the rare earth supply would be cause for considerable concern. To introduce this topic and the context for the rare earth industry transition, a summary of the material from Chapter 2 leading to the emergence of the reference mode behaviour is provided below.

The first indications of the potential for rare earth supply security risk emerged in the late-1990s, when China, following a state-funded national strategy, became a near monopoly in the rare earth market as can be seen in Figure 48 with the rapidly increasing production share for China in the mid-1990s.

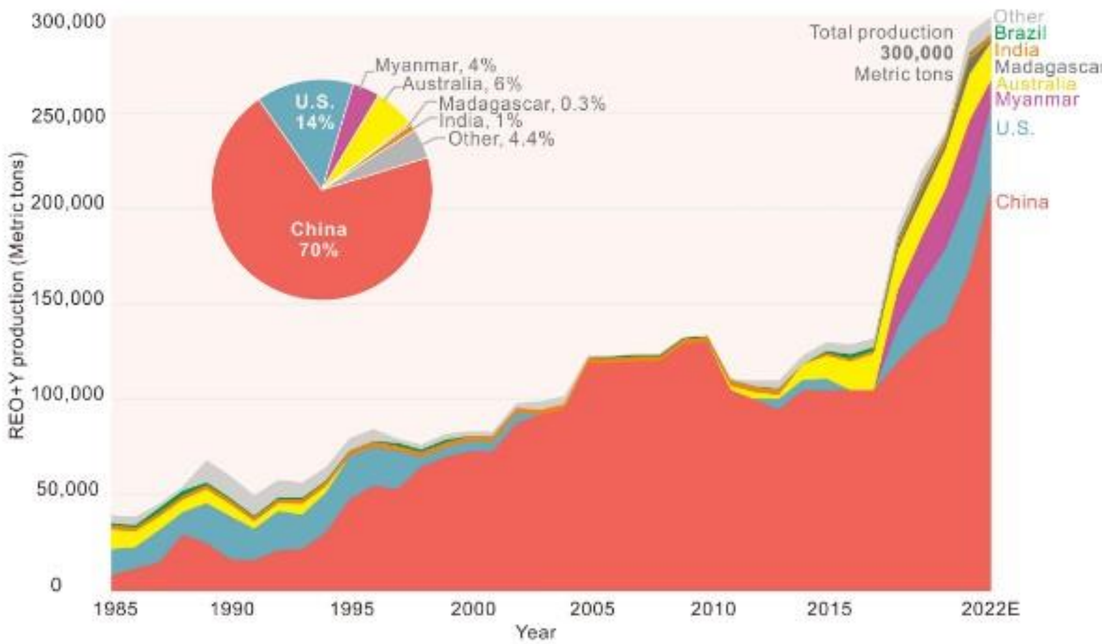


Figure 48. Rare earth production by country 1985 - 2022. China became the dominant producer in the mid-1990s, and a near-monopoly by 2000.

Prior to 1990 the U.S. was the largest producer, with China, Australia and others producing lesser but significant amounts. Between 1990 and 2005 production in China grew rapidly while outside of China it steadily declined. There were three reasons for this shift – state subsidies for Chinese producers made China the low-cost producer, lax and poorly enforced environmental regulations in China further reduced their cost of production, and more stringent environmental regulations for the treatment of rare earth mine tailings increased the cost of production in the U.S. As China continued to use state subsidies to expand its domestic capacity, U.S. and other producers closed their operations or sold them to China. By 2005 there were only two non-Chinese upstream producers – MolyCorp (U.S.) and Lynas (Australia).

By 2005 China was an effective global monopoly with approximately 97% of production, with one U.S., one Australian, and a few other small producers still active. This is the initial oscillation behaviour in the reference mode, with the China-dominated system (H1) rising while investment to support U.S. and Australian production significant but declining.

Industry observers raised concerns of potential supply risks at the time (Dadwal, 2007; Silk & Malish, 2006); these risks materialized in 2010. Rare earth prices had begun to increase following China's introduction of export quota in 2006, and then soared in 2010 by as much as 4,000% for some elements following a diplomatic incident between Japan and China that raised fears of further supply restrictions. This is the second reference mode oscillation, where H2 investments increased and marginally impacted H1 control, but not substantially.

When prices eventually returned to pre-2010 levels by 2015, the dramatic price reductions destabilized the finances of the last U.S. producer, forcing it into bankruptcy, and caused the Australian producer to seek additional capital from its investors, roughly coinciding with the run up to the peak of the third oscillation.

These events triggered the process of finding risk-reduction strategies by impacted industrial nations, including a resumption of H2 investments for U.S. and Australian production, which is shown as the last half of the third reference mode cycle. A further de-risking step, meant to inform policymakers, was creating critical mineral lists. These lists quantify the potential severity and economic impacts resulting from material shortages of a wide range of minerals, including rare earths. Minerals ranking highest in the two dimensions of supply and economic impacts are designated as ‘critical and strategic minerals’.

The critical mineral concept wasn’t new at the time – the Japanese had prepared such a list as early as 1984. Post-2010, however, when the risk profile of rare earth supply disruption increased, and more nations formulated such lists to reflect their national interests. The USA, UK, EU, Canada, Australia, Korea, and Japan formalized their assessment methodologies and published critical mineral lists starting in 2014. Depending on the country, these lists are updated every three to four years.

The selection of which minerals are first considered and then included in the list is based on comprehensive methodologies that examine a number of quantitative and qualitative metrics (European Commission et al., 2017; Nassar & Fortier, 2021). Final lists are usually summarized in graphic form by comparing two composite indicators. In the case of the U.S., the indicators are economic vulnerability and disruption potential; see Figure 49 (Nassar & Fortier, 2021). The UK prefers the terms ‘high economic vulnerability’ and high global risk supply’, which have essentially the same meaning.

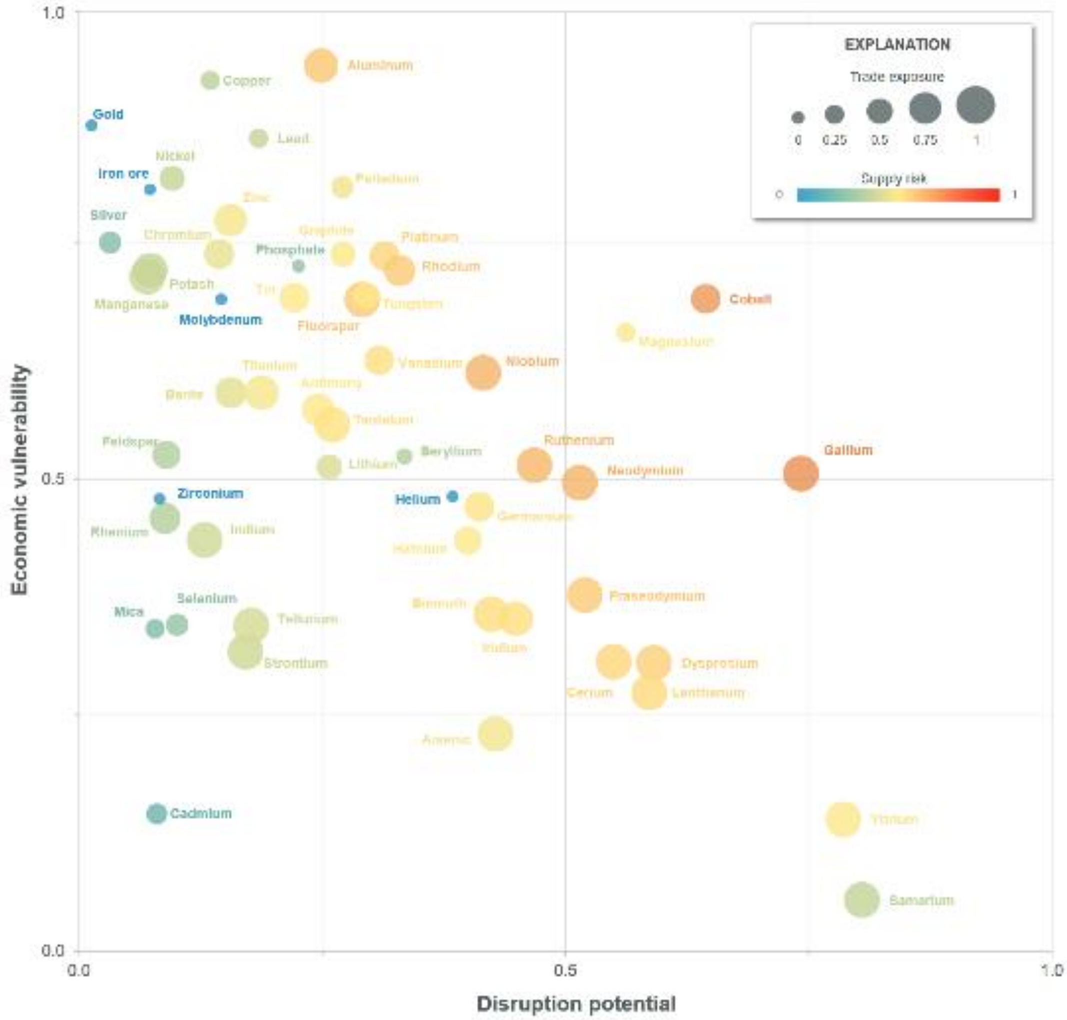


Figure 49. U.S. mineral commodity risk (Nassar & Fortier, 2021)

Table 17 below compares recent critical mineral lists from nine countries (Natural Resources Canada, 2022 Appendix E).

Table 17. Critical minerals lists from nine countries[14] with publication year. The rare earths group entry has been bolded. The only commodity common to all nine country lists is the rare earth elements group (emphasis added).

Commodity	Canada (2021)	EU (2020)	South Korea (2020)	USA (2022)	Japan (2019)	Australia (2022)	South Africa (2022)	India (2016)	UK (2021)
Aluminum	x	x		x		x			
Antimony	x	x	x	x	x	x			x

[14] Of the nine, only South Africa is not a member of the MSP.

Commodity	Canada (2021)	EU (2020)	South Korea (2020)	USA (2022)	Japan (2019)	Australia (2022)	South Africa (2022)	India (2016)	UK (2021)
Arsenic			x	x					
Barium		x	x	x	x				
Beryllium		x	x	x	x	x		x	
Bismuth	x	x	x	x	x	x			x
Boron		x	x		x				
Cadmium			x						
Cesium	x		x	x	x				
Chromium	x		x	x	x	x	x	x	
Cobalt	x	x	x	x	x	x	x		x
Coking Coal		x					x		
Copper	x						x		
Fluorspar	x	x		x	x				
Gallium	x	x	x	x	x	x			x
Germanium	x	x	x	x	x	x		x	
Graphite	x	x		x	x	x		x	x
Hafnium		x	x	x	x	x			
Helium	x					x			
Indium	x	x	x	x	x	x			x
Iridium				x					
Iron ore							x		
Lead							x		
Limestone								x	
Lithium	x	x	x	x	x	x	x		x
Magnesium	x	x	x	x	x	x			x
Manganese	x		x	x	x	x	x		
Molybdenum	x		x		x				
Nickel	x		x	x	x		x		
Niobium	x	x	x	x	x	x		x	x
Platinum Group Metals	x	x	x	x	x	x	x		x
Phosphate		x	x						
Potash	x								
Rare earth elements group	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**
Rhenium			x		x	x		x	
Rubidium				x	x				
Selenium			x		x				
Silicon		x	x		x	x		x	x
Strontium		x	x		x			x	
Tantalum	x	x	x	x	x	x		x	x
Tellurium	x		x	x	x				x

Commodity	Canada (2021)	EU (2020)	South Korea (2020)	USA (2022)	Japan (2019)	Australia (2022)	South Africa (2022)	India (2016)	UK (2021)
Thallium			x		x				
Tin	x		x	x					x
Titanium	x	x	x	x	x	x			
Tungsten	x	x	x	x	x				x
Uranium	x						x		
Vanadium	x	x	x	x	x	x			x
Zinc	x					x	x		
Zirconium			x	x	x	x		x	

4.3 Transition Drivers

Owing to their importance to clean energy technology the four most valuable rare earths metals are individually cited in some lists. The four, also known as the 'magnet metals', are neodymium (Nd), praseodymium (Pr), dysprosium (Dy), and terbium (Tb). A recent Ginger International Trade & Investments presentation (Kruemmer, 2023) describes the common factor for the potential rare earth supply gap is the permanent magnetic electric motor. While the four magnet metals are used in other products, their highest demand is for making permanent magnets. Permanent magnets made using the NdFeB (neodymium-iron-boron) formulation are the strongest known magnets and the most frequently used in making permanent magnet motors (Cui et al., 2022), which in turn are essential for the manufacture of wind turbine generators and electric vehicle traction motors.

Table 18 lists the top 12 of 87 raw materials evaluated for supply chain vulnerability for 15 strategic technologies (Carrara et al., 2023). Nd and Tb are ranked first and second, respectively, while Nd and Pr are in the top 12. Except for boron (a key element in permanent magnets), Dy, Nd, and Pr are used most frequently. Of the top 12, only boron is indicated as required for wind turbines and traction motors (wind icon and engine icon, highlighted). The largest magnet metal fraction in a permanent magnet is Nd, followed by Dy, Pr, and Tb. Nd and Dy enhance magnet performance, while Pr and

Tb enable the magnets to operate at high temperatures. Compared to the most frequently used motor alternative, induction motors, permanent magnet motors are smaller, lighter, and have higher magnet strength and reliability. As a result, permanent magnet motors have become the standard for offshore wind turbines and electric vehicle traction motors, where reliability and performance are key requirements. It is these two commercial applications that create the largest demand for the four magnet metals. Strong demand, costly production, and constrained capacity resulting in high prices are the reasons that magnet metals account for 94% of the total value of the rare earth market, even though they are, on average, only 22% of total rare earth production (Kruemmer, 2023).

Table 18. Top 12 strategic and critical raw materials. The two highlighted columns are wind turbines and electric vehicle traction motors. Source: JRC (2023)

Table 13. Strategic, critical, and non-critical raw materials used in the technologies in scope.

Rank (of 87)	Supply Risk	Material																Count
1	**5.6**	Dysprosium				•	•		•			•	•		•	•	•	**8**
2	**4.9**	Terbium				•						•			•	•	•	**5**
3	**4.8**	Gallium						•			•	•	•		•	•	•	7
4	**4.1**	Magnesium			•							•	•	•	•	•	•	7
5	**4.0**	Cerium		•	•								•		•	•	•	6
6	**3.9**	Iridium		•	•												•	3
7	**3.8**	Boron		•	•	•	•	•	•		•	•	•		•	•	•	12
8	**3.8**	Ruthenium		•	•						•	•	•		•	•		7
9	**3.6**	Neodymium				•	•		•		•	•	•		•	•	•	**9**
10	**3.5**	Samarium									•				•	•	•	4
11	**3.3**	Gadolinium		•	•						•		•		•	•	•	7
12	**3.2**	Praseodymium				•	•		•		•	•	•		•	•		**8**

The acceleration of the energy transition to meet climate sustainability goals is creating rapidly increasing demand for all critical energy transition minerals, including rare earths. Figure 50, from industry analyst Adamas Intelligence, forecasts the value of rare earths will “rise at a compound annual growth rate (CAGR) of 19.1%, from $3.8 billion in 2022 to $36.2 billion in 2035” (Adamas Intelligence, 2023). The rare earths in the forecast are the four magnet metals.

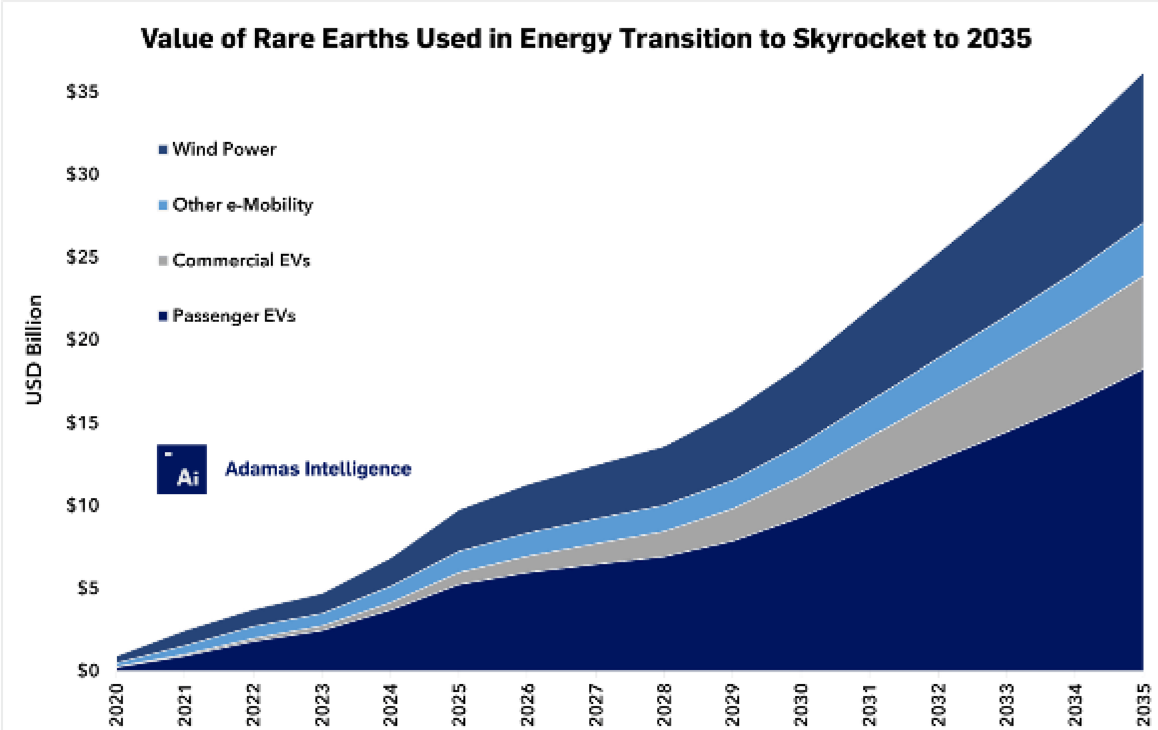


Figure 50. Projected market growth for magnet metals to 2035.

While other clean energy industry analysts have forecasts similar to that from Adamas (BloombergNEF, 2023), the projections for magnet metal material demand is less pronounced. The European Commission Joint Research Centre (JRC) global demand forecast for magnet metal production (Carrara et al., 2023) is shown in Table 19.

Table 19. Low (LDS) and high (HDS) material demand projections for magnet metals.

Metal	Scenario	2020 T	2030 T	2020-2030 CAGR	2050 T	2030-2050 CAGR
Pr	LDS	1056	1018	-0.4%	1086	0.3%
	HDS	- -	2779	10.2%	4851	2.8%
Nd	LDS	7001	12802	6.2%	34592	5.1%
	HDS	- -	28929	15.2%	76843	5.0%
Tb	LDS	238	233	-0.2%	310	1.4%
	HDS	- -	637	10.3%	1078	2.7%
Dy	LDS	733	1033	3.5%	2329	4.1%
	HDS	- -	3345	16.4%	9420	5.3%

T: metric tonnes
CAGR: compound annual growth rate
LDS: low demand scenario, HDS: high demand scenario

The mismatch in production growth compared to market value supports the state of the market as being uncompetitive. In a competitive market, new entrants would emerge to compete for a share of the increasing market value. By using their market position to constrain production, and ownership of midstream and downstream patents and intellectual property to restrict industry growth in MSP and RoW nations, China appears to be aiming to capture most of the growth market value.

While this strategy may appear sound from a China TG perspective, it creates several risks for the MSP and RoW TGs and the clean energy transition in general. Chief among the risks is supply security. China can restrict magnet metal exports to increase their wind and EV market shares, disrupting MSP and RoW manufacturers. Figures 51 and 52 show that the offshore wind is projected to lag demand by 18.3GW by 2030 (Figure 51), which would disproportionately affect net zero emission plans for Europe (Figure 52) if there are supply disruptions.

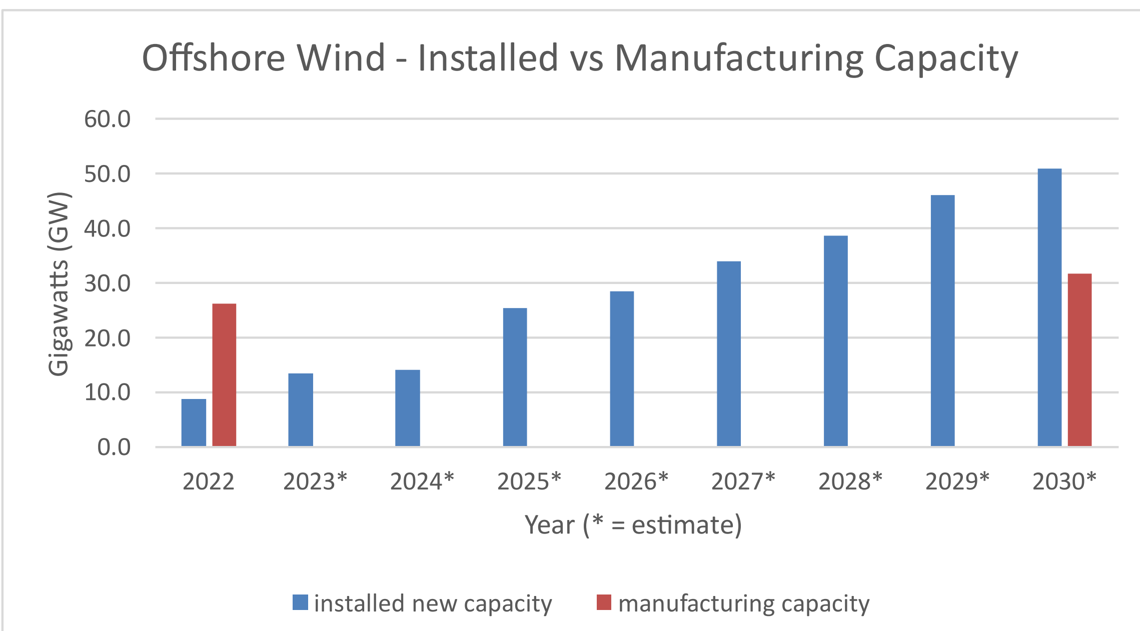
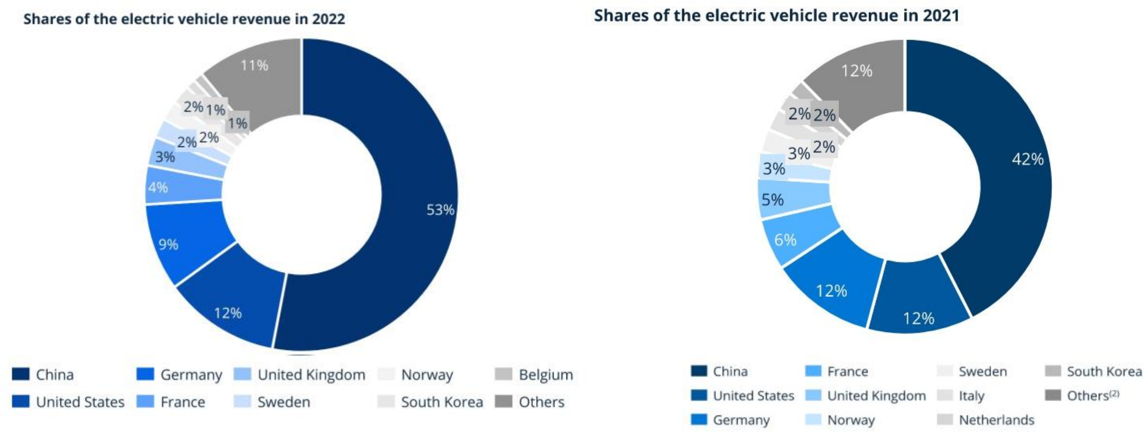


Figure 51. Offshore Wind - Installed vs Manufacturing Capacity (Source: Statista, from the Global Wind Energy Council)

Figure 52. Offshore Wind - New Installations by Region. (Source: Statista, from the Global Wind Energy Council)

A similar analysis for the EV industry is more complicated because the relevant data is for the tier 1 traction motor manufacturers and not the EV manufacturers themselves, as the traction motor suppliers create the permanent magnet demand.

What EV market data does reveal (Figure 53) is that China had the largest share of new sales revenue in both 2021 and 2022, increasing by 26% in 2022 over the previous year (Statista, 2022, 2023). Since regulations prohibiting the import of products containing rare earths, China car manufacturers are sourcing traction motor from China-based tier 1 suppliers. The supply security analysis is therefore the same, in that export restrictions by China on permanent magnets would potentially impact almost 50% of the EV market, and by extension the clean energy transition progress.



(a) (b)

Figure 53. Electric Vehicle new sales revenue, 2021 and 2022. (Source: Statista)

Supply security is therefore the primary driver for the rare earth industry transition from a clean energy transition perspective. As shown previously in Figure 15, a causal analysis shows that supply security can be disaggregated into four drivers – aggregate production, production diversification, and two drivers that form the stimulus management strategy transition cost and transition schedule. An expanded view of the four drivers is shown in Figure 54.

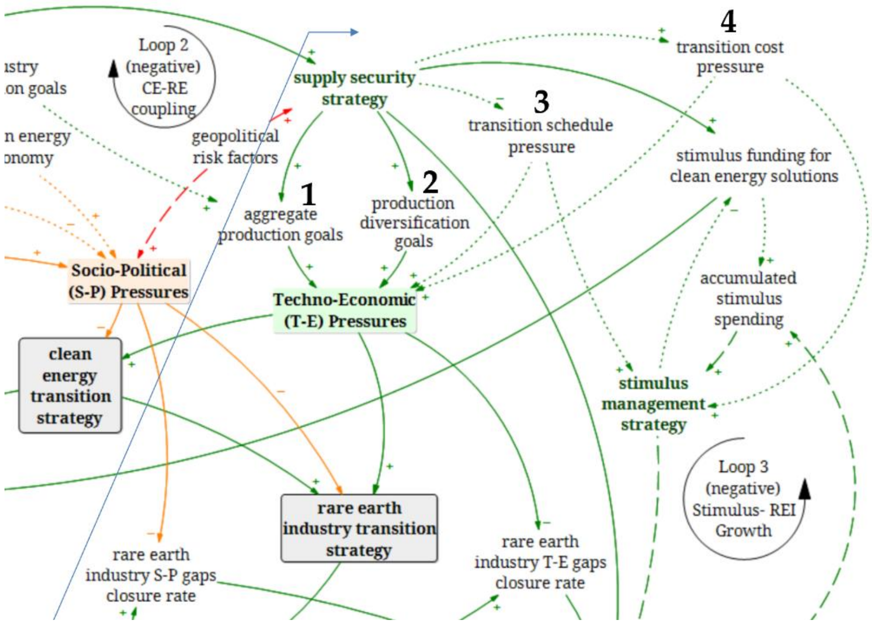


Figure 54. Detail view of the four rare earth industry transition drivers and their relationship to the clean energy and rare earth industry transition strategies.

Ultimately, supply security requires sufficient production (aggregate production driver) from within the MSP TG (production diversification driver). The addition of a stimulus management strategy with drivers transition cost and transition schedule recognizes that the transition is not possible with government support. Stimulus cost and time management is rarely part of the initial discussions, but inevitably are introduced to track progress toward the supply security goals. Given the stimulus amounts in this case are in the billions of dollars, inevitably is likely to be sooner rather than later.

While stimulus management is extremely important from a fiduciary perspective, the deeper concern is the risk of stimulus curtailment before the supply security goals are achieved. Should stimulus curtailment occur before the re-established industry is stable and profitable, the large investments made prior to that event and cascade to clean energy transition destabilization, in the worst-case scenario. Thus, we characterize the second driver not as stimulus management but as long-term rare earth industry stability.

While there are other factors and constraints that must be considered during the transition (Ilankoon et al., 2022) such as sustainable production, minerology and ore grade, and technical complexity, they are supporting factors. Accordingly, we state that supply security and long-term stability are the twin transition drivers.

CHAPTER V:

RARE EARTH INDUSTRY TRANSITION CHALLENGES

This chapter addresses Research Question 2: What actions are needed to address the twin transition drivers of increased supply security and long-term stability?

5.1 Rare Earth Industry Transition Drivers

As noted previously, supply security and stimulus management, as a surrogate for long-term industry stability, are the high-level drivers for a successful rare earth industry transition. Each of these high-level drivers have two key performance indicators (KPIs) that can be used to measure transition success.

For supply security the KPIs are aggregate production and production diversification. These align directly with the aims of the MSP and the broader goal of securing rare earth materials for the clean energy transition.

The KPIs for stimulus management are transition schedule pressure and transition cost pressure. These KPIs will be used to produce a value for the Rare Earth Industry Stability Index. The index will compare stimulus duration and accumulated spending to estimated industry financial performance to provide a qualitative ranking based on the need for additional stimulus funding. An industry that is reliant on stimulus funding beyond an expected transition completion timeframe will rank lower than one that does not.

Figure 55 (previously shown as Figure 15) is a CLD of the industry aggregated at the trade group (TG) level showing the four KPIs. In this CLD, the diamond model determinants are grouped within the rare earth industry transition strategy and the rare earth industry growth rate variables, with the bulk of the feedback structure addressing the salient transition factors noted above.

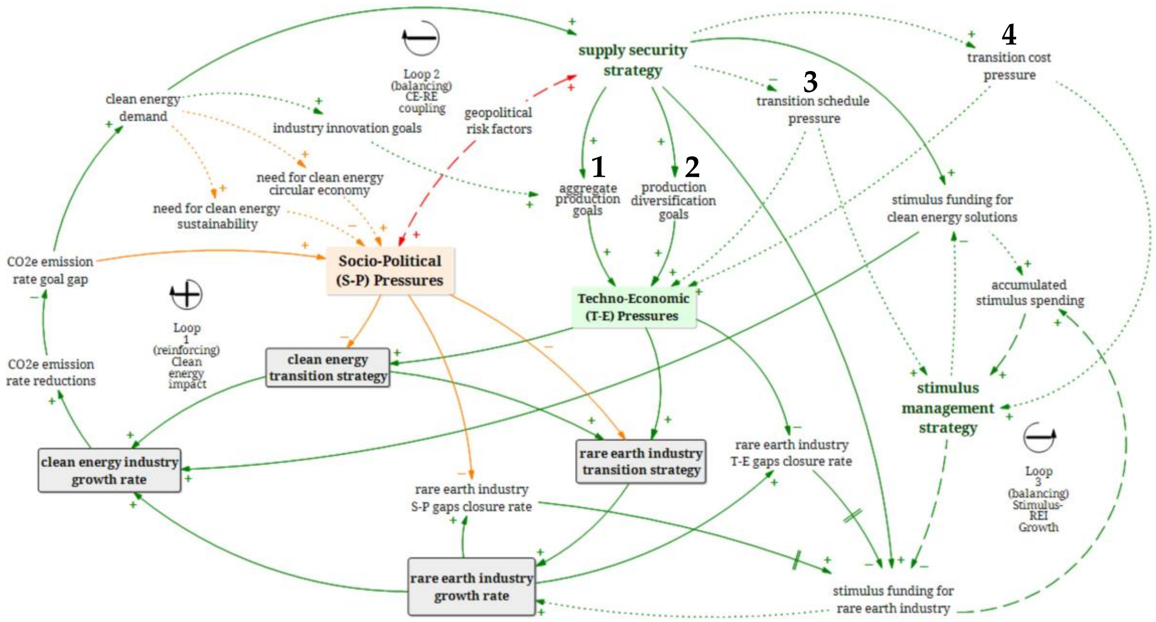


Figure 55. Dynamic hypothesis causal loop diagram (CLD) showing the four KPI variables. (reprise of Figure 15)

The CLD shows the four KPIs and used to determine the degree of transition success. We will refer to this CLD when discussing the four KPIs.

Given the rare earth industry reference mode shown previously in Figure 46 and is replicated in Figure 56 as the Current System segment up to the start of the Transition. The ideal transition scenario, starting with the Transition segment and continuing to the Future System, is one where a future H3 system emerges and becomes dominant and sustainable as shown by the H3 curve. Note that H3 does not depict a zero-sum game. All three TGs continue to coexist in H3, and parts of H1 continue to coexist over the transition time horizon. Rather, H3 represents a shift in production patterns to create, from an MSP perspective, a higher level of supply security.

The Capture and Extension archetype in Figure 56 shows a potential transition success scenario:

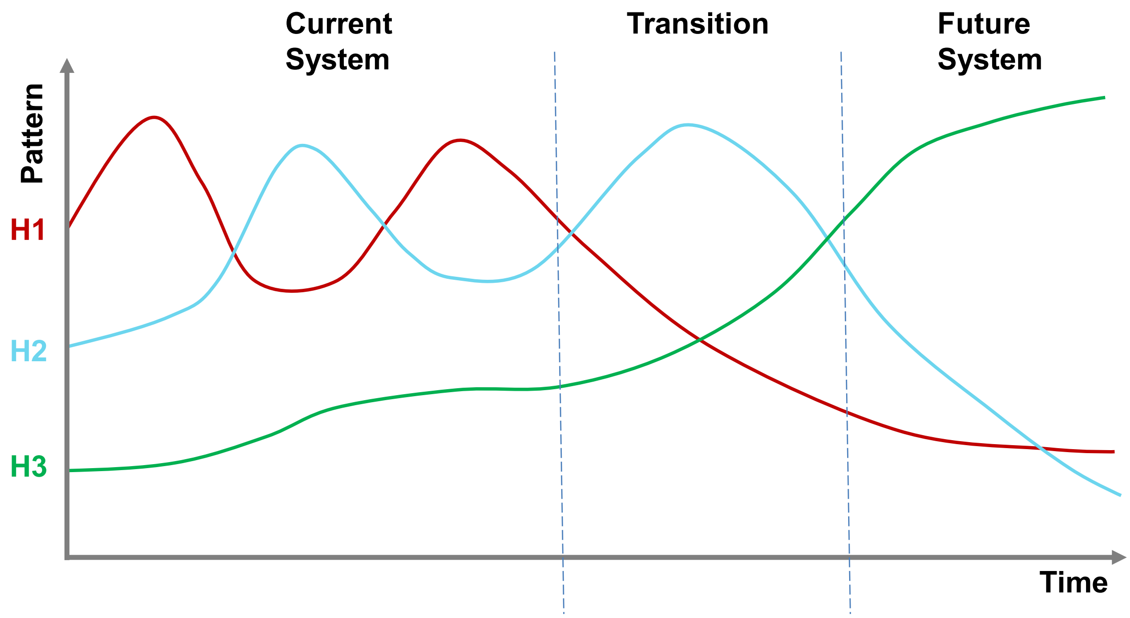


Figure 56. Ideal Transition and Desired Future System State

H3 represents the steady emergence of a future rare earth industry system that has multinational production diversity with increasing aggregate production capacity. H3 reaches an inflection point during the transition period when the rate of adoption of the future system increases as it replaces the H1 system. Achieving long-term stability is represented by the rapid decline of H2 stimulus funding.

The stakes are high for a successful transition. A recent industry report suggests the critical minerals transition (not just rare earths) could cost over $550B (Potter, 2023). This section examines the KPIs to indicate a successful transition.

5.2 Supply Security KPIs

Supply security has two metrics: 1) aggregate production, sufficient to meet forecast global clean energy demands, and 2) diversified production, to mitigate the risks of a dominant producing nation controlling rare earth supply to the clean energy industry.

5.2.1 Aggregate Production KPI

The supply-demand gap for magnet metals is forecast to range from acute to well within existing production. While numerous projections indicate a significant and growing supply gap over the next decade (for example, Detry et al., 2023), projections from the Joint Research Centre of the EU (Alves Dias et al., 2020) are more conservative, with supply-demand gaps forecast only for Dy and Tb and only in the high demand scenarios (Figure 57).

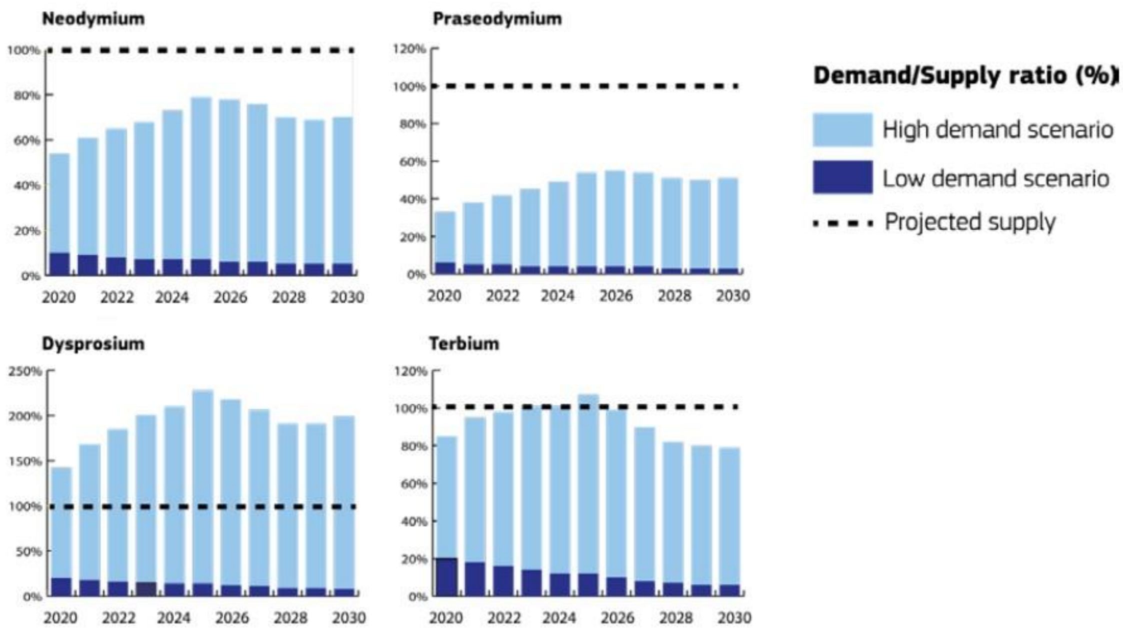


Figure 57. 2020 projections of demand/supply ratios from 2020 to 2030 for magnet rare earths. (Source: JRC, 2020)

Like all forecasts there are many factors and many unknowns. From a supply perspective, two metals (neodymium and praseodymium) are relatively plentiful while two (terbium and dysprosium) are not. Neodymium and praseodymium are light rare earths (LREE) and mostly produced from monazite and bastnaesite deposits, which are the most common rare earth deposits. Of the three largest LREE deposits in production today, one is in China and two are in MSP countries (the U.S. and Australia). Most new deposits being developed are LREE deposits, further reducing the risk of upstream shortages. Terbium and dysprosium, required in small amounts to boost the performance of permanent magnets, are heavy rare earths (HREE). HREE deposits are rare, the most common being ionic adsorption clays in sub-tropical climates. China continues to be the primary source of HREE upstream production, but in recent years Myanmar (formerly Burma) has become an important, if unstable, secondary source.

Forecast uncertainty, and hence the magnitude of production gaps, is largely due to demand uncertainty. This especially true for electric vehicle (EV) demand. EV new car sales projections published by the Energy Information Agency in the 2021 International Energy Outlook (*International Energy Outlook - U.S. Energy Information Administration (EIA)*, 2021) projected new electric (battery and plug-in) light vehicle sales for 2022 as 4.5 million units. Two years later, the 2023 version of the report (Energy Information Administration, 2023) reported actual sales for 2022 as 10.1 million units, a gap of 126%. A smaller but still large gap exists for the 2050 projections – 26.6 million (2021) versus 39.1 million (2023), or 47%.

While these figures relate to the EV industry, they impact the allocation of magnet metals to supply permanent magnets for both EVs and wind. The potential for such large production gaps raises the possibility of three clean energy sector risks – firstly that China will allocate most of its production to domestic demand, creating shortfalls for the rest of the global industry, and secondly that such large shortages will cause significant price increases. In today’s market where China dominates both supply and demand, the typical market analysis for base metals does not apply and there is no reliable method of forecasting price.

Consistent with Figure 56, demand/supply ratio of magnet metals will be used as the aggregate production KPI.

5.2.2 Production Diversification KPI

Due to its complex chemistry, rare earth minerals require processing stages not used with most metals. Thus, we introduce the topic of production diversification KPIs with a brief overview of rare earth production.

As is standard in the mining industry, rare earth production consists of three streams – upstream, midstream, and downstream as shown in Figure 58. Commercial products resulting from these streams are concentrates (upstream product), mixed carbonates, oxides, and medium purity (<99.9% or 3 nines) metals (midstream products), and high purity (> 99.9%) metals and metal alloys (downstream products).

Upstream processing is typically by open pit mining for LREE deposits and historically by in situ leaching for HREE deposits, although this practice is being abandoned due to its severe environmental impacts. Non-ore sources such as lignite coal and coal ash (Farqhi et al., 2021; Park et al., 2020b) and alternative sources such as acid mine drainage (Larochelle et al., 2021) are being actively examined as alternate sources of rare earths. The upstream stages – extraction, crushing, milling and flotation processing – follow standard upstream processes.

Rare earth processing differs from that of base metals. In the midstream, hydrometallurgical processing is required to separate the oxides first from one another, and second to extract pure metals from the oxides.

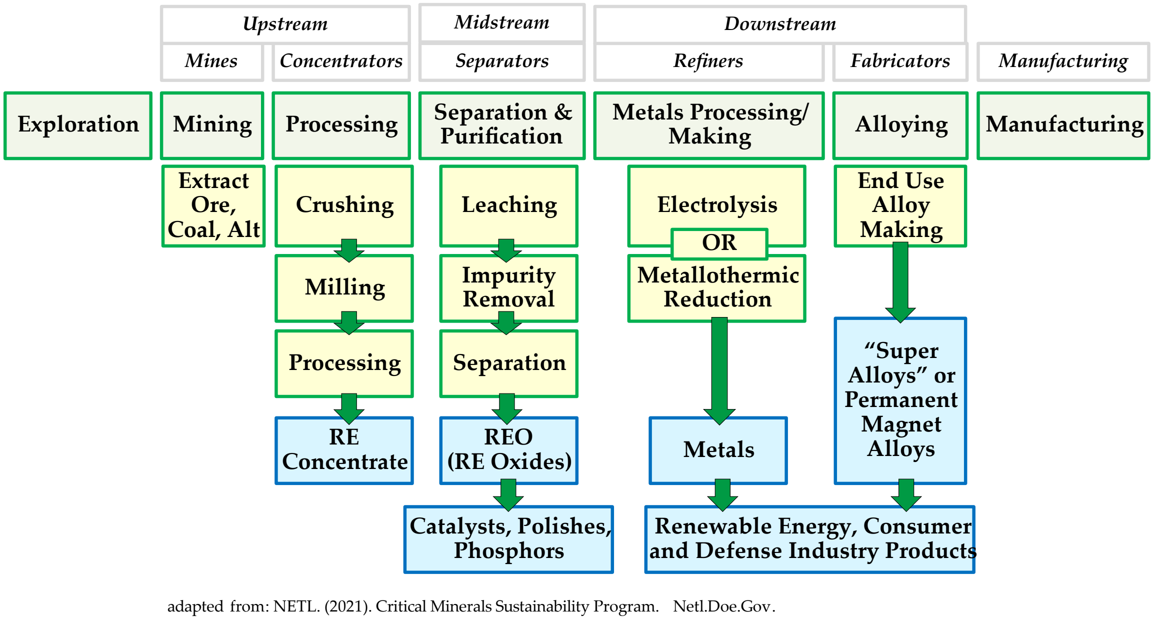


Figure 58. Rare earth production stages.

Each of the production stages are described below in the context of their transition requirements and implications.

The supply security challenge is to diversify production at all three stages. The Herfindahl-Hirschman Index (HHI), a well-known measure of industry concentration, will be used as the production diversification KPI.

While variations of the HHI have been developed to measure diversification (Kim et al., 2019), for our purposes of tracking production concentration at the trade group level the simpler HHI will suffice.

HHI is calculated as follows:

$$HHI = \sum_{i=1}^{n} s_i^2 \text{, } where \sum_{i=1}^{n} s_i = 100$$

The market share, or in our case the trade group share, for each participant is expressed as the integer value. A 40% market share or a 40.2% share are entered as 40, with share scores rounded.

Scores are calculated for each market participant, with the sum of the scores providing an overall indicator of market competitiveness. Scores range from 0 (an inactive market or participant) to 10,000 (a single firm with a 100% monopoly). A market score below 1500 is consider highly competitive market, above 2500 is considered highly concentrated, and above 5000 the market is considered a monopoly.

Table 20 gives examples:

Table 20. HHI calculation examples.

Country	Example 1 Share	Example 1 HHI	Example 2 Share	Example 2 HHI	Example 3 Share	Example 3 HHI
A	33	1089	25	625	100	10000
B	33	1089	25	625	0	0
C	34	1156	25	625	0	0
D	0	0	25	625	0	0
Share Total	100		100		100	
Market HHI		3334		2500		10000

The production share of each country is shown in the first column for each example, with all entered as integers and summing to 100. The second column for each example shows the share value squared. In Example 1 Country D is a new entrant, with no market share therefore an HHI > 2500 indicates a highly concentrated market. In Example 2 the market shares are equal, with an HHI result of 2500, the top end of the competitive market scale. More countries entering the market and taking production share from established entrants would lower the HHI score, indicating stronger competition. In Example 3, a single company gives the maximum HHI score of 10,000 to indicate a perfect monopoly.

Tables 21, 22, and 23 show the HHI calculations for the upstream, midstream and downstream production stages (Source: Austrian Federal Ministry of Finance, 2023). Data has been aggregated by trade group; intermediate calculations are not shown.

Upstream data (Table 21) shows an 18% HHI decrease from 2017 to 2021reflecting strong production growth in the MSP TG; however, the overall market remains in a monopoly condition.

Table 21. HHI results for upstream production for 2017 to 2021

Nation Group Upstream HHI	2017	2018	2019	2020	2021
China	6889	5929	5329	4900	5184
MSP	196	361	576	676	625
RoW	9	9	9	9	9
Total	7094	6299	5914	5585	5818

The midstream HHI results (Table 22) show the magnitude of the challenge to bring on separation capacity, for two reasons: a) provide MSP upstream processors an option for upstream offtake within the TG, and b) diversify separation capacity. The midstream market is in a strong monopoly condition.

Table 22. HHI results for midstream production for 2017 to 2021. (Source - World Mining Data).

Nation Group Midstream HHI	2017	2018	2019	2020	2021
China	7225	7225	7225	7225	7225
MSP	170	170	170	170	170
RoW	4	4	4	4	4
Total	7399	7399	7399	7399	7399

The downstream market (Table 23) is in a strong monopoly condition. The downstream production diversification challenge is even larger than that for midstream. Again, MSP TG capacity must grow significantly and quickly to match the expected growth in upstream and midstream production; however, the time to acquire the technical knowledge and skilled labour for upstream production of magnet metals is significant (Detry et al., 2023). China is understood to be increasing their upstream production by increasing imports (Williams, 2021).

Table 23. HHI results for downstream production for 2017 to 2021.

Nation Group Downstream HHI	2017	2018	2019	2020	2021
China	8464	8464	8464	8464	8464
MSP	64	64	64	64	64
RoW	0	0	0	0	0
Total	8528	8528	8528	8528	8528

5.2.2.1 Upstream Diversification

The upstream process begins with field exploration teams identifying potential rare earth deposits. Orris et al. (2018) have catalogued over 3,900 deposits; of these only 93 have a ‘P_Status’ (Production Status) of ‘Producer’ (38) or ‘Past Producer’ (55), an indication of the complexity in finding commercially viable deposits. For this reason, new exploration continues today.

Rare earths are found in minerals in quantities measured in parts per million (ppm). They appear naturally not as metals but as metal oxides, entrained in the crystal lattice of one or more host minerals, and always occur with most, if not all, of the other rare earths present. Thus, unlike gold, silver, or iron, there are no seams of a single rare earth metal (Anenburg et al., 2020). The minerals that host rare earths frequently contain high grades of more common and valuable metals such as iron, so that rare earths are often secondary products and referred to as ‘hitchhiker metals’. For example, the largest known rare earth-bearing mineral deposits are the Bayan Obo district iron deposits in Inner Mongolia, China. Per 1000 kilograms of raw ore, the iron content is 510 kilograms, or 51% (Li, 2018), while the associated rare earth content in this deposit are nine rare earth oxides totalling 60 kilograms or 6%, of which only 15 kilograms or 1.5% are from the four most valuable rare earth (Dushyantha et al., 2020; Fernandez, 2017).

Crustal abundances for rare earths ranges from roughly 100 times greater than gold to 1,000 times less than iron; see Figure 59.

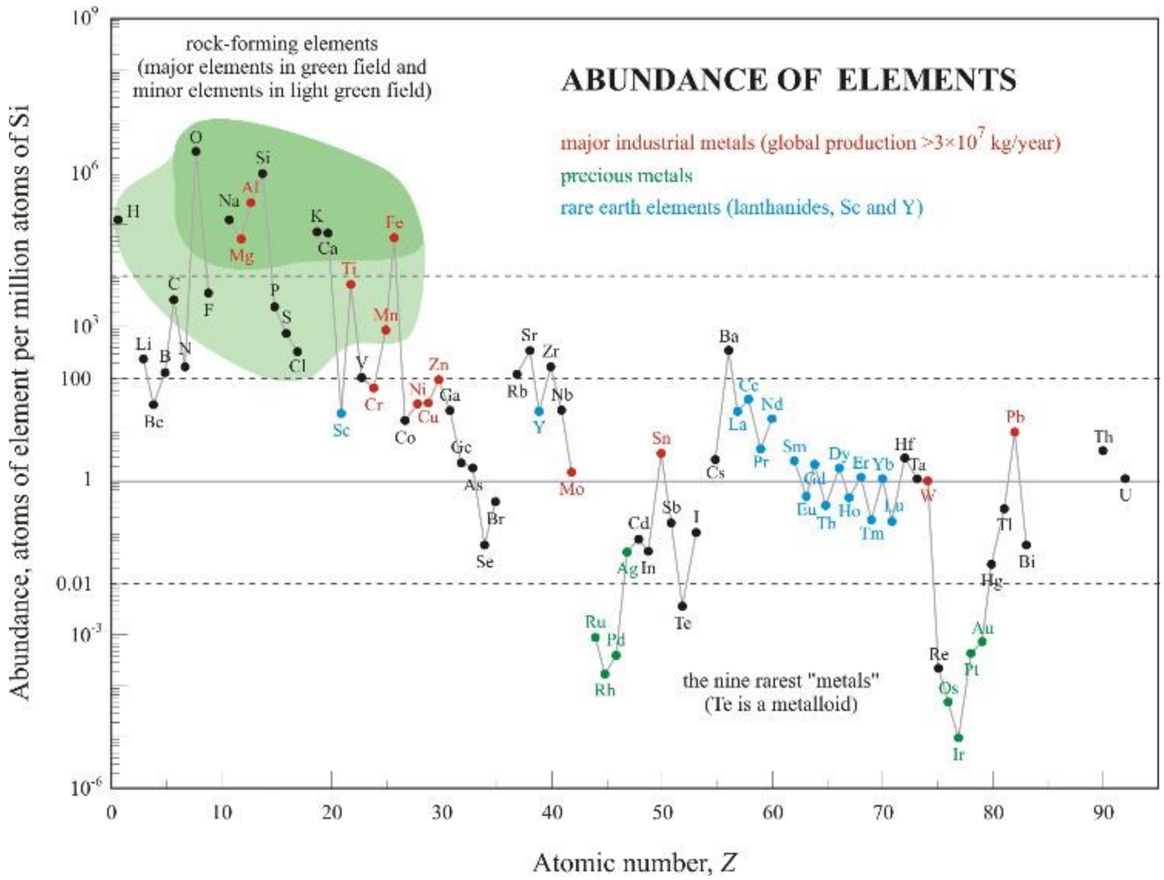


Figure 59. Crustal abundances of elements. The rare earth elements are shown in light blue font.

Given their crustal abundance rare earths cannot be considered rare; however, the 'rare' label is still appropriate when considering the small number deposits that contain rare earth-bearing minerals in viable quantities.

Rare earths elements are further categorized as 'light' or 'heavy', depending on their atomic weight. A summary of basic RE characteristics including type are given in Table 24.

Table 24 - The Rare Earths

Element	Atomic Number	Geochemical Type	Oxide	Element	Atomic Number	Geochemical Type[a]	Oxide
Scandium (Sc)	21	HREE	Sc(III) Sc_2O_3	Gadolinium (Gd)	64	HREE	Gd(III) Gd_2O_3
Yttrium (Y)	37	HREE	Y(III) Y_2O_3	Terbium (Tb)	65	HREE	Tb(III,IV) Tb_2O_3
Lanthanum (La)	57	LREE	La(III) La_2O_3	Dysprosium (Dy)	66	HREE	Dy(III) Dy_2O_3
Cerium (Ce)	58	LREE	Ce(III,IV) Ce_2O_3	Holmium (Ho)	67	HREE	Ho(III) Ho_2O_3
Praseodymium (Pr)	59	LREE	Pr(III,IV) Pr_6O_{11}	Erbium (Er)	68	HREE	Er(III) Er_2O_3
Neodymium (Nd)	60	LREE	Nd(III) Nd_2O_3	Thulium (Tm)	69	HREE	Th(III) Th_2O_3
Promethium[b] (Pm)	61	LREE	-	Ytterbium (Yb)	70	HREE	Yb(II,III) Yb_2O_3
Samarium (Sm)	62	LREE	Sm(II,III) Sm_2O_3	Lutetium (Lu)	71	HREE	Lu(III) Lu_2O_3
Europium (Eu)	63	LREE	Eu(II,III) Eu_2O_3				

a: an alternate categorization Metallurgical Type (not shown) includes Medium REE (MREE) for Sm, Eu, an Gd. These are referred to as the SEG metals.
b: Promethium (61) is not naturally occurring and is of no commercial interest.

Rare earth elements are classified as light (LREE) or heavy (HREE) from a geochemical perspective, or light, medium (MREE), or heavy from a metallurgical perspective (not shown). The type MREE includes one LREE (Sm) and two HREE (Eu and Gd) and are sometimes referred to as the 'SEG' metals.

From a transition perspective, decision indicators that the MSP nations should prioritise are those improving the probability of adding high quality new capacity with potential to qualify for accelerated permitting. Of greatest transition value are mines with high grades of the LREEs Pr and Nd, and the HREEs Tb and Dy – the magnet metals. New mines eligible for accelerated permitting processes should also be favoured.

Key considerations are outlined in Table 25.

Table 25. Upstream investment decision factors

Decision Factor	Decision Indicators	Diamond model mapping
Deposit	• Carbonatites rock minerals typically have high REE concentrations (Anenburg et al., 2020) • Placer deposits with high levels of monazite • Ionic adsorption clays	• FS – investment decisions • Gov – FC support, FS support
Minerology	• Proven flowsheets for commercial-scale production: monazite, bastnaesite, xenotime, ionic adsorption clays, with low levels of thorium	• FS – investment decisions
Tons	• Measured and indicated reserves for long Life of Mine	• FS – economic viability gross revenue potential for concentrate and carbonate products
Grade	• High magnet metal grades (Pr, Nd, Tb, Dy) • High TREO grade	• FS – economic viability gross revenue potential for concentrate and carbonate products
Location	• Favourable logistics – access to site, access to utilities, communications, construction, etc. to establish and operate the mine	• FC – access to site and support infrastructure • FS – permitting considerations; qualification for accelerated permitting • FS – Capex – construction costs • FS – Opex – operating costs, transportation costs

Products from the upstream stage are rare earth concentrate and mixed rare earth carbonate concentrate, assuming the infrastructure and flowsheet are in place.

5.2.2.2 Midstream Diversification

Midstream is the most technically complex stage. Upstream concentrate undergoes chemical processing, called separation, to extract individual rare earth oxides from the mixed concentrate and further eliminate non-rare earth material. The level of purity for a given oxide depends on the intended use. Cerium-based glass polish, for example, only requires 95% purity in oxide form. The majority of rare earth demand is for oxides.

The high cost and complexity of separation is due to the unique properties, requiring that the oxides are separated in order of increasing atomic number. Thus, La (57), must be separated before Ce (58), etc. to Lutetium (71). It is not possible to separate Nd (60), a valuable magnet rare earth, before La, Ce, and Pr (59) are separated. Technically is a matter of time and material. The issue is that La and Ce typically sell for US$1/kg, while costing US$20 to extract Nd. Thus the $19 must be recovered from the price of Ce (also US$1/kg) and Pr before a profit is made.

The profitability equation is determined by China – low-cost producer, and VAT that creates a two-tier price system. Also, 95% of demand is from Chinese industries. So non-China product must overcome a 13% VAT disadvantage to access 5% of the market. And, if the MSP/RoW producer can't guarantee a steady supply no one will buy from them because China won't sell rare earth to a 'disloyal' customer that tried buying from someone else.

5.2.2.3 Downstream Diversification

Downstream consists of refining oxides into pure metals and then increasing metal purity, and fabrication, to alloy the rare earth metals and form them into products. The most valuable product of fabrication today is permanent magnets.

Pure oxides and metals require downstream processing in refineries. The terminology used is 'Ns', the number of 'nines' of purity. Thus, 99.9% is 3Ns (three nines), 99.999% is 5Ns (five nines). Attention is necessary when reviewing market price data to determine if the price is for oxide or pure metal, and the purity in Ns.

After refining, the fabrication stage produces the rare earth in various forms, and to varying specifications, to become intermediate and finished goods. Some are fabricated from their pure metal form, others are alloyed with other rare earth, or with other elements or compounds. Permanent magnets are NdFeB or SmCo. Goods produced at the midstream stage tend to be single or two element oxides Due to their high oxidation state, rare earth appear in the host mineral as trivalent oxides (usually Re_2O_3 form).

5.3 Industry Stability KPIs

Long-term industry stability requires that new sources of competitive advantage be developed to sustain profitable operations when stimulus funding eventually ceases. While stimulus funding is essential in the early transition stages, a protracted and costly transition risks subjecting ongoing stimulus funding to significant curtailment pressures. This could lead to unintended outcomes that compromise the transition objectives and long-term industry viability. We identify two long-term industry stability objectives – transition.

5.3.1 Industry Stability Metrics

For the MSP TG, industry stability and security are measured by the ability of the industry to sustain itself – i.e. – individual firms generating sufficient profit to compete internationally while returning dividends to investors, without stimulus funding. This is in contrast to the Chinese model of providing long-term state funding to further a strategy of global rare earth dominance first established in 1981 (Duan, 2022).

Long-term stability is compromised if government stimulus payments are required to maintain operations, since, unlike China, MSP stimulus funding has no long-term guarantees.

In the CLD this is shown as transition cost pressure and transition schedule pressure. Even seemingly untouchable programs have, in the past, come under considerable scrutiny for potential defunding. This defunding risk leads to uncertainty that could potentially impact the clean energy transition.

Addressing this challenge is akin to developing a stimulus exit strategy at the outset. In the horizon diagram, this is seen as developing a strategy for causing H2, the transition stimulus curve, to trend to zero in the long-term (Figure 60). Accordingly, the key metrics are transition schedule – how long stimulus is required to achieve profitability – and transition cost – the accumulated value of stimulus funding.

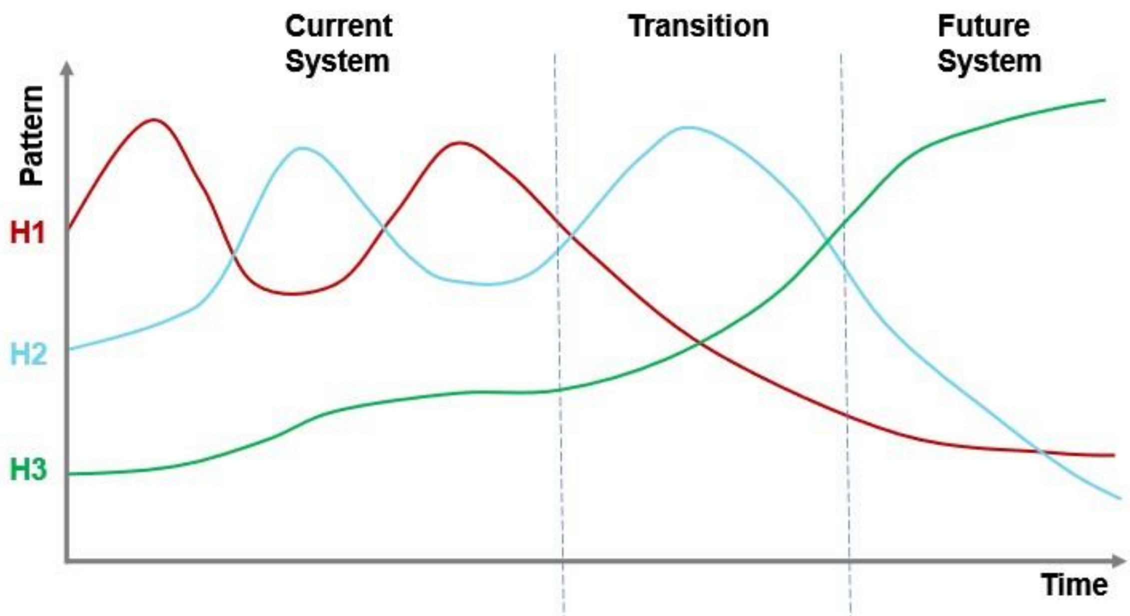


Figure 60. Ideal Transition and Desired Future System State (Reprise of Figure 55).

Industry metrics for the time to bring an new upstream mine online is approximately 15 years, less for midstream and downstream facilities (International Energy Agency, 2021). These values will be used in scenario testing to set H2 planning scenarios.

5.3.2 Transition Schedule and Cost and Cost KPIs

Transition cost and schedule graphs are readily provided by the model. By inspection, stimulus magnitude and occurrence are shown for each of the mine entities in the TG.

5.4 Key Performance Indicators Summary

Table 26 summarizes the key performance indicators (KPIs) used to measure transition progress.

Table 26. Summary of Key Performance Indicators (KPIs)

Action	KPI	Metric
Aggregate Production	Demand/supply gap	Measures the over/under supply of magnet metals at R4 Refining and over/under supply of permanent magnets at the F5 Fabrication stage.
Production Diversification	HHI	Measures the HHI at M1 Mining (upstream), S3 Processing (midstream) and F5 Fabricating (downstream)
Transition Cost	Stimulus Sum	Accumulated stimulus funding at M1 Mining (upstream), S3 Processing (midstream) and F5 Fabricating (downstream)
Transition Schedule	Stimulus Duration	Time period stimulus funding required

The overarching view of these metrics is that they are directly traceable to the motivation for this study – long-term stability and security of the rare earth products to the clean energy transition:

- Fabrication HHI: fabrication of magnet metals within the MSP TG reduces the risk of supply disruption to MSP-based wind and EV manufacturers, and other critical and strategic sectors reliant on rare earths.
- Permanent magnet demand-supply gap: an imbalance in global production ultimately impacts all nations by creating market instability. This was vividly

demonstrated in the rare earth industry in 2010 and led to price increases of up to 4,000% for some metals. A persistent supply gap would not only cause clean energy technology production delays but would likely increase the cost of the technology and disrupt the procurement and implementation of clean energy solutions.

- Investment gap: relying on stimulus funding is a necessary short-term measure but does not lead to a stable and sustainable industry in the long run. Instability in the industry would likely appear near to the critical 2050 timeframe when clean energy demand is likely to accelerate to meet net-zero targets.

Scenario testing is straightforward using the Ventity multi-panel option that allows many entity type diagrams to be observed simultaneously. Figure 61 shows the scenario testing layout.

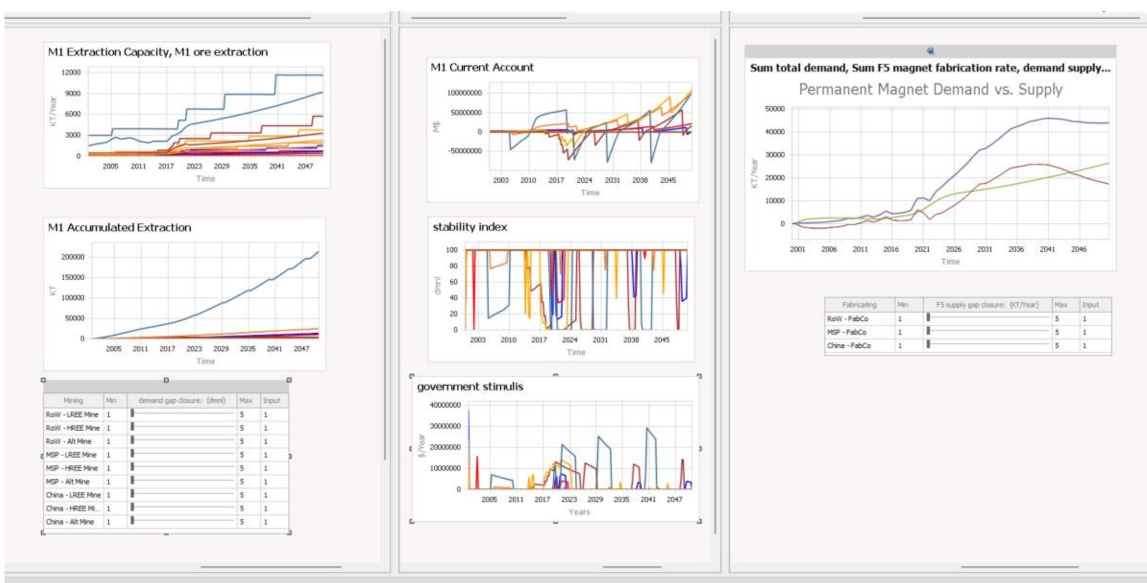


Figure 61. Scenario testing in Ventity using multi-panel displays.

Two useful testing features are visible in the figure – graphs, that can display several variables and entities simultaneously, and sliders, that can vary test variables for the entities in an entity independently. Controls are available to limit the displayed data as necessary.

CHAPTER VI:

TRANSITION STRATEGIES

This chapter addresses Research Question 3: Does the proposed method identify strategies for a successful MSP trade group transition?

As stated previously, a successful transition has two criteria – supply security and long-term stability. The four KPIs for these two criteria developed in the previous chapter are used to test alternative transition strategies.

After a Base Case scenario to establish baseline results, scenarios 2, 3, and 4 vary parameters in the stated diamond model determinant, one at a time. The other determinants are returned to their Base Case settings. Note that the Demand Conditions determinant remains in its Base Case state for all scenarios. The last scenario, Multi-Determinants, attempts to determine an effective strategy using results from the previous scenarios.

Results are reported in graphical format, as five graphs per case. The five are:

- (a) Production Diversification #1: Upstream HHI
- (b) Production Diversification #2: Downstream HHI
- (c) Aggregate Supply: Permanent Magnet Demand (Clean Energy Demand and Total Demand) vs. Total Magnet Supply
- (d) Transition Cost & Schedule #1: M1 Stimulus Amount
- (e) Transition Cost & Schedule #2: C2 Stimulus Amount

As a reminder, the results data is only indicative of industry performance. The five graphs for each scenario are labelled (a) through (e) as a single Figure.

Table 27 summarizes the parameter values for each of the five scenarios.

Table 27. Transition strategy scenarios.

Variable	Base Case (BC)	Firm Strategy (FS)	Factor Conditions (FC)	Government (GV)	Multi-Determinant (MD)	Variable Effect
Stimulus share	20%	20%	20%	40%	40%	Stimulus share of new capacity investment
Initial capacity	M1: 1000/500 C2: 350/100 S3: 300/150	M1: 5250/1000 C2: 350/100 S3: 300/150	M1: 3500/1000 C2: 350/100 S3: 300/150	M1: 3500/1000 C2: 350/100 S3: 300/150	M1: 5250/1000 C2: 350/100 S3: 300/150	Time to first capacity expansion
Capacity adjustment fraction	M1: 40% C2: 50% S3: 50%	M1: 50% C2: 50% S3: 50%	M1: 40% C2: 50% S3: 50%	M1: 20% C2: 30% S3: 30%	M1: 40% C2: 50% S3: 50%	Time to next expansion vs. expansion cost
M1 Desired Mining	1.0 (no change from forecast)	1.05 (+5%)	1.1 (2030 – 2040)	1.0	1.1 (2030 – 2040)	Additional growth over baseline forecast (BAU)
Process Improvements	upgrade ratio: 1.0 mass pull: 1.0 recovery: 1.0	upgrade ratio: 1.0 mass pull: 1.0 recovery: 1.0	upgrade ratio: 1.05 mass pull: 1.05 recovery: 1.005	upgrade ratio: 1.05 mass pull: 1.05 recovery: 1.005	upgrade ratio: 1.05 mass pull: 1.05 recovery: 1.005	Increase value
MSP Processing of China Imports	no change	no change	no change	S3: 20% R4: 20%	S3: 20% R4: 20%	Process 20% of China S3, R4

6.1 Scenario 1: Base Case

This scenario uses parameters that reflect the current industry to provide baseline results.

The scenario variables are in Entity Initialization file PM_BD_init.

The initialization values for this scenario are based on published data for stream variables and demand. Settings for key variables are in Table 28.

Table 28. Variable settings for the Base Case scenario.

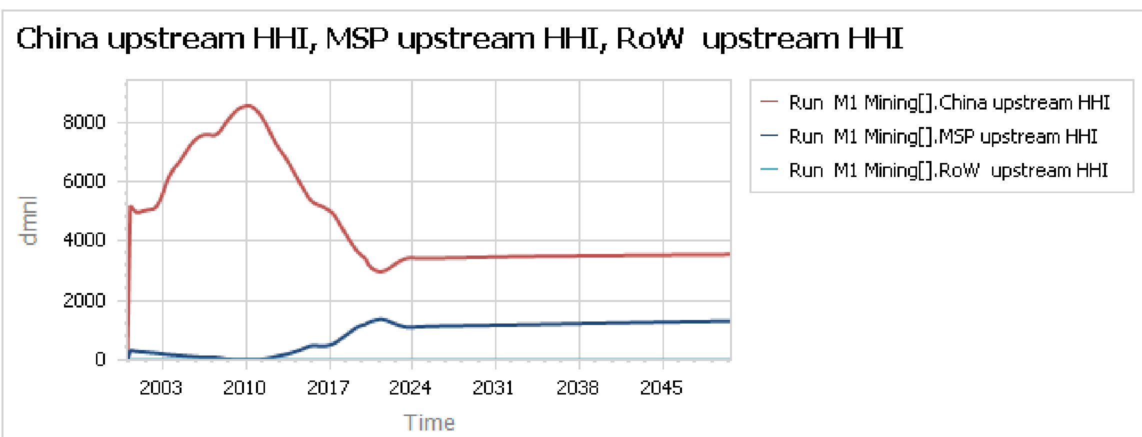
Variable	Affects	MSP Setting (units)	Effect
M1 stimulus share C2 stimulus share S3 stimulus share	M1 stimulus amount C2 stimulus amount S3 stimulus amount	0.2 (dmnl)	20% of the investment required for expansion is provided as stimulus funding
M1 initial extraction capacity (LREE/HREE)	Capacity utilization and rate of adjustments	1000/500 KT/Year	Time to first capacity adjustment, initial stimulus draw
M1 capacity adjustment fraction	Size of capacity adjustment	0.4 (dmnl)	Percentage of existing capacity used the expansion amount

C2 initial concentration capacity (LREE/HREE)	Capacity utilization and rate of adjustments	350/150 KT/Year	Time to first capacity adjustment, initial stimulus draw
C2 capacity adjustment fraction	Size of capacity adjustment	0.5	Percentage of existing capacity used the expansion amount
S3 initial separation capacity (LREE/HREE)	Capacity utilization and rate of adjustments	300/150 KT/Year	Time to first capacity adjustment, initial stimulus draw
S3 capacity adjustment fraction	Size of capacity adjustment	0.5	Percentage of existing capacity used the expansion amount
M1 Desired Mining	M1 production and downstream	2023 – 2050 annual production increase 2.5%	Annual M1 production increases

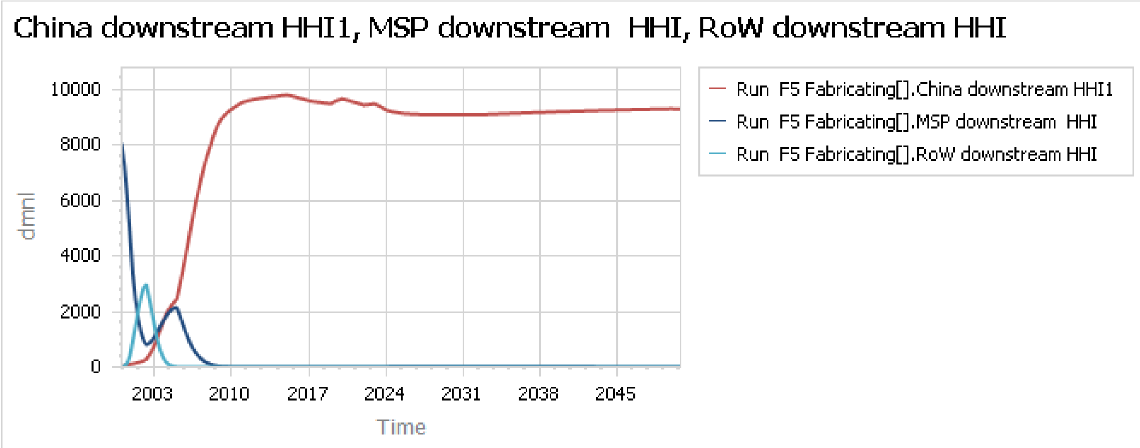
These settings result in the expected result that as demand increases with time the China TG retains its dominant market position and the transition cost and schedule KPIs show the need for ongoing MSP stimulus funding.

Graphs:

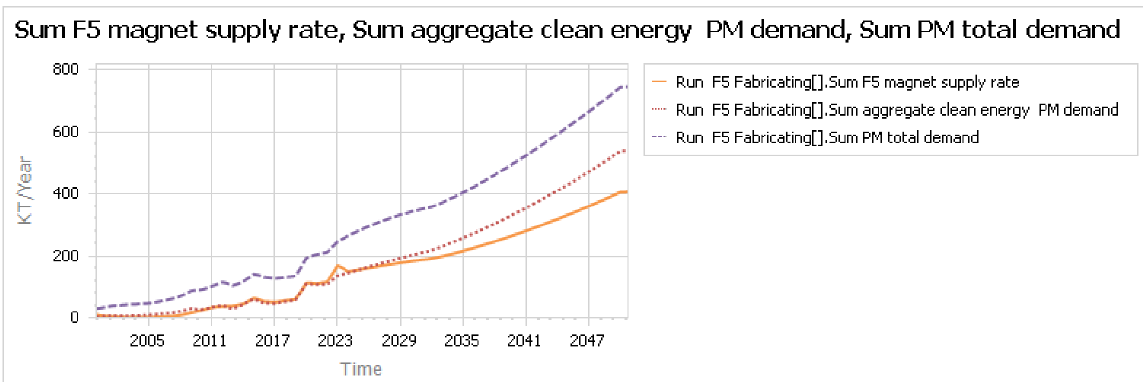
(a)



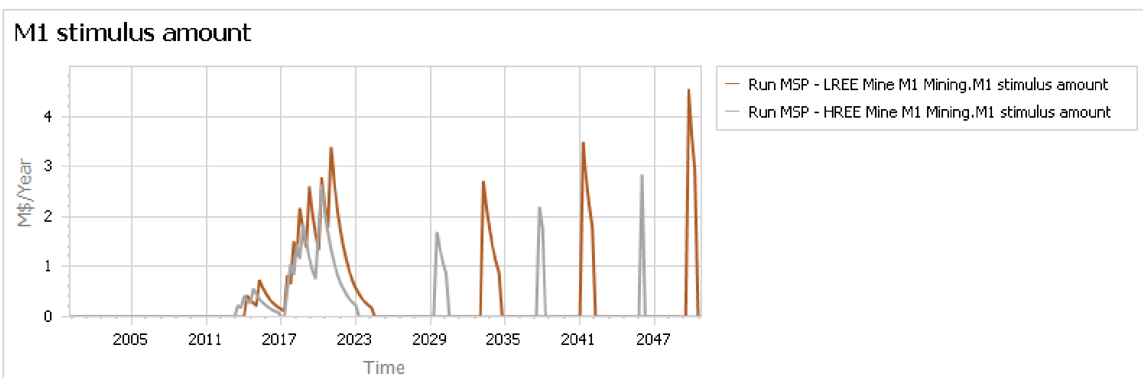
(b)


China downstream HHI1, MSP downstream HHI, RoW downstream HHI
dmnl
10000
8000
6000
4000
2000
0
2003
2010
2017
2024
2031
2038
2045
Time
Run F5 Fabricating[].China downstream HHI1
Run F5 Fabricating[].MSP downstream HHI
Run F5 Fabricating[].RoW downstream HHI

(c)


Sum F5 magnet supply rate, Sum aggregate clean energy PM demand, Sum PM total demand
KT/Year
800
600
400
200
0
2005
2011
2017
2023
2029
2035
2041
2047
Time
Run F5 Fabricating[].Sum F5 magnet supply rate
Run F5 Fabricating[].Sum aggregate clean energy PM demand
Run F5 Fabricating[].Sum PM total demand

(d)


M1 stimulus amount
M$/Year
4
3
2
1
0
2005
2011
2017
2023
2029
2035
2041
2047
Time
Run MSP - LREE Mine M1 Mining.M1 stimulus amount
Run MSP - HREE Mine M1 Mining.M1 stimulus amount

(e)

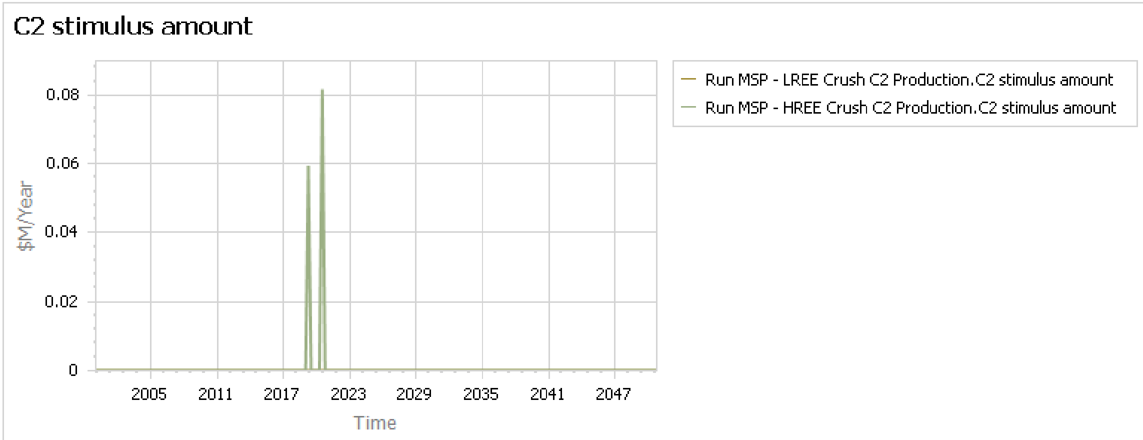


Figure 62. Base Case scenario results (graphs (a) through (e)).

Results:

- Production Diversity: as expected, the HHI graphs show China very near the top of the scale through to 2050 for downstream magnet fabrication. This is the expected result since the in this scenario China TG production growth will keep pace with new production coming online in the MSP and RoW TGs. This result would persist, all other things equal, until China mineral resources start to decline. For the very large China TG Bayan Obo LREE mine this is not expected in the in the model timeframe, however, HREE resources in south China and Myanmar may experience resource decline due the growth rate of permanent magnet demand. China is mitigating this risk by allowing unrestricted, tax-free imports of mineral concentrate and mixed rare earth carbonate to reduce trade group HREE extraction rates. This strategy would see the MSP TG HHI increase for downstream production but remain low for midstream and upstream production.

- Aggregate Production: consistent with industry forecasts, this KPI shows downstream aggregate F5 Fabrication permanent magnet production keeping pace with clean energy demand until approximately 2030 due to strong demand growth driven by EV production. The size of the demand/supply gap assumes upstream and midstream production will continue to grow linearly during the model period.
- Transition Cost and Schedule: The fabrication demand gap provides growth feedback to upstream and midstream production. As a result, M1 stimulus (d) for both MSP LREE and HREE mines shows long-term need for stimulus funding to keep pace with upstream demand. C2 stimulus does not appear to be required, likely due to the higher revenue generated due to C2 value-add processing.

6.2 Scenario 2: Firm Strategy

This scenario considers actions in the mine to magnet process. The scenario variables are in Entity Initialization file PM_FS_init. The initialization values for this scenario are based on published data for stream variables and demand. Settings for key variables are in Table 29.

Table 29. Variable settings for Firm Strategy scenario.

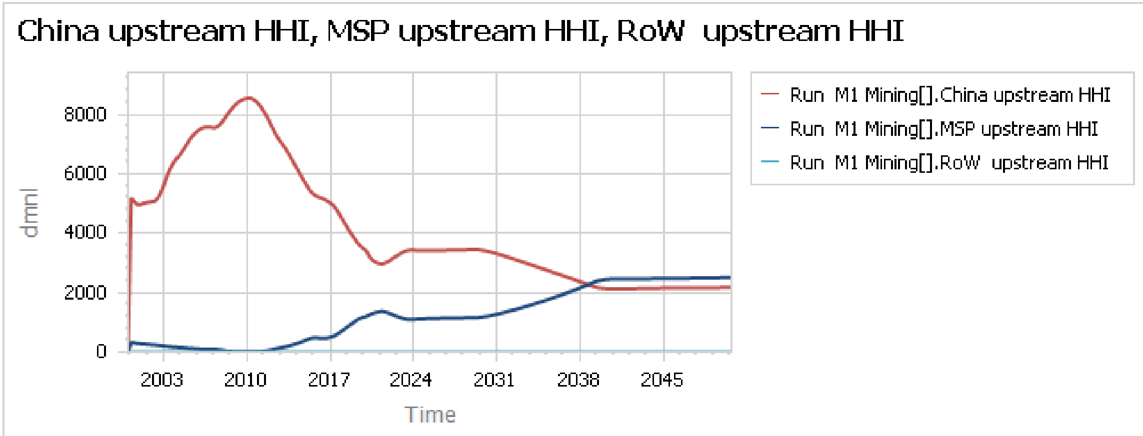
Variable	Affects	MSP Setting (units)	Effect
M1 stimulus share C2 stimulus share S3 stimulus share	M1 stimulus amount C2 stimulus amount S3 stimulus amount	0.2 (dmnl)	20% of the investment required for expansion is provided as stimulus funding

M1 initial extraction capacity (LREE/HREE)	Capacity utilization and rate of adjustments	5250/1000 KT/Year	Time to first capacity adjustment, initial stimulus draw; 1.5x increases from
M1 capacity adjustment fraction	Size of capacity adjustment	0.2 (dmnl)	Percentage of existing capacity used the expansion amount
C2 initial concentration capacity (LREE/HREE)	Capacity utilization and rate of adjustments	350/150 KT/Year	Time to first capacity adjustment, initial stimulus draw
C2 capacity adjustment fraction	Size of capacity adjustment	0.5	Percentage of existing capacity used the expansion amount
S3 initial separation capacity (LREE/HREE)	Capacity utilization and rate of adjustments	300/150 KT/Year	Time to first capacity adjustment, initial stimulus draw
S3 capacity adjustment fraction	Size of capacity adjustment	0.5	Percentage of existing capacity used the expansion amount
M1 Desired Mining	M1 production and downstream to C2, S3, etc.	2030 – 2050 increased annual production by 10%	

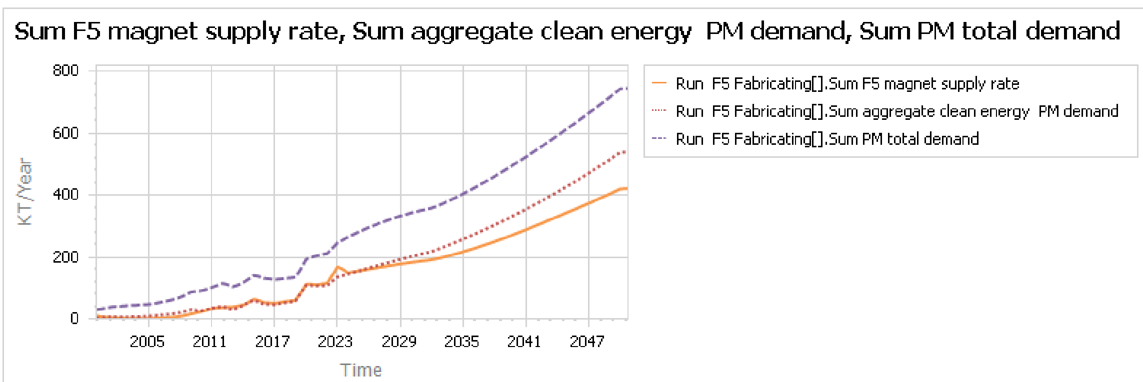
For this scenario MSP M1 Mining initial capacity is increased by 50% with no changes for the other TGs. Production demand for the MSP LREE is also increased to reflect a high growth scenario for wind and EVs in the MSP TG countries that is directed to MSP processors.

Graphs:

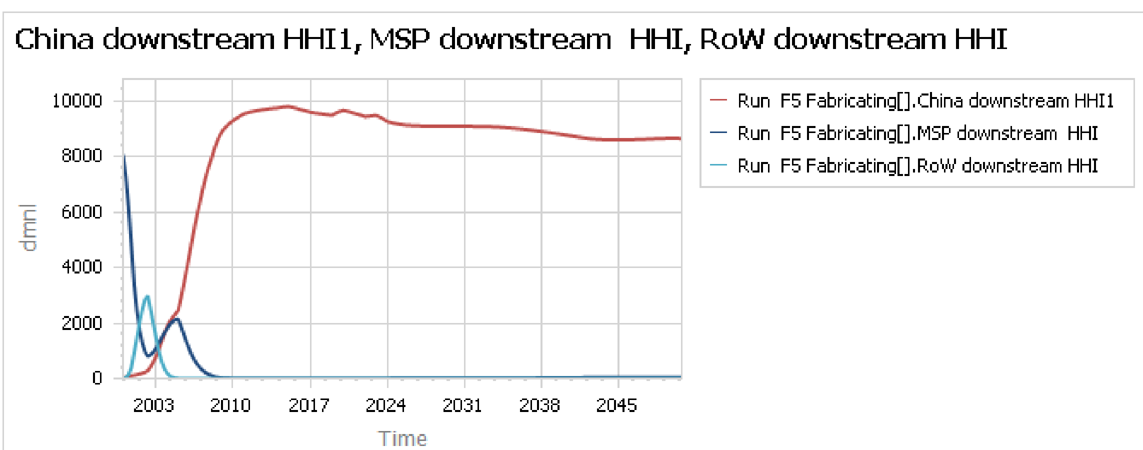
(a)


China upstream HHI, MSP upstream HHI, RoW upstream HHI
Run M1 Mining[].China upstream HHI
Run M1 Mining[].MSP upstream HHI
Run M1 Mining[].RoW upstream HHI
dmnl
8000
6000
4000
2000
0
2003
2010
2017
2024
2031
2038
2045
Time

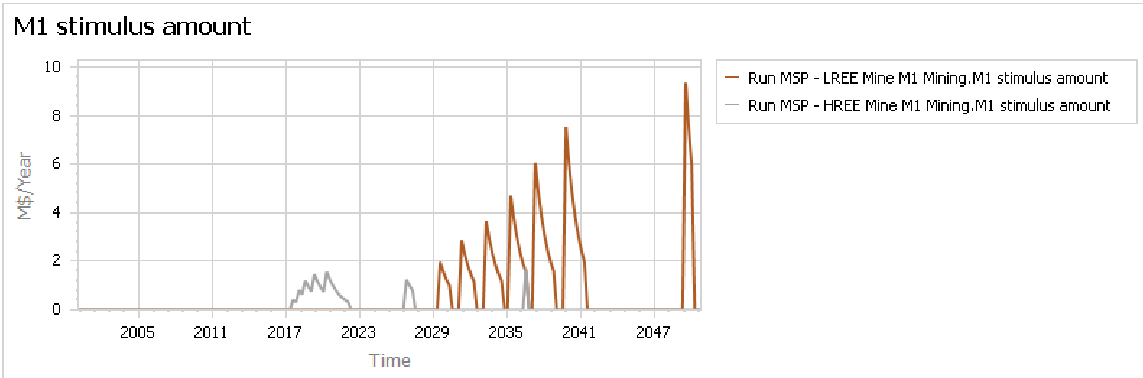
(b)


Sum F5 magnet supply rate, Sum aggregate clean energy PM demand, Sum PM total demand
Run F5 Fabricating[].Sum F5 magnet supply rate
Run F5 Fabricating[].Sum aggregate clean energy PM demand
Run F5 Fabricating[].Sum PM total demand
KT/Year
800
600
400
200
0
2005
2011
2017
2023
2029
2035
2041
2047
Time

(c)


China downstream HHI1, MSP downstream HHI, RoW downstream HHI
Run F5 Fabricating[].China downstream HHI1
Run F5 Fabricating[].MSP downstream HHI
Run F5 Fabricating[].RoW downstream HHI
dmnl
10000
8000
6000
4000
2000
0
2003
2010
2017
2024
2031
2038
2045
Time

(d)



(e)

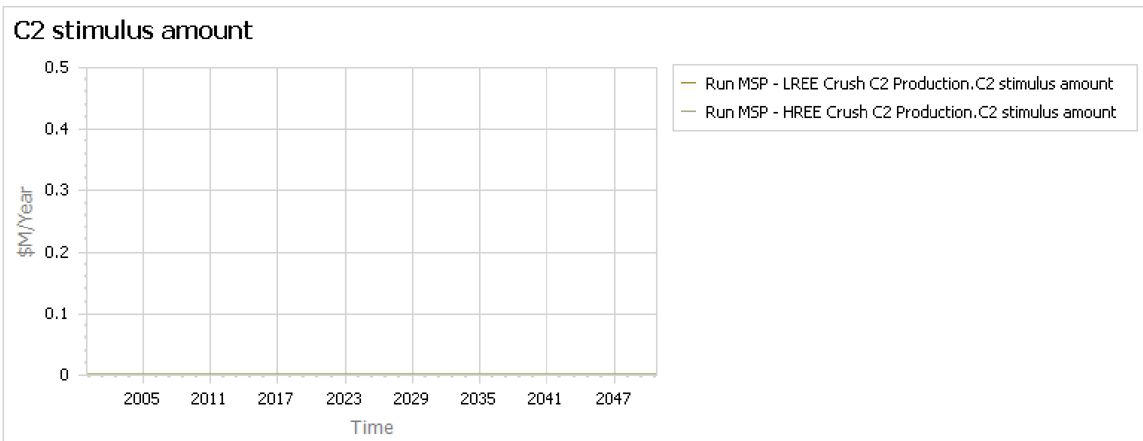


Figure 63. Firm Strategy scenario results (graphs (a) through (e)).

Results:

- Production Diversity: As a result of increasing MSP Desired Mining by 10% from 2.5%/year from 2030 to 2040 to 3.75%/year for the same period, the upstream MSP HHI and the China TG score became roughly equal from 2030 until 2050. The downstream HHI showed China TG market dominance continuing to hold. This reflects China TG continued strength in midstream and downstream processing and fabricating to service their large demand market.

The increased production assumes the MSP TG can meet the required mine growth rate and find downstream markets to receive the increased mine output.

- Aggregate Production: The aggregate demand vs supply gap did not change from the base case, as neither China TG nor MSP TG capacity had accelerated growth in this scenario. This is reflective of a transition strategy that does not coordinate mid and downstream capacity with upstream capacity.
- Transition Cost and Schedule: Due to the increased MSP mine production, M1 stimulus for MSP LREE mining continues to be required through to 2050. MSP HREE mining requires less stimulus funding in this scenario, and none past 2038, due to increased Tb and Dy production, albeit in smaller quantities, from LREE mines..

6.3 Scenario 3: Factor Conditions

This scenario considers actions in the effects of innovation including circular economy contributing to production. The scenario variables are in Entity Initialization file PM_FC_init. The initialization values for this scenario are based on published data for stream variables and demand. Settings for key variables are in Table 30.

Table 30. Variable settings for Firm Strategy scenario.

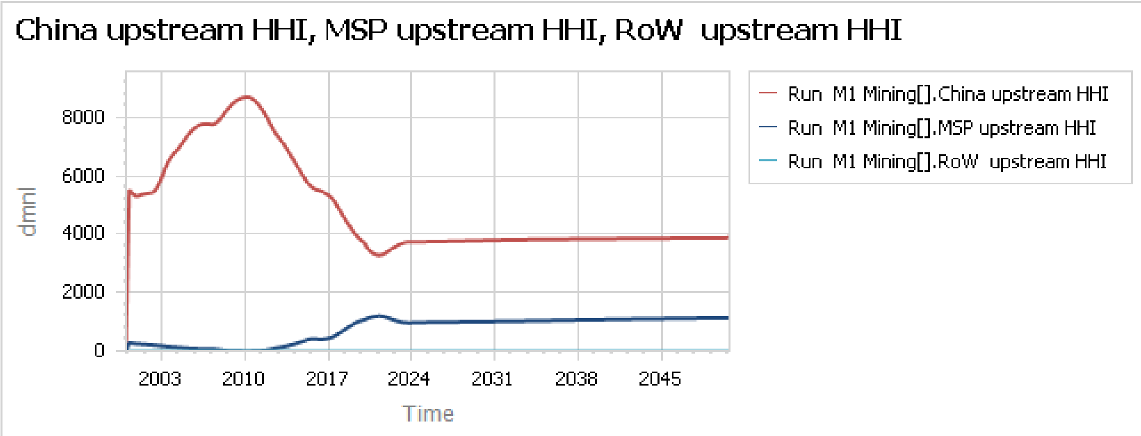
Variable	Affects	MSP Setting (units)	Effect
M1 stimulus share C2 stimulus share S3 stimulus share	M1 stimulus amount C2 stimulus amount S3 stimulus amount	0.2 (dmnl)	20% of the investment required for expansion is provided as stimulus funding

M1 initial extraction capacity (LREE/HREE)	Capacity utilization and rate of adjustments	3500/1000 KT/Year	Time to first capacity adjustment, initial stimulus draw; 1.5x increases from
M1 capacity adjustment fraction	Size of capacity adjustment	0.2 (dmnl)	Percentage of existing capacity used the expansion amount
C2 initial concentration capacity (LREE/HREE)	Capacity utilization and rate of adjustments	350/150 KT/Year	Time to first capacity adjustment, initial stimulus draw
C2 capacity adjustment fraction	Size of capacity adjustment	0.5	Percentage of existing capacity used the expansion amount
S3 initial separation capacity (LREE/HREE)	Capacity utilization and rate of adjustments	300 KT/Year	Time to first capacity adjustment, initial stimulus draw
S3 capacity adjustment fraction	Size of capacity adjustment	0.5	Percentage of existing capacity used the expansion amount
M1 mass upgrade ratio C2 mass upgrade ratio S3 mass upgrade ratio	Grade after processing	1.05	5% increase in mass upgrade ratio to increase the metal grade after processing and increase value
M1 mass reduction C2 mass reduction S3 mass reduction	Percent rare earths in process output	1.05	5% increase in mass reduction to remove gangue and increase value
M1 recovery fraction C2 recovery fraction S3 recovery fraction	Amount of rare earths in process output	1.005	0.05% increase in metal recovery to increase value

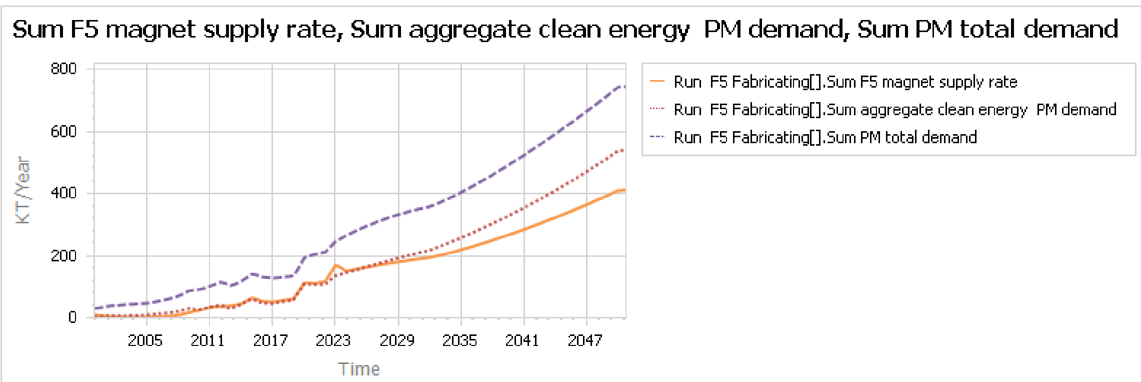
This scenario tests one aspect of innovation, process improvement, by increasing three variables: mass upgrade ratio, mass reduction, and recovery fraction.

Graphs:

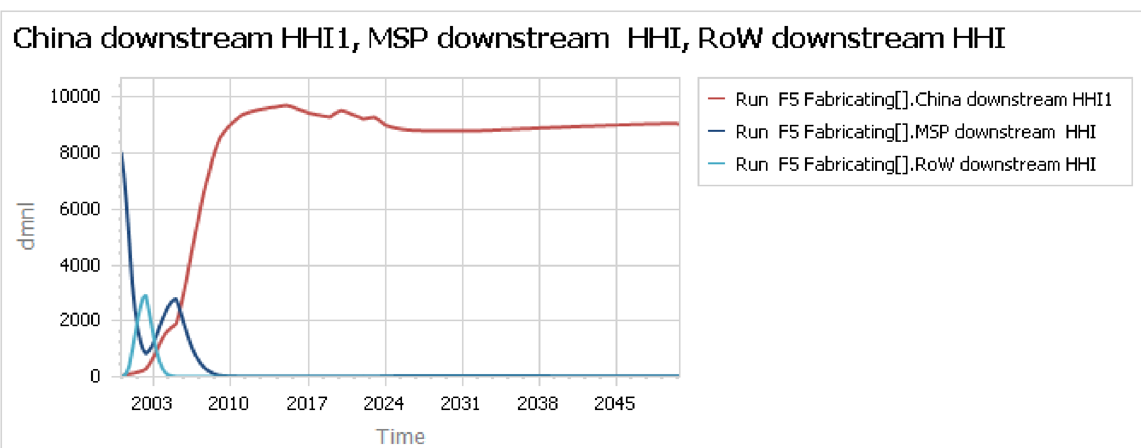
(a)


China upstream HHI, MSP upstream HHI, RoW upstream HHI
Run M1 Mining[].China upstream HHI
Run M1 Mining[].MSP upstream HHI
Run M1 Mining[].RoW upstream HHI
8000
6000
4000
2000
0
dmnl
2003
2010
2017
2024
2031
2038
2045
Time

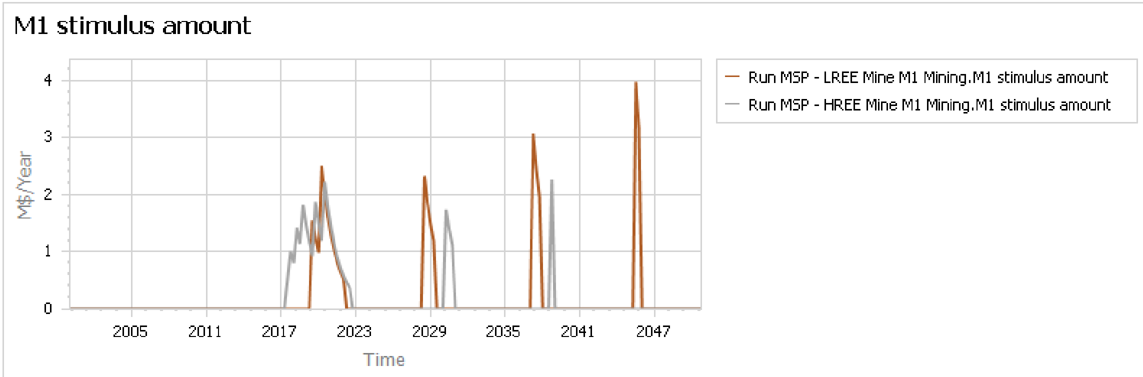
(b)


Sum F5 magnet supply rate, Sum aggregate clean energy PM demand, Sum PM total demand
Run F5 Fabricating[].Sum F5 magnet supply rate
Run F5 Fabricating[].Sum aggregate clean energy PM demand
Run F5 Fabricating[].Sum PM total demand
800
600
400
200
0
KT/Year
2005
2011
2017
2023
2029
2035
2041
2047
Time

(c)


China downstream HHI1, MSP downstream HHI, RoW downstream HHI
Run F5 Fabricating[].China downstream HHI1
Run F5 Fabricating[].MSP downstream HHI
Run F5 Fabricating[].RoW downstream HHI
10000
8000
6000
4000
2000
0
dmnl
2003
2010
2017
2024
2031
2038
2045
Time

(d)



(e)

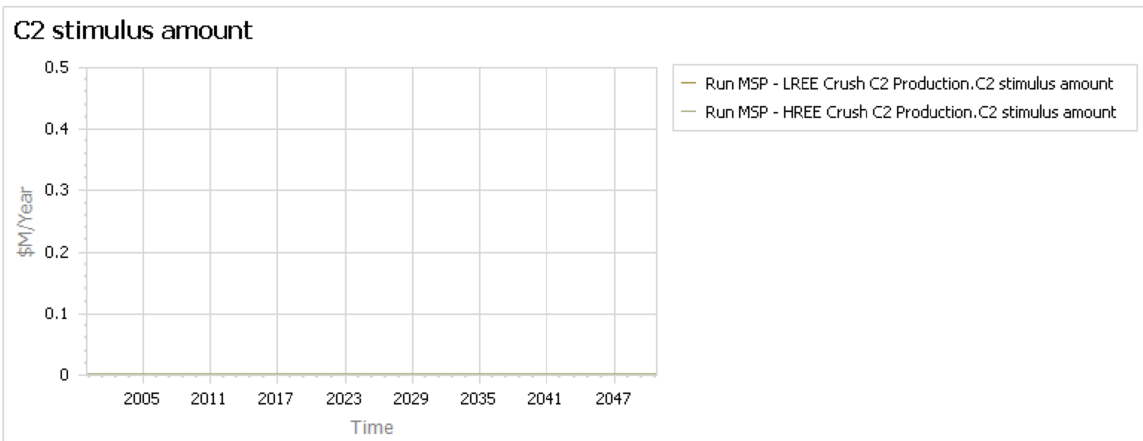


Figure 64. Factor Condition scenario results (graphs (a) through (e)).

Results:

- Production Diversity: As this innovation-centric scenario does not increase production, production diversity did not change from the base case.
- Aggregate Production: As this innovation-centric scenario does not increase production, production diversity did not change from the base case.
- Transition Cost and Schedule: The innovations did increase oxide and metal grades but not significantly enough to increase gross revenue from M1 concentrate sales. As a result, M1 stimulus cost and schedule remained the same

as for the Base Case scenario. The increased grade did positively affect C2 carbonate sales, eliminating the need for C2 stimulus.

6.4 Scenario 4: Government

This scenario considers actions in the effects of government interventions. The scenario variables are in Entity Initialization file PM_GV_init. The initialization values for this scenario are based on published data for stream variables and demand. Settings for key variables are in Table 31.

Table 31. Variable settings for Government scenario.

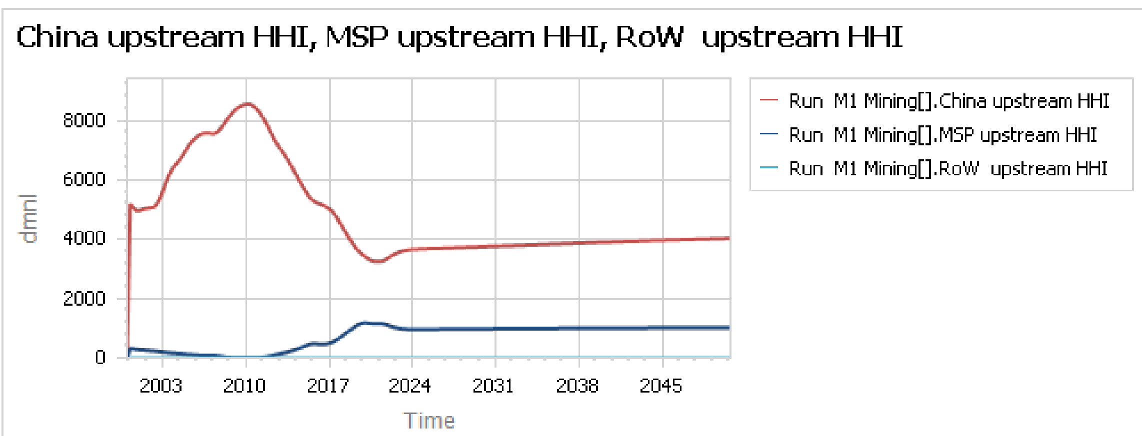
Variable	Affects	MSP Setting (units)	Effect
M1 stimulus share C2 stimulus share S3 stimulus share	M1 stimulus amount C2 stimulus amount S3 stimulus amount	0.4 (dmnl)	40% of the investment required for expansion is provided as stimulus funding
M1 initial extraction capacity (LREE/HREE)	Capacity utilization and rate of adjustments	3500/1000 KT/Year	Time to first capacity adjustment, initial stimulus draw; 1.5x increases from
M1 capacity adjustment fraction	Size of capacity adjustment	0.2 (dmnl)	Percentage of existing capacity used the expansion amount
C2 initial concentration capacity (LREE/HREE)	Capacity utilization and rate of adjustments	350/150 KT/Year	Time to first capacity adjustment, initial stimulus draw
C2 capacity adjustment fraction	Size of capacity adjustment	0.5	Percentage of existing capacity used the expansion amount
S3 initial separation capacity (LREE/HREE)	Capacity utilization and rate of adjustments	300/150 KT/Year	Time to first capacity adjustment, initial stimulus draw
S3 capacity adjustment fraction	Size of capacity adjustment	0.5	Percentage of existing capacity used the expansion amount
SepCoRefco TG allocations	Percentage of TG S3 separation output shipping to R4 refineries	60% of MSP TG S3 production, 30% of RoW TG S3 production	Increase midstream production diversification

Variable	Affects	MSP Setting (units)	Effect
RefCoFabCo TG allocations	Percentage of TG R4 refining output shipping to F5 fabrication	80% of MSP TG R4 production, 30% of RoW TG R4 production	Increase upstream production diversification

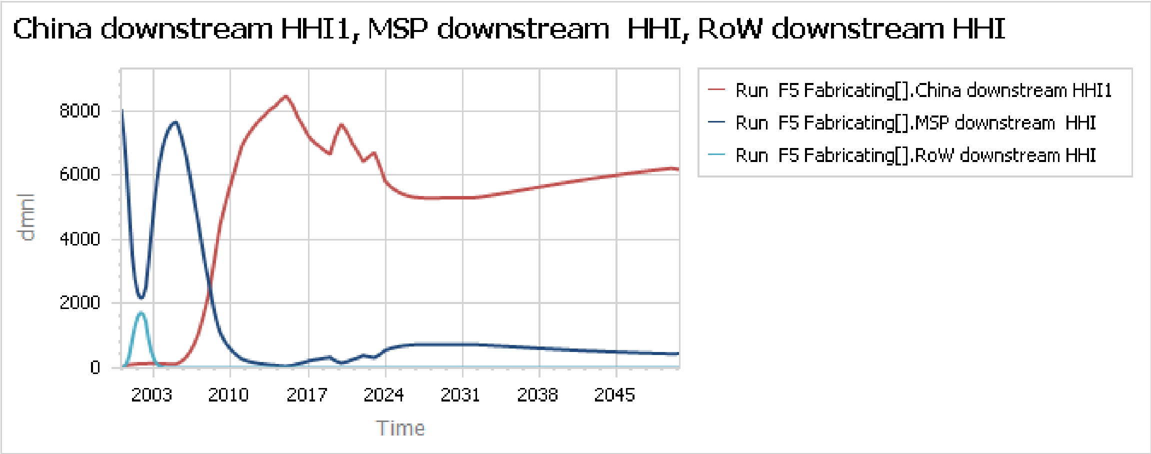
For this scenario the MSP TG Government determinant has negotiated offtake trade agreements with the RoW TG Government determinant to provide R4 Refining and F5 Fabrication processing. This scenario assumes such R4 and F5 facilities are available. M1 production returns to base case levels.

Graphs:

(a)



(b)


China downstream HHI1, MSP downstream HHI, RoW downstream HHI
Run F5 Fabricating[].China downstream HHI1
Run F5 Fabricating[].MSP downstream HHI
Run F5 Fabricating[].RoW downstream HHI
dmnl
8000
6000
4000
2000
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2003
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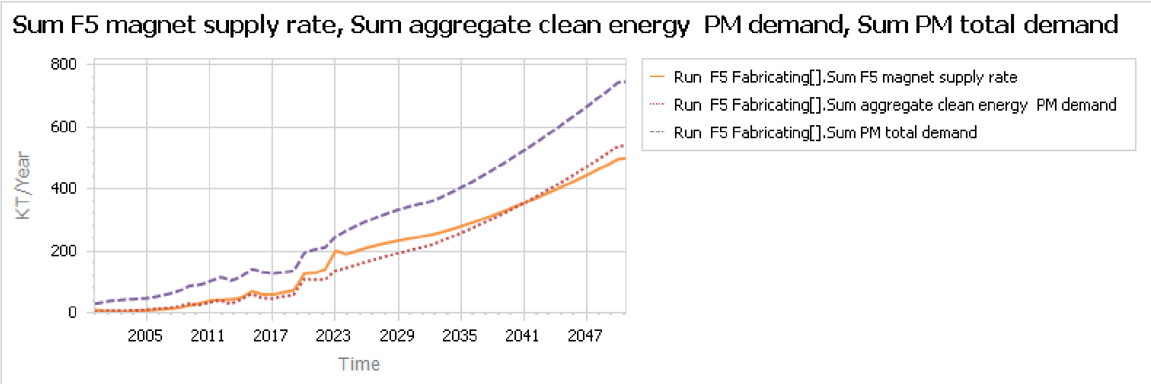
2017
2024
2031
2038
2045
Time

(c)


Sum F5 magnet supply rate, Sum aggregate clean energy PM demand, Sum PM total demand
Run F5 Fabricating[].Sum F5 magnet supply rate
Run F5 Fabricating[].Sum aggregate clean energy PM demand
Run F5 Fabricating[].Sum PM total demand
KT/Year
800
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2005
2011
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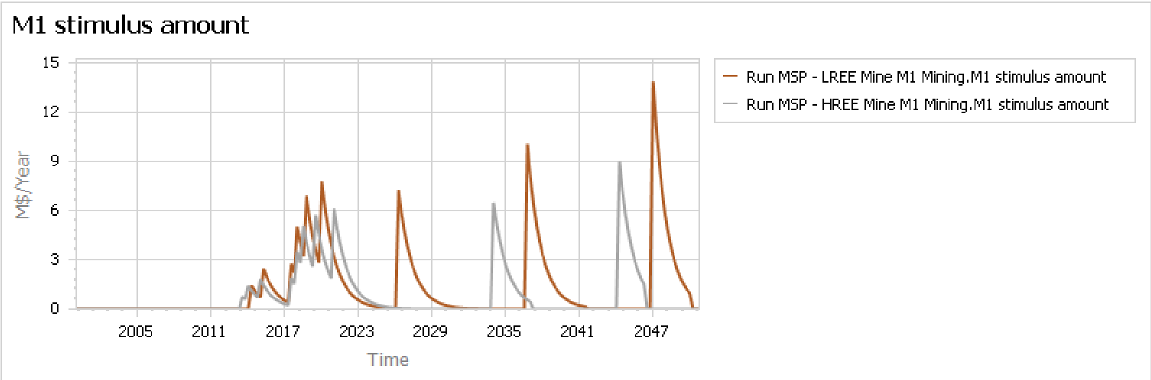
2029
2035
2041
2047
Time

(d)


M1 stimulus amount
Run MSP - LREE Mine M1 Mining.M1 stimulus amount
Run MSP - HREE Mine M1 Mining.M1 stimulus amount
M$/Year
15
12
9
6
3
0
2005
2011
2017
2023
2029
2035
2041
2047
Time

(e)

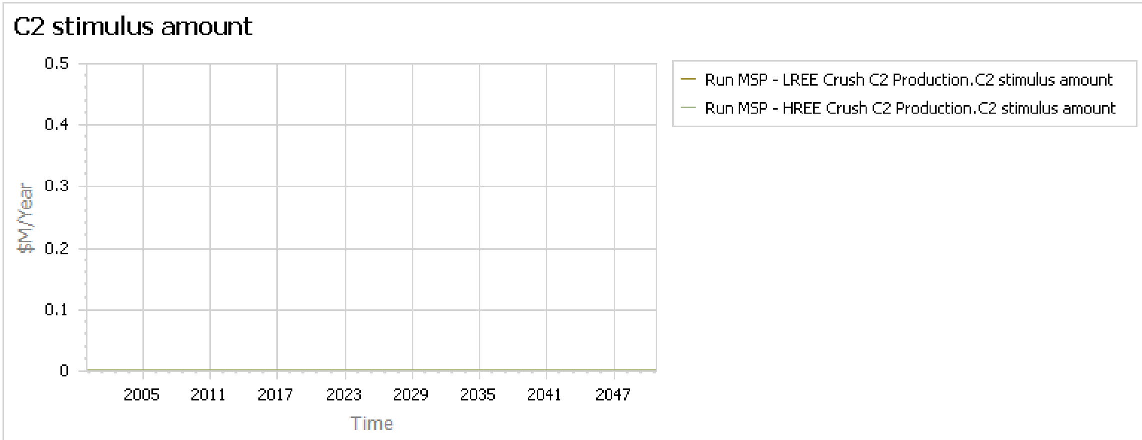


Figure 65. Government scenario results (graphs (a) through (e)).

Results:

- Production Diversity: This Government determinant action improved the MSP TG HHI scores for downstream fabrication from near zero to near 1000 from 2025 to 2050, while. China TG scores remained near 6000 for that period. This marked improvement is due to hypothetical trade negotiations that provided MSP TG downstream producers with demand from China TG midstream S3 and upstream R4 refiners producers.
- Aggregate Production: Reallocation of RoW S3 and R4 offtake improved aggregate production, essentially eliminating the permanent magnet demand/supply gap through to 2050.
- Transition Cost and Schedule: M1 production in this scenario is the same as the base case, therefore M1 stimulus is the same. C2 stimulus was eliminated due to increased carbonate demand from S3 separation.

6.5 Scenario 5: Multi-Determinant

This scenario considers actions in the effects from multiple determinants acting concurrently. The variables chosen for this scenario are based on results from the previous scenarios. The scenario variables are in Entity Initialization file PM_MD_init. Settings for key variables are in Table 32.

The most pronounced effect on the MSP TG KPIs from the previous scenarios occurred in Scenario 2 – Firm Strategy by increasing MSP TG mine production and in Scenario 4 – Government by increasing R4 refining and F5 fabrication allocation through trade agreements. In this scenario we combine the actions from scenarios 2 and 4.

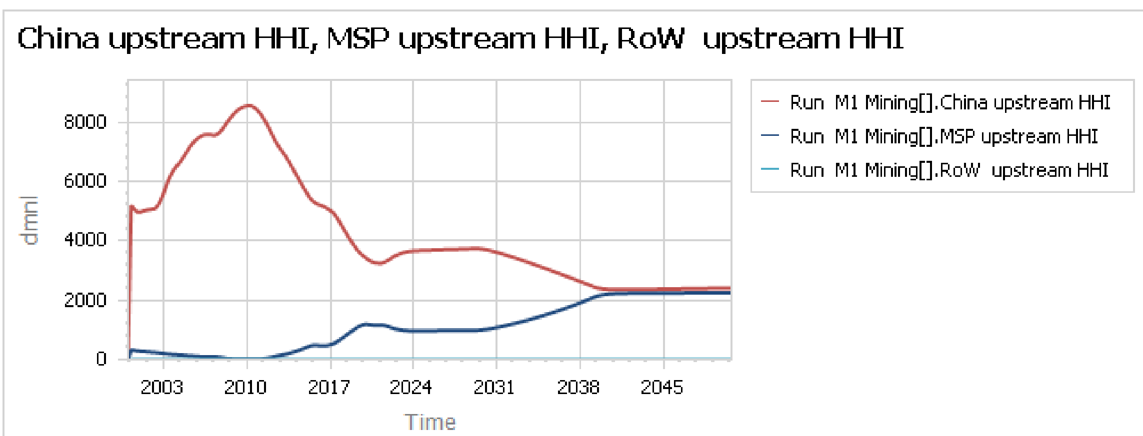
Table 32. Variable settings for Firm Strategy scenario.

Variable	Affects	MSP Setting (units)	Effect
M1 stimulus share C2 stimulus share S3 stimulus share	M1 stimulus amount C2 stimulus amount S3 stimulus amount	0.2 (dmnl)	20% of the investment required for expansion is provided as stimulus funding
M1 initial extraction capacity (LREE/HREE)	Capacity utilization and rate of adjustments	5250/1000 KT/Year	Time to first capacity adjustment, initial stimulus draw; 1.5x increases from
M1 capacity adjustment fraction	Size of capacity adjustment	0.2 (dmnl)	Percentage of existing capacity used the expansion amount
C2 initial concentration capacity (LREE/HREE)	Capacity utilization and rate of adjustments	350/150 KT/Year	Time to first capacity adjustment, initial stimulus draw
C2 capacity adjustment fraction	Size of capacity adjustment	0.5	Percentage of existing capacity used the expansion amount
S3 initial separation capacity (LREE/HREE)	Capacity utilization and rate of adjustments	300/150 KT/Year	Time to first capacity adjustment, initial stimulus draw
S3 capacity adjustment fraction	Size of capacity adjustment	0.5	Percentage of existing capacity used the expansion amount
M1 stimulus share C2 stimulus share S3 stimulus share	Size of capacity adjustment	0.5	Percentage of existing capacity used the expansion amount

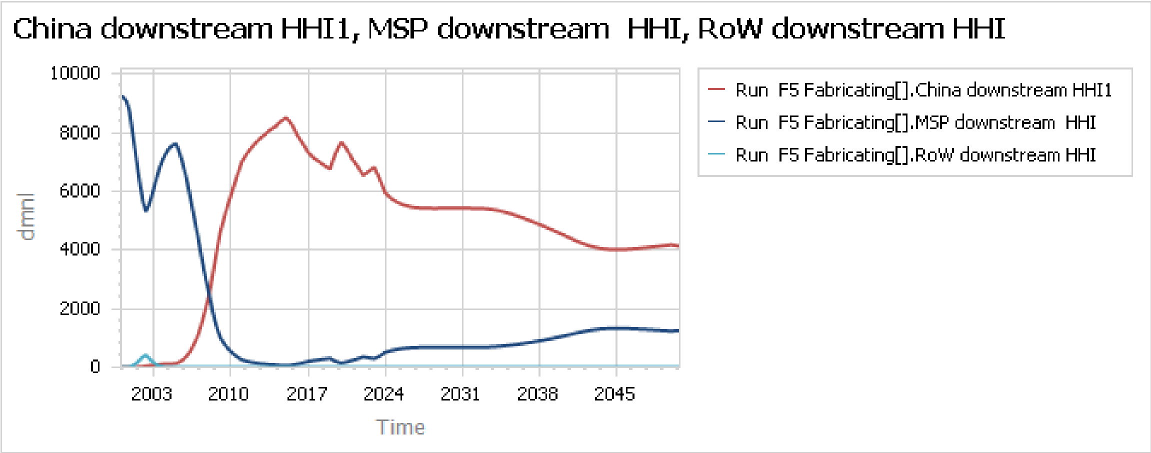
Variable	Affects	MSP Setting (units)	Effect
M1 Desired Mining	M1 production and downstream to C2, S3, etc.	2030 – 2050 increased annual production by 10%	
SepCoRefco TG allocations	Percentage of TG S3 separation output shipping to R4 refineries	60% of MSP TG S3 production, 30% of RoW TG S3 production	Increase midstream production diversification
RefCoFabCo TG allocations	Percentage of TG R4 refining output shipping to F5 fabrication	80% of MSP TG R4 production, 30% of RoW TG R4 production	Increase upstream production diversification

Graphs:

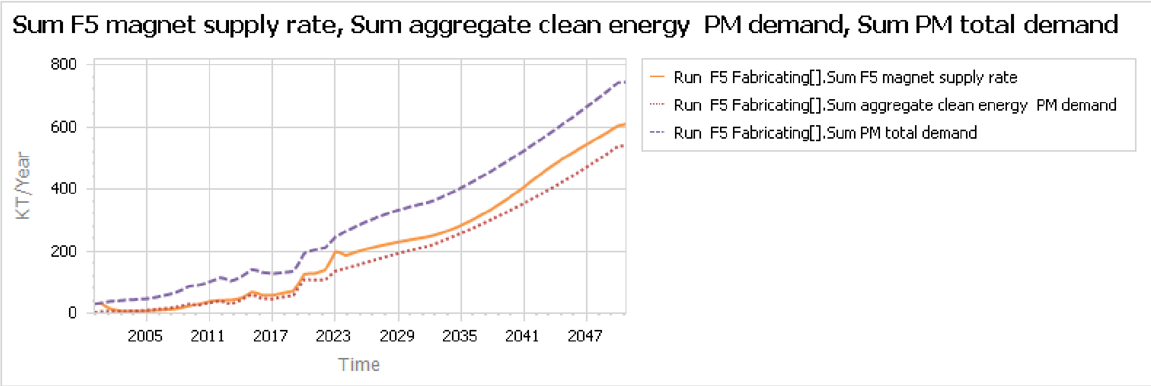
(a)



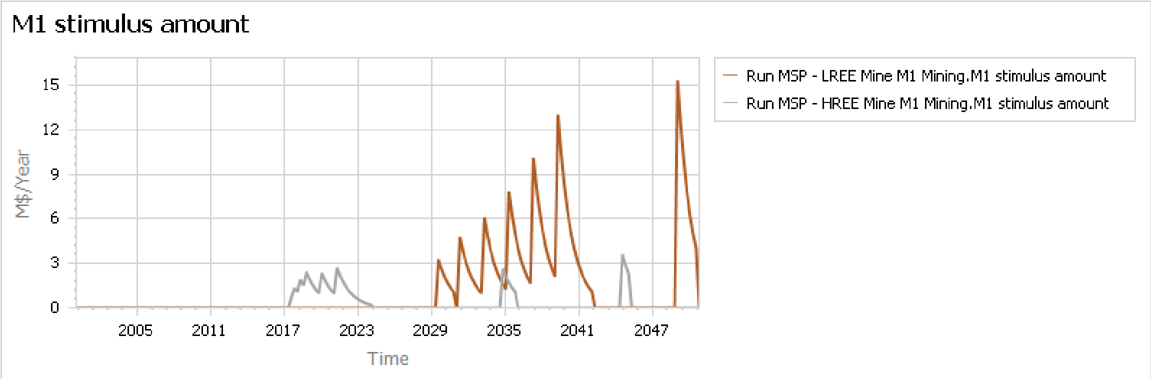
(b)


China downstream HHI1, MSP downstream HHI, RoW downstream HHI
10000
8000
6000
4000
2000
0
dmnl
2003
2010
2017
2024
2031
2038
2045
Time
Run F5 Fabricating[].China downstream HHI1
Run F5 Fabricating[].MSP downstream HHI
Run F5 Fabricating[].RoW downstream HHI

(c)


Sum F5 magnet supply rate, Sum aggregate clean energy PM demand, Sum PM total demand
800
600
400
200
0
KT/Year
2005
2011
2017
2023
2029
2035
2041
2047
Time
Run F5 Fabricating[].Sum F5 magnet supply rate
Run F5 Fabricating[].Sum aggregate clean energy PM demand
Run F5 Fabricating[].Sum PM total demand

(d)


M1 stimulus amount
15
12
9
6
3
0
M$/Year
2005
2011
2017
2023
2029
2035
2041
2047
Time
Run MSP - LREE Mine M1 Mining.M1 stimulus amount
Run MSP - HREE Mine M1 Mining.M1 stimulus amount

(e)

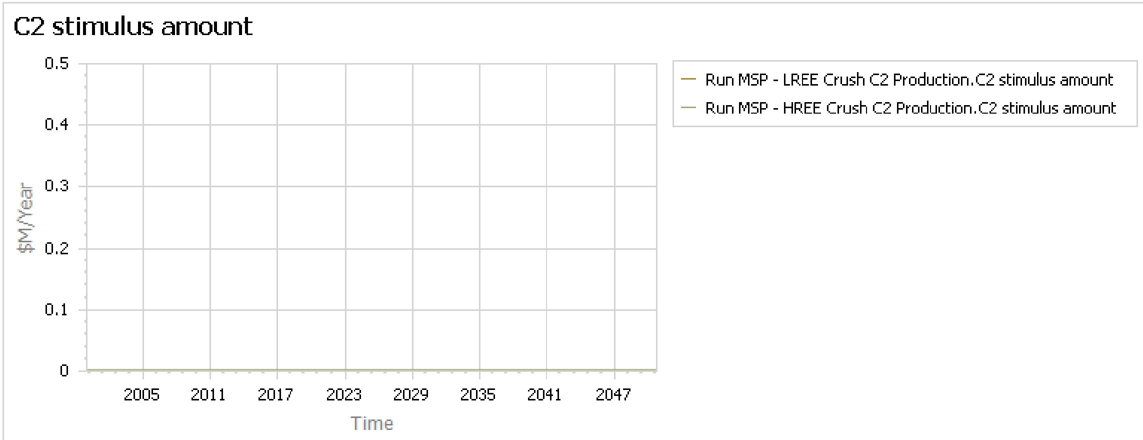


Figure 66. Multi-determinant scenario results (graphs (a) through (e)).

Results:

- The combined Firm Strategy and Government determinant actions replicated the MSP HHI scores marginally from Scenario 4. MSP TG upstream HHI achieved the production diversification goal, and showing downstream HHI improvement.
- Aggregate Production: Permanent magnet supply exceeded clean energy magnet demand for the entire model period, achieving the MSP TG aggregate production goal.
- Transition Cost and Schedule: This scenario required M1 stimulus for both LREE and HREE mine due to increased production. The same factors that eliminated the need for C1 stimulus funding in scenario 4 (GV) were present here.

CHAPTER VII

FINDINGS

The results show that the diamond model determinant scenarios show transition progress based on the KPIs; however, the level of improvement attained for production diversity in downstream operations was lower than the desired MSP TG goal. Better outcomes were achieved for aggregate production; transition cost and schedule for upstream operations did not achieve its goal.

The government and multi-determinant scenarios were able to achieve the production diversification goal for upstream operations by aggressive increases in extraction.

Permanent magnet aggregate production exceeded aggregate demand in the multi-determinant scenario when government negotiated agreements with the China TG permitted MSP TG mid and downstream producers greater access those markets. These results suggest that government policy design and industry strategy implementation in the MSP nations should be multi-tracked, emphasizing the diamond model determinants Firm Strategy and Government. Firm Strategy would benefit from coordinated expansion of capacity in all streams to achieve mine to magnet processing for both the MSP and RoW TGs. Government actions that emphasize trade policies to open China TG clean energy demand to MSP TG producers would maximize global capacity in meeting celan energy demand.

Bown and Clausing (2023) provide insight into such trade negotiation strategies, using a detailed analysis of the ‘gives’ (costs) and ‘gets’ (benefits) and the overall gains of trade cooperation for the clean energy transition. Figure 67 summarizes an example of their coordinated approach.

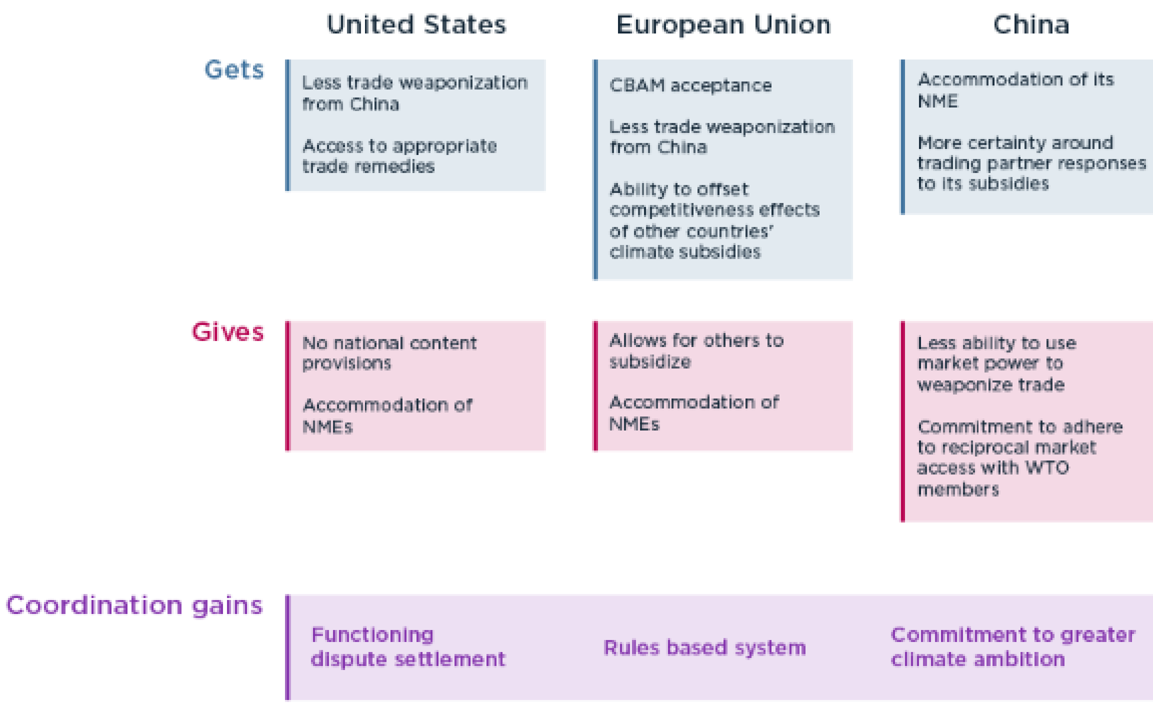


Figure 67. Coordinated trade action gains for clean energy transition. Source Bown and Clausing (p.27)

In their presented scenario, from an MSP perspective (combined U.S. and the European Union), the China 'gives' – less ability to use market power to weaponize trade and commitment to reciprocal market access – would reestablish a degree of global supply security and provide the market access required to match the model allocations. In return China would 'get' less scrutiny of its non-market economy (NME) and market subsidies, which for rare earths are the use of state-owned enterprises.

The largest improvements in the four transition KPIs over the Base Case scenario was seen in Scenario 2- Firm Strategy. As expected, increased production was the cause of the KPI improvement, but the nature of the increased production – coming from MSP clean energy demand – signals a policy strategy with win-win outcomes for supply security and long-term stability. The strong role of Government in negotiating trade agreements for mid and upstream processing with the ROW TG can establish the international competitive advantage that the diamond model was designed to achieve.

While Scenario 3 – Factor Conditions did not appreciably improve the KPIs, the innovation selected – process improvements to increase oxide and metal grades – would have a stronger effect if process increase for magnet metals, as expected. Care must be taken, however, because as with most metal industries rare earths is cyclic and over-reliance on short-term profits can lead to financial pressure. Also, we did not test for the effect of a skilled labour force on transition cost and schedule, an important Factor condition.

CHAPTER VIII:

CONCLUSION AND FUTURE WORK

This study examined a novel method for formulating the rare earth industry transition strategy. Using a hybrid dynamic simulation model that integrated a systems engineering approach to mine to magnet analysis with diamond model theory, we were able to test the ability of the model to capture key indicators of transition success for various scenarios.

While the scenarios did not discover a ‘home run’ transition scenario, it did provide support for more complex policy choices. These policies could, by reducing transition cost and schedule, lower the overall cost of reestablishing the MSP rare earth industry to lower supply security risks while providing better long-term stability for the industry.

In this study we proceeded methodically by first determining the rare earth industry transition drivers (research question 1), identifying the key performance indicators need to measure the success of the transition (research question 2), and lastly determining if the proposed interdisciplinary method could identify strategies for a successful transition (research question 3).

The findings indicate that method was successful, with limitations. The limitations can largely be attributed to the continued dominance of China in the market in all scenarios. There are two reasons for this conclusion. First, the very large wind and EV markets in China are effectively closed to non-China sourced rare earth products, thus U.S. and EU companies must compete with China, and each other, in the smaller non-China markets. Second, even if those markets were open, China does not permit – at this time – the export of upstream rare earth processing technology or the IP for that technology. These restrictions, unless softened or removed, will delay the time until MSP TG companies are able to compete at scale in the wind and EV sectors. The net combined effect is that the reconstituted MSP TG rare earth industries, which operate under market rules, will likely not be able to achieve the level of supply risk mitigation they seek.

Future work recommendations include the following:

- Expanding this exploratory model into an explanatory model for foresight studies of the rare earth industry transition that bridge policy design and policy implementation.
- Disaggregating the TGs to the mine and plant level to provide greater granularity in examining diamond model determinant effects.
- Expanding the scope of critical minerals included in the model to include lithium, cobalt, and others.
- More detailed modeling of geopolitical risk, for example incorporating the GPR methodology of Caldara and Iacoviello (2022).

The findings support the conclusion that this research has contributed to the knowledge base by demonstrating a new method for analyzing the rare earth industry transition. By showing that a multi-determinant strategy that includes both short- and long-term transition success criteria can improve long-term outcomes we have demonstrated the benefit of bringing long-term industry stability factors into consideration during initial transition policy design.

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APPENDICES

Appendix A Model Documentation

The model documentation generated by Ventity using the View → Equations → Export command is on the following pages.

Component	Component Type	Element	Element Type	Expression	Units	Element Properties	Description
Model	Entity						
Model	Entity	C2 Production TG	Attribute				
Model	Entity	F5 Fabricating TG	Attribute				
Model	Entity	M1 Mining TG	Attribute				
Model	Entity	cost escalation	Auxiliary	if(simulationyear()< 2001) {1} else {(1+0.027/4)^(simulationyear()-2000)}		Value	US Bureau of Labour Statistics, 2000 - 2022
Model	Entity	Dy fraction of PM	Auxiliary	0.0165	dmnl	Value	REE are 35% of PM wt, Dy = 16% of REE = 0.056 KT/KT
Model	Entity	EV permanent magnet fraction	Auxiliary	4.0/1000000	KT/unit	Value	Kruemmer 2013 adjusted to Bureau of Industry & Security 2023 forecast
Model	Entity	Final Time	Auxiliary	120	Year	Constant Value	
Model	Entity	FS M1 Desired Mining Step End	Auxiliary	2040	dmnl	Value	
Model	Entity	FS M1 Desired Mining Step Start	Auxiliary	2029	dmnl	Value	
Model	Entity	Initial Time	Auxiliary	0	Year	Constant Value	
Model	Entity	Nd fraction of PM	Auxiliary	0.27	KT/KT	Value	REE are 35% of PM wt, Nd = 77% of REE = 0.27 KT/KT
Model	Entity	Noise Seed	Auxiliary	-1	Year	Constant Value	
Model	Entity	Offshore permanent magnet fraction	Auxiliary	0.00065*1.44	KT/MW	Value	Pavel et al. (2017) 650kg/MW; adjusted for Bureau I&S forecast
Model	Entity	Onshore permanent magnet fraction	Auxiliary	0.0006*1.44	KT/MW	Value	Pavel et al. (2017) 650kg/MW low-speed direct drive PMSG (no gears) adjusted for Bureau I&S forecast
Model	Entity	policy year	Auxiliary	2019	dmnl	Constant Value	
Model	Entity	Pr fraction of PM	Auxiliary	0.021	dmnl	Value	REE are 35% of PM wt, Pr = 6% of REE = 0.021 KT/KT
Model	Entity	REE fraction per PM	Auxiliary	0.35	dmnl	Constant Value	
Model	Entity	sim year	Auxiliary	SimulationYear()	dmnl	Value	

Model	Entity	Tb fraction of PM	Auxiliary	0.004	dmnl	Value	REE are 35% of PM wt, Tb = 1% of REE = 0.004 KT/KT
Model	Entity	Time	Auxiliary	0	Year	Value	
Model	Entity	Time Step	Auxiliary	1	Year	Constant Value	
Model	Entity	World Event	Auxiliary	if(world event switch=1) {Pulse(35.5,0.25)} else {0}	dmnl	Value	
Model	Entity	world event switch	Auxiliary	1	dmnl	Constant Value	
Model	Entity	C2 Production	Reference	Condition: C2 Production TG C2 Production TG		Target Type: C2 Production	
Model	Entity	F5 Fabricating	Reference	Condition: F5 Fabricating TG F5 Fabricating TG		Target Type: F5 Fabricating	
Model	Entity	Fabricating Collection	Reference			Target Type: F5 Fabricating[]	
Model	Entity	M1 Mining	Reference	Condition: M1 Mining TG M1 Mining TG		Target Type: M1 Mining	
Model	Entity	M1 Mining Collection	Reference			Target Type: M1 Mining[]	
M1 Mining	Entity						
M1 Mining	Entity	C2 Production TG	Attribute				
M1 Mining	Entity	F5 FabCo TG	Attribute				
M1 Mining	Entity	M1 Mining TG	Attribute			key	
M1 Mining	Entity	mine state	Attribute				
M1 Mining	Entity	mineral type	Attribute				
M1 Mining	Entity	accounting period	Auxiliary	1	Year	Value	
M1 Mining	Entity	Ce1 basket share	Auxiliary	Metal Price.CeX Price*Ce1 relative grade	$/kg	Value	
M1 Mining	Entity	Ce1 grade	Auxiliary	0	KT/KT	Constant Value	Ce oxide in resource (ore)
M1 Mining	Entity	Ce1 relative grade	Auxiliary	Ce1 grade/M1 ore grade	KT/KT	Value	
M1 Mining	Entity	China M1 mining	Auxiliary	if(M1 Mining TG="China - LREE Mine" OR M1 Mining TG="China - HREE Mine" OR M1 Mining TG="China - Circ Mine") { C2 feed rate} else {0}	KT/Year	Value	
M1 Mining	Entity	concentrate price fraction	Auxiliary	1-0.25	dmnl	Constant Value	25% discount on concetrate
M1 Mining	Entity	convert kg to KT	Auxiliary	1000	kg/KT	Value	
M1 Mining	Entity	Dy1 Basket Share	Auxiliary	Metal Price.DyX Price*Dy1 relative grade	$/kg	Value	

M1 Mining	Entity	Dy1 grade	Auxiliary	0	KT/KT	Constant Value	Dy oxide in resource (ore)
M1 Mining	Entity	Dy1 relative grade	Auxiliary	Dy1 grade/M1 ore grade	KT/KT	Value	
M1 Mining	Entity	expansion project duration	Auxiliary	5	Year	Value	
M1 Mining	Entity	F5 gap adjustment	Auxiliary	(1+F5 Fabricating.policy year demand supply gap by TG)*F5 gap adjustment switch	dmnl	Value	
M1 Mining	Entity	F5 gap adjustment switch	Auxiliary	1	dmnl	Constant Value	
M1 Mining	Entity	La1 basket share	Auxiliary	Metal Price.LaX Price* La1 relative grade	$/kg	Value	
M1 Mining	Entity	La1 grade	Auxiliary	0	KT/KT	Constant Value	La oxide in resource (ore)
M1 Mining	Entity	La1 relative grade	Auxiliary	La1 grade/M1 ore grade	KT/KT	Value	
M1 Mining	Entity	M1 annual opex	Auxiliary	M1 ore extraction*(M1 Opex/1000*Model.cost escalation)	M$/Year	Value	
M1 Mining	Entity	M1 capacity adjustment	Auxiliary	if(M1 capacity utilization > M1 capacity utilization threshold) { M1 C2 Production.M1 Desired Mining*M1 capacity adjustment fraction} else {0}	KT/Year/Year	Value	
M1 Mining	Entity	M1 capacity adjustment fraction	Auxiliary	0.1	dmnl	Constant Value	
M1 Mining	Entity	M1 capacity evaluation period	Auxiliary	1	year	Value	
M1 Mining	Entity	M1 capacity obsalesence fraction	Auxiliary	0.0001	1/Year	Constant Value	
M1 Mining	Entity	M1 capacity utilization	Auxiliary	M1 production plan/((M1 Ore Extraction Capacity/M1 capacity evaluation period))	dmnl	Value	percentage utilization of capacity
M1 Mining	Entity	M1 capacity utilization threshold	Auxiliary	.9	dmnl	Constant Value	percentage of existing capacity remaining to double existing capacity
M1 Mining	Entity	M1 Capex	Auxiliary	0.0005	M$/KT	Constant Value	
M1 Mining	Entity	M1 concentrate grade	Auxiliary	M1 ore grade*M1 upgrade ratio	dmnl	Value	
M1 Mining	Entity	M1 concentrate initial inventory	Auxiliary	0	KT	Constant Value	
M1 Mining	Entity	M1 Concentrate TREO wt	Auxiliary	oreTREO wt*M1 recovery fraction	KT/Year	Value	
M1 Mining	Entity	M1 extraction capacity utilization fraction	Auxiliary	.95	dmnl	Constant Value	
M1 Mining	Entity	M1 initial extraction capacity	Auxiliary	0	KT/Year	Constant Value	

M1 Mining	Entity	M1 investment requirement	Auxiliary	if(M1 Current Account/M1 stimulus period<2*expansion cost per upgrade) {expansion cost per upgrade} else {0}	M$/Year	Value	
M1 Mining	Entity	M1 mass reduction	Auxiliary	.85	dmnl	Constant Value	
M1 Mining	Entity	M1 max stimulus	Auxiliary	10	M$/Year	Constant Value	
M1 Mining	Entity	M1 Mine Gross Revenue	Auxiliary	((Mine Concentrate Basket Price*convert kg to KT)*concentrate price fraction*C2 feed rate)/1000000	M$/Year	Value	Concentrate revenue is based on world concentrate price. Estimated concentrate price = Basket price x discount fraction = .25
M1 Mining	Entity	M1 MSP LREE Stim	Auxiliary	if(M1 Mining TG="MSP - LREE Mine") { M1 stimulus amount} else {0}	M$/Year	Value	
M1 Mining	Entity	M1 Opex	Auxiliary	0.003	M$/KT	Constant Value	
M1 Mining	Entity	M1 ore extraction	Auxiliary	if(mine state="active") {(Min(M1 production plan,M1 Ore Extraction Capacity))*M1 extraction capacity utilization fraction} else {0}	KT/Year	Value	
M1 Mining	Entity	M1 ore grade	Auxiliary	0	KT/KT	Constant Value	TREO wt, ppm (KT/KT) in resource (ore)
M1 Mining	Entity	M1 production plan	Auxiliary	M1 C2 Production.M1 Desired Mining+M1 C2 Production.M1 Desired Mining*F5 gap adjustment	KT/Year	Value	
M1 Mining	Entity	M1 recovery fraction	Auxiliary	.6	dmnl	Constant Value	
M1 Mining	Entity	M1 stability index	Auxiliary	M1 stability LU(M1 stability LU xvar)	dmnl	Value	
M1 Mining	Entity	M1 stability LU xvar	Auxiliary	M1 stimulus amount/M1 max stimulus	dmnl	Value	
M1 Mining	Entity	M1 stimulus amount	Auxiliary	M1 investment requirement*M1 stimulus share	M$/Year	Value	
M1 Mining	Entity	M1 stimulus period	Auxiliary	10	Year	Value	
M1 Mining	Entity	M1 stimulus share	Auxiliary	0.2	dmnl	Constant Value	
M1 Mining	Entity	M1 upgrade ratio	Auxiliary	6	dmnl	Constant Value	
M1 Mining	Entity	mine activation offset	Auxiliary	0	Year	Constant Value	

M1 Mining	Entity	Mine Concentrate Basket Price	Auxiliary	Pr1 basket share+Nd1 basket share+Tb1 basket share+Dy1 Basket Share+La1 basket share+Ce1 basket share	$/kg	Value	
M1 Mining	Entity	mine expansion Opex per KT	Auxiliary	12000/1000000	M$/KT	Constant Value	
M1 Mining	Entity	MSP M1 mining	Auxiliary	if(M1 Mining TG="MSP - LREE Mine" OR M1 Mining TG="MSP - HREE Mine" OR M1 Mining TG="MSP - Circ Mine") { C2 feed rate} else {0}	KT/Year	Value	
M1 Mining	Entity	Nd1 basket share	Auxiliary	Metal Price.NdX Price* Nd1 relative grade	$/kg	Value	
M1 Mining	Entity	Nd1 grade	Auxiliary	0	KT/KT	Constant Value	Nd oxide in resource (ore)
M1 Mining	Entity	Nd1 relative grade	Auxiliary	Nd1 grade/M1 ore grade	KT/KT	Value	
M1 Mining	Entity	oreTREO wt	Auxiliary	M1 ore extraction*M1 ore grade	KT/Year	Value	
M1 Mining	Entity	Pr1 basket share	Auxiliary	Metal Price.PrX Price*Pr1 relative grade	$/kg	Value	
M1 Mining	Entity	Pr1 grade	Auxiliary	0	KT/KT	Constant Value	Pr oxide in resource (ore)
M1 Mining	Entity	Pr1 relative grade	Auxiliary	Pr1 grade/M1 ore grade	KT/KT	Value	
M1 Mining	Entity	production period	Auxiliary	1	Year	Value	
M1 Mining	Entity	ResKT	Auxiliary	0	KT	Constant Value	Resource inferred & indicated amounts, kilotonnes
M1 Mining	Entity	RoW M1 mining	Auxiliary	if(M1 Mining TG="RoW - LREE Mine" OR M1 Mining TG="RoW - HREE Mine" OR M1 Mining TG="RoW - Circ Mine") { C2 feed rate} else {0}	KT/Year	Value	
M1 Mining	Entity	Startup Cost	Auxiliary	0	$	Constant Value	
M1 Mining	Entity	Startup Financing	Auxiliary	0	M$	Constant Value	
M1 Mining	Entity	Tb1 basket share	Auxiliary	Metal Price.TbX Price*Tb1 relative grade	$/kg	Value	
M1 Mining	Entity	Tb1 grade	Auxiliary	0	KT/KT	Constant Value	Tb oxide in resource (ore)
M1 Mining	Entity	Tb1 relative grade	Auxiliary	Tb1 grade/M1 ore grade	KT/KT	Value	
M1 Mining	Entity	M1 stability LU	TableFunction	0,1,0,100,0,100,0.1,100,0.2,75,0.5,60,0.8,25,1,0,10,0			

M1 Mining	Entity	Accumulated Stimulus	Stock	0	M$		
M1 Mining	Entity	stimulus accumulation rate	Flow	M1 stimulus amount	M$/Year	Inflow (Accumulated Stimulus)	
M1 Mining	Entity	Cost of Capacity	Stock	Startup Cost	M$		
M1 Mining	Entity	expansion cost per upgrade	Flow	expansion annual expenditure	M$/Year	Inflow (Cost of Capacity)	
M1 Mining	Entity	M1 Accumulated Extraction	Stock	0	KT		
M1 Mining	Entity	extraction rate	Flow	if(2*M1 ore extraction<M1 Resource Ore Quantity) {M1 ore extraction} else {0}	KT/Year	Inflow (M1 Accumulated Extraction)	
M1 Mining	Entity	M1 Concentrate	Stock	M1 concentrate initial inventory	KT		concentrate after comminution and flotation (primary concentrate)
M1 Mining	Entity	M1 mass pull rate	Flow	M1 ore extraction*(1-M1 mass reduction)	KT/Year	Inflow (M1 Concentrate)	
M1 Mining	Entity	C2 feed rate	Flow	M1 Concentrate/production period	KT/Year	Outflow (M1 Concentrate)	
M1 Mining	Entity	M1 Current Account	Stock	Startup Financing	M$		
M1 Mining	Entity	M1 annual net revenue	Flow	M1 Mine Gross Revenue-M1 annual opex+ M1 stimulus amount	M$/Year	Inflow (M1 Current Account)	
M1 Mining	Entity	M1 annual spend rate	Flow	expansion cost per upgrade	M$/Year	Outflow (M1 Current Account)	
M1 Mining	Entity	M1 Ore Extraction Capacity	Stock	M1 initial extraction capacity	KT/Year		
M1 Mining	Entity	M1 capacity expansion rate	Flow	if(M1 capacity adjustment=0) {0} else {M1 Ore Extraction Capacity+M1 capacity adjustment}	KT/Year/Year	Inflow (M1 Ore Extraction Capacity)	
M1 Mining	Entity	M1 extraction capacity reduction rate	Flow	M1 Ore Extraction Capacity*M1 capacity obsalesence fraction	KT/Year/Year	Outflow (M1 Ore Extraction Capacity)	
M1 Mining	Entity	M1 Resource Ore Quantity	Stock	ResKT	KT		
M1 Mining	Entity	resource depletion rate	Flow	if(M1 Resource Ore Quantity > M1 ore extraction) {M1 ore extraction} else {M1 Resource Ore Quantity}	KT/Year	Outflow (M1 Resource Ore Quantity)	
M1 Mining	Entity	Uncapitalized Expansion Cost	Stock	0	M$/Year		
M1 Mining	Entity	expansion approved expenditure	Flow	(M1 capacity adjustment*M1 Capex)*Model.cost escalation/accounting period	M$/Year	Inflow (Uncapitalized Expansion Cost)	

M1 Mining	Entity	expansion annual expenditure	Flow	Uncapitalized Expansion Cost - (Uncapitalized Expansion Cost/expansion project duration)	M$/Year	Outflow (Uncapitalized Expansion Cost)	
M1 Mining	Entity	C2 Production	Reference	Condition: C2 Production TG C2 Production TG		Target Type: C2 Production	
M1 Mining	Entity	F5 Fabricating	Reference	Condition: F5 Fabricating TG F5 FabCo TG		Target Type: F5 Fabricating	
M1 Mining	Entity	M1 C2 Production	Reference	Condition: M1 Mining TG M1 Mining TG		Target Type: M1 C2 Production	
M1 Mining	Entity	Metal Price	Reference			Target Type: Metal Price	
M1 Mining	Entity	Model	Reference			Target Type: Model	
M1 Mining	Entity	Transition	Reference			Target Type: Transition	
M1 Mining	Entity	Activate M1 Mine Production Trigger	Trigger	mine state="inactive" AND Model.Time>=mine activation offset		Action to Invoke: Activate M1 Mine Production, When: PeriodStart, Sequence No.: 1	
M1 Mining	Entity	Add M1 Resources Trigger	Trigger	M1 Resource Ore Quantity<ResKT*.25		Action to Invoke: Add M1 Resources, When: PeriodStart, Sequence No.: 1	
M1 Mining	Entity	Deactivate M1 Mine Production Trigger	Trigger	(M1 Resource Ore Quantity<=0) || (M1 Current Account<-500000000)		Action to Invoke: Deactivate M1 Mine Production, When: PeriodStart, Sequence No.: 1	make inactive if no reamaining ore OR (||) no cash
M1 Mining[]	Collection						
M1 Mining[]	Collection	China M1 share	Auxiliary	(ZIDZ(Sum China M1 mining,Sum C2 feed rate))*100	dmnl	Value	
M1 Mining[]	Collection	China upstream HHI	Auxiliary	China M1 share^2	dmnl	Value	
M1 Mining[]	Collection	Count	Auxiliary		dmnl	Value	Built-in variable. Reports the number of entities of this type existing at the end of each time slice.
M1 Mining[]	Collection	La1 basket	Auxiliary	Metal Price.LaX Price*Sum La1 grade	$/kg	Value	

M1 Mining[]	Collection	MSP M1 share	Auxiliary	(ZIDZ(Sum MSP M1 mining,Sum C2 feed rate))*100	dmnl	Value	
M1 Mining[]	Collection	MSP upstream HHI	Auxiliary	MSP M1 share^2	dmnl	Value	
M1 Mining[]	Collection	RoW M1 share	Auxiliary	Sum RoW M1 mining/Sum C2 feed rate	dmnl	Value	
M1 Mining[]	Collection	RoW upstream HHI	Auxiliary	RoW M1 share^2	dmnl	Value	
M1 Mining[]	Collection	Sum C2 feed rate	Aggregate	Sum	KT/Year	Target Variable: C2 feed rate	
M1 Mining[]	Collection	Sum Ce1 grade	Aggregate	Sum	KT/KT	Target Variable: Ce1 grade	
M1 Mining[]	Collection	Sum China M1 mining	Aggregate	Sum	KT/Year	Target Variable: China M1 mining	
M1 Mining[]	Collection	Sum Dy1 grade	Aggregate	Sum	KT/KT	Target Variable: Dy1 grade	
M1 Mining[]	Collection	Sum La1 grade	Aggregate	Sum	KT/KT	Target Variable: La1 grade	
M1 Mining[]	Collection	Sum MSP M1 mining	Aggregate	Sum	KT/Year	Target Variable: MSP M1 mining	
M1 Mining[]	Collection	Sum Nd1 grade	Aggregate	Sum	KT/KT	Target Variable: Nd1 grade	
M1 Mining[]	Collection	Sum Pr1 grade	Aggregate	Sum	KT/KT	Target Variable: Pr1 grade	
M1 Mining[]	Collection	Sum RoW M1 mining	Aggregate	Sum	KT/Year	Target Variable: RoW M1 mining	
M1 Mining[]	Collection	Sum Tb1 grade	Aggregate	Sum	KT/KT	Target Variable: Tb1 grade	
M1 Mining[]	Collection	Metal Price	Reference			Target Type: Metal Price	
M1 Mining[]	Collection	Model	Reference			Target Type: Model	
M1 Mining[M1 Mining TG]	Collection						
M1 Mining[M1 Mining TG]	Collection	M1 Mining TG	Attribute			key	
M1 Mining[M1 Mining TG]	Collection	Count	Auxiliary		dmnl	Value	Built-in variable. Reports the number of entities of this type existing at the end of each time slice.
M1 Mining[M1 Mining TG]	Collection	Sum Ce1 grade	Aggregate	Sum	KT/KT	Target Variable: Ce1 grade	

M1 Mining[M1 Mining TG]	Collection	Sum Dy1 grade	Aggregate	Sum	KT/KT	Target Variable: Dy1 grade	
M1 Mining[M1 Mining TG]	Collection	Sum La1 grade	Aggregate	Sum	KT/KT	Target Variable: La1 grade	
M1 Mining[M1 Mining TG]	Collection	Sum M1 mass pull rate	Aggregate	Sum	KT/Year	Target Variable: M1 mass pull rate	
M1 Mining[M1 Mining TG]	Collection	Sum M1 MSP LREE Stim	Aggregate	Sum	M$/Year	Target Variable: M1 MSP LREE Stim	
M1 Mining[M1 Mining TG]	Collection	Sum M1 stimulus amount	Aggregate	Sum	M$/Year	Target Variable: M1 stimulus amount	
M1 Mining[M1 Mining TG]	Collection	Sum Nd1 grade	Aggregate	Sum	KT/KT	Target Variable: Nd1 grade	
M1 Mining[M1 Mining TG]	Collection	Sum Pr1 grade	Aggregate	Sum	KT/KT	Target Variable: Pr1 grade	
M1 Mining[M1 Mining TG]	Collection	Sum Tb1 grade	Aggregate	Sum	KT/KT	Target Variable: Tb1 grade	
M1 Mining[M1 Mining TG]	Collection	Model	Reference			Target Type: Model	
M1 C2 Alt Production	Entity						
M1 C2 Alt Production	Entity	M1 Mining TG	Attribute			key	
M1 C2 Alt Production	Entity	M1 Planned Alt Capacity	Data			Straight	
M1 C2 Alt Production	Entity	M1 Planned Alt Capacity Raw	Data			Raw	
M1 C2 Alt Production	Entity	M1 Planned Alt Extraction	Data			Straight	
M1 C2 Alt Production	Entity	M1 Planned Alt Extraction Raw	Data			Raw	
M1 C2 Alt Production[]	Collection						
M1 C2 Alt Production[]	Collection	Count	Auxiliary		dmnl	Value	Built-in variable. Reports the number of entities of this type existing at the end of each time slice.
M1 C2 Alt Production[]	Collection	Model	Reference			Target Type: Model	
C2 Production	Entity						
C2 Production	Entity	C2 Production TG	Attribute			key	
C2 Production	Entity	M1 Mining TG	Attribute				
C2 Production	Entity	S3 Separation TG	Attribute				

C2 Production	Entity	annual expansion cost per upgrade	Auxiliary	(C2 capacity expansion rate*expansion annual completion fraction)*C2 Capex	$M/Year	Value	
C2 Production	Entity	C2 annual opex	Auxiliary	C2 Opex*C2 mass pull rate	M$/Year	Value	
C2 Production	Entity	C2 capacity adjustment	Auxiliary	if(C2 capacity utilization> C2 capacity utilization threshold) {C2 Concentration Capacity*C2 capacity adjustment fraction} else {0}	KT/Year/Year	Value	
C2 Production	Entity	C2 capacity adjustment fraction	Auxiliary	.4	dmnl	Constant Value	
C2 Production	Entity	C2 capacity evaluation period	Auxiliary	1	Year	Value	
C2 Production	Entity	C2 capacity obsolesence fraction	Auxiliary	0.0001	1/Year	Constant Value	
C2 Production	Entity	C2 capacity utilization	Auxiliary	C2 production plan/(C2 Concentration Capacity/C2 capacity evaluation period)	dmnl	Value	M1 production plan/((M1 Ore Extraction Capacity/M1 capacity evaluation period))
C2 Production	Entity	C2 capacity utilization threshold	Auxiliary	0.6	dmnl	Constant Value	
C2 Production	Entity	C2 Capex	Auxiliary	0.25	M$/KT	Constant Value	
C2 Production	Entity	C2 Concentrate Basket Price	Auxiliary	La2 basket share+Ce2 basket share+Pr2 basket share+Nd2 basket share+Tb2 basket share+Dy2 basket share	$/kg	Value	
C2 Production	Entity	C2 concentrate grade	Auxiliary	M1 Mining.M1 concentrate grade*C2 upgrade ratio	dmnl	Value	
C2 Production	Entity	C2 concentrate initial inventory	Auxiliary	0	KT	Constant Value	
C2 Production	Entity	C2 concentrate price fraction	Auxiliary	1-.75	dmnl	Value	
C2 Production	Entity	C2 Gross Revenue	Auxiliary	((C2 Concentrate Basket Price*convert kg to KT)*S3 separation feed rate*C2 concentrate price fraction)/1000000	$M/Year	Value	Concentrate revenue is based on world concentrate price. Estimated concentrate price = Basket price x discount fraction = .25
C2 Production	Entity	C2 initial concentration capacity	Auxiliary	0	KT/Year	Constant Value	

C2 Production	Entity	C2 investment required	Auxiliary	if(Upstream Current Account/C2 stimulus period<2*annual expansion cost per upgrade) {annual expansion cost per upgrade} else{0}		Value	
C2 Production	Entity	C2 mass reduction	Auxiliary	0.4	dmnl	Constant Value	
C2 Production	Entity	C2 Opex	Auxiliary	0	M$/KT	Constant Value	
C2 Production	Entity	C2 production capacity utilization fraction	Auxiliary	.95	dmnl	Constant Value	
C2 Production	Entity	C2 production plan	Auxiliary	Min(M1 Mining.C2 feed rate,M1 C2 Production.C2 Desired Processing)*C2 production capacity utilization fraction	KT/Year	Value	M1 C2 Production.M1 Desired Mining+M1 C2 Production.M1 Desired Mining*F5 gap adjustment
C2 Production	Entity	C2 recovery fraction	Auxiliary	.9	dmnl	Constant Value	
C2 Production	Entity	C2 stimulus amount	Auxiliary	C2 investment required*C2 stimulus share	$M/Year	Value	
C2 Production	Entity	C2 stimulus period	Auxiliary	1	Year	Value	
C2 Production	Entity	C2 stimulus share	Auxiliary	.2	dmnl	Constant Value	
C2 Production	Entity	C2 upgrade ratio	Auxiliary	1.5	dmnl	Constant Value	
C2 Production	Entity	Ce2 basket share	Auxiliary	Metal Price.CeX Price* Ce2 relative grade	$/kg	Value	
C2 Production	Entity	Ce2 grade	Auxiliary	M1 Mining.Ce1 grade*M1C2 upgrade ratio	KT/KT	Value	
C2 Production	Entity	Ce2 production	Auxiliary	S3 separation feed rate*Ce2 grade	KT/Year	Value	
C2 Production	Entity	Ce2 relative grade	Auxiliary	Ce2 grade/C2 concentrate grade	dmnl	Value	
C2 Production	Entity	convert kg to KT	Auxiliary	1000	kg/KT	Value	
C2 Production	Entity	Dy2 basket share	Auxiliary	Metal Price.DyX Price*Dy2 relative grade	$/kg	Value	
C2 Production	Entity	Dy2 grade	Auxiliary	M1 Mining.Dy1 grade*M1C2 upgrade ratio	KT/KT	Value	
C2 Production	Entity	Dy2 production	Auxiliary	S3 separation feed rate*Dy2 grade	KT/Year	Value	
C2 Production	Entity	Dy2 relative grade	Auxiliary	Dy2 grade/ C2 concentrate grade	dmnl	Value	
C2 Production	Entity	expansion annual completion fraction	Auxiliary	1/5	1/Year	Value	
C2 Production	Entity	La2 basket share	Auxiliary	Metal Price.LaX Price* La2 relative grade	$/kg	Value	
C2 Production	Entity	La2 grade	Auxiliary	M1 Mining.La1 grade*M1C2 upgrade ratio	KT/KT	Value	
C2 Production	Entity	La2 production	Auxiliary	S3 separation feed rate*La2 grade	KT/Year	Value	

C2 Production	Entity	La2 relative grade	Auxiliary	La2 grade/C2 concentrate grade	dmnl	Value	
C2 Production	Entity	M1C2 upgrade ratio	Auxiliary	C2 upgrade ratio*M1 Mining.M1 upgrade ratio	dmnl	Value	
C2 Production	Entity	Nd2 basket share	Auxiliary	Metal Price.NdX Price*Nd2 relative grade	$/kg	Value	
C2 Production	Entity	Nd2 grade	Auxiliary	M1 Mining.Nd1 grade*M1C2 upgrade ratio	KT/KT	Value	
C2 Production	Entity	Nd2 production	Auxiliary	S3 separation feed rate*Nd2 grade	KT/Year	Value	
C2 Production	Entity	Nd2 relative grade	Auxiliary	Nd2 grade/C2 concentrate grade	dmnl	Value	
C2 Production	Entity	Pr2 basket share	Auxiliary	Metal Price.PrX Price*Pr2 relative grade	$/kg	Value	
C2 Production	Entity	Pr2 grade	Auxiliary	M1 Mining.Pr1 grade*M1C2 upgrade ratio	KT/KT	Value	
C2 Production	Entity	Pr2 production	Auxiliary	S3 separation feed rate*Pr2 grade	KT/Year	Value	
C2 Production	Entity	Pr2 relative grade	Auxiliary	Pr2 grade/C2 concentrate grade	dmnl	Value	
C2 Production	Entity	production period	Auxiliary	1	Year	Value	
C2 Production	Entity	S3 TREO weight	Auxiliary	M1 Mining.M1 Concentrate TREO wt*C2 recovery fraction	KT/Year	Value	
C2 Production	Entity	Tb2 basket share	Auxiliary	Metal Price.TbX Price*Tb2 relative grade	$/kg	Value	
C2 Production	Entity	Tb2 grade	Auxiliary	M1 Mining.Tb1 grade*M1C2 upgrade ratio	KT/KT	Value	
C2 Production	Entity	Tb2 production	Auxiliary	S3 separation feed rate*Tb2 grade	KT/Year	Value	
C2 Production	Entity	Tb2 relative grade	Auxiliary	Tb2 grade/C2 concentrate grade	dmnl	Value	
C2 Production	Entity	C2 Concentrate	Stock	C2 concentrate initial inventory	KT		concentrate after comminution, flotaion (primary concentrate), and leaching (secondary concentrate) or equivalent per flowsheet
C2 Production	Entity	C2 mass pull rate	Flow	C2 production plan*(1-C2 mass reduction)	KT/Year	Inflow (C2 Concentrate)	
C2 Production	Entity	S3 separation feed rate	Flow	C2 Concentrate/production period	KT/Year	Outflow (C2 Concentrate)	
C2 Production	Entity	C2 Concentration Capacity	Stock	C2 initial concentration capacity	KT/Year		

C2 Production	Entity	C2 capacity expansion rate	Flow	if(C2 capacity adjustment=0) {0} else {C2 Concentration Capacity+C2 capacity adjustment}	KT/Year/Year	Inflow (C2 Concentration Capacity)	
C2 Production	Entity	C2 processing capacity reduction rate	Flow	C2 Concentration Capacity*C2 capacity obsolesence fraction	KT/Year/Year	Outflow (C2 Concentration Capacity)	
C2 Production	Entity	Upstream Current Account	Stock	0	M$/Year		
C2 Production	Entity	upstream annual net revenue	Flow	C2 Gross Revenue-C2 annual opex+C2 stimulus amount	M$/Year	Inflow (Upstream Current Account)	
C2 Production	Entity	upstream annual spend	Flow	annual expansion cost per upgrade	M$/Year	Outflow (Upstream Current Account)	
C2 Production	Entity	M1 C2 Production	Reference	Condition: M1 Mining TG M1 Mining TG		Target Type: M1 C2 Production	
C2 Production	Entity	M1 Mining	Reference	Condition: M1 Mining TG M1 Mining TG		Target Type: M1 Mining	
C2 Production	Entity	Metal Price	Reference			Target Type: Metal Price	
C2 Production	Entity	Mining Collection	Reference			Target Type: M1 Mining[]	
C2 Production	Entity	Model	Reference			Target Type: Model	
C2 Production	Entity	S3 Processing	Reference	Condition: S3 Separation TG S3 Separation TG		Target Type: S3 Processing	
C2 Production[]	Collection						
C2 Production[]	Collection	Count	Auxiliary		dmnl	Value	Built-in variable. Reports the number of entities of this type existing at the end of each time slice.
C2 Production[]	Collection	Model	Reference			Target Type: Model	
C2 Production[C2 Production TG]	Collection						
C2 Production[C2 Production TG]	Collection	C2 Production TG	Attribute			key	
C2 Production[C2 Production TG]	Collection	Count	Auxiliary		dmnl	Value	Built-in variable. Reports the number of entities of this type existing at the end of each time slice.

C2 Production[C2 Production TG]	Collection	Sum La2 production	Aggregate	Sum	KT/Year	Target Variable: La2 production
C2 Production[C2 Production TG]	Collection	Model	Reference			Target Type: Model
S3 Processing	Entity					
S3 Processing	Entity	C2 Production TG	Attribute			
S3 Processing	Entity	R4 Refining TG	Attribute			
S3 Processing	Entity	S3 Separation TG	Attribute			key
S3 Processing	Entity	annual expansion cost per upgrade	Auxiliary	S3 Capex*S3 capacity expansion rate*expansion annual completion fraction	M$/Year	Value
S3 Processing	Entity	Ce3 grade	Auxiliary	C2 Production.Ce2 grade*S3 upgrade ratio	KT/KT	Value
S3 Processing	Entity	Ce3 production	Auxiliary	R4 refining feed rate*Ce3 grade	KT/Year	Value
S3 Processing	Entity	Ce3 relative grade	Auxiliary	Ce3 grade/S3 grade	dmnl	Value
S3 Processing	Entity	Ce3 revenue	Auxiliary	Metal Price.CeX Price*Ce3 relative grade	$/kg	Value
S3 Processing	Entity	convert kg to KT	Auxiliary	1000	kg/KT	Value
S3 Processing	Entity	Dy3 grade	Auxiliary	C2 Production.Dy2 grade*S3 upgrade ratio	KT/KT	Value
S3 Processing	Entity	Dy3 production	Auxiliary	R4 refining feed rate*Dy3 grade	KT/Year	Value
S3 Processing	Entity	Dy3 relative grade	Auxiliary	Dy3 grade/S3 grade	dmnl	Value
S3 Processing	Entity	Dy3 revenue	Auxiliary	Metal Price.DyX Price*Dy3 relative grade	$/kg	Value
S3 Processing	Entity	expansion annual completion fraction	Auxiliary	1/3	1/Year	Value
S3 Processing	Entity	La3 grade	Auxiliary	C2 Production.La2 grade*S3 upgrade ratio	KT/KT	Value
S3 Processing	Entity	La3 production	Auxiliary	R4 refining feed rate*La3 grade	KT/Year	Value
S3 Processing	Entity	La3 relative grade	Auxiliary	La3 grade/S3 grade	dmnl	Value
S3 Processing	Entity	La3 revenue	Auxiliary	Metal Price.LaX Price*La3 relative grade	$/kg	Value
S3 Processing	Entity	Nd3 grade	Auxiliary	C2 Production.Nd2 grade*S3 upgrade ratio	KT/KT	Value
S3 Processing	Entity	Nd3 production	Auxiliary	R4 refining feed rate*Nd3 grade	KT/Year	Value
S3 Processing	Entity	Nd3 relative grade	Auxiliary	Nd3 grade/S3 grade	dmnl	Value
S3 Processing	Entity	Nd3 revenue	Auxiliary	Metal Price.NdX Price*Nd3 relative grade	$/kg	Value
S3 Processing	Entity	Pr3 grade	Auxiliary	C2 Production.Pr2 grade*S3 upgrade ratio	KT/KT	Value
S3 Processing	Entity	Pr3 production	Auxiliary	R4 refining feed rate*Pr3 grade	KT/Year	Value
S3 Processing	Entity	Pr3 relative grade	Auxiliary	Pr3 grade/S3 grade	dmnl	Value

S3 Processing	Entity	Pr3 revenue	Auxiliary	Metal Price.PrX Price*Pr3 relative grade	$/kg	Value	
S3 Processing	Entity	S3 annual opex	Auxiliary	S3 Opex*Model.cost escalation*S3 feed rate	M$/Year	Value	
S3 Processing	Entity	S3 capacity adjustment	Auxiliary	if(S3 capacity utilization>S3 capacity utilization threshold) {S3 Separation Capacity*S3 capacity adjustment fraction} else {0}	dmnl	Value	
S3 Processing	Entity	S3 capacity adjustment fraction	Auxiliary	.4	dmnl	Constant Value	
S3 Processing	Entity	S3 capacity evaluation period	Auxiliary	1	Year	Value	
S3 Processing	Entity	S3 capacity obsolesence fraction	Auxiliary	0.005	1/Year	Value	
S3 Processing	Entity	S3 capacity utilization	Auxiliary	C2 Production.S3 separation feed rate/(S3 Separation Capacity/S3 capacity evaluation period)	dmnl	Value	
S3 Processing	Entity	S3 capacity utilization threshold	Auxiliary	.6	dmnl	Constant Value	
S3 Processing	Entity	S3 Capex	Auxiliary	0.35*Model.cost escalation	M$/KT	Value	
S3 Processing	Entity	S3 grade	Auxiliary	C2 Production.C2 concentrate grade*S3 upgrade ratio	dmnl	Value	
S3 Processing	Entity	S3 Gross Revenue	Auxiliary	(S3 magnet oxide gross revenue*convert kg to KT)*R4 refining feed rate/1000000	M$/Year	Value	
S3 Processing	Entity	S3 initial separation capacity	Auxiliary	100	KT/Year	Constant Value	
S3 Processing	Entity	S3 innovation rate limit	Auxiliary	1.05	KT/Year	Constant Value	
S3 Processing	Entity	S3 innovation rate normal	Auxiliary	0.01	1/Year	Constant Value	
S3 Processing	Entity	S3 investment required	Auxiliary	if(Midstream Current Account/S3 stimulus period < 2*annual expansion cost per upgrade) { annual expansion cost per upgrade} else {0}	M$/Year	Value	if(Upstream Current Account/C2 stimulus period<2*annual expansion cost per upgrade) {annual expansion cost per upgrade} else{0}
S3 Processing	Entity	S3 La Ce oxide revenue	Auxiliary	La3 revenue+Ce3 revenue	$/kg	Value	
S3 Processing	Entity	S3 magnet oxide gross revenue	Auxiliary	Pr3 revenue+Nd3 revenue+Tb3 revenue+Dy3 revenue	$/kg	Value	
S3 Processing	Entity	S3 mass reduction	Auxiliary	.4	dmnl	Constant Value	

S3 Processing Entity	S3 Opex	Auxiliary	0.35	M$/KT	Value	Sykes "Resource Capital and Cost 602 Rare Earth Mine Costs"
S3 Processing Entity	S3 recovery fraction	Auxiliary	.95	dmnl	Constant Value	
S3 Processing Entity	S3 separated initial inventory	Auxiliary	0	KT	Constant Value	
S3 Processing Entity	S3 separation capacity utilization fraction	Auxiliary	0.95	dmnl	Constant Value	
S3 Processing Entity	S3 separation processing	Auxiliary	Min(C2 Production.S3 separation feed rate,S3 Separation Capacity)*S3 separation capacity utilization fraction	KT/Year	Value	
S3 Processing Entity	S3 stimulus amount	Auxiliary	S3 investment required*S3 stimulus share	M$/Year	Value	
S3 Processing Entity	S3 stimulus period	Auxiliary	1	Year	Value	
S3 Processing Entity	S3 stimulus share	Auxiliary	.2	dmnl	Constant Value	
S3 Processing Entity	S3 TREO recovery	Auxiliary	S3 separation processing*S3 recovery fraction	KT/Year	Value	C2 concentrate processing*C2 recovery fraction
S3 Processing Entity	S3 upgrade ratio	Auxiliary	4.5	dmnl	Constant Value	
S3 Processing Entity	separation plant production period	Auxiliary	1	Year	Value	
S3 Processing Entity	Tb3 grade	Auxiliary	C2 Production.Tb2 grade*S3 upgrade ratio	KT/KT	Value	
S3 Processing Entity	Tb3 production	Auxiliary	R4 refining feed rate*Tb3 grade	KT/Year	Value	
S3 Processing Entity	Tb3 relative grade	Auxiliary	Tb3 grade/S3 grade	dmnl	Value	
S3 Processing Entity	Tb3 revenue	Auxiliary	Metal Price.TbX Price*Tb3 relative grade	$/kg	Value	
S3 Processing Entity	Midstream Current Account	Stock	0	M$		
S3 Processing Entity	midstream annual net revenue	Flow	S3 Gross Revenue-S3 annual opex+S3 stimulus amount	M$/Year	Inflow (Midstream Current Account)	
S3 Processing Entity	midstream annual spend	Flow	annual expansion cost per upgrade	M$/Year	Outflow (Midstream Current Account)	
S3 Processing Entity	S3 Midstream Separated	Stock	S3 separated initial inventory	KT		
S3 Processing Entity	S3 feed rate	Flow	S3 TREO recovery/S3 grade*(1-S3 mass reduction)	KT/Year	Inflow (S3 Midstream Separated)	
S3 Processing Entity	R4 refining feed rate	Flow	S3 Midstream Separated/separation plant production period	KT/Year	Outflow (S3 Midstream Separated)	
S3 Processing Entity	S3 Separation Capacity	Stock	S3 initial separation capacity	KT/Year		

S3 Processing	Entity	S3 capacity expansion rate	Flow	if(S3 capacity adjustment=0) {0} else {S3 Separation Capacity+S3 capacity adjustment}	KT/Year/Year	Inflow (S3 Separation Capacity)	
S3 Processing	Entity	S3 capacity reduction rate	Flow	S3 Separation Capacity*S3 capacity obsolesence fraction	KT/Year/Year	Outflow (S3 Separation Capacity)	
S3 Processing	Entity	S3 Separation Growth	Stock	1	KT/Year		
S3 Processing	Entity	C2 Production	Reference	Condition: C2 Production TG C2 Production TG		Target Type: C2 Production	
S3 Processing	Entity	Metal Price	Reference			Target Type: Metal Price	
S3 Processing	Entity	Model	Reference			Target Type: Model	
S3 Processing	Entity	Production Collection	Reference			Target Type: C2 Production[]	
S3 Processing[]	Collection						
S3 Processing[]	Collection	Count	Auxiliary		dmnl	Value	Built-in variable. Reports the number of entities of this type existing at the end of each time slice.
S3 Processing[]	Collection	S3 separated rate	Auxiliary	Sum La3 production+Sum Ce3 production+Sum Pr3 production+Sum Nd3 production+Sum Tb3 production+Sum Dy3 production	KT/Year	Value	
S3 Processing[]	Collection	separated Basket6 TREO	Auxiliary	separated La percent+separated Ce percent+separated Pr percent+separated Nd percent+separated Tb percent+separated Dy percent	KT/KT	Value	
S3 Processing[]	Collection	separated Ce percent	Auxiliary	Sum Ce3 production/S3 separated rate	KT/KT	Value	
S3 Processing[]	Collection	separated Dy percent	Auxiliary	Sum Dy3 production/S3 separated rate	KT/KT	Value	
S3 Processing[]	Collection	separated La percent	Auxiliary	Sum La3 production/S3 separated rate	KT/KT	Value	
S3 Processing[]	Collection	separated Nd percent	Auxiliary	Sum Nd3 production/S3 separated rate	KT/KT	Value	
S3 Processing[]	Collection	separated Pr percent	Auxiliary	Sum Pr3 production/S3 separated rate	KT/KT	Value	

S3 Processing[]	Collection	separated Tb percent	Auxiliary	Sum Tb3 production/S3 separated rate	KT/KT	Value
S3 Processing[]	Collection	Sum Ce3 production	Aggregate	Sum	KT/Year	Target Variable: Ce3 production
S3 Processing[]	Collection	Sum Dy3 production	Aggregate	Sum	KT/Year	Target Variable: Dy3 production
S3 Processing[]	Collection	Sum La3 production	Aggregate	Sum	KT/Year	Target Variable: La3 production
S3 Processing[]	Collection	Sum Nd3 production	Aggregate	Sum	KT/Year	Target Variable: Nd3 production
S3 Processing[]	Collection	Sum Pr3 production	Aggregate	Sum	KT/Year	Target Variable: Pr3 production
S3 Processing[]	Collection	Sum Tb3 production	Aggregate	Sum	KT/Year	Target Variable: Tb3 production
S3 Processing[]	Collection	Model	Reference			Target Type: Model
SepcoRefco	Entity					
SepcoRefco	Entity	RefCo	Attribute			key
SepcoRefco	Entity	SepCo	Attribute			key
SepcoRefco	Entity	R4 Ce feed	Auxiliary	S3 Processing.Ce3 production*R4 initial distribution fraction	KT/Year	Value
SepcoRefco	Entity	R4 Dy feed	Auxiliary	S3 Processing.Dy3 production*R4 initial distribution fraction	KT/Year	Value
SepcoRefco	Entity	R4 initial distribution fraction	Auxiliary	0	dmnl	Constant Value
SepcoRefco	Entity	R4 La feed	Auxiliary	S3 Processing.La3 production*R4 initial distribution fraction	KT/Year	Value
SepcoRefco	Entity	R4 Nd feed	Auxiliary	S3 Processing.Nd3 production*R4 initial distribution fraction	Kt/Year	Value
SepcoRefco	Entity	R4 Pr feed	Auxiliary	S3 Processing.Pr3 production*R4 initial distribution fraction	KT/Year	Value
SepcoRefco	Entity	R4 Tb feed	Auxiliary	S3 Processing.Tb3 production*R4 initial distribution fraction	KT/Year	Value
SepcoRefco	Entity	Model	Reference			Target Type: Model
SepcoRefco	Entity	S3 Processing	Reference	Condition: S3 Separation TG SepCo		Target Type: S3 Processing
SepcoRefco[RefCo]	Collection					
SepcoRefco[RefCo]	Collection	RefCo	Attribute			key

SepcoRefco[RefCo]	Collection	Count	Auxiliary		dmnl	Value	Built-in variable. Reports the number of entities of this type existing at the end of each time slice.
SepcoRefco[RefCo]	Collection	R4 refinery feed rate	Auxiliary	Sum R4 La feed+Sum R4 Ce feed+Sum R4 Pr feed+Sum R4 Nd feed+Sum R4 Tb feed+Sum R4 Dy feed	KT/Year	Value	
SepcoRefco[RefCo]	Collection	Sum R4 Ce feed	Aggregate	Sum	KT/Year	Target Variable: R4 Ce feed	
SepcoRefco[RefCo]	Collection	Sum R4 Dy feed	Aggregate	Sum	KT/Year	Target Variable: R4 Dy feed	
SepcoRefco[RefCo]	Collection	Sum R4 La feed	Aggregate	Sum	KT/Year	Target Variable: R4 La feed	
SepcoRefco[RefCo]	Collection	Sum R4 Nd feed	Aggregate	Sum	Kt/Year	Target Variable: R4 Nd feed	
SepcoRefco[RefCo]	Collection	Sum R4 Pr feed	Aggregate	Sum	KT/Year	Target Variable: R4 Pr feed	
SepcoRefco[RefCo]	Collection	Sum R4 Tb feed	Aggregate	Sum	KT/Year	Target Variable: R4 Tb feed	
SepcoRefco[RefCo]	Collection	Model	Reference			Target Type: Model	
SepcoRefco[RefCo]	Collection	R4 Feed	Reference	Condition: RefCo RefCo		Target Type: SepcoRefco[RefCo]	
SepcoRefco[]	Collection						
SepcoRefco[]	Collection	Count	Auxiliary		dmnl	Value	Built-in variable. Reports the number of entities of this type existing at the end of each time slice.
SepcoRefco[]	Collection	Model	Reference			Target Type: Model	
R4 Refining	Entity						
R4 Refining	Entity	D6 Demand TG	Attribute				
R4 Refining	Entity	R4 Refining TG	Attribute			key	
R4 Refining	Entity	initial refined Dy	Auxiliary	1	KT	Constant Value	
R4 Refining	Entity	initial refined Nd	Auxiliary	1	KT	Constant Value	
R4 Refining	Entity	initial refined Pr	Auxiliary	1	KT	Constant Value	
R4 Refining	Entity	initial refined Tb	Auxiliary	1	KT	Constant Value	
R4 Refining	Entity	Nd gap	Auxiliary	ZIDZ(Demand.EV Nd demand,R4	dman	Value	

				refined Nd supply rate)			
R4 Refining	Entity	R4 capacity adjustment	Auxiliary	if(R4 capacity utilization > R4 capacity utilization threshold) {R4 Refining Capacity*R4 capacity adjustment fraction} else {0}	dmnl	Value	if(S3 capacity utilization>S3 capacity utilization threshold) {S3 Separation Capacity*S3 capacity adjustment fraction} else {0}
R4 Refining	Entity	R4 capacity adjustment fraction	Auxiliary	.4	dmnl	Constant Value	
R4 Refining	Entity	R4 capacity evaluation period	Auxiliary	1	Year	Value	
R4 Refining	Entity	R4 capacity obsalesence fraction	Auxiliary	0.001	1/Year	Value	
R4 Refining	Entity	R4 capacity utilization	Auxiliary	SepcoRefco by RefCo.R4 refinery feed rate/(R4 Refining Capacity/R4 capacity evaluation period)	dmnl	Value	
R4 Refining	Entity	R4 capacity utilization threshold	Auxiliary	.6	dmnl	Constant Value	
R4 Refining	Entity	R4 DyX recovery	Auxiliary	SepcoRefco by RefCo.Sum R4 Dy feed*R4 recovery fraction	KT/Year	Value	
R4 Refining	Entity	R4 grade	Auxiliary	0.999	dmnl	Constant Value	
R4 Refining	Entity	R4 NdX recovery	Auxiliary	SepcoRefco by RefCo.Sum R4 Nd feed*R4 recovery fraction	KT/Year	Value	
R4 Refining	Entity	R4 PrX recovery	Auxiliary	SepcoRefco by RefCo.Sum R4 Pr feed*R4 recovery fraction	KT/Year	Value	
R4 Refining	Entity	R4 recovery fraction	Auxiliary	.95	dmnl	Constant Value	
R4 Refining	Entity	R4 refining capacity utilization fraction	Auxiliary	0.95	dmnl	Constant Value	
R4 Refining	Entity	R4 refining processing	Auxiliary	Min(SepcoRefco by RefCo.R4 refinery feed rate,R4 Refining Capacity)*R4 refining capacity utilization fraction	KT/Year	Value	
R4 Refining	Entity	R4 TbX recovery	Auxiliary	SepcoRefco by RefCo.Sum R4 Tb feed*R4 recovery fraction	KT/Year	Value	
R4 Refining	Entity	refining initial capacity	Auxiliary	100	KT/Year	Constant Value	
R4 Refining	Entity	refining plant production period	Auxiliary	1	Year	Value	
R4 Refining	Entity	R4 Refined Dy	Stock	initial refined Dy	KT		
R4 Refining	Entity	R4 DyX input rate	Flow	R4 DyX recovery/R4 grade	KT/Year	Inflow (R4 Refined Dy)	

R4 Refining	Entity	R4 refined Dy supply rate	Flow	if(R4 Refined Dy/refining plant production period > 0.000009) {R4 Refined Dy/refining plant production period} else {0}	KT/Year	Outflow (R4 Refined Dy)
R4 Refining	Entity	R4 Refined Nd	Stock	initial refined Nd	KT	
R4 Refining	Entity	R4 NdX input rate1	Flow	R4 NdX recovery/R4 grade	KT/Year	Inflow (R4 Refined Nd)
R4 Refining	Entity	R4 refined Nd supply rate	Flow	if(R4 Refined Nd/refining plant production period > 0.000009) {R4 Refined Nd/refining plant production period} else {0}	KT/Year	Outflow (R4 Refined Nd)
R4 Refining	Entity	R4 Refined Pr	Stock	initial refined Pr	KT	
R4 Refining	Entity	R4 PrX input rate	Flow	R4 PrX recovery/R4 grade	KT/Year	Inflow (R4 Refined Pr)
R4 Refining	Entity	R4 refined Pr supply rate	Flow	if(R4 Refined Pr/refining plant production period > 0.000009) {R4 Refined Pr/refining plant production period} else {0}	KT/Year	Outflow (R4 Refined Pr)
R4 Refining	Entity	R4 Refined Tb	Stock	initial refined Tb	KT	
R4 Refining	Entity	R4 TbX input rate	Flow	R4 TbX recovery/R4 grade	KT/Year	Inflow (R4 Refined Tb)
R4 Refining	Entity	R4 refined Tb supply rate	Flow	if(R4 Refined Tb/refining plant production period > 0.000009) {R4 Refined Tb/refining plant production period} else {0}	KT/Year	Outflow (R4 Refined Tb)
R4 Refining	Entity	R4 Refining Capacity	Stock	refining initial capacity	KT/Year	
R4 Refining	Entity	R4 capacity expansion rate	Flow	if(R4 capacity adjustment=0) {0} else {R4 Refining Capacity+R4 capacity adjustment}	KT/Year/Yea r	Inflow (R4 Refining Capacity)
R4 Refining	Entity	R4 capacity obsalesence rate	Flow	R4 Refining Capacity*R4 capacity obsalesence fraction	KT/Year/Yea r	Outflow (R4 Refining Capacity)
R4 Refining	Entity	Demand	Reference	Condition: D6 PM Demand TG D6 Demand TG		Target Type: Demand
R4 Refining	Entity	Model	Reference			Target Type: Model
R4 Refining	Entity	Processing Collection	Reference			Target Type: S3 Processing[]
R4 Refining	Entity	SepcoRefco by RefCo	Reference	Condition: RefCo R4 Refining TG		Target Type: SepcoRefco[RefCo]
R4 Refining[]	Collection					

R4 Refining[]	Collection	Count	Auxiliary		dmnl	Value	Built-in variable. Reports the number of entities of this type existing at the end of each time slice.
R4 Refining[]	Collection	R4 refined rate	Auxiliary	Sum R4 refined Pr supply rate+Sum R4 refined Nd supply rate+Sum R4 refined Tb supply rate+Sum R4 refined Dy supply rate	KT/Year	Value	
R4 Refining[]	Collection	refined Basket6 TREO	Auxiliary	refined Pr percent+refined Nd percent+refined Tb percent+refined Dy percent	KT/KT	Value	
R4 Refining[]	Collection	refined Dy percent	Auxiliary	Sum R4 refined Dy supply rate/R4 refined rate	KT/KT	Value	
R4 Refining[]	Collection	refined Nd percent	Auxiliary	Sum R4 refined Nd supply rate/R4 refined rate	KT/KT	Value	
R4 Refining[]	Collection	refined Pr percent	Auxiliary	Sum R4 refined Pr supply rate/R4 refined rate	KT/KT	Value	
R4 Refining[]	Collection	refined Tb percent	Auxiliary	Sum R4 refined Tb supply rate/R4 refined rate	KT/KT	Value	
R4 Refining[]	Collection	Sum R4 refined Dy supply rate	Aggregate	Sum	KT/Year	Target Variable: R4 refined Dy supply rate	
R4 Refining[]	Collection	Sum R4 refined Nd supply rate	Aggregate	Sum	KT/Year	Target Variable: R4 refined Nd supply rate	
R4 Refining[]	Collection	Sum R4 refined Pr supply rate	Aggregate	Sum	KT/Year	Target Variable: R4 refined Pr supply rate	
R4 Refining[]	Collection	Sum R4 refined Tb supply rate	Aggregate	Sum	KT/Year	Target Variable: R4 refined Tb supply rate	
R4 Refining[]	Collection	Model	Reference			Target Type: Model	
RefcoFabco	Entity						
RefcoFabco	Entity	FabCo	Attribute			key	
RefcoFabco	Entity	RefCo	Attribute			key	
RefcoFabco	Entity	F5 Dy feed	Auxiliary	R4 Refining.R4 refined Dy supply rate*F5 initial distribution fraction	KT/Year	Value	
RefcoFabco	Entity	F5 initial distribution fraction	Auxiliary	.1	dmnl	Constant Value	
RefcoFabco	Entity	F5 Nd feed	Auxiliary	R4 Refining.R4 refined Nd supply rate*F5 initial distribution fraction	KT/Year	Value	
RefcoFabco	Entity	F5 Pr feed	Auxiliary	R4 Refining.R4 refined Pr supply rate*F5 initial distribution fraction	KT/Year	Value	

RefcoFabco	Entity	F5 Tb feed	Auxiliary	R4 Refining.R4 refined Tb supply rate*F5 initial distribution fraction	KT/Year	Value	
RefcoFabco	Entity	F5 Fabricating	Reference	Condition: F5 Fabricating TG FabCo		Target Type: F5 Fabricating	
RefcoFabco	Entity	Model	Reference			Target Type: Model	
RefcoFabco	Entity	R4 Refining	Reference	Condition: R4 Refining TG RefCo		Target Type: R4 Refining	
RefcoFabco[FabCo]	Collection						
RefcoFabco[FabCo]	Collection	FabCo	Attribute			key	
RefcoFabco[FabCo]	Collection	Count	Auxiliary		dmnl	Value	Built-in variable. Reports the number of entities of this type existing at the end of each time slice.
RefcoFabco[FabCo]	Collection	Sum F5 Dy feed	Aggregate	Sum	KT/Year	Target Variable: F5 Dy feed	
RefcoFabco[FabCo]	Collection	Sum F5 Nd feed	Aggregate	Sum	KT/Year	Target Variable: F5 Nd feed	
RefcoFabco[FabCo]	Collection	Sum F5 Pr feed	Aggregate	Sum	KT/Year	Target Variable: F5 Pr feed	
RefcoFabco[FabCo]	Collection	Sum F5 Tb feed	Aggregate	Sum	KT/Year	Target Variable: F5 Tb feed	
RefcoFabco[FabCo]	Collection	Model	Reference			Target Type: Model	
RefcoFabco[]	Collection						
RefcoFabco[]	Collection	Count	Auxiliary		dmnl	Value	Built-in variable. Reports the number of entities of this type existing at the end of each time slice.
RefcoFabco[]	Collection	Model	Reference			Target Type: Model	
F5 Fabricating	Entity						
F5 Fabricating	Entity	D6 Demand TG	Attribute				
F5 Fabricating	Entity	F5 Fabricating TG	Attribute			key	
F5 Fabricating	Entity	aggregate clean energy PM demand	Auxiliary	FabcoDemand.sum CleanEnergy PM demand	KT/Year	Value	
F5 Fabricating	Entity	demand gap by TG	Auxiliary	FabcoDemand by F5 Fabricating TG.Sum sum Clean Energy MREE demand/F5 Fabricating by F5 Fabricating TG.Sum F5 magnet fabrication rate	dmnl	Value	

F5 Fabricating	Entity	Dy max	Auxiliary	RefcoFabco by FabCo.Sum F5 Dy feed/Dy per PM	KT/Year	Value	
F5 Fabricating	Entity	Dy per PM	Auxiliary	.056	KT/KT	Constant Value	5.6% of 35% mag metal content
F5 Fabricating	Entity	Dy pull	Auxiliary	Min(Dy max, Nd pull)	KT/Year	Value	
F5 Fabricating	Entity	ev	Auxiliary	FabcoDemand by D6 PM Demand TG.Sum EV MREE demand	KT/Year	Value	
F5 Fabricating	Entity	F5 China fabrication	Auxiliary	if(F5 Fabricating TG="China - FabCo") { F5 magnet supply rate} else {0}	KT/Year	Value	
F5 Fabricating	Entity	F5 MSP fabrication	Auxiliary	if(F5 Fabricating TG="MSP - FabCo") { F5 magnet supply rate} else {0}	KT/Year	Value	
F5 Fabricating	Entity	F5 PM initial	Auxiliary	5	KT	Constant Value	
F5 Fabricating	Entity	F5 RoW fabrication	Auxiliary	if(F5 Fabricating TG="RoW - FabCo") { F5 magnet supply rate} else {0}	KT/Year	Value	
F5 Fabricating	Entity	fabricating plant production period	Auxiliary	1	Year	Value	
F5 Fabricating	Entity	Nd max	Auxiliary	RefcoFabco by FabCo.Sum F5 Nd feed/Nd per PM	KT/Year	Value	
F5 Fabricating	Entity	Nd per PM	Auxiliary	.27	KT/KT	Constant Value	27% of 35% mag metal content
F5 Fabricating	Entity	Nd pull	Auxiliary	Nd max	KT/Year	Value	
F5 Fabricating	Entity	Other PM demand	Auxiliary	SMOOTH((FabcoDemand.sum CleanEnergy PM demand/(1-Other PM demand fraction))*Other PM demand fraction,3)	KT/Year	Value	
F5 Fabricating	Entity	Other PM demand fraction	Auxiliary	LU Other PM Demand(Model.sim year)	dmnl	Value	
F5 Fabricating	Entity	PM total demand	Auxiliary	FabcoDemand.sum CleanEnergy PM demand+Other PM demand	KT/Year	Value	
F5 Fabricating	Entity	policy year demand supply gap by TG	Auxiliary	if(SimulationYear()> Model.policy year) {demand gap by TG} else {0}	dmnl	Value	
F5 Fabricating	Entity	Pr max	Auxiliary	RefcoFabco by FabCo.Sum F5 Pr feed/Pr per PM	KT/Year	Value	
F5 Fabricating	Entity	Pr per PM	Auxiliary	.021	KT/KT	Constant Value	2.1% of 35% mag metal content
F5 Fabricating	Entity	Pr pull	Auxiliary	Min(Pr max, Nd pull)	KT/Year	Value	
F5 Fabricating	Entity	RE magnet fraction	Auxiliary	0.35	dmnl	Value	

F5 Fabricating	Entity	Tb max	Auxiliary	RefcoFabco by FabCo.Sum F5 Tb feed/Tb per PM	KT/Year	Value	
F5 Fabricating	Entity	Tb per PM	Auxiliary	0.004	KT/KT	Constant Value	0.4% of 35% mag metal content
F5 Fabricating	Entity	Tb pull	Auxiliary	Min(Tb max, Nd pull)	KT/Year	Value	
F5 Fabricating	Entity	total demand	Auxiliary	wind+ev	KT/Year	Value	
F5 Fabricating	Entity	wind	Auxiliary	FabcoDemand by D6 PM Demand TG.Sum Wind MREE demand	KT/Year	Value	
F5 Fabricating	Entity	LU Other PM Demand	TableFunction	2000,2050,0,1,2000,0.9,2020,0.797,2030,0.345,2050,0.283	dmnl		
F5 Fabricating	Entity	F5 NdFeB Permanent Magnets	Stock	F5 PM initial	KT		accumulation of 75/25 permanent magnets
F5 Fabricating	Entity	F5 magnet fabrication rate	Flow	Nd pull/ RE magnet fraction	KT/Year	Inflow (F5 NdFeB Permanent Magnets)	
F5 Fabricating	Entity	F5 magnet supply rate	Flow	Min(F5 NdFeB Permanent Magnets/fabricating plant production period, FabcoDemand.sum CleanEnergy PM demand+Other PM demand)	KT/Year	Outflow (F5 NdFeB Permanent Magnets)	
F5 Fabricating	Entity	F5 Fabricating by F5 Fabricating TG	Reference	Condition: F5 Fabricating TG F5 Fabricating TG		Target Type: F5 Fabricating[F5 Fabricating TG]	
F5 Fabricating	Entity	FabcoDemand	Reference	Condition: D6 PM Demand TG D6 Demand TG, Condition: F5 Fabricating TG F5 Fabricating TG		Target Type: FabcoDemand	
F5 Fabricating	Entity	FabcoDemand by D6 PM Demand TG	Reference	Condition: D6 PM Demand TG D6 Demand TG		Target Type: FabcoDemand[D6 PM Demand TG]	
F5 Fabricating	Entity	FabcoDemand by F5 Fabricating TG	Reference	Condition: F5 Fabricating TG F5 Fabricating TG		Target Type: FabcoDemand[F5 Fabricating TG]	
F5 Fabricating	Entity	FabcoDemand Collection	Reference			Target Type: FabcoDemand[]	
F5 Fabricating	Entity	Fabricating Collection	Reference			Target Type: F5 Fabricating[]	
F5 Fabricating	Entity	Model	Reference			Target Type: Model	
F5 Fabricating	Entity	RefcoFabco by FabCo	Reference	Condition: FabCo F5 Fabricating TG		Target Type: RefcoFabco[FabCo]	

F5 Fabricating	Entity	Refining Collection	Reference			Target Type: R4 Refining[]	
F5 Fabricating[]	Collection						
F5 Fabricating[]	Collection	China downstream HHI1	Auxiliary	China F5 Share^2	dmnl	Value	
F5 Fabricating[]	Collection	China F5 Share	Auxiliary	(ZIDZ(Sum F5 China fabrication, Sum F5 magnet supply rate))*100	dmnl	Value	
F5 Fabricating[]	Collection	China share	Auxiliary	Round((Average F5 China fabrication/F5 sum)*100)	dmnl	Value	
F5 Fabricating[]	Collection	Count	Auxiliary		dmnl	Value	Built-in variable. Reports the number of entities of this type existing at the end of each time slice.
F5 Fabricating[]	Collection	F5 sum	Auxiliary	Average F5 China fabrication+Average F5 MSP fabrication+Average F5 RoW fabrication	KT/Year	Value	
F5 Fabricating[]	Collection	MSP downstream HHI	Auxiliary	MSP F5 Share^2	dmnl	Value	
F5 Fabricating[]	Collection	MSP F5 Share	Auxiliary	(ZIDZ(Sum F5 MSP fabrication,Sum F5 magnet supply rate))*100	dmnl	Value	
F5 Fabricating[]	Collection	MSP HHI	Auxiliary	MSP share^2	dmnl	Value	
F5 Fabricating[]	Collection	MSP share	Auxiliary	Round((Average F5 MSP fabrication/F5 sum)*100)	dmnl	Value	
F5 Fabricating[]	Collection	RoW downstream HHI	Auxiliary	RoW F5 Share^2	dmnl	Value	
F5 Fabricating[]	Collection	RoW F5 Share	Auxiliary	(ZIDZ(Sum F5 RoW fabrication,Sum F5 magnet supply rate))*100	dmnl	Value	
F5 Fabricating[]	Collection	RoW HHI	Auxiliary	RoW share^2	dmnl	Value	
F5 Fabricating[]	Collection	RoW share	Auxiliary	Round((Average F5 RoW fabrication/F5 sum)*100)	dmnl	Value	
F5 Fabricating[]	Collection	sum of sums	Auxiliary	Sum wind+Sum ev	KT/Year	Value	
F5 Fabricating[]	Collection	Average F5 China fabrication	Aggregate	Average	KT/Year	Target Variable: F5 China fabrication	
F5 Fabricating[]	Collection	Average F5 MSP fabrication	Aggregate	Average	KT/Year	Target Variable: F5 MSP fabrication	
F5 Fabricating[]	Collection	Average F5 RoW fabrication	Aggregate	Average	KT/Year	Target Variable: F5 RoW fabrication	

F5 Fabricating[]	Collection	Sum aggregate clean energy PM demand	Aggregate	Sum	KT/Year	Target Variable: aggregate clean energy PM demand	
F5 Fabricating[]	Collection	Sum ev	Aggregate	Sum	KT/Year	Target Variable: ev	
F5 Fabricating[]	Collection	Sum F5 China fabrication	Aggregate	Sum	KT/Year	Target Variable: F5 China fabrication	
F5 Fabricating[]	Collection	Sum F5 magnet fabrication rate	Aggregate	Sum	KT/Year	Target Variable: F5 magnet fabrication rate	
F5 Fabricating[]	Collection	Sum F5 magnet supply rate	Aggregate	Sum	KT/Year	Target Variable: F5 magnet supply rate	
F5 Fabricating[]	Collection	Sum F5 MSP fabrication	Aggregate	Sum	KT/Year	Target Variable: F5 MSP fabrication	
F5 Fabricating[]	Collection	Sum F5 RoW fabrication	Aggregate	Sum	KT/Year	Target Variable: F5 RoW fabrication	
F5 Fabricating[]	Collection	Sum PM total demand	Aggregate	Sum	KT/Year	Target Variable: PM total demand	
F5 Fabricating[]	Collection	Sum total demand	Aggregate	Sum	KT/Year	Target Variable: total demand	
F5 Fabricating[]	Collection	Sum wind	Aggregate	Sum	KT/Year	Target Variable: wind	
F5 Fabricating[]	Collection	FabCo	Reference			Target Type: F5 Fabricating[]	
F5 Fabricating[]	Collection	Model	Reference			Target Type: Model	
F5 Fabricating[F5 Fabricating TG]	Collection						
F5 Fabricating[F5 Fabricating TG]	Collection	F5 Fabricating TG	Attribute			key	
F5 Fabricating[F5 Fabricating TG]	Collection	China HHI	Auxiliary	China share^2	dmnl	Value	
F5 Fabricating[F5 Fabricating TG]	Collection	China Share	Auxiliary	ZIDZ(Sum F5 China fabrication, F5 Sum)	dmnl	Value	
F5 Fabricating[F5 Fabricating TG]	Collection	Count	Auxiliary		dmnl	Value	Built-in variable. Reports the number of entities of this type existing at the end of each time slice.

F5 Fabricating[F5 Fabricating TG]	Collection	F5 Sum	Auxiliary	Sum F5 China fabrication+Sum F5 MSP fabrication+Sum F5 RoW fabrication	KT/Year	Value
F5 Fabricating[F5 Fabricating TG]	Collection	MSP HHI	Auxiliary	MSP Share^2	dmnl	Value
F5 Fabricating[F5 Fabricating TG]	Collection	MSP Share	Auxiliary	ZIDZ(Sum F5 MSP fabrication,F5 Sum)	dmnl	Value
F5 Fabricating[F5 Fabricating TG]	Collection	RoW HHI	Auxiliary	RoW Share^2	dmnl	Value
F5 Fabricating[F5 Fabricating TG]	Collection	RoW Share	Auxiliary	ZIDZ(Sum F5 RoW fabrication, F5 Sum)	dmnl	Value
F5 Fabricating[F5 Fabricating TG]	Collection	sum of sums	Auxiliary	Sum wind+Sum ev	KT/Year	Value
F5 Fabricating[F5 Fabricating TG]	Collection	Sum ev	Aggregate	Sum	KT/Year	Target Variable: ev
F5 Fabricating[F5 Fabricating TG]	Collection	Sum F5 China fabrication	Aggregate	Sum	KT/Year	Target Variable: F5 China fabrication
F5 Fabricating[F5 Fabricating TG]	Collection	Sum F5 magnet fabrication rate	Aggregate	Sum	KT/Year	Target Variable: F5 magnet fabrication rate
F5 Fabricating[F5 Fabricating TG]	Collection	Sum F5 magnet supply rate	Aggregate	Sum	KT/Year	Target Variable: F5 magnet supply rate
F5 Fabricating[F5 Fabricating TG]	Collection	Sum F5 MSP fabrication	Aggregate	Sum	KT/Year	Target Variable: F5 MSP fabrication
F5 Fabricating[F5 Fabricating TG]	Collection	Sum F5 RoW fabrication	Aggregate	Sum	KT/Year	Target Variable: F5 RoW fabrication
F5 Fabricating[F5 Fabricating TG]	Collection	Sum total demand	Aggregate	Sum	KT/Year	Target Variable: total demand
F5 Fabricating[F5 Fabricating TG]	Collection	Sum wind	Aggregate	Sum	KT/Year	Target Variable: wind
F5 Fabricating[F5 Fabricating TG]	Collection	Model	Reference			Target Type: Model
FabcoDemand	Entity					
FabcoDemand	Entity	D6 PM Demand TG	Attribute			key
FabcoDemand	Entity	F5 Fabricating TG	Attribute			key

FabcoDemand	Entity	EV mag4 demand	Auxiliary	Demand.EV permanent magnet demand*EV mag4 fraction	KT/Year	Value	
FabcoDemand	Entity	EV mag4 fraction	Auxiliary	0.35	dmnl	Constant Value	
FabcoDemand	Entity	EV MREE demand	Auxiliary	EV mag4 demand*F5 initial distribution fraction	KT/Year	Value	
FabcoDemand	Entity	F5 initial distribution fraction	Auxiliary	.1	dmnl	Constant Value	
FabcoDemand	Entity	sum Clean Energy MREE demand	Auxiliary	EV MREE demand+Wind MREE demand	KT/Year	Value	
FabcoDemand	Entity	sum CleanEnergy PM demand	Auxiliary	Demand.EV permanent magnet demand+Demand.wind permanent magnet demand	KT/Year	Value	
FabcoDemand	Entity	Wind mag4 demand	Auxiliary	Demand.wind permanent magnet demand*Wind mag4 fraction	KT/Year	Value	
FabcoDemand	Entity	Wind mag4 fraction	Auxiliary	0.35	dmnl	Constant Value	
FabcoDemand	Entity	Wind MREE demand	Auxiliary	Wind mag4 demand*F5 initial distribution fraction	KT/Year	Value	
FabcoDemand	Entity	Demand	Reference	Condition: D6 PM Demand TG D6 PM Demand TG		Target Type: Demand	
FabcoDemand	Entity	F5 Fabricating	Reference	Condition: F5 Fabricating TG F5 Fabricating TG		Target Type: F5 Fabricating	
FabcoDemand	Entity	Model	Reference			Target Type: Model	
FabcoDemand[]	Collection						
FabcoDemand[]	Collection	Count	Auxiliary		dmnl	Value	Built-in variable. Reports the number of entities of this type existing at the end of each time slice.
FabcoDemand[]	Collection	Sum sum Clean Energy MREE demand	Aggregate	Sum	KT/Year	Target Variable: sum Clean Energy MREE demand	
FabcoDemand[]	Collection	Model	Reference			Target Type: Model	
FabcoDemand[F5 Fabricating TG]	Collection						
FabcoDemand[F5 Fabricating TG]	Collection	F5 Fabricating TG	Attribute			key	

FabcoDemand[F5 Fabricating TG]	Collection	Count	Auxiliary		dmnl	Value	Built-in variable. Reports the number of entities of this type existing at the end of each time slice.
FabcoDemand[F5 Fabricating TG]	Collection	sum MREE demand	Auxiliary	Sum Wind MREE demand+Sum EV MREE demand	KT/Year	Value	
FabcoDemand[F5 Fabricating TG]	Collection	Sum EV MREE demand	Aggregate	Sum	KT/Year	Target Variable: EV MREE demand	
FabcoDemand[F5 Fabricating TG]	Collection	Sum sum Clean Energy MREE demand	Aggregate	Sum	KT/Year	Target Variable: sum Clean Energy MREE demand	
FabcoDemand[F5 Fabricating TG]	Collection	Sum sum CleanEnergy PM demand	Aggregate	Sum	KT/Year	Target Variable: sum CleanEnergy PM demand	
FabcoDemand[F5 Fabricating TG]	Collection	Sum Wind MREE demand	Aggregate	Sum	KT/Year	Target Variable: Wind MREE demand	
FabcoDemand[F5 Fabricating TG]	Collection	Model	Reference			Target Type: Model	
FabcoDemand[D6 PM Demand TG]	Collection						
FabcoDemand[D6 PM Demand TG]	Collection	D6 PM Demand TG	Attribute			key	
FabcoDemand[D6 PM Demand TG]	Collection	Count	Auxiliary		dmnl	Value	Built-in variable. Reports the number of entities of this type existing at the end of each time slice.
FabcoDemand[D6 PM Demand TG]	Collection	Sum EV MREE demand	Aggregate	Sum	KT/Year	Target Variable: EV MREE demand	
FabcoDemand[D6 PM Demand TG]	Collection	Sum Wind MREE demand	Aggregate	Sum	KT/Year	Target Variable: Wind MREE demand	
FabcoDemand[D6 PM Demand TG]	Collection	Model	Reference			Target Type: Model	
Demand	Entity						
Demand	Entity	D6 PM Demand TG	Attribute			key	
Demand	Entity	EV Dy demand	Auxiliary	EV permanent magnet demand*Model.Dy fraction of PM	KT/Year	Value	

Demand	Entity	EV Nd demand	Auxiliary	EV permanent magnet demand*Model.Nd fraction of PM	KT/Year	Value
Demand	Entity	EV permanent magnet demand	Auxiliary	Ev Demand.EV Unit Demand*Model.EV permanent magnet fraction	KT/Year	Value
Demand	Entity	Ev Pr demand	Auxiliary	EV permanent magnet demand*Model.Pr fraction of PM	KT/Year	Value
Demand	Entity	EV Tb demand	Auxiliary	EV permanent magnet demand*Model.Tb fraction of PM	KT/Year	Value
Demand	Entity	offshore permanent magnet demand	Auxiliary	Model.Offshore permanent magnet fraction*wind offshore capacity	KT/Year	Value
Demand	Entity	onshore permanent magnet demand	Auxiliary	wind onshore capacity*Model.Onshore permanent magnet fraction	KT/Year	Value
Demand	Entity	wind Dy demand	Auxiliary	wind permanent magnet demand*Model.Dy fraction of PM	KT/Year	Value
Demand	Entity	wind Nd demand	Auxiliary	wind permanent magnet demand*Model.Nd fraction of PM	KT/Year	Value
Demand	Entity	wind offshore capacity	Auxiliary	Wind Demand.Wind Capacity Demand*Wind Demand.Offshore fraction	MW/Year	Value
Demand	Entity	wind onshore capacity	Auxiliary	Wind Demand.Wind Capacity Demand*Wind Demand.Onshore fraction	MW/Year	Value
Demand	Entity	wind permanent magnet demand	Auxiliary	onshore permanent magnet demand+offshore permanent magnet demand	KT/Year	Value
Demand	Entity	wind Pr demand	Auxiliary	wind permanent magnet demand*Model.Pr fraction of PM	KT/Year	Value
Demand	Entity	wind Tb demand	Auxiliary	wind permanent magnet demand*Model.Tb fraction of PM	KT/Year	Value
Demand	Entity	Ev Demand	Reference	Condition: D6 EV Demand TG D6 PM Demand TG		Target Type: Ev Demand
Demand	Entity	Model	Reference			Target Type: Model
Demand	Entity	Wind Demand	Reference	Condition: D6 PM Demand TG D6 PM Demand TG		Target Type: Wind Demand
Demand[]	Collection					

Demand[]	Collection	Count	Auxiliary		dmnl	Value	Built-in variable. Reports the number of entities of this type existing at the end of each time slice.
Demand[]	Collection	Model	Reference			Target Type: Model	
Lace Demand	Entity			Not used			
Lace Demand	Entity	Metal Demand Scenario	Attribute	Not used		key	
Lace Demand	Entity	CeX Demand	Data	Not used		Straight	
Lace Demand	Entity	CeX Demand Raw	Data	Not used		Raw	
Lace Demand	Entity	LaX Demand	Data	Not used		Straight	
Lace Demand	Entity	LaX Demand Raw	Data	Not used		Raw	
Lace Demand[]	Collection			Not used			
Lace Demand[]	Collection	Count	Auxiliary	Not used	dmnl	Value	Built-in variable. Reports the number of entities of this type existing at the end of each time slice.
Lace Demand[]	Collection	Model	Reference	Not used		Target Type: Model	
Deactivate M1 Mine Production	Action						
Deactivate M1 Mine Production	Action	Parent●mine state	Attribute	"inactive"			
Deactivate M1 Mine Production	Action	Invoker	Reference	Condition: M1 Mining TG		Target Type: M1 Mining	
Deactivate M1 Mine Production	Action	Parent	Reference	Condition: M1 Mining TG		Target Type: M1 Mining	
Add M1 Resources	Action						
Add M1 Resources	Action	increase period	Auxiliary	1	Year	Value	
Add M1 Resources	Action	Resource increase	Auxiliary	Invoker.ResKT*.25	KT	Value	
Add M1 Resources	Action	Invoker	Reference	Condition: M1 Mining TG		Target Type: M1 Mining	
Add M1 Resources	Action	Parent	Reference	Condition: M1 Mining TG		Target Type: M1 Mining	
Activate M1 Mine Production	Action						
Activate M1 Mine Production	Action	Parent●mine state	Attribute	"active"			
Activate M1 Mine Production	Action	Invoker	Reference	Condition: M1 Mining TG		Target Type: M1 Mining	

Activate M1 Mine Production	Action	Parent	Reference	Condition: M1 Mining TG		Target Type: M1 Mining	
EntityType	Entity						
EntityType	Entity	MetalMarket	Attribute			key	
EntityType	Entity	C2 Carbonate Price	Data			Straight	
EntityType	Entity	C2 Carbonate Price Raw	Data			Raw	
EntityType	Entity	Ce Price	Data			Straight	
EntityType	Entity	Ce Price Raw	Data			Raw	
EntityType	Entity	CeX Price	Data			Straight	
EntityType	Entity	CeX Price Raw	Data			Raw	
EntityType	Entity	Dy Price	Data			Straight	
EntityType	Entity	Dy Price Raw	Data			Raw	
EntityType	Entity	DyX Price	Data			Straight	
EntityType	Entity	DyX Price Raw	Data			Raw	
EntityType	Entity	La Price	Data			Straight	
EntityType	Entity	La Price Raw	Data			Raw	
EntityType	Entity	LaX Price	Data			Straight	
EntityType	Entity	LaX Price Raw	Data			Raw	
EntityType	Entity	M1 Concentrate Price	Data			Straight	
EntityType	Entity	M1 Concentrate Price Raw	Data			Raw	
EntityType	Entity	Nd Price	Data			Straight	
EntityType	Entity	Nd Price Raw	Data			Raw	
EntityType	Entity	NdX Price	Data			Straight	
EntityType	Entity	NdX Price Raw	Data			Raw	
EntityType	Entity	Pr Price	Data			Straight	
EntityType	Entity	Pr Price Raw	Data			Raw	
EntityType	Entity	PrX Price	Data			Straight	
EntityType	Entity	PrX Price Raw	Data			Raw	
EntityType	Entity	Tb Price	Data			Straight	
EntityType	Entity	Tb Price Raw	Data			Raw	
EntityType	Entity	TbX Price	Data			Straight	
EntityType	Entity	TbX Price Raw	Data			Raw	
EntityType[]	Collection						
EntityType[]	Collection	Count	Auxiliary		dmnl	Value	Built-in variable. Reports the number of entities of this type existing at the end of each time slice.
EntityType[]	Collection	Model	Reference			Target Type: Model	
C2 Circ Production	Entity						

C2 Circ Production	Entity	M1 Mining TG	Attribute		key	
C2 Circ Production	Entity	China Circ Capacity	Data		Straight	
C2 Circ Production	Entity	China Circ Capacity Raw	Data		Raw	
C2 Circ Production	Entity	M1 Planned Alt Capacity	Data		Straight	
C2 Circ Production	Entity	M1 Planned Alt Capacity Raw	Data		Raw	
C2 Circ Production	Entity	M1 Planned Alt Extraction	Data		Straight	
C2 Circ Production	Entity	M1 Planned Alt Extraction Raw	Data		Raw	
C2 Circ Production[]	Collection					
C2 Circ Production[]	Collection	Count	Auxiliary	dmnl	Value	Built-in variable. Reports the number of entities of this type existing at the end of each time slice.
C2 Circ Production[]	Collection	Model	Reference		Target Type: Model	
Ev Demand	Entity					
Ev Demand	Entity	D6 EV Demand TG	Attribute		key	
Ev Demand	Entity	EV Unit Demand	Data	unit/Year	Straight	
Ev Demand	Entity	EV Unit Demand Raw	Data	unit/Year	Raw	
Ev Demand[]	Collection					
Ev Demand[]	Collection	Count	Auxiliary	dmnl	Value	Built-in variable. Reports the number of entities of this type existing at the end of each time slice.
Ev Demand[]	Collection	Model	Reference		Target Type: Model	
M1 C2 Production	Entity					
M1 C2 Production	Entity	M1 Mining TG	Attribute		key	
M1 C2 Production	Entity	C2 Capacity Offset	Data		Straight	
M1 C2 Production	Entity	C2 Capacity Offset Raw	Data		Raw	
M1 C2 Production	Entity	C2 Concentrate Quota	Data		Straight	
M1 C2 Production	Entity	C2 Concentrate Quota Raw	Data		Raw	
M1 C2 Production	Entity	C2 Desired Processing	Data		Straight	
M1 C2 Production	Entity	C2 Desired Processing Raw	Data		Raw	
M1 C2 Production	Entity	M1 Capacity Offset	Data		Straight	
M1 C2 Production	Entity	M1 Capacity Offset Raw	Data		Raw	
M1 C2 Production	Entity	M1 Desired Mining	Data	KT/Year	Straight	

M1 C2 Production	Entity	M1 Desired Mining Raw	Data	KT/Year	Raw	
M1 C2 Production	Entity	M1 Mining Quota	Data		Straight	
M1 C2 Production	Entity	M1 Mining Quota Raw	Data		Raw	
M1 C2 Production[]	Collection					
M1 C2 Production[]	Collection	Count	Auxiliary	dmnl	Value	Built-in variable. Reports the number of entities of this type existing at the end of each time slice.
M1 C2 Production[]	Collection	Model	Reference		Target Type: Model	
Magnet Demand	Entity					
Magnet Demand	Entity	Dy Demand	Data		Straight	
Magnet Demand	Entity	Dy Demand Raw	Data		Raw	
Magnet Demand	Entity	Nd Demand	Data		Straight	
Magnet Demand	Entity	Nd Demand Raw	Data		Raw	
Magnet Demand	Entity	Pr Demand	Data		Straight	
Magnet Demand	Entity	Pr Demand Raw	Data		Raw	
Magnet Demand	Entity	Tb Demand	Data		Straight	
Magnet Demand	Entity	Tb Demand Raw	Data		Raw	
Metal Price	Entity					
Metal Price	Entity	Ce Price	Data		Straight	
Metal Price	Entity	Ce Price Raw	Data		Raw	
Metal Price	Entity	CeX Price	Data	$/kg	Straight	
Metal Price	Entity	CeX Price Raw	Data	$/kg	Raw	
Metal Price	Entity	Dy Price	Data		Straight	
Metal Price	Entity	Dy Price Raw	Data		Raw	
Metal Price	Entity	DyX Price	Data		Straight	
Metal Price	Entity	DyX Price Raw	Data		Raw	
Metal Price	Entity	La Price	Data		Straight	
Metal Price	Entity	La Price Raw	Data		Raw	
Metal Price	Entity	LaX Price	Data	$/kg	Straight	
Metal Price	Entity	LaX Price Raw	Data	$/kg	Raw	
Metal Price	Entity	Nd Price	Data		Straight	
Metal Price	Entity	Nd Price Raw	Data		Raw	
Metal Price	Entity	NdX Price	Data	$/kg	Straight	
Metal Price	Entity	NdX Price Raw	Data	$/kg	Raw	
Metal Price	Entity	Pr Price	Data		Straight	
Metal Price	Entity	Pr Price Raw	Data		Raw	

Metal Price	Entity	PrX Price	Data	$/kg	Straight	
Metal Price	Entity	PrX Price Raw	Data	$/kg	Raw	
Metal Price	Entity	Tb Price	Data		Straight	
Metal Price	Entity	Tb Price Raw	Data		Raw	
Metal Price	Entity	TbX Price	Data	$/kg	Straight	
Metal Price	Entity	TbX Price Raw	Data	$/kg	Raw	
S3 R4 Production	Entity					
S3 R4 Production	Entity	MineCapacity	Attribute		key	
S3 R4 Production	Entity	China R4 Capacity	Data		Straight	
S3 R4 Production	Entity	China R4 Capacity Raw	Data		Raw	
S3 R4 Production	Entity	China R4 Quota	Data		Straight	
S3 R4 Production	Entity	China R4 Quota Raw	Data		Raw	
S3 R4 Production	Entity	China S3 Capacity	Data		Straight	
S3 R4 Production	Entity	China S3 Capacity Raw	Data		Raw	
S3 R4 Production	Entity	China S3 Quota	Data		Straight	
S3 R4 Production	Entity	China S3 Quota Raw	Data		Raw	
S3 R4 Production	Entity	MSP R4 Capacity	Data		Straight	
S3 R4 Production	Entity	MSP R4 Capacity Raw	Data		Raw	
S3 R4 Production	Entity	MSP S3 Capacity	Data		Straight	
S3 R4 Production	Entity	MSP S3 Capacity Raw	Data		Raw	
S3 R4 Production	Entity	RoW R4 Capacity	Data		Straight	
S3 R4 Production	Entity	RoW R4 Capacity Raw	Data		Raw	
S3 R4 Production	Entity	RoW S3 Capacity	Data		Straight	
S3 R4 Production	Entity	RoW S3 Capacity Raw	Data		Raw	
S3 R4 Production[]	Collection					
S3 R4 Production[]	Collection	Count	Auxiliary	dmnl	Value	Built-in variable. Reports the number of entities of this type existing at the end of each time slice.
S3 R4 Production[]	Collection	Model	Reference		Target Type: Model	
Wind Demand	Entity					
Wind Demand	Entity	D6 PM Demand TG	Attribute		key	
Wind Demand	Entity	Offshore fraction	Data	dmnl	Straight	
Wind Demand	Entity	Offshore fraction Raw	Data	dmnl	Raw	
Wind Demand	Entity	Onshore fraction	Data	dmnl	Straight	

Wind Demand	Entity	Onshore fraction Raw	Data		dmnl	Raw	
Wind Demand	Entity	Wind Capacity Demand	Data		MW/Year	Straight	
Wind Demand	Entity	Wind Capacity Demand Raw	Data		MW/Year	Raw	
Wind Demand[]	Collection						
Wind Demand[]	Collection	Count	Auxiliary		dmnl	Value	Built-in variable. Reports the number of entities of this type existing at the end of each time slice.
Wind Demand[]	Collection	Model	Reference			Target Type: Model	
Transition	Entity						
Transition	Entity	C2 Production TG XN	Attribute				
Transition	Entity	M1 Mining TG XN	Attribute				
Transition	Entity	Production Group Capex Target	Attribute				
Transition	Entity	Production Mine Capex Target	Attribute				
Transition	Entity	S3 Separation TG XN	Attribute				
Transition	Entity	C2 max stimulus	Auxiliary	10	M$/Year	Value	
Transition	Entity	C2 stability index	Auxiliary	C2 stability LU(C2 stability LU xvar)	dmnl	Value	M1 stability LU(M1 stability LU xvar)
Transition	Entity	C2 stability LU xvar	Auxiliary	C2 Production.C2 stimulus amount/C2 max stimulus	dmnl	Value	
Transition	Entity	M1 max stimulus	Auxiliary	10	M$/Year	Value	
Transition	Entity	M1 stability index	Auxiliary	M1 stability LU(M1 stability LU xvar)	dmnl	Value	
Transition	Entity	M1 stability LU xvar	Auxiliary	M1 Mining.M1 stimulus amount/M1 max stimulus	dmnl	Value	
Transition	Entity	C2 stability LU	TableFunction	0,10,-1,100,0,100,0.25,50,0.5,25,1,0,10,0			
Transition	Entity	M1 stability LU	TableFunction	0,10,-1,100,0,100,0.25,50,0.5,25,1,0,10,0			
Transition	Entity	S3 stability LU	TableFunction	0,10,-1,100,0,100,0.25,50,0.5,25,1,0,10,0			
Transition	Entity	C2 Production	Reference	Condition: C2 Production TG C2 Production TG XN		Target Type: C2 Production	
Transition	Entity	M1 Mining	Reference	Condition: M1 Mining TG M1 Mining TG XN		Target Type: M1 Mining	
Transition	Entity	Model	Reference			Target Type: Model	