Rare Earth Materials

Insights and Concerns

CENTER FOR ENERGETIC CONCEPTS DEVELOPMENT SERIES

ENERGETICS SCIENCE AND TECHNOLOGY SERIES

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Foreword

This book provides insight into the current status of the global supply chain of rare earth elements, and addresses their availability and processing for the commercial and defense sectors of our national economy. Particular attention is given to the role of China since it is currently the largest worldwide provider of these elements. Recent developments in the availability of some of these materials has heightened the concern of policy makers regarding the application of these special elements in current and future systems. The status of these materials vis-à-vis U.S. considerations is reviewed as many of these materials are critical components of commercial and defense-related products.

It is important that our scientists and engineers in the technical community possess an awareness of the issues relating to strategic materials such as these. The purpose of this book is to continue the dialogue on the subject of rare earth elements which are essential materials used in the support of national security and a vibrant commercial marketplace.

John W. Fischer, Ph.D.
Director, Defense Laboratory Office

Preface and Acknowledgements

Rare earth elements (which are seventeen elements on the periodic table) are used in an ever-growing variety of applications that are key to our modern technology. In addition they are essential for a wide variety of defense technologies that are critical to national security. Global demand for rare earth materials is projected to grow, fueled in part by continued development and deployment of emerging energy technologies, and as a result, a global shortage of rare earths is anticipated in the near future. Although the United States has 13 percent of the world's exploitable reserves, nearly all rare earth materials used in the country are imported from China. In contrast, China has only 48.3 percent of the world's rare earth reserves, yet accounts for more than 97 percent of global rare earth production. Furthermore, China has been reducing its export quotas in order to satisfy growing domestic demand, and is placing further emphasis on strengthening its vertically integrated supply chain in the rare earth industry by focusing on downstream rare earth products.

Prices for rare earths experienced a dramatic increase throughout the first half of 2011 – for instance, prices for some key REEs, such as europium and dysprosium, increased by more than eightfold from January to August. Several key factors contributed to this significant increase. An incident in 2010 between Japan and China resulted in rare earth exports to Japan being stopped for a month, indicating to the rest of the world that China's supply could be constrained at any time. During the same period the Chinese government continued to reduce export quotas, and the country's rare earth producers began to account for the cost of excessive resource exploitation and environmental damage through increases in government taxation.

To address a possible rare earth shortage crisis, the United States needs to actively pursue policies to ensure supply security. In addition to developing domestic resources and stockpiling specific rare earths, we must support the development of new technologies for their mining and processing. We must also develop more efficient manufacturing and recycling methods for consumer goods containing rare earths, investigate synthetic rare earth substitute compounds, and continue research into rare-earth-free technologies.

The authors take particular note of the special contributions made by Xin Song in researching several aspects of this subject. We also acknowledge the copyediting done by Eric Hazell and Ania Picard for the overall production of this book. We would also like to thank Elan Moritz for reviewing the book and John Fischer for many helpful discussions during its development. This book is the result of a study performed to create a body of knowledge, and is not intended to be an original work, but rather a compendium of open literature. Its purpose is to provide timely information in sufficient detail to support the development of appropriate policy decisions, as well as to provide a resource for U.S. commercial concerns. The book provides an insight into the current status of availability, processing and uses of rare earths in the world. Particular attention is given to the role of China, since it is by far the largest provider of these elements worldwide. The status of the U.S. is also reviewed, as are the implications of current and future policies relating to rare earths.

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Author Biographies

Davinder K. Anand is Professor of Mechanical Engineering and Director of the Center for Energetic Concepts Development, both at the University of Maryland, College Park. He received his doctorate from George Washington University in 1965. Dr. Anand was Senior Staff at The Applied Physics Laboratory of the Johns Hopkins University from 1965-1974. From 1991-2002, he chaired the Department of Mechanical Engineering at College Park. He has served as a Director of the Mechanical Systems Program at the National Science Foundation, and his research has been supported by NIH, NASA, DOE, DOD, and industry. He has lectured internationally, founded two high technology research companies (most recently Iktara and Associates, LLC), published three books and over one hundred and seventy papers, and has one patent. He is a Distinguished Alumnus of George Washington University, and was awarded the Outstanding and Superior Performance Award by the National Science Foundation. Dr. Anand is a Fellow of ASME and is listed in *Who's Who in Engineering*.

Dylan A. Hazelwood is a Systems Analyst with the Center for Energetic Concepts Development, in the Department of Mechanical Engineering at the University of Maryland. He received a Bachelor's degree of Applied Computing from the University of Tasmania, Australia. His main expertise is in information technology systems and development. As Assistant Director of Information Technology for the Department of Mechanical Engineering, he was involved in information technology infrastructure development and management, high performance computing cluster development and implementation as well as development and implementation of distance learning technologies. Since joining the CECD in 2009, he has worked in the areas of energetics informatics and rare earth materials research.

Robert E. Kaczmarek is a senior staff member to the Technical Director of the Naval Surface Warfare Center, Indian Head Division (NSWC-IHD). Mr. Kaczmarek has over thirty years of extensive weapon system development, acquisition, and organizational leadership experience. Mr. Kaczmarek during 2011 was assigned as a Senior Visiting Research Scholar to the University of Maryland's Department of Mechanical Engineering at College Park. Mr. Kaczmarek earned a Bachelor's degree in Chemical Engineering from the State University of New York at Buffalo in 1981 and a Master's degree in Engineering Administration from the George Washington University in 1987.

Robert A. Kavetsky is currently the Executive Director of the Energetics Technology Center, where he leads a Policy Development Group for a number of Department of Defense clients. He was the founder of the N-STAR (Naval Research – Science and Technology for America's Readiness) initiative at the Office of Naval Research, a Navy-wide effort aimed at reinvigorating the science and technology community within the Navy's Warfare Centers. He received a Bachelor of Science Mechanical Engineering in 1975, a Master of Science Mechanical Engineering in 1977, and a Master of Science Engineering Administration in 1978, all from Catholic University. He was head of the Explosion Damage Branch, Program Manager for the Undersea Warheads Program, and Program Manager for Undersea Weapons at the Naval Surface Warfare Center. At the Pentagon, he helped develop science and technology programs for organic mine countermeasures and expeditionary logistics, and then at Naval Surface Warfare Center Indian Head created "Workforce 2010," a government, industry, and academic consortium focused on developing Indian Head's next generation workforce. He has authored a number of technical and workforce policy and program publications for the American Society for Engineering Education, the American Society of Mechanical Engineers, the American Institute of Aeronautics and Astronautics, and other forums.

Michael G. Pecht is a visiting Professor in Electronic Engineering at City University in Hong Kong. He has an M.S. in Electrical Engineering and an M.S. and Ph.D. in Engineering Mechanics from the University of Wisconsin at Madison. He is a Professional Engineer, an IEEE Fellow, an ASME Fellow, an SAE Fellow and an IMAPS Fellow. In 2010, he received the IEEE Exceptional Technical Achievement Award. In 2008, he was awarded the highest reliability honor, the IEEE Reliability Society's Lifetime Achievement Award. He has previously received the European Micro and Nano-Reliability Award for outstanding contributions to reliability research, 3M Research Award for electronics packaging, and the IMAPS William D. Ashman Memorial Achievement Award for his contributions in electronics reliability analysis. He served as chief editor of the *IEEE Transactions on Reliability* for eight years and on the advisory board of *IEEE Spectrum*. He is chief editor for *Microelectronics Reliability* and an associate editor for the *IEEE Transactions on Components and Packaging Technology*. He is the founder of CALCE (Center for Advanced Life Cycle Engineering) at the University of Maryland, which is funded by more than 150 of the world's leading electronics companies. He is also a Chair Professor in Mechanical Engineering and a Professor in Applied Mathematics at the University of Maryland. He has written more than twenty books on electronic products development, use and supply chain management and over 400 technical articles. He has also written books on India's, Korea's and China's Electronics Industry. He consults for 22 major international electronics companies, providing expertise in strategic planning, design, test, prognostics, IP and risk assessment of electronic products and systems.

Xin Song is an expert on rare earths. She has prepared numerous reports for industrial leaders, including Boeing and Emerson, communicates closely with Chinese rare earth experts, and is one of the few people in the U.S. who has visited Chinese rare earth mines. She was invited by Dr. Zhanheng Chen, Director of the Chinese Rare Earth Association's Academic Department, to attend the 2010 Third China Rare Earth Forum, and was also a guest speaker at the 2011 Emerson Innovation and Technology Conference. Dr. Song is a hydrogeologist/environmental engineer at ARCADIS, with expertise in soil and groundwater assessment and remediation, and groundwater flow and contaminant transport modeling in the subsurface. She earned a B.S. from Dalian University of Science and Technology, Dalian, China, an M.S. in Environmental Science from Tsinghua University, Beijing, China, and a Ph.D. in Civil and Environmental Engineering from the University of Maryland, College Park. She is a registered Professional Engineer in California.

Acronyms

ACREI	Association of China Rare Earth Industry
ARPA-E	Advanced Research Projects Agency Energy
ARRA	American Recovery and Reinvestment Act
ATVM	Advanced Technology Vehicle Manufacturing
Au	gold
BDF	Beijing Density Functional
BEEST	Batteries for Electric Energy Storage in Transportation
BGS	British Geological Survey
BRIRE	Baotou Research Institute of Rare Earths
CAS	Chinese Academy of Sciences
CCFL	cold cathode fluorescent lamp
Ce	cerium
CFL	compact fluorescent lamp

Chinalco	Aluminum Corporation of China (also known as CHALCO for Aluminum Corporation of China Limited)
CIS	Commonwealth of Independent States (Armenia, Azerbaijan, Belarus, Kazakhstan, Kyrgyzstan, Moldova, Russia, Tajikistan, Turkmenistan, Ukraine, Uzbekistan)
CLD	Central Lanthanide Deposit
CNAS	Center for a New American Security
CNMC	China Non-Ferrous Metal Mining Group Co. Ltd.
CNOOC	China National Offshore Oil Corporation
CR	concentration ratio, also expressed as CR(n)
CREIJ	China Rare Earth Information Journal
CREME	Centre for Research in Energy and Mineral Economics
CRI	color rendering index
CRT	cathode ray tube
CSC	Chinese State Council (also SCPRC – State Council of the People’s Republic of China)
CSRE	Chinese Society of Rare Earths
DARPA	Defense Advanced Research Projects Agency
DLASM	Defense Logistics Agency Strategic Materials
DoD	Department of Defense
DoE	Department of Energy
DoI	Department of Interior

DNSC	Defense National Stockpile Center
Dy	dysprosium
DyFe	dysprosium iron metal (also Dy-Fe)
EEC	Electron Energy Corporation
EERE	Energy Efficiency and Renewable Energy
EL	electro luminescence
EOL	end-of-life
EPA	Environmental Protection Agency
EPAct	Energy Policy Act
ERI	Electronic Recyclers International
Er	erbium
Eu	europium
EU	European Union
FIRB	Australian Foreign Investment Review Board
GAO	U.S. Government Accountability Office
GATT	General Agreement on Tariffs and Trade
Gd	gadolinium
GE	General Electric
GM	General Motors
GRINM	General Research Institute for Nonferrous Metals
GWMG	Great Western Minerals Group
JOGMEC	Japan Oil, Gas, and Metals National Corporation

Hci	coercivity
HEV	hybrid electric vehicle
HI	Herfindahl index (also known as Herfindahl–Hirschman Index, or HHI)
Ho	holmium
IMCOA	Industrial Mineral Company of Australia
IREL	Indian Rare Earths Limited
ISRI	Institute of Scrap Recycling Industries Inc.
JXTC	Jiangxi Rare Earth and Rare Metals Tungsten Group Co. Ltd.
KORES	Korea Resources Corporation
La	lanthanum
LED	light-emitting diode
LGP	Loan Guarantee Program
Li-ion	lithium-ion
Lu	lutetium
LCD	liquid crystal display
LREE	Light Rare Earth Elements
MLCC	multilayer ceramic capacitor
MEP	Ministry of Environmental Protection
METI	Ministry for Economy, Trade, and Investment, Japan
MGOe	The stored energy in a magnet, called *magnet performance* or *maximum energy product* (often

	abbreviated BH_{max}), is typically measured in units of megagauss-oersteds (MGOe)
Min FOB	minimum freight on board
MIIT	China Ministry of Industry and Information Technology
MLCC	multilayer ceramic capacitor
MLR	China Ministry of Land and Resources of the People's Republic of China
MOFTEC	Ministry of Foreign Trade and Economic Cooperation
MOC	Ministry of Commerce, China
MoF	Ministry of Finance, China
Molycorp	Molycorp, Inc.
MOST	Ministry of Science and Technology of the People's Republic of China
MRI	magnetic resonance imaging
Nd	neodymium
NDS	National Defense Stockpile
NdFeB	neodymium iron boron
NHI	normalized Herfindahl index
Ni-MH	nickel-metal hydride
NRC	U.S. National Research Council
pc-LED	phosphor converted LED
PDA	personal digital assistant
PDP	plasma display panel

PET	positron emission tomography
Pm	promethium
Pr	praseodymium
Program 863	China's National High Technology Research and Development Program 863
Program 973	China's National High Technology Research and Development Program 973
R&D	Research and Development
RARE	Resource Assessment of Rare Earths
REACT	Rare Earth Alternatives in Critical Technologies for Energy
REE	Rare Earth Element
REO	Rare Earth Oxide
RESTART	Rare Earths Supply-Chain Technology and Resources Transformation
RI	risk index
ROW	Rest Of World, typically referring to countries outside China
Sc	scandium
Sm	samarium
SmCo	samarium cobalt
SDPC	State Development and Planning Commission
SETC	State Economic and Trade Commission
SPC	State Planning Commission
TCC	temperature coefficient of capacitance

Tb	terbium
TFBSO	Task Force for Business and Stability Operations
Th	thorium
Tm	thulium
TMR	Technology Metals Research
TREI	Toyotsu Rare Earths India
TWT	traveling wave tube
UNCLOS	U.N. Convention on the Law of the Sea
USCC	U.S.-China Economic and Security Review Commission
USGS	U.S. Geological Survey
USEPA	U.S. Environmental Protection Agency
WTO	World Trade Organization
Yb	ytterbium
Y	yttrium

Executive Summary

Global demand for rare earth materials is expected to grow dramatically. Primarily fueled by the continued development and implementation of emerging technologies, this demand will be exacerbated by the fact that in recent years China has been reducing its export quotas in order to both satisfy growing domestic demand and to further develop a vertically integrated supply chain in its rare earth industry. At the same time, there is currently minimal rare earth mine production and processing in the U.S., with most materials being obtained from foreign sources, almost exclusively from China. A supply disruption of essential rare earths to the U.S. could clearly threaten the economic status and national security of the country, and this book reports on a range of rare earth issues in light of this concern.

The rare earth elements consist of seventeen chemical elements. They are typically categorized into two groups – light rare earth elements and heavy rare earth elements. The light rare earth elements are lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), promethium (Pm), and samarium (Sm). The heavy rare earth elements include those with atomic numbers ranging from 63 to 71: europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), lutetium (Lu), as well as scandium (Sc) and yttrium (Y) (atomic numbers 21 and 39). Rare earth materials, including ores, oxides, metals, and alloys, consist of one or more rare earth elements.

Trillions of dollars' worth of modern devices depend upon rare earths. The two most important commercial end uses for rare earths in the U.S. are for automotive catalytic converters and petroleum refining catalysts, which together account for almost half of total rare earth usage. Metallurgical additives and alloys are ranked third in rare earth applications. Other major end uses include permanent magnet motors and

rechargeable batteries for both hybrid and full electric vehicles, phosphors for lighting and flat panel displays, glass polishing and ceramics, numerous medical devices, and in agriculture, mainly in China. In addition to widespread applications in commercial products, rare earth materials are also widely used in defense and dual-use systems. Examples of such applications include precision guided munitions, lasers, communication systems, radar systems, avionics, night-vision equipment, and satellites. In these applications, rare earth materials are very difficult to replace without compromising performance.

Most rare earth reserves are located throughout the world in deposits of bastnaesite and monazite. Bastnaesite deposits in the U.S. and China account for the largest concentrations, while monazite deposits in Australia, South Africa, China, Brazil, Malaysia, and India account for the second-largest concentrations of rare earths. The USGS has identified approximately 114 million metric tons of exploitable rare earth reserves worldwide: China has 48.3%, CIS/Russia has 16.7%, the U.S. has 11.4%, India has 2.7% and Australia has 1.4%. Five of the world's richest rare earth deposits include the Bayan Obo deposit in China, the Mountain Pass deposit in U.S., the Mount Weld carbonatite deposit in Australia, placer deposits in Australia and the Seven Provinces ion adsorption clay deposit in Southern China. Other large deposits have been found within Russia, Afghanistan, South Korea, and other countries, although in many cases due to their location they are extremely difficult to mine. While many reserves have already been discovered, the USGS has estimated that undiscovered resources are very large relative to expected future demand.

Aside from the well-known Mountain Pass deposit in California, other rare earth resources exist within North America. Another promising resource is the Bear Lodge property in northeast Wyoming. Bear Lodge is reported to contain 384,000 metric tons of high-grade rare earths, as well as extensive gold resources within the same deposit. Significant deposits also exist within Canada, Alaska, Nebraska, Illinois, Colorado, Idaho, New York, New Mexico, Missouri and New Jersey, with varying concentrations of rare earth elements. Regarding global resources, a large number of deposits have been identified, with some currently being mined, and others in the development stage. Key deposits include Steenkamskraal in South Africa, Kvanefjeld in Greenland, Dong Pao in Vietnam, and Dubbo, Nolans and Mt Weld in Australia. Other significant deposits discovered within countries such as Russia and Afghanistan are considered highly valuable, but are not actively exploited due to the challenges of their location.

Global demand for rare earth materials grew steadily by between 8–12 percent per year until 2008, before falling due to the global recession.

Demand levels then recovered, and continued to follow a similar growth trend from mid-2009 onwards, with demand projected to continue to steadily grow out to 2016. China is not only the world's leading producer of rare earth materials but also the leading consumer, with total consumption of 70,000 metric tons of global production in 2011. Japan and northeast Asia are the second-largest consumers of rare earth materials, accounting for approximately 22 percent of world consumption, and the U.S. follows as the third leading consumer, at about 12 percent. Experts are predicting that China's internal needs for rare earths will continue to take up the majority of its production.

There are currently no exchanges where rare earth metals are traded, and any pricing information available for large purchases is reported from spot transactions, where the price reported may be significantly different than what was actually paid. It should be noted, however, that pricing within the rare earths market has shown enough volatility to illustrate clear trends. The global rare earth market was relatively stable in the 2000s, and then in early 2011, due to significant global concerns over Chinese supplies, the prices for rare earth metals and oxides were reported to have risen as far as 800% from January to August. As a result, companies outside China looked to their rare earth material stockpiles or illegal Chinese exports, or simply reduced their level of production. Almost as quickly as prices had gone up they began to fall again, with the Chinese government enacting production shutdowns late in 2011, possibly in order to stop prices from falling further. As of April 2012, pricing for some heavy rare earths (Nd, Dy) had begun to increase once again.

The current global rare earth supply situation has been caused by unbalanced global supply and production – China produced 94% of world supply of REEs in 2011, leaving only 6% of the world's supply provided by facilities outside China, despite sizable deposits worldwide. China is facing growing domestic demand, and as such its supply to the outside world will be limited to what is left over after that demand is satisfied. China's drive to build stronger downstream REE industries will only further decrease exports, resulting in shortages if producers from the rest of the world do not step in to fill the gap. Supplies may become available soon however, as companies in a number of countries are actively developing rare earth mines and processing facilities, either within their own countries or in partnerships with other countries. Germany, Japan and others have set up partnerships and other agreements with industry members and governments in Australia, Malaysia, India, South Korea, Vietnam, Kyrgyzstan, Kazakhstan and more in an effort to assure future rare earth supplies from non-Chinese sources.

Until the 1990s, most of the world's rare earths were supplied by the United States, from the Mountain Pass mining and processing facility in California. Mountain Pass was closed in 2002 amid falling rare earth prices and environmental concerns, marking the point at which control over the rare earth supply chain shifted to China. Approximately 20 years ago the U.S. had twelve rare earth oxide magnet factories, employing 6,000 workers and participating in a global market valued at $600 million. As of 2010, only four factories remained, with approximately 600 workers, while the global market had grown to a value of over $7 billion. The Mountain Pass facility has since been redeveloped and reopened, however, and under the direction of a newly formed Molycorp is looking to become a major supplier to the U.S. domestic market at a projected 40,000 metric tons per year of rare earth oxides.

In the early 1990s, China became the principal producer, supplier and consumer of the rare earth industry. The country has made remarkable progress in rare earth science, technology and resource utilization while only possessing half of the world’s rare earth reserves. China showed significant interest in rare earths, particularly in R&D, even in the early years of the country’s development of its resources. As a result of two national programs focused on fundamental research, Programs 863 and 973, today China is home to the largest rare earth R&D institute in the world (BRIRE) with nearly 500 employees, as well as a number of key state laboratories working on rare earth research.

Despite the country’s success in rare earth production, the industry in China has been rife with unrestrained mine development, environmental issues and poor resource management practices. Chinese leaders have expressed their concern that the country’s future demand for rare earths may not be met if existing mining practices are allowed to continue without further regulation. The environmental damage done to mining areas in China is extensive, and as a result the government has begun to enact and enforce new environmental taxes and laws designed to curb excessive, dangerous and illegal mining. They have also begun to combine existing mining and processing firms into a handful of larger firms in order to exert stronger governmental control over the industry.

China has also been reducing export quotas for rare earth oxides and in 2012 has placed specific restrictions on heavy and light rare earths for the first time. The combination of these restrictions and increasing export tariffs on rare earth metals and oxides is designed to lead rare earth material consumers to move their manufacturing enterprises into China. If the Chinese government is successful, the result will be growth in numbers of higher value downstream rare earth goods being exported, rather than rare earth oxides. Accordingly, there is growing concern about the security of future rare earth oxide and metal supplies among upstream rare earth consumers outside China.

China's reduction in export quotas in recent years and the rising price of rare earths has spurred global interest in recycling cast-off electronics products that contain rare earth materials, finding substitutes, performing research to minimize usage, and finding new supplies to build complete supply chains. After a temporary rare earth trade stoppage with China in 2010, Japan has led these efforts with aggressive government targets designed for both greater recycling and a reduction in usage of rare earths. Japanese companies such as Toyota Tsusho have also begun to secure alternative sources for their entire rare earth supply chain, investing in rare earth projects worldwide. As a result of concerns about both future price and availability, companies around the world have also invested heavily in the development of rare earth free technologies, with many beginning to arrive in the marketplace.

A complete rare earth supply chain is currently lacking in the U.S., and it must be further developed, either nationally or in conjunction with our allies. An aggressive R&D agenda is recommended for REE alternatives, reduction strategies, processing optimization, new applications, alternative REE-free technologies and REE recycling, with an accompanying intellectual development component. While the DoD and the U.S. Government do not have any sense of urgency regarding this issue based on their prediction of future domestic capabilities, a call to action at the national level is required. In order to ensure national security, a stockpile of the most critical materials should be created, in the form of a public-private (government-industry) partnership. We should also look to Japan as a role model for the actions required to address a situation currently considered critical but not yet a crisis.

National security, as well as future economic growth from emerging technologies, is dependent upon the steady availability of rare earth elements, which will be supplied to the world in the foreseeable future primarily by a single potentially hostile supplier. Our challenge is to address this issue head on, and in an imaginative way.

Contents

Chapter 1

Introduction

Global demand for rare earth materials is expected to grow dramatically. Primarily fueled by the continued development and implementation of emerging technologies, this demand will be exacerbated by the fact that in recent years China has been reducing its export quotas in order to satisfy domestic demand and further develop a vertically integrated supply chain in the rare earth industry. At the same time, there is currently very minimal rare earth mine production and processing in the U.S., with most necessary materials being obtained from foreign sources, almost exclusively China. A supply disruption of essential rare earths to the U.S. could clearly threaten the economic status and national security of the country, and this book reports on a range of rare earth issues in light of this concern.

1.1 Definition of Rare Earth Elements

The rare earth elements consist of seventeen chemical elements, fifteen of which have atomic numbers 57 through 71, from lanthanum to lutetium (the “lanthanides”). The two additional elements are scandium (atomic number 21), and yttrium (atomic number 39), both of which are chemically similar to the lanthanides, and thus typically included with the rare earth elements. Rare earth elements are typically categorized into two groups – light and heavy. The light rare earth elements are lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), promethium (Pm), and samarium (Sm) (atomic numbers 57–62). The heavy rare earth elements include those with atomic numbers ranging from 63 to 71: europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), and lutetium (Lu), plus scandium (Sc) and yttrium (Y) (atomic numbers 21 and 39). Heavy rare earth elements can be further divided into the categories middle (Eu, Gd, Tb, Dy, Ho) and heavy (Er, Tm, Yb, Lu, Sc, Y). Table 1.1 shows the light, heavy and middle rare earth elements in the periodic table and in tabular form. Rare earth materials, including rare earth ores, oxides, metals, and alloys, consist of one or more rare earth elements.

Most rare earth elements are not as rare as the group's name suggests. For example, Lutetium (Lu) is approximately 125 times more abundant than gold (Au) [1]. The name originated in the eighteenth and nineteenth centuries, primarily because most rare earths were identified as oxide components within seemingly rare materials. Figure 1.1 (see color insert) shows the abundance of rare earth elements in the upper continental crust, where they are often found together, along with other chemical elements for comparison. Differences in the amount of individual rare earth elements in the upper continental crust are due to two reasons, one nuclear and the other geochemical. First, there is a greater concentration of rare earth elements with even atomic numbers (e.g., Ce [58], Nd [60]) in both the Earth and the universe than of rare earth elements with odd atomic numbers (e.g., La [57], Pr [59]). Second, lighter rare earth elements are less compatible with other minerals because they have larger ionic radii, and so are more strongly concentrated in the continental crust than the heavier rare earth elements. As a result, the first four rare earth elements, ([57-60] – La/Ce/Pr/Nd), make up 80–99 percent of the total in most rare earth deposits [3].

Rare earth metals are generally lustrous in appearance, with a color range from iron grey to silver, and they are characteristically soft, malleable, ductile and typically reactive. The melting points of rare earth elements, ranging from 798°C for cerium to 1663°C for lutetium, have direct implications for the reduction process used in metal production [4]. Most rare earth elements, with the exception of Sc, Y, La, Yb and Lu, are strongly paramagnetic, and have strong magnetic anisotropy [5]. They can be difficult to separate from one another as they share some common properties:

- Their metallic luster is quite high, but they easily become tarnished with exposure to air.
- They occur naturally with minerals such as monazite.
- They have similar ionic radii.
- Their oxidation state is usually a trivalent charge ($^{3+}$).
- They have high electrical conductivity.

Table 1.1: Rare Earth Elements [6]

	Element	Symbol	Atomic Number	Atomic Weight	Density (gcm-3)	Melting Point (^{o}C)	Vicker's Hardness (10kg load, kg/mm^{2})
Light	Lanthanum	La	57	138.90	6.146	918	37
	Cerium	Ce	58	140.11	8.160	798	24
	Praseodymium	Pr	59	140.90	6.773	931	37
	Neodymium	Nd	60	144.24	7.008	1021	35
	Promethium	Pm	61	145.00	7.264	1042	-
	Samarium	Sm	62	150.36	7.520	1074	45
Middle	Europium	Eu	63	151.96	5.244	822	17
	Gadolinium	Gd	64	157.25	7.901	1313	57
	Terbium	Tb	65	158.92	8.230	1356	46
	Dysprosium	Dy	66	162.50	8.551	1412	42
	Holmium	Ho	67	164.93	8.795	1474	42
Heavy	Erbium	Er	68	167.26	9.066	1529	44
	Thulium	Tm	69	168.93	9.321	1545	48
	Ytterbium	Yb	70	173.04	6.966	819	21
	Lutetium	Lu	71	174.97	9.841	1663	77
	Scandium	Sc	21	44.95	2.989	1541	85
	Yttrium	Y	39	88.90	4.469	1522	38

1.2 Classification of Rare Earths

According to Kanazawa and Kamitani in 2006, about 200 distinct species of rare earth minerals have been discovered – these are minerals in which one or more rare earth elements are found [7]. As seen in Table 1.2, rare earth elements are distributed across a wide variety of mineral classes. Carbonates and phosphates are rich in light rare earth elements, and oxides – such as titanates, niobates, and tantalates, as well as some phosphates – are rich in heavy rare earth elements.

A collection of major global rare earth deposits is classified into igneous, sedimentary and secondary types, as summarized in Table 1.3. The largest rare earth deposit in the world, Bayan Obo, located in Inner Mongolia, China, is the only deposit in this group formed by hydrothermal replacement of carbonate rocks of sedimentary origin. Carbonatite deposits constitute many of rest of the world's rare earth resources, such as Mountain Pass in the United States, Mount Weld in Australia and Maoniuping in China [8]. A detailed description of global rare earth deposits is provided in Chapter 2.

1.3 Uses of Rare Earth Elements

Trillions of dollars' worth of modern devices depend on rare earths, and Table 1.4 provides a summary of rare earths' major end uses.

As seen in Figure 1.2 (see color insert), the two most important commercial end uses for rare earths in the U.S. are for automotive catalytic converters (25%) and petroleum refining catalysts (22%), which together account for almost half of total rare earth usage. Metallurgical additives and alloys, (20%), are ranked third in rare earth applications. Other major end uses for rare earths include permanent magnets and rechargeable batteries for both hybrid and full electric vehicles, phosphors for lighting and flat panel displays, glass polishing and ceramics, and numerous medical devices. Many of these are referred to as rare earth dependent technologies, as without rare earth materials they would not be commercially viable.

In addition to widespread applications in commercial products, rare earth materials are also widely used in defense and dual-use systems. Examples of such applications include precision guided munitions, lasers, communication systems, radar systems, avionics, night-vision equipment, and satellites. In these applications, rare earth materials are very difficult to replace without losing performance. For instance, fin actuators used in precision-guided munitions are designed based on the capabilities of neodymium-iron-boron (NdFeB) rare earth magnets [10].

Table 1.2: Classification of Rare Earth Minerals [11]

Mineral Class	Mineral Examples and Chemical Formulae
Halides	Fluocerite, CeF_3
Carbonates	
with fluoride	Bastnaesite, $(Ce,La)(CO_3)F$
without fluoride	Ancylite, $(Ce,Sr,Ca)(CO_3)(OH,H_2O))$
Borates	Braistschite, $(Ca,Na_2)_7CeB_{22}O_{43}\bullet 7H_2O$
Oxides and hydrates	
AO_2-type	Cerianite, $(Ce^{4+},Th^{4+})O_2$
ABO_3-type	Perovskite group, $(Ca,Ce,Na,Sr)(Ti,Nb,Ta)O_3$
ABO_4-type	Fergusonite-Formanite, $Y(Nb,Ta)O_4$-$Y(Ta,Nb)O_4$
$AB_2(O,OH)_6$-type	Euxenite group, $(Y,Ca,Ce,U,Th)(Nb,Ta,Ti)_2O_6$
$AB_2O6(O,OH,F)_6$-type	Pyrochlore group, $(Na,RE,K,U)_2(Nb,Ta,Ti)_2(O,OH,F)$
Others	Hibonite, $(Ca,Ce)(Al,Ti,Mg)_{12}O_{19}$
Phosphates, arsenates and vanadates	Apatite, $(Ca,RE,Sr,Na,K)_3Ca_2(PO_4)_3(F,OH)$
	Monazite, $(Ce,La)PO_4$
	Xenotime, YPO_4
Silicates (The following groups are categorized based on the linkage manner of tetrahedral anionic group.)	
Isolated group	Cerite, $(Ce,La,Ca)_9(Fe^{3+},Mg)(SiO_4)_6[SiO_3(OH)](OH)_3$
	Garnet, $(Ca,Fe,Mg,Mn,Y)_3(Al,Cr,Fe,Mn,Ti,V,Zr)_2(Si,Al)_3O_{12}$
	Sphene, $CaTiSiO_4$
Diortho group	Allanite, $Ca(Ca,Y,Ca)Al(Al,Fe)(Fe,Al)(SiO_4)_3(OH)$
Chain group	Stillwellite, $CeBSiO_5$
Ring group	Eudialyte, $(Na,Ca,Ce)_6(Zr,Fe)_2Si_7(O,OH,Cl)_{22}$
Sheet group	Gadolinite, $(Y,Ce)_2Fe^{2+}Be_2Si_2O_{10}$
Framework group	Kainosite, $Ca_2(Y,RE)_2(Si_4O_{12})CO_3\bullet H_2O$
Others	Iimoriite, $Y_2(SiO_4)(CO_3)$

Table 1.3: Classification of Rare Earth Deposits [12]

	Deposit-type	Mines
Igneous	Hydrothermal	Bayan Obo (China)
	Carbonatites	Mountain Pass (USA) Maoniuping (China) Mount Weld (Australia) Araxa, Catalao (Brazil)
	Alkaline rocks	Khibiny, Lovozeiro (Russia) Posos de Caklas (Brazil)
	Alkaline granites	Strange Lake (Canada)
Sedimentary	Placer	Kerala (India) Western Australia, Queensland State (Australia) Richards Bay (South Africa)
	Conglomerate	Elliot Lake (Canada)
Secondary	Weathered residual of granite (Ion-adsorption clay)	Longnan, Xunwu (China)

Major Categories of Rare Earth Applications

In the U.S., rare earth applications can be categorized into catalysts, green energy, hybrid and electric vehicles, defense, and high-tech applications.

Catalysts

Rare earths are essential in automotive catalytic converters, devices used to transform exhaust gas emissions from internal combustion engines into non-toxic compounds as a method of pollution control. In the U.S., as shown in Figure 1.2 (see color insert), usage in automotive catalytic converters accounts for 25 percent of the rare earth market. Cerium carbonates and oxides serve two purposes in this application, as a catalyst substrate and as a component of a converter's oxidizing catalyst system [13]. Such use of rare earths in catalytic converters increases their effectiveness and reduces the amount of platinum and other precious metals required, thereby decreasing the overall cost [14]. A hybrid electric vehicle and its rare earth element usage – and other rare earths found in various HEV components, from small motors to auxiliary systems – is shown in Figure 1.3. Note the cerium (Ce) and lanthanum (La) critical to the function of the catalytic converter.

Rare earths also account for 22 percent of petroleum refining catalysts in the U.S., as seen in Figure 1.2 (see color insert). They are utilized in fluid cracking catalysts that are essential to crude oil refinement, "transforming heavy molecules into lighter compounds that make up petrol and other fuels such as gas, jet fuel and diesel" [15]. Rare earth metals cerium and lanthanum are used as stabilizers in some fluid cracking catalysts as part of the molecular filtering process.

Table 1.4. Rare Earth Elements: Selected End Uses [16]

	Rare Earth Element	**Major End Use**
Light Rare Earths (more abundant)	Lanthanum	hybrid engines, metal alloys
	Cerium	auto catalyst, petroleum refining, metal alloys
	Praseodymium	magnets
	Neodymium	auto catalyst, petroleum refining, hard drives in laptops, headphones, hybrid engines
	Samarium	magnets
	Europium	red color for television and computer screens
	Gadolinium	magnets
Heavy Rare Earths (less abundant)	Terbium	phosphors, permanent magnets
	Dysprosium	permanent magnets, hybrid engines
	Erbium	phosphors
	Yttrium	red color, fluorescent lamps, ceramics, metal alloy agent
	Holmium	glass coloring, lasers
	Thulium	medical X-ray units
	Lutetium	catalysts in petroleum refining
	Ytterbium	lasers, steel alloys

Green Energy

Table 1.5 provides a summary of rare earth materials in green energy technologies and components. There are three major rare earth applications in the green energy sector: magnets, batteries, and phosphors. Rare earth elements used in the production of magnets mainly include praseodymium (Pr), neodymium (Nd), samarium (Sa) and dysprosium (Dy), while praseodymium (Pr) and neodymium (Nd), along with lanthanum (La) and cerium (Ce), are also used in batteries. In phosphor applications, the major rare earth elements used are lanthanum (La), cerium (Ce), europium (Eu), terbium (Tb), and yttrium (Y).

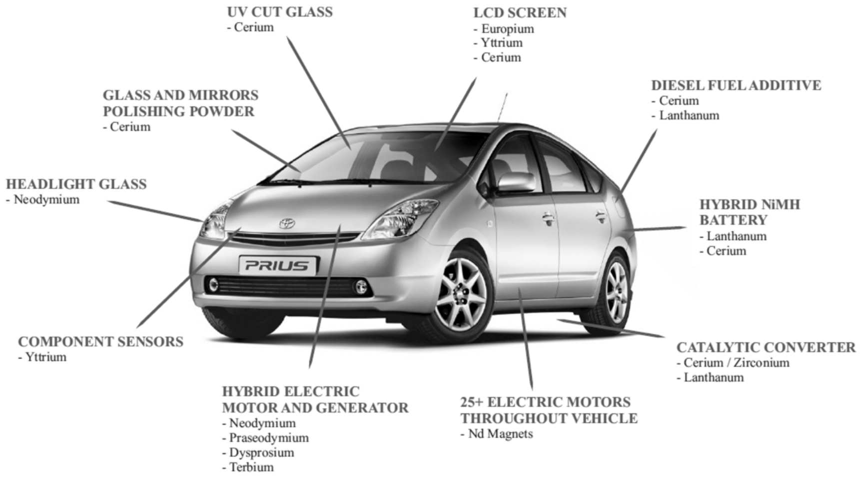


Figure 1.3: Rare Earths Used in a Hybrid Electric Vehicle (HEV) [17]

Table 1.5: Rare Earth Materials in Green Energy Technologies and Components [18]

Rare Earth Elements	**Wind Turbines**	**Hybrid and Electric Vehicles**		**Lighting**
	Magnets	Magnets	Batteries	Phosphors
Lanthanum			●	●
Cerium			●	●
Praseodymium	●	●	●	
Neodymium	●	●	●	
Samarium	●	●		
Europium				●
Terbium				●
Dysprosium	●	●		
Yttrium				●

The use of NdFeB magnets in hydropower turbines, batteries, and motors is of significant importance. These magnets can produce as much as 60 megagauss–oersteds (MGOes), compared to a typical iron magnet with an energy product of only 4 MGOes or a refrigerator magnet at a mere 0.5 MGOes [19]. Additionally, rare earth materials enable many other technologies with vehicular applications, found throughout both standard gasoline and diesel powered vehicles and hybrid and electric vehicles. A sizeable amount of neodymium is required for some of these technologies: the electric motor in the Toyota Prius utilizes 2.2lbs of neodymium for every vehicle, the Chevrolet Volt uses 7 lbs of rare-earth magnets, and for every utility-scale wind turbine 661 lbs of neodymium is required [20].

The battery packs used in HEVs also rely on rare earths to store energy recovered from regenerative braking systems. In the vehicle shown in Figure 1.3, the nickel-metal hydride (NiMH) batteries used consist of 22-33 lbs of lanthanum and, to a much lesser extent, cerium. However, many NiMH batteries also use battery-grade mischmetal, an alloy of rare earths in various naturally occurring proportions, rather than pure lanthanum and cerium. Mischmetal typically contains 50-55 percent cerium, 18-28 percent lanthanum, 12-18 percent neodymium, and 4-6 percent praseodymium, as well as other trace rare earth elements, in its natural form [21]. Hybrid NiMH batteries are a major breakthrough in battery technology, as they can pack more power into a smaller space and are about twice as efficient as the standard lead-acid car battery. The U.S. Environmental Protection Agency (USEPA) estimates that each HEV will have twice the mpg and only half the emissions of an equivalent gas or diesel vehicle – this environmental and financial benefit to consumers will guarantee growing usage of rare earths for HEVs in coming years.

Energy efficient lighting is another green application of rare earth materials. Compact fluorescent lamps (CFLs) use phosphors of europium, applied to the inside of their tubes, and this fluorescent coating generates light when energy is applied. CFLs are rapidly replacing incandescent bulbs, due to their significant energy savings with similar levels of light output. By comparison, incandescent bulbs convert only 5 percent of input energy to visible light, while CFLs convert 25 percent, and they use only a quarter of the power to produce the same amount of light. Lower lamp temperatures are another benefit of CFLs, leading to significantly longer life (more than 6 times longer than incandescent bulbs) and less total energy consumption over time [22]. Countries around the globe have already begun to mandate that incandescent light bulbs be phased out in favor of LED and CFL lighting, guaranteeing a growing need for rare earths in this sector. Brazil and Venezuela began in 2005, the European Union, Switzerland and Australia began in 2009, and other countries are also beginning phase-outs, including Argentina, Russia and Canada in 2012, and the U.S. and Malaysia in 2014 [23].

Europium is also utilized in white LED-based lights, which are more energy-efficient than CFLs. Mixing various colored LEDs produces their white light, and europium red is an ingredient in outputting the particular high-quality shade of white considered appropriate for lighting applications.

Defense and Military Applications

Rare earths are critical to the national security of the U.S., in that they are used in the manufacturing and operation of defense and weapons systems. Figure 1.4 shows the U.S. Navy's USS *New York*, a ship containing a large number of electronic devices that use rare earths. Listed below are just some of the applications of rare earth elements in defense technology [24].

- Jet fighter engines and other aircraft components, including samarium-cobalt magnets used in generators that produce electricity for aircraft electrical systems;
- Precision-guided munitions that include both missiles and "smart" bombs, for which rare earths provide directional capabilities;
- Satellite power and communication systems, including traveling wave tubes (TWTs), rare earth speakers, defense system control panels, radar systems, electronic counter-measures, and optical equipment;
- Lasers used in rangefinders, target designators, and target interrogators;
- Detection devices for underwater mines;
- Sonar, in which rare earth alloys are replacing piezoceramic materials in certain devices.

High-Tech Consumer Goods Sector

Rare earth materials have enabled electronic components to be miniaturized, by allowing high magnetic anisotropy and large magnetic moment in a small form factor. For example, NdFeB magnets play significant roles in the miniaturization of cell phones, media players, cameras, earbud headphones, computers and associated computing devices, microphones, and a host of other items. Other rare earths can be found in these devices as well, such as lanthanum and cerium. NdFeB magnets are also used heavily in speakers, hard disk drives and DVD players, among other electronic devices.

Figure 1.4: Rare earths are used in many electronic devices on U.S. Navy ships, such as the USS *New York* [25]

Additional rare earth materials such as europium, yttrium, cerium, and terbium appear in flat panel displays, both in liquid crystal displays (LCDs) and plasma screens. Optical lenses, such as those found in digital cameras, camcorders, and glass plates found in scanners and copiers, require lanthanum and other rare earths as additives. Figure 1.5 shows an overview of some of the uses of rare earth materials in optical components, electronics, and displays. Medical applications of rare earths include X-ray screening systems, magnetic resonance imaging (MRI) machines, and positron emission tomography (PET) medical imaging devices, as well as fiber optics and lasers used in various medical systems.

In addition, rare earth dopants are effective in increasing the lifetime of ceramic capacitors with perovskite dielectric (such as $BaTiO_3$). Elements with an intermediate ionic radius (Y, Ho, Dy, and Er) are highly effective and are used in multilayer ceramic capacitor (MLCC) applications. These dopants can increase the lifetime of MLCCs and can be used for high-temperature applications.

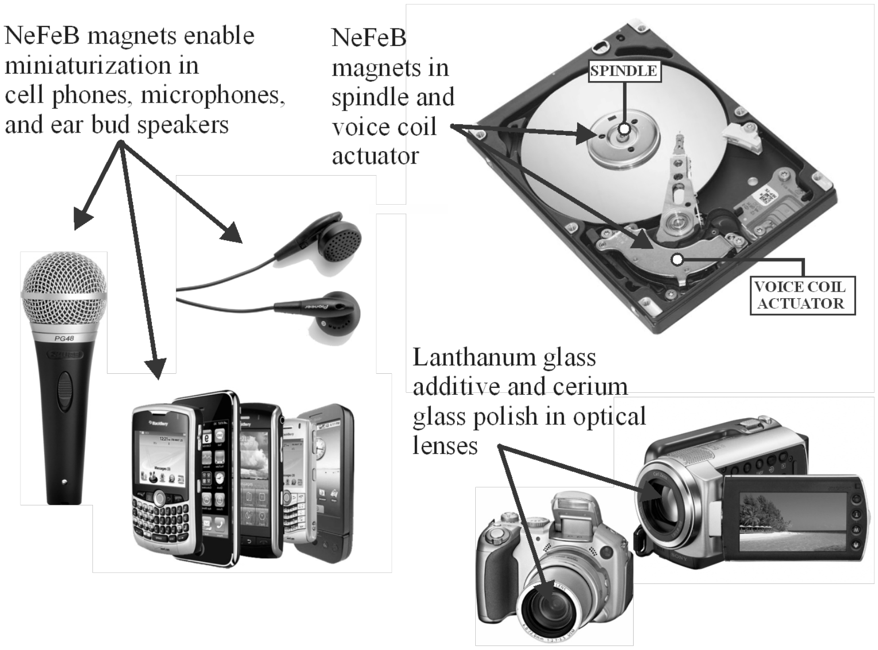


Figure 1.5: Overview of Uses of Rare Earth Materials in Optical Components and Displays [26]

Emerging Rare Earth Applications

Examples of new rare earth applications include sub-light-speed computer processors, advanced superconductors (materials through which electricity flows with zero resistance), magnetic refrigeration, and water treatment. In addition, rare earths continue to be utilized in agriculture, mainly in China.

Rare earth applications in magnetic refrigeration have made the technology more efficient and environmentally friendly than traditional refrigeration methods, due to higher cooling efficiency, which in turn results in low carbon dioxide release and does not involve the use of ozone-depleting chemicals. Although the NdFeB magnet is considered one of the most practical options for a magnetic field source in household refrigeration applications, there are currently still a number of technical issues to be resolved before commercial units can appear on the market. If successfully commercialized, magnetic refrigeration could have a significant impact on global rare earth demand [27].

The area of water treatment has also seen the application of rare earth materials. The U.S. company Molycorp announced its successful commercial launch of a new rare earth-based water purification technology, named "XSORBX$^{\text{TM}}$," in September 2010 [28]. XSORBX$^{\text{TM}}$ is a non-toxic, end-use water product that is destined for commercial use in wastewater, recreational, pool and spa, industrial processes, and other water treatment markets. The technology's purification capability extends to pathogens such as protozoa, fungi, bacteria, and viruses; organic toxins such as nerve active pesticides and organic acids; and heavy metals such as arsenic, selenium, and chromium. Additionally, the company reports that it has used its XSORBX$^{\text{TM}}$ arsenic sequestration process in the mining and smelting industries, removing arsenic by converting it to a concentrated and stable compound, then filtering it out [29].

Beginning in China in 1980, the use of commercial rare earth fertilizers in crop production has grown quickly over the past 30 years. Common commercial rock phosphates, used for the production of phosphoric acid, elemental phosphorus and different types of phosphorus fertilizers, contain different amounts of rare earth elements. Research has shown that rare earth phosphate fertilizers containing between 0.04 and 0.16 percent rare earths can decrease diseased plant rates and increase crop yields and quality [30]. According to the USGS, 8,500 metric tons of rare earth fertilizer containing cerium, lanthanum, neodymium, praseodymium, samarium, and gadolinium are used on crops in China each year [31].

Chapter 2

Global Rare Earths

Most rare earth reserves are located throughout the world in deposits of bastnaesite and monazite. Bastnaesite deposits in the U.S. and China account for the largest concentrations of rare earths, while monazite deposits in Australia, South Africa, China, Brazil, Malaysia, and India account for the second-largest concentrations of rare earths. Apatite, cheralite, eudialyte, loparite, phosphorites, rare earth-bearing (ion-adsorption) clays, secondary monazite, spent uranium solutions, and xenotime make up most of the remaining resources. Figure 2.1 (see color insert) shows currently known global rare earth resources – while China produces 97 percent of the rare earths consumed globally, the country has only 48 percent of rare earth reserves. While many reserves have already been discovered, the USGS reports that undiscovered resources are still thought to be very large relative to expected future demand [32]. This section provides an overview of the world's distribution of rare earth reserves, along with ever-evolving sites of global production, and includes an in-depth discussion of production development.

A Swedish army officer, Lieutenant Carl Axel Arrhenius, discovered the first rare earth mineral, ytterbite, in 1787 in Ytterby, Sweden. Yttrium, terbium, erbium and ytterbium were all subsequently named after the original location in Sweden, with holmium, scandium, lutetium and europium also named after the surrounding regions. Later rare earth elements were discovered in minerals from Sweden and Russia, after which most of the world's rare earth supply came from placer sand deposits in Brazil and India until the 1940s, when Australia and Malaysia began production of monazite. In the 1950s, South Africa became the primary source, with U.S. supplies ramping up from the 1960s and topping the world's suppliers in the late 1980s [34]. China began production of rare earths in the 1980s, and since the 1990s, it has been the principal supplier, as shown in Figure 2.2 (see color insert).

2.1 Current Global Rare Earth Reserves and Production

Due to the quality and availability of resource data, there is not an accurate surveyed figure for global rare earth resource distribution. The USGS, however, has estimated the total world reserves of rare earth oxides (REOs) as of January 2012 at approximately 114 million metric tons (Table 2.1). China currently dominates world reserves with 48.3 percent, followed by the Commonwealth of Independent States (CIS) with 16.7 percent, the U.S. with 11.4 percent, and India with 2.7 percent.

Major Deposits

Five of the world's richest rare earth deposits are the Bayan Obo deposit in China, the Mountain Pass deposit in the U.S., the Mount Weld carbonatite deposit in Australia, placer deposits in Australia, and the Seven Provinces ion adsorption clay deposit in Southern China. Brief descriptions of these rare earth deposits are provided below.

Bayan Obo Deposit, China

The Bayan Obo deposit, located 84 miles northwest of Baotou in the Inner Mongolia Autonomous Province, is the largest rare earth deposit in the world. According to Kanazawa and Kamitani in 2006, the total reported reserves at Bayan Obo are "at least 1.5 billion tonnes of iron (average grade 35%), at least 48 million tonnes of RE Oxides (REO) (average grade 6%), and about 1 million tonnes of niobium (average grade 0.13%). Recent statistics show 89 million tonnes of REO in China." [36] Rare earth elements in the deposit mainly occur as REE fluorcarbonate series minerals: bastnaesite, parisite, cordylite, huanghoite, and cebaite and monazite hosted in dolomite marbles [37]. Carbonate rocks found at Bayan Obo fall into one of four different categories: sedimentary limestone and dolostone, deformed mineralized coarse-grained dolomite marble, fine-grained dolomite marble and carbonatite dikes [38].

The host dolomites at Bayan Obo extend approximately 11 miles from east to west and approximately 1.24 miles in width, with three main ore mining zones, known as the Main, East, and West ore bodies. The Main and East ore bodies were being actively exploited as of 2006, with the Main Ore Body consisting of tabular and/or lenticular REOs, bearing magnetite and hematite iron ores [39]. While there have been many discussions on the genesis of the Bayan Obo deposit, the most accepted theory is that "the original iron (hematite) ore bodies were formed syngenetically before REE–Nb mineralization. The hydrothermal fluid with an alkaline–carbonatite chemistry was derived from the upper mantle, and printed the REE–Nb mineralization over the original iron bodies" [40]. Yang et al. studied the trace element and isotopic compositions of carbonate from ore bodies at Bayan Obo, and the results "imply that the carbonate minerals in the Bayan Obo deposit have resulted from sedimentary carbonate rocks being metasomatised by mantle-derived fluids, likely derived from a REE-enriched carbonatitic magma." [41] Additional information on this deposit can be found in Section 4.1.

Table 2.1: Estimated Exploitable Global REO Reserves [42]

Country	**Reserves (metric tons)**	**Percentage**
China	55,000,000	48.3%
Commonwealth of Independent States	19,000,000	16.7%
United States of America	13,000,000	11.4%
India	3,100,000	2.7%
Australia	1,600,000	1.4%
Brazil	48,000	0.04%
Malaysia	30,000	0.03%
Other Countries	22,000,000	19.3%
World Total (rounded)	**113,778,000**	**100%**

Note: Reserves are defined by the USGS as that part of the reserve base that could be economically extracted or produced at the time of determination. The term reserves need not signify that extraction facilities are in place and operative. Reserves include only recoverable materials.

Mountain Pass Deposit, USA

The Mountain Pass carbonatite deposit in the United States is the second largest rare earth deposit in the world, located near the border between southern California and Nevada, where Precambrian metaphoric rocks are widely distributed. The main deposit, a carbonatite body dubbed “the Sulphide Queen” is approximately 0.62 miles long and 820 feet in width, and is composed mainly of dolomite and calcite. It is also accompanied by barite and a considerable amount of bastnaesite [43]. From 1965 to 1995, this deposit supplied most of the world’s rare earth metal needs, before mining at the site was stopped in 2002. Remaining reserves at the site have been calculated at 20 million metric tons, with an average grade of 8.9 percent rare earth oxides based on a 5 percent cut-off grade [44]. The ore from the deposit typically contains 10–15 percent bastnaesite, 65 percent calcite and (or) dolomite, and 20–25 percent barite. Nine other rare earth minerals occur at Mountain Pass, although only bastnaesite was being processed [45]. The carbonatite at Mountain Pass, which has been dated at approximately 1.4 × 109 years, “is a moderately dipping, tabular intrusion into granulite grade gneiss.” [46] The deposit is “associated with ultrapotassic alkaline plutons of similar age, size and orientation, as well as with abundant carbonatite and alkaline dikes, and is in a narrow north-trending zone of ultrapotassic alkaline igneous rocks.” [47]

Mount Weld Deposit, Australia

The Mount Weld carbonatite deposit, about 1.9 miles in diameter, is located approximately 21 miles south of Laverton, Western Australia, and is owned by the Lynas mining corporation. Rare earth elements occur in this deposit at highly concentrated grades, mainly within the mineral bastnaesite. The richest area of rare earths within Mount Weld is known as the Central Lanthanide Deposit (CLD), where the estimated reserve is 7.7 million metric tons, (917,000 metric tons in equivalent of rare earth oxides), at an average grade of 12 percent [48]. The CLD is considered by some to be the largest and highest grade deposit of its type in the world, and if actively mined would represent the largest source of rare earth elements in the world outside of China [49].

Placer Deposits, Australia

Placer deposits, a sedimentary accumulation of rare earth minerals, are distributed widely along the Australian coastline. Monazite and xenotime are the most common rare earth minerals found in placer sand deposits. Rutile-zircon-ilmenite deposits are found on the east coast, ilmenite deposits on the southwest coast, and ilmenite-zircon-rutile deposits in the Eneabba region of the west coast [50]. The deposits of the east coast have been formed by wave and/or wind forces, while the west coast deposits are composed mainly of paleo-beach placers.

Seven Provinces in South of China Deposits, China

The “Seven Provinces in South of China” refer to a widely distributed collection of small ion adsorption clay rare earth deposits, located in southern China. These deposits occurred as a result of lateritic weathering of granites. The climate of the subtropic zone in South China has caused the granites to undergo strong weathering forces, both chemical and biological. As a result, rare earth elements have been adsorbed over time onto mineral clays within the deposits [51]. There are two conditions necessary for the formation of ion adsorption clay deposits: “first, there must be a sufficient quantity of RE-bearing host rock. Second, the weathering or lateritic processes must be preserved for a long period without erosion.” [52] Ion adsorption clay type deposits are typically rich in the less common heavy rare earth elements, and are estimated to contain approximately 80 percent of the world’s resources of heavy rare earths [53].

In general, ion adsorption clay type deposits have much lower grades of rare earths, with a concentration ranging from 0.05-0.2 percent. However, mining processes for these deposits are comparatively easy, as they can be mined by open-pit methods, with no milling and/or ore dressing needed. In addition, ion adsorption clay type deposits have a low concentration of radioactive elements, making mining safer and less environmentally toxic [54]. Additional information on this deposit can be found in Section 4.1.

Newly Discovered Rare Earth Deposits

In July 2011, a Japanese team led by Yasuhiro Kato, an associate professor of earth sciences at Tokyo University, discovered deep-sea mud containing high concentrations of rare-earth elements and yttrium at numerous sites throughout the eastern South and central North regions of the Pacific Ocean [55]. The team estimated the size of the discovery at around 80-100 billion metric tons, almost a thousand times more than 2011 USGS estimates of proven reserves of 113.8 million metric tons of rare earth oxides worldwide [56]. However, proving the commercial viability of mining rare earth minerals from 2 to 3 miles below the surface of the Pacific Ocean will be a significant challenge. While the rare earth elements contained within the deep-sea mud are easily recovered by acid leaching, the process of moving large amounts of material to the surface is difficult, and it also believed that mining activities on the sea floor might cause harm to the ecology of the surrounding area.

In South Korea, rare earth deposits exist within Hongcheon, in the Ganwon Province, and Chungju, in the North Chungcheong Province. However, these areas were not exploited commercially due to low mineral grades, and difficult locations near residential areas. While redeveloping a previously closed iron mine, Korea Resources Corp., a state-run mineral exploration group, discovered a large rare earth mineral deposit in Yangyang, in the Gangwon province, in November 2010 [57]. According to an official from the company, “the deposits found in the early stage seem to be of low quality, but there seems to be a large deposit of high-quality metals to be found when full-scale exploration of the huge mine gets underway.” [58] Full-scale production at the site is expected to begin in 2012.

Afghanistan’s Helmand Province is believed to contain a major deposit of light rare earths in carbonatite, including lanthanum, cerium, and neodymium. The country’s rare earth resources were surveyed under difficult wartime conditions from 2009 to 2011 by USGS researchers, funded by the DoD’s Task Force for Business and Stability Operations (TFBSO). They uncovered an estimated 1 million metric ton deposit at Khanneshin, and consider it to be “comparable in grade to world-class deposits like Mountain Pass, CA, and Bayan Obo in China.” [59]

In October 2011, the U.S. mining company Molycorp announced the discovery of a new heavy rare earth deposit near the company’s Mountain Pass mine in California. The rare earth concentration at the site was 4 to 6 percent, with dysprosium, neodymium, terbium and europium all found within the deposit [60]. In December 2011, the company was given permission by the U.S. Bureau of Land Management to begin exploratory drilling at the site, with results due in the second quarter of 2012 [61].

Major Rare Earth Production

While data regarding supplies of rare earth materials often remains private, public data reports on rare earth deposits, such as those provided by USGS, are published regularly. The U.S. DoE has compiled data from the USGS and others, and has summarized global rare earth resources by source mineral type, as provided in Table 2.2.

Table 2.2 shows that bastnaesite – the mineral type in Bayan Obo, Inner Mongolia, China, Xunwu, Jiangxi province, China, and in Mountain Pass, California – typically contains a high percentage of light rare earth elements, including lanthanum, cerium, praseodymium, and neodymium. However, some heavy rare earth elements occur only in a

Table 2.2: Rare Earth Types and Contents of Major Contributing Source Minerals Supplying Rare Earth Elements to the Global Market (Percentage of Total REOs) [62]

		LIGHT				MEDIUM			HEAVY								
Type	**Location(s)**	**Lanthanum (La)**	**Cerium (Ce)**	**Praseodymium (Pr)**	**Neodymium (Nd)**	**Samarium (Sm)**	**Europium (Eu)**	**Gadolinium (Gd)**	**Terbium (Tb)**	**Dysporium (Dy)**	**Holminium (Ho)**	**Erbium (Er)**	**Thulium (Tm)**	**Ytterbium (Yb)**	**Lutetium (Lu)**	**Yttrium (Y)**
Currently Active:																	
Bastnasite	Bayan Obo, Inner Mongolia	23.0	50.0	6.2	18.5	0.8	0.2	0.7	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0
Xenotime	Lahat, Perak, Malaysia	1.2	3.1	0.5	1.6	1.1	0.0	3.5	0.9	8.3	2.0	6.4	1.1	6.8	1.0	61.0
Rare earth laterite	Xunwu, Jiangxi Province, China	43.4	2.4	9.0	31.7	3.9	0.5	3.0	0.0	0.0	0.0	0.0	0.0	0.3	0.1	8.0
Ion adsorption clays	Longnan Jiangxi Province, China	1.8	0.4	0.7	3.0	2.8	0.1	6.9	1.3	6.7	1.6	4.9	0.7	2.5	0.4	65.0
Loparite	Lovozerskaya, Russia	28	57.5	3.8	8.8	0.0	0.1	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0
Various	India	23	46	5	20	4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Various	Brazil	N/A														

very limited group of minerals and in a relatively low concentration. For example, dysprosium, a critical rare earth element used to improve the coercivity of high efficiency, high performance permanent magnets, exists only in two locations with contents that are economically feasible for mining. The first of these is an ion-adsorption clay deposit with 6.7 percent Dy_2O_3 at Longnan, in China's Jiangxi Province, and the second is a xenotime deposit with 8.3 percent Dy_2O_3 at Lahat, Parek in Malaysia. However, the production output from Malaysia is very minor in relation to China's output, with total rare earth oxide production across all elements at only 380 metric tons in 2009 (Table 2.3). Therefore, the majority of the world's supply of dysprosium comes from the ion-adsorption clay deposit found in Longnan.

Similarly, europium, one of the most expensive of the rare earth elements, occurs at Xunwu, also in China's Jiangxi province, with the highest content among current active deposits (0.5 percent). Yttrium, predicted to be in the critical category due to its importance to the clean energy economy and its risk of supply disruption, is abundant at the Longnan deposit, at 65 percent of total REO content.

Table 2.3: World Production and Reserves of Rare Earth Oxides in 2011 [63]

	2011			
	Production		**Reserves**	
Country	**Total REO (metric tons)**	**Share (percent)**	**Total REO (metric tons)**	**Share (percent)**
Australia	0	0	1,600,000	1.4
Brazil	550	0.4	48,000	0.04
China	130,000	97	55,000,000	48.3
Commonwealth of Independent States	Not Available	Not Available	19,000,000	16.7
India	3,000	2.2	3,100,000	2.72
Malaysia	30	0.02	30,000	0.03
United States	0	0	13,000,000	11.4
Other	0	0	22,000,000	19.3
Total	**133,580**		**113,778,000**	

Table 2.3 summarizes the world's rare earth mine reserves and production in 2011. It illustrates that the only countries reliably known to be actively producing rare earth oxides at the time were China, India, CIS, Brazil and Malaysia. Rare earths also may be produced in other

countries, including “Kazakhstan, Democratic P.R. of Korea, Republic of Korea, Kyrgyzstan, and Vietnam but reliable estimates of quantities are difficult to obtain.” [64]

China has only 48 percent of the world’s rare earth reserves (as of 2012 USGS commercially exploitable reserve estimates), yet accounts for the vast majority of global rare earth production [65]. Production in other parts of the world has been low during the last decade, primarily due to China’s aggressive market presence. Its production techniques and labor costs have been among the cheapest available, and the Chinese have made it almost impossible for other countries to compete. Furthermore, the mining of rare earths is a chemically intensive process, and significant and expensive precautions must be taken to prevent environmental contamination. Chinese regulatory policies are not as strict, nor are they as strictly enforced as in other countries, further lowering production costs. In addition, much of the world’s alternative energy technology production occurs in China, and therefore, to meet its own domestic demands, the country must use roughly two-thirds of the rare earths it produces for internal manufacturing purposes.

Production output from the Commonwealth of Independent States originates from rare earths recovered as a by-product of major metal mines, such as Norilsk Nickel, as well as from Russia’s single active rare earths mine, Lovozersky GOK. The mine’s loparite concentrate output in 2010 was 11,000 metric tons, and the company expected this to rise to 12,000 metric tons in 2011 [66].

India is also engaged in the production of rare earths, primarily from placer deposits in beach sands, and is the second largest producer worldwide. The major rare earth companies in the country include Indian Rare Earth Ltd., producing yttrium oxide, and Kerala Minerals and Metals Ltd., extracting rare earth laden monazite from heavy mineral sands [67].

Brazil’s Indústrias Nucleares do Brasil (INB) exports rare earths in the form of monazite to China (as of early 2012), and the only rare earth oxide production in the country is at the Buena Norte mine in Rio de Janeiro, with an annual output of 650 metric tons. In 2009, plans were prepared to produce rare earths as a by-product from the xenotime minerals found in the tailings of Brazil’s Taboca Pitinga tin mine, in a two-year agreement between Canada’s Neo Material Technologies Inc. and Mineracao Taboca SA, a Brazil-based mining and processing subsidiary of Peruvian miner Minsur SA. As of late 2011, tailings were still being successfully processed at the site for heavy rare earths, with Taboca planning to mine greater hard rock deposits at the site [68].

Malaysia previously produced monazite and xenotime as a byproduct of tin mining, but due to radioactivity problems the country’s two processing plants were closed. Australia's Lynas Corp is in the construction phase of building a rare earth processing plant in Kuantan, Malaysia, with plans to produce 11,000 metric tons of rare earth oxides per year by the middle of 2012 [69]. Their $200 million Advanced Materials Processing plant was 98% complete as of March 31st, 2012, and will be fed by the output of the Mount Weld mine and concentration plant in Australia [70]. However, the company faces continued development hurdles in Malaysia, due to local concerns over possible environmental issues involved with the plant's operation.

According to the USGS in *The Principal Rare Earth Elements Deposits of the United States,* the potential mineral products from a mining project can be divided into principal products and by-products. The principal product (e.g., zinc, in a zinc mine) contributes most to the value of the minerals produced, which usually generate sufficent return to pay the costs of mining and processing. All other products are referred to as by-products. When two or more products of essential value contribute to the overall profitability of a mine, they are called co-products. Rare earths are typically obtained as a by-product or co-product of mining other mineral commodities. Table 2.4 presents a summary of the world's rare earth production in 2009, mined as both principal products and byproducts. Approximately 55,000 out of a total 120,000 metric tons were produced as a byproduct of China's Bayan Obo iron mine, meaning that at least 44 percent of world rare earth elements production was a byproduct [71].

2.2 Global Demand and Supply

In the mid-1980s, the Chinese government decided to subsidize loans to the rare earth industry in an attempt to boost employment. As a result, rare earth production increased annually by an average of 40 percent throughout the decade, doubled from 1990-95, and then doubled again during the 2000s. With rare earth overproduction in China, market prices predictably dropped by an average of 95 percent, and this led to a revolution in modern technology over the last two decades in terms of rare earth applications (see Section 1.3). The fast pace of technology development, in turn, has created an increasing level of global demand for rare earths, as discussed in detail below.

Global Demand

Global demand for rare earth materials grew steadily by between 8–12 percent per year until 2008 (Figure 2.3 – see color insert), before falling due to the global recession. Demand levels then recovered and continued to follow a similar growth trend from mid-2009 onwards, and demand has been projected to continue to grow steadily until 2016. China is not only the world's leading producer of rare earth materials but also consumed 70,000 metric tons of global production in 2011, and this figure is forecast to continue to rise to 80,000 metric tons in 2012 [73]. Japan and northeast Asia are the second-largest consumers of rare earth materials, accounting for approximately 22 percent of world consumption, and the U.S. follows as the third leading consumer, at about 12 percent. Experts predict that China's internal needs for rare earths will continue to take up the majority of the country's production. Concurrently, global needs for rare earths outside China are also projected to grow dramatically, fueled by the growth of emerging green energy technologies such as HEVs, wind power, and energy-efficient lighting.

Table 2.4: World Rare Earth Production Mined as Principal Products and By-Products in 2009 [74]

Country	Mine	2009 Output (metric tons TREO)	Primary Product	By-Product
Brazil	Buena Norte	650	Ilmenite concentrate	Monazite concentrate
China	Bayan Obo	55,000	Iron ore	Bastnaesite concentrate
	Sichuan[1]	10,000	Bastnaesite concentrate	
	South China[1]	45,000	Rare earth elements	
India	Heavy-mineral sands	2,700	Ilmenite concentrate	Monazite concentrate
Malaysia	Ipoh sand plant	380	Cassiterite concentrate	Xenotrime concentrate
Russia	Lovozero	2,500	Loparite concentrate	Rare earth elements chloride

[1] Many small producers and a few medium-large producers. The Chinese rare earth elements mining industry is currently undergoing government-directed rationalization to reduce the number of producers. TREO=total rare earth oxides.

Rare earth demand and consumption by application are shown in Figure 2.4 and Table 2.5. Demand for magnetic and electronic applications shows the strongest growth over the past twelve years (Figure 2.3 – see color insert).

At the February 2012 Technology Metals Summit, industry expert Dudley Kingsnorth projected global demand for rare earth oxides to 2016 and 2020. By 2016, ROW (Rest Of World) demand will grow from 35,000 to 55,000 metric tons, while Chinese demand will grow from 70,000 to 105,000 metric tons, with global demand at 160,000 metric tons. Global demand in 2020 will grow to 200-240,000 metric tons, with ROW demand forecast to be 70-90,000 metric tons [75].

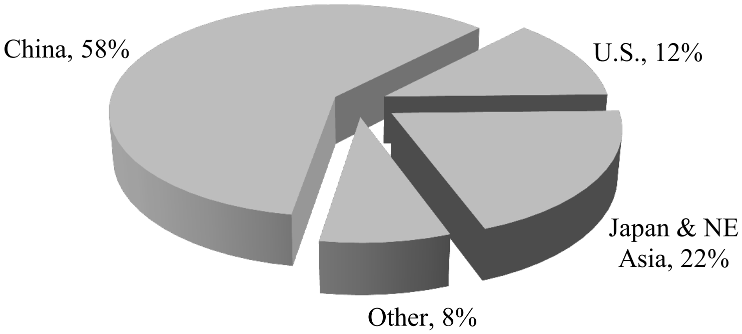


Figure 2.4: Estimated Global Rare Earths Demand by Region [76]

Global Supply

The global rare earth supply situation has been caused by unbalanced global supply and production – China produced 94% of world supply of REEs in 2011, leaving only 6% of the world's supply available from ROW facilities, despite sizable deposits worldwide. China is facing growing domestic demand, and so its supply to ROW will be limited to what is left over after satisfying internal needs. China's drive to build its downstream REE industries will only decrease ROW supply, resulting in shortages if ROW producers do not step in to fill the gap. ROW supply is an issue that many producers are working to correct over the next 3-4 years, both within the U.S. and in numerous other countries where rich REE deposits are found.

Table 2.5: Global Rare Earths Demand, 2010 (TREO ±10 percent) [77]

Application	China	Japan & NE Asia	U.S.	Others	Total
Catalysts	9,000	3,000	9,000	3,500	24,500
Glass	7,000	1,500	1,000	1,500	11,000
Polishing	9,500	7,000	1,000	1,500	19,000
Metal Alloys	14,500	5,500	1,000	1,000	22,000
Magnets	20,500	4,000	500	1,000	26,000
Phosphors	5,500	2,000	500	500	8,500
Ceramics	2,500	2,500	1,500	500	7,000
Other	4,000	2,000	500	500	7,000
Total	72,500	27,500	15,000	10,000	125,000

The USGS compiled a table in 2010 (Table 2.6) comparing the supply situation of rare earths with other selected internationally traded minerals. It used four measures of concentration: two concentration ratios (CR2 and CR3), normalized Herfindahl index (NHI), and country risk index (RI). These measures are typically used by economists to study market concentration and by regulators for antitrust purposes. The concentration ratios CR2 and CR3 measure the total percent share of U.S. imports and world production of the top two or top three supplier countries. The high percentage of CR3, at 96 percent for rare earths, (excluding yttrium and scandium), indicates that world production is principally derived from one or two countries, almost exclusively China. The NHI, derived from the Herfindahl index (HI), ranges from 0 to 1.0 and was originally developed to measure the degree of competition in an industry [78].

An NHI of 1.0 indicates that the mineral commodity is concentrated in a single country; an index of 0 indicates that all countries have exactly the same share in U.S. imports and world production. RI is the country risk index, and higher values indicate a high supply risk for a metal commodity.

As shown in Table 2.6, all indices place rare earths (including yttrium) at the top of all mineral commodities in terms of concentration of world production. According to the USGS, a high concentration of supply raises issues related to the reliability of supply as well as to price manipulation – a single source of supply is inherently more risky than multiple sources of supply. The National Research Council has recommended a criticality matrix as a tool for assessing mineral supply risk, in which rare earths are ranked high for supply risk and moderately high for the effect on supply restriction (see Figures 5.2 and 5.3 in the color section) [79].

Table 2.6: Measures of Concentration for Selected World Metal Mining Industries [80]

Mineral Commodity	**Import Reliance (percent)**	**United States Imports (percent)**				**World Production (percent)**			
		CR2	CR3	NHI	RI	CR2	CR3	NHI	RI
Antimony	86	90	98	0.42	1.9	91	94	0.77	2.3
Bauxite and Alumina	100	50	64	0.19	4.6	46	58	0.16	2.8
Bismuth	95	62	80	0.26	0.8	75	90	0.29	2.3
Cobalt	78	43	56	0.13	1.7	52	63	0.20	1.4
Copper	37	75	88	0.32	1.5	44	51	0.16	2.4
Gallium	99	57	73	0.21	1.3	51	65	0.19	1.9
Indium	100	72	81	0.31	1.3	68	76	0.36	1.4
Manganese	100	54	65	0.21	2.9	46	64	0.17	2.8
Nickel	17	59	68	0.23	1.0	32	46	0.10	2.6
Niobium	100	96	97	0.79	2.7	100	100	0.90	2.9
Platinum	94	50	65	0.17	1.5	91	94	0.63	2.9
Rare Earth Elements	***100***	***94***	***96***	***0.83***	***1.9***	***99***	***100***	***0.94***	***2.0***
Rhenium	86	95	98	0.81	1.8	59	68	0.26	2.3
Tantalum	100	35	50	0.13	1.6	75	85	0.35	2.0
Tin	79	69	79	0.31	3.2	74	91	0.30	3.3
Titanium	64	85	94	0.39	3.3	55	77	0.23	2.2
Tungsten	70	50	69	0.19	3.3	81	86	0.57	2.3
Vanadium	100	66	74	0.35	1.5	72	97	0.33	1.5
Yttrium	***100***	***96***	***99***	***0.78***	***1.8***	***100***	***100***	***0.98***	***2.0***
Zinc	58	67	82	0.19	1.1	52	66	0.19	1.9

[CR2 and CR3 are two-country and three-country concentration ratios, respectively. NHI is the normalized Herfindahl index. The higher the index, the more concentrated are mineral production and United States imports. CR2 and CR3 are rounded to the nearest percent, resulting, in some cases, in a slight discrepancy between the concentration ratios and the normalized Herfindahl index. RI is the country risk index. Data is for 2007.]

In addition, a European Union study used the World Bank's World Governance Indicators as a measure of political risk and concluded that rare earths ranked the highest among mineral raw materials of critical concern, given the uncertainty of future supplies and their importance to advanced industrial economies.

2.3 Imports and Exports

According to a November 2011 British Geological Survey report on rare earths, the two dominant importers of both rare earth compounds and metals as of 2009 were the U.S., at 16,500 metric tons, and Japan, with 13,500 metric tons. Germany imported 8,200 metric tons, followed by France at 7,000 metric tons, and Austria at 4,500 metric tons. Regarding rare earth metal imports alone, Japan leads the group by more than tenfold at 4,800 metric tons, followed by France with 400 metric tons. India, Belgium and Austria imported approximately 300 metric tons, with the U.S., Brazil and China importing approximately 200 metric tons each [81].

Rare earth compound exports for 2009 were led by China, at 38,500 metric tons, followed by Austria at 10,000 metric tons, Japan with 6,000 metric tons, and Russia at 4,600 metric tons. China also led rare earth metal exports, at 5,300 metric tons, followed by the U.S. at 4,100 metric tons, Hong Kong at 460 metric tons, Belgium at 270 metric tons and Austria at 240 metric tons [82].

China has been reducing export quotas for rare earth oxides as well as increasing export tariffs on rare earth metals and oxides (see details in Section 4.3), which may lead rare earth material consumers to move their manufacturing enterprises into China. The result would be a growth in numbers of higher value downstream rare earth goods being exported, rather than rare earth oxides. Accordingly, there is growing concern about the security of future supplies among rare earth consumers.

2.4 Rare Earth Prices

Rare earth prices are typically driven by multiple physical, financial and political factors, such as deposit availability, global market demand and supply, and government policies. The following section examines historical pricing trends for rare earths, more recent pricing developments and related issues.

There are currently no exchanges where rare earth metals are traded, a situation that is not uncommon as they are considered to be minor metals. While China’s largest producer, Baotou Steel Rare Earth (Group) Hi Tech, won approval in May 2011 to set up a rare earth metals exchange in the city of Baotou, there was no available evidence in April 2012 to suggest it had begun operation. Specialist trading companies trade in rare earth metals and oxides, where producers set prices, and oxides are often supplied on long-term confidential contracts [83]. It is

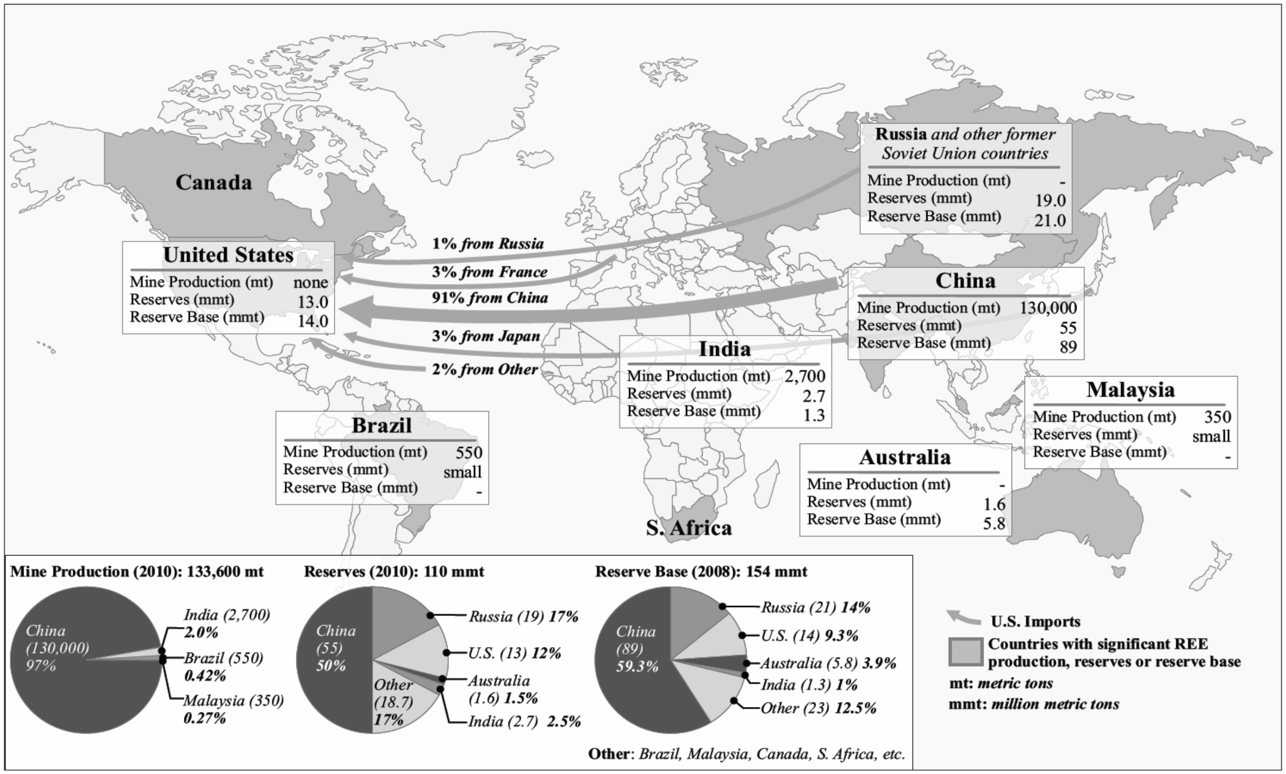


Figure 2.5: Rare Earth Elements: World Production, Reserves and U.S. Imports [84]

important to note (as stated by industry analyst Gareth Hatch in early 2012), that limited data is available on rare earth pricing; the prices typically reported are spot prices, typically where the buyer or seller has chosen to disclose the value of the transaction, and in some cases they may be as much as 100% higher than prices actually being paid in rare earth transactions [85].

There is a difficult imbalance in the rare earth raw materials industry – most deposits contain rare earth elements in a fixed ratio. However, producers are interested only in those particular elements currently in high demand, leading to "stockpiling of unmarketable rare earth fractions and products." [86] Rare earth economics are complex to navigate, and producers must face the challenge of how to balance production against market demand. For example, during the 1980s, Molycorp's Mountain Pass operation in the U.S. was able to sell most of its low-cost cerium oxide production to the glass industry, due to strong demand at the time. Their output of samarium was sold on consignment because of high demand in the magnet industry, and europium was easily sold at high prices due to high levels of production of cathode ray tubes for color televisions. However, during the same period, the company had oversupplies of lanthanum and other rare earth elements mined from the same deposits. During the 1990s the balance of supply and demand changed again for certain elements, as strong demand was created for high-purity cerium (automotive catalytic converters), neodymium (high performance magnets), and lanthanum (fluid cracking catalysts).

As mentioned, heavy rare earths are generally more desirable than light rare earths, and are therefore more valuable. Also, as seen in Table 2.7, they can be an order of magnitude more expensive than light rare earths. In December 2010, the DoE investigated the pricing of key mineral materials, and their report concluded that three factors contributed to rare earth prices in the years leading up to the report [87]. First, the decline of the value of the U.S. dollar contributed to higher metal prices. Second, Asia's rapid industrialization resulted in a sustained demand boom for commodities, driving prices to historically high levels. And third, mine capacity expansions and new production did not keep pace with rising demand – the economic crisis in 2009 caused some promising mining projects to have difficulty in obtaining the necessary financing to move forward. Figure 2.6 (see color insert) illustrates the historical average prices of individual rare earth oxides between 2001 and 2010. There were two economic recessions in this period: 2001 to 2003 and 2008 to 2009, and the rare earth industry was affected significantly by both. For example, the price of terbium fell to US$360 per kilogram, a decrease of 50 percent from its previous peak price of US$740 per kilogram in 2008 [89].

Figure 2.6 (see color insert) shows that heavy rare earth prices have risen fairly steadily since 2003 due to the rising domestic demand in China and escalating export controls. Although reductions in export quotas were for total rare earths, an unexpected drop in the supply of light rare earths occurred due to producers focusing their output on the more profitable heavy rare earths. As a result, a much greater increase in price was observed for light rare earths than for heavy rare earths [90].

China currently has export quotas in place on all rare earth metals and oxides, and these have been a key driver of growth in international prices. Table 2.7 summarizes rare earth metal prices quoted on January 5th, 2010, January 4th and August 6th, 2011, and February 7th, 2012. As an example of rapidly rising prices, the quoted price for europium metal was US$485 per kg in January 2010, and the quoted price as of August 2011 was US$6,620 per kg, representing an approximate increase of 1,364 percent.

Table 2.7: Quoted Representative Prices for Rare Earth Metals, 2010-2012 [91]

Rare Earth (Metal, 99% min FOB China)	**Price on 1/5/2010 in US$/Kg**	**Price on 1/4/2011 in US$/Kg**	**Price on 7/6/2011 in US$/Kg**	**Price on 2/7/2012 in US$/Kg**
Europium	485	800	6620	5210
Terbium	365	790	5120	3690
Dysprosium	117.25	415	3420	2550
Praseodymium	21.50	113	282	255
Neodymium	22.50	115	470	225
Gadolinium	6.75	56	228	203
Yttrium	10.25	83	205	160
Samarium	3.95	62	192	138
Cerium	4.15	53	170	81
Lanthanum	5.60	62	167	70

In 2011 prices for rare earths experienced a dramatic increase, as reflected in Figures 2.7 (see color insert) and 2.8, as a result of a number of factors. Perhaps the most important of these factors were global concerns over the continued availability of rare earths from China. In July 2010 a reduction in the yearly export quota was announced, followed by an incident where China stopped exports to Japan of rare earths for a month over an unrelated dispute, which was further followed by an announcement of a 35% reduction in export quotas for the first half of 2011. Export taxes were also raised in early 2011 on certain rare earth elements, moving from 15% to 25%. Additionally, Chinese mining companies were beginning to be forced to account for the cost of environmental damage reclamation and resource exploitation. Chinese rare earth resource tax standards increased as of April 1, 2011, moving to US$7.40/metric ton for light rare earths and US$3.70/metric ton for middle and heavy rare earths. Prior to April 1, 2011, the tax standard for all rare earths was US$0.47/metric ton. According to a representative of Baogang Rare Earth, China's largest producer, the company now needs to pay US$112 million as an annual rare earth resource tax fee to mine 12 million metric tons of iron-rare earth ores, a significant increase in cost over previous years. In addition, to comply with newly issued rare earth industry waste discharge standards, Baogang Rare Earth is planning to invest US$93.85-109.5 million on environmental protection, which will also contribute to an increase in rare earth pricing.

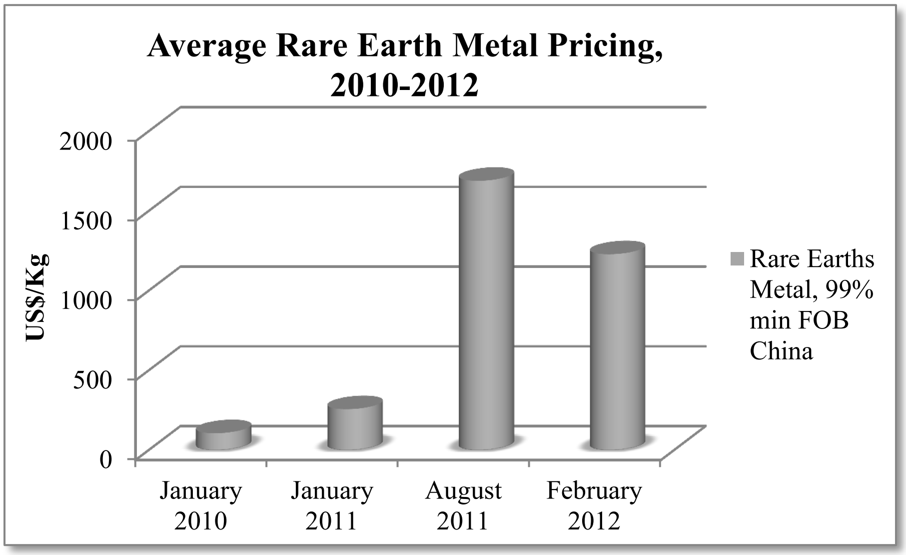


Figure 2.8: Average Representative Prices across 10 Rare Earth Metals, 2010-2012 [93]

A boom in new rare earth functional material application industries, as discussed in Section 1.3, significantly increased the demand for rare earths, which in turn also helped to contribute to rare earth price increases. Chinese Commerce Minister Chen Deming indicated that China would consider measures to address rare earth mineral price rises during a meeting with visiting Japanese trade minister Banri Kaieda in Beijing, on July 18, 2011. According to Chen, “surges in rare earth prices are not desirable for the Chinese economy as they will induce import inflation” [94]. Inner Mongolia Baotou Steel Rare-Earth (Group) Hi-Tech Company announced on August 10, 2011 that the company's net profit surged to US$307.69 million between January and June, an increase of 45.85 percent year-on-year [95]. The company's net profit was US$8.83 million in 2009, and the figure skyrocketed to US$118.95 million in 2010.

As a result of the massive price growth of many rare earths during 2011, consumers began to scale back purchasing, with some retreating to private stockpiles to avoid affecting cost-sensitive downstream businesses with higher material costs. The March 2011 tsunami in Japan also halted a number of high tech manufacturing facilities, the aftereffects of which meant that some companies had little immediate need for new rare earth supplies. The result was that rare earth prices began to fall in the second half of 2011 almost as quickly as they ascended in the first half.

The Chinese government responded by shutting down certain operations within the domestic rare earth industry as rare earth pricing continued to fall in late 2011, to both curb overproduction and to perform comprehensive validation of rare earth production facilities and practices. This shutdown has lasted into early 2012, after late 2011 saw almost half of the country’s production capacity sitting idle “as inspection teams scour the country to enforce the quotas and industry consolidation targets, as well as new environmental regulations” [96]. The shutdown included China’s largest producer, Inner Mongolia Baotou Steel Rare-Earth Group, and as of February 2012, the company still had not been granted an export license for the year under the auspices of environmental infractions.

Chapter 3

Rare Earths in the United States

Until the 1990s, most of the world's rare earths were supplied by the United States, from Mountain Pass in California. By 2003, Mountain Pass was closed, and the level of rare earth output in the U.S. had dropped to zero. Plenty of rare earth supply remained in the ground, but it no longer made financial sense to continue mining deposits when cheap rare earths were available from Chinese producers. They were able to take advantage of significantly lower labor costs, fewer environmental regulations, and the fact that they were mining rare earths as part of an already profitable iron mining process. This chapter discusses the history of rare earths in the U.S., the issues that the U.S. is facing today in rare earths, and strategies being employed to redevelop the country’s rare earth industry.

3.1 Rare Earth Resources in the United States

Aside from California’s Mountain Pass (covered in Section 2.1), another important U.S. rare earth resource is at the Bear Lodge property in northeast Wyoming, currently being explored by Rare Element Resources Ltd. The Bear Lodge property contains significant quantities of high-grade light and heavy rare earth elements in carbonatite dikes, as well as extensive gold resources within the same deposit [97]. In February 2012, mineral resource estimates of rare earth deposits showed “an indicated resource of 6.8 million tons @ 3.75% REO and an inferred resource of 24.2 million tons @ 2.75% REO” [98].

The Bokan Mountain project in Alaska is another significant U.S. rare earth deposit, currently being explored by Ucore Rare Metals, Inc. The company’s 19 square mile property includes the site of the former Ross

Adams uranium mine, with an estimated untapped resource of 11+ million pounds of U_3O_8, and a USGS estimated deposit of 374 million pounds of rare earth oxides [99]. Bokan has been described by Ucore as having “near term production potential, and is located in an area of Alaska specifically set aside for natural resource development, with no residential or indigenous populations in proximity”. Ucore also states that Bokan Mountain is “the largest heavy rare earth deposit in the U.S.” [100].

Figure 3.1: Locations of Rare Earth Deposits in North America [101]

Rare earth resources are also present in the United States within Nebraska, Illionois, Colorado, New Mexico, Utah, New York, Idaho, Missouri and Montana [102]. Mill tailings from historic processing of magnetite deposits at Mineville, New York are a rare earth resource of moderate size, due to 11 percent REO concentrations within apatite, including approximately 2 percent yttrium oxide [103]. The Pea Ridge iron deposit in Missouri (location shown on Figure 3.1) contains "a variety of lanthanide-bearing minerals, including the principal ore minerals monazite and xenotime," also within apatite [104]. Additional estimates include a possible 600,000 metric tons of REE-bearing material at the site, at an REO concentration of approximately 12 percent.

Table 3.1: U.S. Domestic Reserves and Resources of Rare Earth Elements, Excluding Heavy-mineral Placer and Phosphate Deposits [105]

(TREO=total rare earth oxides. Reserves proven and probable classified according to definitions and standards of the SEC. Inferred resources classified according to the standards of the Canadian National Instrument 43-101. Unclassified resources based on little or no drilling.)

Deposit		**Tonnage (metric tons)**	**Grade (percent REO)**	**Contained TREO (metric tons)**
Reserves – Proven and probable				
Mountain Pass	California	13,588,000	8.24	1,120,000
Resources - Inferred				
Bear Lodge	Wyoming	10,678,000	3.60	384,000
Resources - Unclassified				
Bald Mountain	Wyoming	18,000,000	0.08	14,400
Bokan Mountain	Alaska	34,100,000	0.48	164,000
Diamond Creek	Idaho	5,800,000	1.22	70,800
Elk Creek	Nebraska	39,400,000		
Gallinas Mtns.	New Mexico	46,000	2.95	1,400
Hall Mountain	Idaho	100,000	0.05	50
Hick's Dome	Illinois	14,700,000	0.42	62,000
Iron Hill	Colorado	2,424,000,000	0.40	9,696,000
Lemhi Pass	Idaho	500,000	0.33	1,650
Mineville	New York	9,000,000	0.90	80,000
Music Valley	California	50,000	8.60	4,300
Pajarito	New Mexico	2,400,000	0.18	4,000
Pea Ridge	Missouri	600,000	12.00	72,000
Scrub Oaks	New Jersey	10,000,000	0.38	38,000
Wet Mountains	Colorado	13,957,000	0.42	59,000

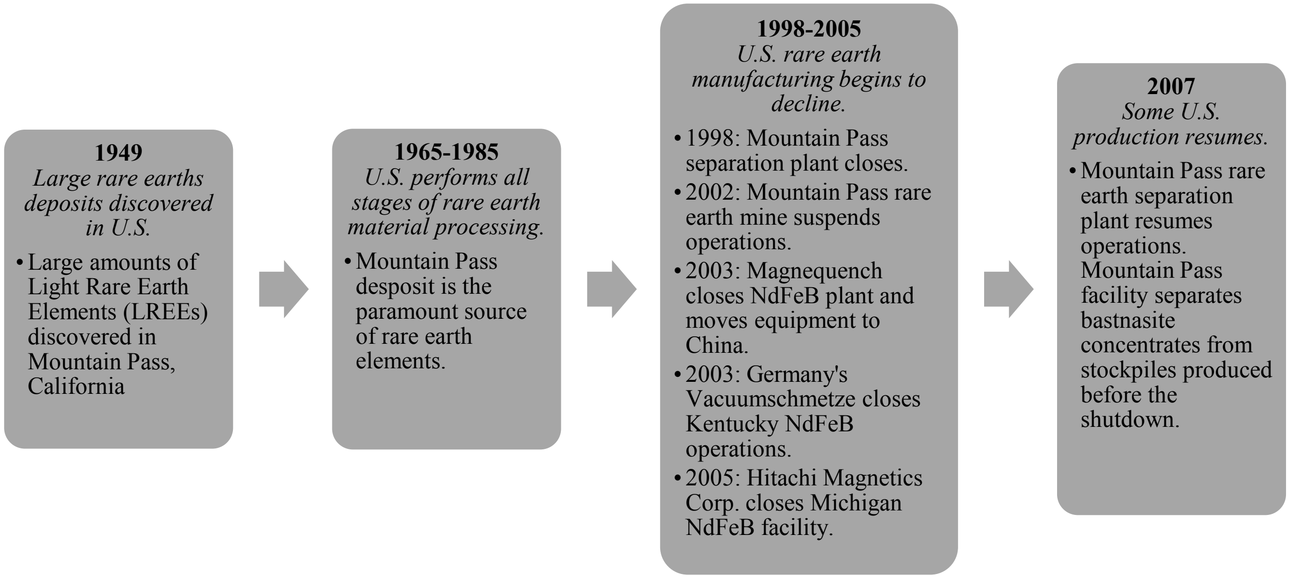
An in-depth examination of rare earth deposits in the United States can be found in the United States Geological Survey's Scientific Investigations Report 2010–5220, entitled *The Principal Rare Earth Elements Deposits of the United States—A Summary of Domestic Deposits and a Global Perspective,* by Keith R. Long, Bradley S. Van Gosen, Nora K. Foley, and Daniel Cordier.

3.2 Rare Earth Production History in the United States

U.S. industry used to be involved in all stages of the rare earth material supply chain, as seen in Figure 3.2, which shows a brief overview of the history of the U.S. rare earth industry. Approximately 20 years ago, the U.S. had twelve rare earth oxide magnet factories, employing 6,000 workers, participating in a global market valued at US$600 million. As of 2010, only four factories remained, with approximately 600 workers, while the global market had grown to a value of over US$7 billion [106].

Beginning in 1954, the Mountain Pass mine in California was exclusively mined for rare earths by the Molybdenum Corporation of America, which later changed its name to Molycorp in 1974. From 1965 to 1985, the mine produced the majority of the world's supply of rare earth materials (Figure 3.3 – see color insert). However, in the early 1990s, cheaper Chinese imports caused a steady decline in prices, and the mine's market share began a similar decline. At the same time, environmental problems raised production costs at Mountain Pass, and as a result, production ceased in 2002.

In 2008, the mine was sold to a private group named Molycorp Minerals LLC headquartered in Greenwood Village, Colorado, which plans to restart rare earth oxide production at the site. Molycorp expects to achieve full-scale production of praseodymium, cerium, neodymium and lanthanum oxides in Q4 2012. However, the Mountain Pass facility does not currently have the capacity to refine the oxides into pure rare earth metals. According to Molycorp spokesman Jim Sims, "by 2012 Molycorp expects to produce 20,000 tonnes of REOs per year, and under its current mining permits could double capacity to 40,000 tonnes" [108]. In addition, Sims notes that in 2012 the company will produce rare earth products at half the cost of current Chinese producers through implementation of several process changes, such as eliminating the production of waste saltwater. "Molycorp will use a closed-loop system, converting the waste back into the acids and bases required for separation and eliminating the need to buy such chemicals. The company will also install a natural-gas power co-generation facility onsite to cut energy costs." [109]



1949
Large rare earths deposits discovered in U.S.

- Large amounts of Light Rare Earth Elements (LREEs) discovered in Mountain Pass, California

1965-1985
U.S. performs all stages of rare earth material processing.

- Mountain Pass desposit is the paramount source of rare earth elements.

1998-2005
U.S. rare earth manufacturing begins to decline.

- 1998: Mountain Pass separation plant closes.
- 2002: Mountain Pass rare earth mine suspends operations.
- 2003: Magnequench closes NdFeB plant and moves equipment to China.
- 2003: Germany's Vacuumschmetze closes Kentucky NdFeB operations.
- 2005: Hitachi Magnetics Corp. closes Michigan NdFeB facility.

2007
Some U.S. production resumes.

- Mountain Pass rare earth separation plant resumes operations. Mountain Pass facility separates bastnasite concentrates from stockpiles produced before the shutdown.

Figure 3.2: History of the U.S. Rare Earth Industry [110]

Some believe that even if Molycorp is successful in a 50% reduction in separation costs, the next step in production – refining oxides into metals – may be a significant challenge. While rare earth oxides are very useful, they must be further processed into metals for popular rare earth element applications such as magnets, and this is an environmentally dangerous process typically performed in China [111].

The Mountain Pass mine has faced environmental issues in the past, as the EPA suspended chemical processing in 1998 due to multiple wastewater spill incidents. The spilled waste contained unacceptable levels of the radioactive elements thorium and radium, even though the bastnasite produced at the mine had relatively low thorium content (approximately 100 ppm) [112].

Rare earth metals must next be made into alloys suitable for magnets, another capability that is concentrated overseas, mostly in Japan and Germany. The company's goal is to control every step in the supply chain, through production of alloys and, eventually, magnets. Molycorp previously lacked the necessary infrastructure and intellectual property rights within the U.S., so the company announced in November 2011 that it had "formed a joint venture with Japan's Daido Steel, Ltd. and the Mitsubishi Corporation to manufacture neodymium-iron-boron (NdFeB) magnets" [113]. As of 2011 Molycorp purified REOs and refined them into metals in a facility in Estonia, and refined REOs into metals and metals into alloys in small volumes at a facility in Tolleson, Arizona.

By going public in July 2011, Molycorp raised US$379 million of the US$511 million the company estimated was necessary for operations through 2012, and bills in the U.S. House and Senate would have offered loan guarantees for Molycorp and other investors in rare earth mines. However, these bills never became law. Molycorp also applied to the Department of Energy (DoE) for loan guarantees in 2010 and currently awaits a decision in the second round of the process [114]. The main questions that will decide the future of rare earth production at Mountain Pass are: (1) will the Chinese government continue to control rare earth exports and as a result drive rare earth prices higher; and (2) are there still significant markets in the U.S. for domestically produced rare earths that can be recaptured by Molycorp?

The U.S. currently does not have manufacturing facilities of an appropriate scale to refine oxides into metals in large quantities. As illustrated in Figure 3.4, the United States is, at best, weak at each of the five stages of mining, separation, refining oxides into metal, fabrication of alloys, and manufacturing magnets and other components [115]. Currently, in the U.S. there is limited production of mine rare earth ores, REOs are processed into metals in only extremely small quantities, and

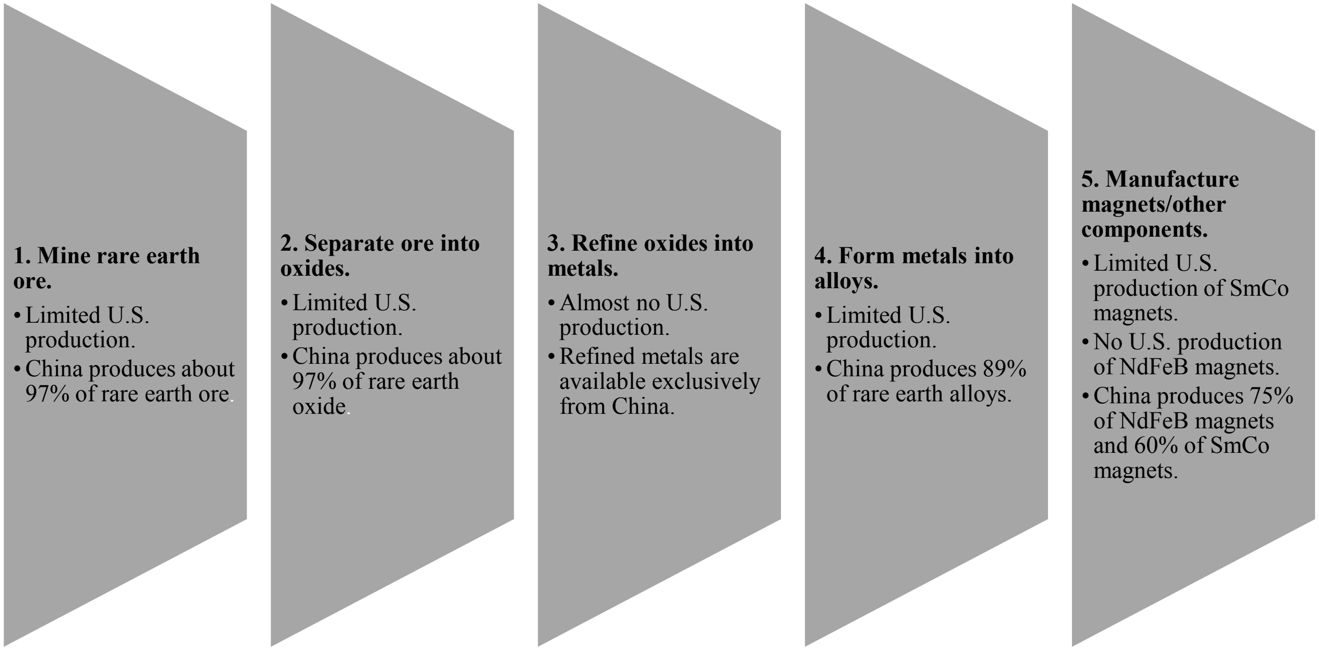


Figure 3.4: Example of Permanent-magnet Rare Earth Supply Chain [116]

only limited processing of metals into alloys is performed. Therefore, even if rare earth production ramps up in the U.S., many of the processes in the supply chain would still occur in China and other countries in the short term.

Table 3.2 provides a summary of the producers of rare earth products participating in the rare earth supply chain and sharing the non-Chinese market. The Electron Energy Corporation (EEC) in Landisville, PA is the only U.S. company producing SmCo permanent magnets, while there are no current producers of the more desirable NdFeB magnets. EEC uses small amounts of gadolinium, for which there is currently no U.S. production. In addition, the EEC imports magnet alloys from China for use in magnet production.

Santoku America, Inc., of Tolleson, Arizona and Neo Material Technologies are the only listed U.S. producers of NdFeB alloys. It is worth pointing out that there were 11 distributors and/or fabricators of magnets in the U.S. as of 2010, as shown in Table 3.2, indicating a large demand for NdFeB and SmCo magnets, with distributors and fabricators typically importing overseas materials to resell them to domestic customers.

Table 3.2. Non-Chinese Producers of Rare Earth Products [117]

Materials	Company	Country
Oxides	Japan Oil, Gas and Metals National Corp.	Japan
	Lynas (expected production 2011)	Australia
	Molycorp (expected production 2012)	U.S.
Metals, Alloys and Powders	Santoku Corporation	Japan, U.S.
	Shin Etsu	Japan
	Great Western Minerals Group/Less Common Metals	Canada, U.K.
	Neo Material Technologies	Thailand, U.S.
Phosphors	Rhodia	U.S., France
Magnets: Distributors/Fabricators	Adams (NdFeB, SmCo)	U.S.
	Allstar (NdFeB)	U.S.
	Bunting (NdFeB, SmCo)	U.S.

In March 2012 a deal was announced between Molycorp Inc. and Neo Material Technologies, a global producer of rare earth engineered materials and applications, including NdFeB magnetic powders under the Magnequench brand, and other rare earth metals under the Performance Materials division. Neo Material Technologies has 1,375 employees at 19 locations across 10 countries, and Molycorp plans to purchase the company for US$1.3 billion, completing Molycorp's supply chain and greatly strengthening its mine-to-magnets strategy. The deal has great significance for ROW supply, particularly from the U.S., as now Molycorp will have access to the magnetic alloy patents and more advanced processing technology it needs to make better use of the output of its Mountain Pass rare earths facility. Molycorp would be in the unexpected position of both importing some REEs from China and supplying rare earth products to China, a strange turn of events given the company's drive to secure U.S. supplies. The company will also absorb Neo Material Technologies' production facilities in China, Thailand and the U.S., joining Molycorp's existing facilities in the U.S. and Estonia.

The deal is expected to be completed by the second or third quarter of 2012, pending regulatory approval, and if successful would address many of the concerns regarding the rare earth supply chain in the U.S. [118]. In the words of Mark Smith, CEO of Molycorp Inc., "Bottom line, this all means that Neo Materials gains a stable supply both in and outside of China while still maintaining and growing their relationships with their customers. And Molycorp gains an outlet for production and processing of current resources and greater financial stability as we ramp up Project Phoenix production." [119] (See Section 5.2 for an explanation of Molycorp's Project Phoenix).

3.3 Rare Earth Issues the United States Faces

The U.S. currently obtains all of its rare earth materials from foreign sources, almost exclusively from China. As noted by the USGS, import dependence upon a single country raises serious concerns about supply security. In a global context, U.S. rare earth resources are modest and of uncertain value; hence, securing resources from traditional trading partners such as Canada and Australia is of great interest for diversifying sources of supply [120]. However, Molycorp states that the "best route to ensuring security of rare earth magnet supply for the needs of American industry and defense purposes is to follow the example of China and develop a strong domestic rare earth industry from mining to final magnet production, based on the responsible exploitation of America's own strategic rare earth reserves" [121].

According to a 2010 GAO report, many factors constrain the rebuilding of the U.S. supply chain. First, the U.S. does not have a substantial amount of heavy rare earths, such as dysprosium, a rare earth element that provides heat resistance for permanent magnets and is used in commercial and defense systems. Second, the mining industry lacks the manufacturing assets and facilities to process rare earth ore into finished products, such as permanent magnets. Large capital investments need to be secured to build processing facilities, but investors are concerned that China will continue to undercut U.S. prices and negatively affect their return on investment. Third, there are significant environmental concerns related to rare earth mining. Radioactive elements, such as thorium and radium, often accompany rare earth materials in mineral deposits. This not only raises significant environmental concerns but also makes the extraction of rare earths difficult and costly [122].

Mining and processing facilities in the U.S. must comply with stricter environmental regulations than those in China and other countries. As a result, U.S. manufacturers will continue to use rare earth materials sourced from China and other countries in the foreseeable future, particularly in Department of Defense (DoD) systems, where military products have long system life cycles. For example, the Aegis Spy-1 radar, with an expected life of 35 years, uses SmCo magnet components that need to be replaced during the radar's lifetime. Due to a lack of effective substitutes for rare earths, future generations of many defense system components, such as transmit and receive modules in radar systems, will continue to depend on rare earth materials [123].

China's export restrictions and tax policies continue to raise significant issues for the international community. On June 23, 2009 the U.S., Mexico, and the European Union (EU) filed separate complaints with the World Trade Organization (WTO), alleging that China unfairly favors domestic industries by restricting exports of certain raw materials, including coke, bauxite, magnesium, manganese, silicon metal, silicon carbide, yellow phosphorus, and zinc, among others [124]. Export quotas can be challenged under the General Agreement on Tariffs and Trade (GATT) article XI, which states that "No prohibitions or restrictions other than duties, taxes or other charges, whether made effective through quotas, import or export licenses or other measures shall be instituted or maintained by any contracting party on the importation of any product of the territory of any other contracting party or on the exportation or sale for export of any product destined for the territory of any other contracting party" [125]. On July 14th, 2011, at a joint news briefing with European Union Trade Commissioner Karel De Gucht, Chen Deming, minister of MOC, stated that he was unconcerned about possible WTO challenges to Beijing's policy on rare earths. The Chinese government maintains that a combination of environmental damage and diminishing supplies caused by excessive rare earth mining led to the introduction of policies (including export taxes and quotas) to guard against further over-exploitation [126].

When the Chinese government announced rare earth export quotas for the first half of 2011 at a level 35% lower compared with the quotas set for the first half of 2010, it appeared that the overall export quota for the year would be down significantly. On July 14th, 2011 however, the quota for the second half of 2011 was announced, and with an increase of 97% from second half 2010 quotas, resulting in the overall 2011 quota staying virtually unchanged from 2010 (see Section 4.3 for more discussion of export quotas). Even though it did not directly concern rare earth materials, the higher second round quota may have been influenced by the July 5th, 2011 WTO expert panel ruling that "China's export restrictions on nine raw materials used in the manufacture of high-technology products are inconsistent with its WTO obligations" [127]. On August 10, 2011, it was reported that the U.S. and Mexico "filed a memorandum with the WTO, charging the Chinese government with protectionism towards its rare earth resources" [128]. In January 2012, the WTO ruled against China in the aforementioned 2009 case filed by the U.S., the European Union and Mexico, requiring the Chinese government to scrap its export and quota policies relating to nine industrial minerals. While this did not include rare earth minerals, it was believed it could pave the way for a similar ruling on rare earth policies [129].

In March 2012, President Barack Obama announced that the U.S., Japan and the E.U. would be jointly filing a case with the WTO contesting China's export and trade policies on rare earths, citing the importance of China's adherence to global trade rules. The case may take several years to conclude and have no effect on China's policies for some time, even if the WTO were to eventually rule against them. The process involves 60 days of discussion between the countries involved, then up to two years of review by a WTO panel before a decision is made [130].

Such continued appeals to the WTO reflect growing outside pressure on China due to its restrictive policies on rare earth exports, as well as the country's status as the dominant supplier. A combination of export taxes and quotas characterizes the Chinese government's efforts to prevent over-exploitation and to direct resources as needed for domestic applications, despite global demand for rare earths.

3.4 U.S. Efforts to Redevelop the Domestic Rare Earth Industry

Recent developments in rare earth trade highlight the current level of U.S. dependence on foreign resources. It is clearly in the best interest of the country to develop domestic rare earth resources and to conduct R&D into areas related to the use of rare earths. The scientific community is currently researching new processes and technologies for mining and processing rare earths, developing recycling methods for consumer goods that contain rare earths, and investigating more efficient utilization of rare earth materials in products and systems.

As noted, the current level of dependence on China for a supply of rare earths puts the U.S. at a disadvantage. As Pecht and Zuga note, "with foreign control of rare earths now estimated at 97% and the realization that America's electronics production – and thus its ability to produce hybrid electric cars and alternative energy systems – could come to a halt should China decide to curtail access to these materials, it is clear that the U.S. must be proactive and make up ground in terms of developing industrial policy aimed at protecting its industrial base" [131]. To effectively provide for the future energy needs of the U.S., it is critical that the country's policy makers have a strategic plan in place to address the acquisition and efficient use of rare earths.

Christine Parthemore, in a report from the Center for a New American Security, puts forth recommendations for steps the U.S. government should take to protect the country against dependence risks for critical minerals such as rare earths [132]:

- Administration officials and Congress should identify the minerals most important to defense acquisitions, energy innovation and other key functions as they build tailored strategies to mitigate potential supply disruptions.
- The Department of Defense should conduct new assessments of defense supply chains.
- To protect the U.S. government's ability to manage critical minerals appropriately, Congress should protect the government's role in analyzing critical mineral vulnerabilities and producing its own data.
- The Department of Defense should integrate conflicts over minerals and raw materials into relevant war games.
- Congress and the executive branch should update stockpiling policies.
- The U.S. government should create incentives to reduce consumption when its interests are on the line.

- The Senate should ratify the U.N. Convention on the Law of the Sea (UNCLOS).
- Finally, Congress and the executive branch should promote information sharing with the private sector and internationally.

In December 2010, the DoE developed three pillars to address the critical materials that are at risk of supply disruptions in the short term (rare earth materials were a major component), and that would impact several clean energy technologies – including wind turbines, electric vehicles, photovoltaic cells, and fluorescent lighting. The three pillars specified in *Critical Materials Strategy* are that (1) it is essential to have a diversified global supply chain, which means taking steps to facilitate extraction, processing, and manufacturing in the United States, as well as encouraging other nations to participate in this process. It is important to note that all extraction and processing should be carried out in an environmentally sound manner; (2) substitutes must be developed. Research into developing material and technology substitutes will help to meet the material demand of the clean energy industry; and (3) recycling, reuse and more efficient use of critical materials will improve flexibility in the critical material supply and lower world demand for these material resources. It is hoped that research into recycling processes will help make recycling economically viable over time [133].

Additionally, a number of bills were introduced in 2010 regarding rare earth materials, as summarized by the U.S.-China Economic and Security Review Commission (USCC) [134]:

- In March 2010, Representative Mike Coffman (R-CO) introduced the Rare Earths Supply-Chain Technology and Resources Transformation (RESTART) Act of 2010 (H.R. 4866), a bill calling for the stockpiling of rare earths and the establishment of rare earth production facilities in the United States [135]. This bill did not become law.
- In May 2010, Representative Coffman also introduced an amendment to the National Defense Authorization Act for Fiscal Year 2011 (H.R. 5136) requiring the DoD to define which rare earths, if any, were critical to national security and to provide an assessment of the rare earth supply chain. If any of the rare earths were found to be critical, the Defense Secretary would be required to come up with a plan to ensure long-term availability of the materials by 2015 [136].This bill did not become law.
- In June 2010, the U.S. House of Representatives passed an amendment to the Ike Skelton National Defense Authorization Act for Fiscal Year 2011 (H.R. 6523), aiming to revive the

country's production of NdFeB magnets. The NdFeB magnet industry is a key end-market for rare earths, and the bill outlined an "urgent need" to reduce the vulnerability in the rare earths supply chain due to U.S. reliance on foreign supplies. The amendment was written into law, under Section 843 of the Act, entitled "Assessment and Plan for Critical Rare Earth Materials in Defense Applications" [137].

- In September 2010, Rep. Kathleen Dahlkemper (D-PA) introduced the Rare Earths and Critical Materials Revitalization Act of 2010 (H.R. 6160). The bill directed the DoE to support new rare earth technology through public and private sector collaboration, and coordination with the European Union. The bill also called for loan guarantee commitments for rare-earth-related investments such as the Mountain Pass mine [138]. The House approved H.R. 6160 with a vote of 325-98 on September 29, 2010, but the bill was not passed in the Senate and did not become law.

In January 2011, U.S. legislators and industry groups such as the Alliance for American Manufacturing put pressure on President Barack Obama to "seek supply assurances on rare earth availability from Chinese President Hu Jintao in their meetings" [139]. Additional bills during 2011 included:

- In April 2011 the 'Resource Assessment of Rare Earths Act of 2011' (H.R. 1314) was sponsored by Rep. Henry Johnson. The act requests that the Secretary of the Interior, in partnership with the USGS, submit a report on global REE resources and potential global supply sources. It would include recommendations on research areas relating to those elements likely to have constrained future supply [140].
- In December 2011, President Obama signed the National Defense Authorization Act for Fiscal Year 2012 (H.R. 1540) into law. Colorado congressman Mike Coffman successfully submitted an amendment to H.R. 1540 relating to rare earths, in Section 853, requiring the Defense Logistics Agency Strategic Materials (formerly the Defense National Stockpile Center) to develop a plan to establish an inventory of rare earth materials for defense purposes [141].

On March 16, 2012, President Obama signed a National Defense Resources Preparedness Executive Order into effect. Section 306 of the order pertains to critical materials that include rare earths, stating "The

Secretary of Defense, and the Secretary of the Interior in consultation with the Secretary of Defense as the National Defense Stockpile Manager, are each delegated the authority of the President…to encourage the exploration, development, and mining of strategic and critical materials and other materials." [142]

Also in March 2012, responding to the requirements of Section 843 of the Ike Skelton National Defense Authorization Act for Fiscal Year 2011, the Under Secretary of Defense for Acquisition, Technology and Logistics presented a report to Congress entitled "Rare Earth Materials in Defense Applications." The Pentagon examined the findings of a case study on rare earth-based magnet supply chains, finding that DoD-related applications require 175 tons of NdFeB magnets per year, and while there is currently no U.S. production for NdFeB magnets, "a post-assessment announcement by Hitachi indicates U.S. production by April 2013 will reach 500 tons per year." [143] For samarium cobalt magnets, U.S. production was deemed to be enough to satisfy defense needs. When examining the top seven rare earth elements used by the defense industrial base, the DoD found that only yttrium was forecast to be in deficit in 2013 (by 93 tons), with a projected total U.S. output of 26 tons for the year. This is a sizeable deficit, however, as according to the USGS there was no U.S. yttrium production in 2011, with total imports of 620 tons [144].

While rare earths are widely used in U.S. defense operations, the report stated "the growing U.S. supply of these materials is increasingly capable of meeting the consumption of the defense industrial base." [145] It also concluded that due to recent positive changes within the rare earth marketplace, including lower prices, forecast decreased ROW consumption, and increased investment in domestic efforts, by 2015 markets will have stabilized and rare earth availability will be improved. According to Brett Lambert, U.S. Deputy Assistant Secretary of Defense for Manufacturing and Industrial Policy, if any restrictions were seen in the supply of rare earths for defense applications, "we would look to activate one of many countermeasures, including contingency contracting." [146] The Pentagon is actively monitoring the rare earths market, and if an emerging shortage of a particular material is detected the DoD may seek additional approval from Congress to stockpile the material.

3.5 Advanced Research Projects and Incentive Programs

In 2007, Congress created the Advanced Research Projects Agency-Energy (ARPA-E) program within the Department of Energy (DoE) to look into major energy challenges. ARPA-E was created in order to fund what is known as "high-risk/high-reward" research, often not pursued through traditional channels due to lack of a guaranteed return, in a similar manner to DARPA's military technology funding. The agency was created without funding, with its initial budget of US$400 million coming as a result of the economic stimulus bill of February 2009. According to the DoE, in 2010, two initial rare earth projects, totaling US$6.6 million, were awarded to develop substitutes for rare earth magnets. The goal of the first US$4.4 million project was to develop materials to allow the U.S. to fabricate the next generation of permanent magnets, with an energy density up to twice that of the strongest available NdFeB magnets [147].

In the second ARPA-E project, General Electric Global Research (GE) also aimed to develop the next generation of permanent magnets, specifically those with a lower content of rare earth materials. The focus of this US$2.2 million project was to create a nanostructured version of NdFeB, eliminating the need for a high content of neodymium.

The DoE's Office of Energy Efficiency and Renewable Energy (EERE) is also investing in REE projects, supporting an applied magnet research project valued at US$2 million in fiscal year (FY) 2010, at Iowa State University's Ames Laboratory. The lab is a government-owned, contractor-operated research facility of the DoE, and is widely considered to be the nation's historic leader in rare earth research. The focus of this project was to fabricate high-performance and cost-effective permanent magnets that can be used for traction motors, with an internal permanent magnet rotor design. Furthermore, EERE supported two projects with a total value of US$1.4 million in FY 2010 at Oak Ridge National Laboratory, investigating alternative motor designs that do not use rare earth permanent magnets [148].

To address the challenge of rare earth material applications in HEVs, ARPA-E's Batteries for Electric Energy Storage in Transportation (BEEST) program invested US$35 million in demonstrating new batteries and storage chemistry, structure, and technology [149]. In this high-technology/high-impact program, disruptive technology approaches are being investigated, for example, magnesium-ion and rechargeable metal-air batteries from earth-abundant resources. The goal of this program was to develop new batteries that would exceed the current capabilities of lithium-ion battery technology.

ARPA-E further funded REE-related research in 2011, particularly in the area of magnet and wind technology. In November 2011, their Rare Earth Alternatives in Critical Technologies for Energy (REACT) program funded 14 rare earth research projects at a total value of US$31.6 million. The projects included the discovery, design and fabrication of rare earth free magnet materials, rare-earth free vehicle motors, and superconducting wires for wind generators [150].

The DoE's December 2010 report, *Critical Materials Strategy*, lists additional incentive programs administered by the DoE that provide financial support for clean energy deployment, in the form of loans and tax credits. These programs authorize the DoE to support domestic manufacturing of component technologies, but not to provide financial support for mineral extraction or material processing. The Loan Guarantee Program (LGP), established under Title XVII of the 2005 Energy Policy Act (EPAct), provides loan guarantees to support manufacturing of component technologies that use critical materials, such as rare earths. These guarantees, however, are dependent on technologies passing statutory tests as "new or significantly improved technologies to avoid, reduce or sequester air pollutants or anthropogenic emissions of greenhouse gases" [151]. The 2009 American Recovery and Reinvestment Act (ARRA) also added Section 1705 to the EPAct, establishing loan guarantees for "renewable energy systems, including incremental hydropower, that generate electricity or thermal energy, and facilities that manufacture related components" [152].

As of 2010, the LGP had issued loan guarantees under Section 1705 to companies such as Solyndra, LLC (US$535 million), Kahuku Wind Power (US$117 million) and Beacon Power Corporation (US$43 million), where all three companies make use of rare earth materials (DoE, 2010). In 2011, LPG issued further loans to Record Hill Wind, LLC (US$102 million), Brookfield (US$168.9 million), and Caithness Energy (US$1.3 billion) for wind power generation projects that utilized rare earths [153].

The Department of Energy's Advanced Technology Vehicle Manufacturing (ATVM) Loan Program provides loans to automobile and automobile part manufacturers to assist in production of advanced technology vehicles or qualified components, as well as their associated engineering integration costs. As with the LGP, the ATVM lacks authority to issue loans to key material extraction and production firms. However, the ATVM does have the authority to issue loans for companies that may affect the market demand of NiMH or Li-ion batteries and NdFeB permanent magnet motors. As of 2010, loans have been issued to Tesla Motors (US$465 million), Ford Motor Company (US$5.9 billion), Nissan North America (US$1.5 billion), and Fisker Automotive (US$529 million), all related to production of electric or hybrid-electric vehicles [154].

3.6 Future Program and Policy Direction

To address key materials risks, constraints and opportunities across the supply chain, the DoE's 2010 *Critical Materials Strategy* report examined programs and policies, with rare earths being a major component. The eight program and policy categories studied included: (1) research and development, (2) data collection, (3) permits for domestic production, (4) financial assistance for domestic production and processing, (5) stockpiling, (6) recycling, (7) education, and (8) diplomacy. The DoE identified three ultimate goals to address the challenges in key materials:

- Achieve globally diverse supplies.
- Identify appropriate substitutes.
- Improve recycling, reuse and more efficient use of critical materials.

In the area of research and development, the DoE has identified specific high-priority research areas, and they are summarized as follows.

For permanent magnets, motors and generators, high-priority research topics in the report include [155]:

- Materials
- Nano-structured permanent magnets, including core-shell structures and composites
- Improved high-temperature performance of NdFeB magnets
- Enhanced magnetic coercivity for rare earth, alnico, and other magnets
- Fundamentals of anisotropy and new anisotropic mechanisms
- High-flux soft magnets
- Molecular design of magnets
- Manufacturing
- Adapting advanced casting methods to enhance magnetic performance of alloys
- Improved process control to minimize waste
- Systems
- Optimized thermal management to reduce need for high-temperature-tolerance
- Optimized motor and turbine geometries to reduce friction and other operational losses

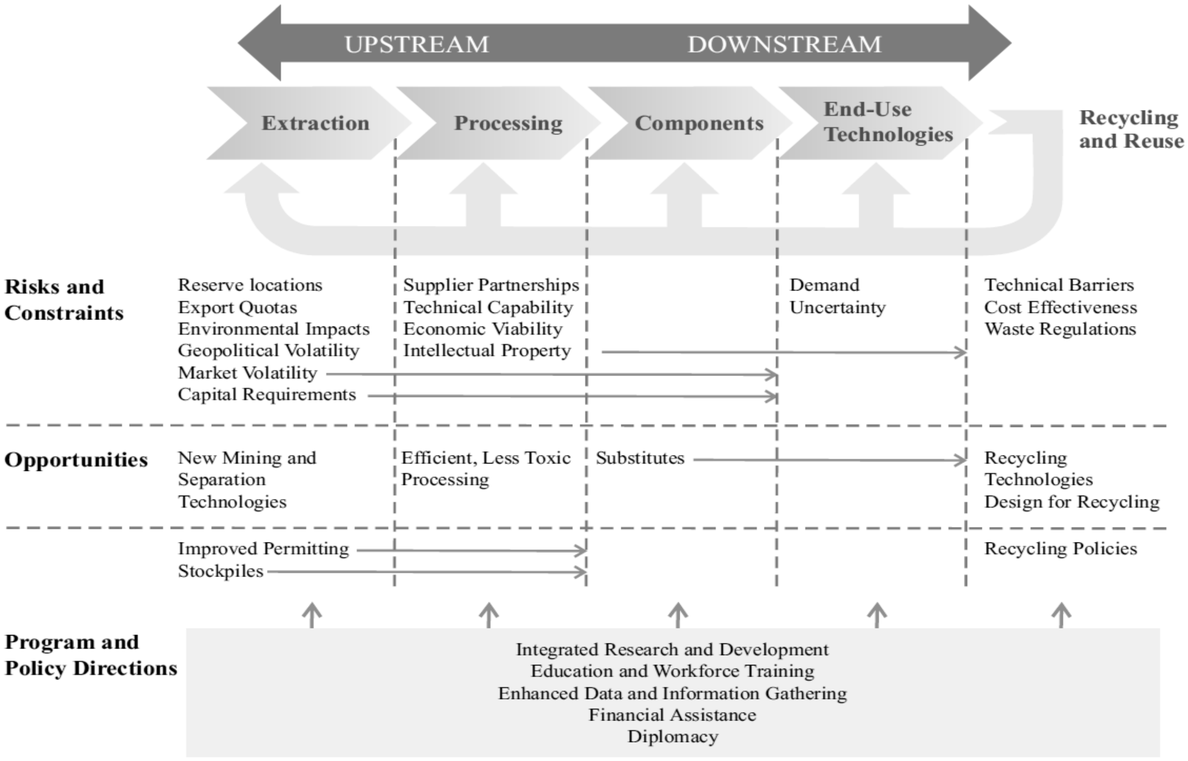


Figure 3.5: Future Program and Policy Directions across the Rare Earth Supply Chain [156]

For batteries and lighting, high-priority research areas included:

- Continued R&D supporting advanced technologies that utilize abundant elements, such as iron and zinc
- Alternative phosphor materials, including the use of quantum dots that minimize or eliminate the use of cadmium or rare earth elements. The most difficult material issues in lighting are likely to be the supply of terbium (used for green phosphors) and europium (used for red and blue phosphors)
- Organic LEDs, with improvements to luminous efficacy, cost and color rendering

For environmentally sound mining, the following research areas were prioritized:

- Non-traditional water source use (e.g., treated waste water, saline aquifer)
- Long-term interaction between groundwater and mine excavations
- Alternatives to tailing impoundments
- Optimized blasting and efficient crushing for lower energy consumption

For rare earth mining research, the following innovations were considered beneficial to the processing of ores:

- Molecular design of solvent extraction reagents
- Advanced ion exchange
- High-performance organic modifiers
- Advanced liquid membranes
- Improved processes for extracting rare earths from mining tailings

In the field of recycling, the following topics were prioritized:

- Technology, component, and material design for disassembly and recycling
- Collection, logistics, and reverse supply chain optimization
- Recycling process development
- Recycling and reconditioning rare earths from spent fluorescent lamps

- Recycling and reconditioning rare earths from manufacturing yield loss
- Methods for efficient demagnetization of rotating-machine components
- Metallic flux processes for recovering rare earths

Chapter 4

Rare Earths in China

In the early 1990s, China became the principal producer, supplier and consumer of the rare earth industry. The country has made remarkable progress in rare earth science, technology and resource utilization while only possessing half of the world's rare earth reserves. This chapter provides an overview of rare earth resources, production, consumption and the major industry players in China. Furthermore, it provides an in-depth discussion of rare earth policies and R&D in China, and covers the country's rise to become the dominant power in the global rare earth market. Finally, it covers the issues that the rare earth industry in China is facing, and the steps the country is taking to address them.

4.1 Rare Earth Resources in China

In 1927 Ding Daoheng, a Chinese professor and geologist, discovered iron deposits at Bayan Obo in the western region of Inner Mongolia, China. Rare earth minerals were discovered at the site in 1935, and by the 1950s the Baotou Iron and Steel Company began operation of a mine at the site, harvesting Bayan Obo's significant iron deposit. By the late 1950s the company began the process of recovering rare earth ores as a by-product of the iron and steel production process [157]. Today, China has some of the richest rare earth deposits in the world, within 21 provinces and autonomous regions – Fujian, Gansu, Guangdong, Guangxi, Guizhou, Hainan, Henan, Hubei, Hunan, Jiangxi, Jilin, Liaoning, Inner Mongolia, Qinghai, Shaanxi, Shandong, Shanxi, Sichuan, Xinjiang, Yunan and Zhejiang (Figure 4.1 – see color insert).

Rare earth mines are distributed widely in China, but about 98 percent of these deposits are concentrated in four areas. Specifically, 80 percent of the resources are located in Bayan Obo, Baotou, Inner Mongolia; 10 percent in Shandong province; 6 percent in the seven provinces in the south of China, represented by Jiangxi province (middle and heavy rare earth deposits); and 2 percent in Sichuan province (light rare earth deposits). Table 3.3 summarizes China's rare earth reserve distribution, and these deposits will be further discussed below.

Table 4.1: China's Rare Earth Reserves (Unit: 10,000 Metric Tons) [159]

Area	Proven Reserves	Industrial Reserves	Long-term Reserves
Bayan Obo, Baotou	10,600	4,350	>13,500
Weishan, Shandong	1,270	400	>1,300
Seven provinces in the South	840	150	5,000
Mianning, Sichuan	240	150	>500
Zhijin, Guizhou	70	-	>150
Others	150	150	>225
Total	13,170	5,200	>21,000

Note that these numbers are larger than those estimated by the USGS in 2010, due to USGS definitions of reserves.

Bayan Obo, Baotou

Located 92 miles to the north of Baotou city, Bayan Obo is mined using an approach known as open-pit or opencast mining from two large open pits at the site (Figure 4.2 – see color insert). The deposit is described as highly paragenetic, containing 71 different elements, such as iron, neodymium, thorium, fluorine, scandium, niobium, phosphorous and potassium, among others. Proven reserves of iron minerals in the mining district are 1.46 billion metric tons, while rare earth reserves of 106 million metric tons make it the largest deposit in the world. The basic reserves in Bayan Obo have been described as accounting for 80 percent of China's overall reserves, equivalent to more than 40 percent of global reserves. The site also contains the world's second largest reserves of thorium and niobium, and contains significant amounts of scandium, fluorite and kalium-rich slates [161]. However, even though Bayan Obo is described as the "rare earths capitol of the world," with up to 6,000 people working onsite, it is inaccessible to the outside world [162]. Due to the size of the REE deposit and the level of output at Bayan Obo, outsiders often characterize the site as primarily an REE mine, while its primary function is as an iron ore mine, with rare earths simply a byproduct of the tailings [163].

Seven Provinces in the South of China

Although the proven reserves of the seven provinces in the south of China are only 8.4 million metric tons (Table 4.1), the rare earth mines in this region are very valuable, due to their richness in middle and heavy rare earths. This is particularly true of those from Ganzhou, in China's Jiangxi province, an ion-adsorption type rare earth deposit discovered in the early 1970s. Ganzhou's rare earth ores are rich in samarium, yttrium, europium, terbium, dysprosium, and erbium. The region's industrial reserves of 1.5 million metric tons account for 50 percent of this type of resource, including the highest grade yttrium-rich ores in the world.

Maoniuping (Mianning, Sichuan)

The Maoniuping rare earth deposit, discovered in 1986 in the region of Mianning County, Sichuan Province, is China's second largest light rare earth deposit. It is comprised of single bastnaesite, considered easier to mine than the Baotou deposit. The deposit is located on the northwest margin of the Panxi (Panzhihua-Xichang) region, and is 1,400 meters long and 260–350 meters wide. It consists of carbonatite sills composed of coarse-grained calcite, including aegirine, microcline, arfvedsonite, biotite and apatite and rare earth minerals [164]. The principal rare earth mineral in the deposit is bastnäsite-(Ce), while parisite-(Ce) and monazite-(Ce) also occur as sporadic very fine crystals in calcite (less than 15 μm) [165]. Wang et al. reported that "the Maoniuping REE deposit is similar to the Mountain Pass REE deposit in many respects, such as the high contents of bastnaesite and barite, the low content of niobium, and the common occurrence of sulfides." [166] The size of the rare earth industrial deposit is listed at 1.5 million metric tons (Table 4.1), and further associated reserves include 0.33 million tons of lead, 174 tons of silver, 3.78 million tons of barite, and 2.4 million tons of fluorite. An unpublished report by the Chinese No.109 Geological Team shows the concentrations of primary ores varying from 2.7-3.9 percent R_2O_3, while secondary oxidized and weathered ores range from 10-13.6 percent R_2O_3 [167]. However, while the size of the rare earth industrial deposit is only 3.4% of that at Bayan Obo (Table 4.1), the output of rare earth concentrate has been estimated at up to 20% of that of Bayan Obo, indicating that continued mining at Sichuan may not be sustainable over the long term [168].

Daluxiang

The Daluxiang deposit is located at the central margin of the Panxi region, also in Sichuan province. The deposit is 1,400 meters long and 600–800 meters wide, consisting of syenite and carbonatite veins. The carbonatite is “medium- to coarse-grained, consisting of calcite and subordinate microcline, quartz, arfvedsonite, barium-rich celestine, strontiobarite, fluorite, aegirine, apatite, REE minerals and sulfides.” [169] The principal rare earth minerals found within the deposit are fluorocarbonates and monazite [$(Ce,La,Nd,Th)PO_4$]. As of 2008, the level of rare earth oxide reserves in the Daluxiang deposit had not been quantified.

4.2 Production and Major Players in China

In a response to global demand, China’s annual rare earth production grew 40 percent between 1978 and 1989, with the country becoming one of the world’s largest producers [170]. There was a plunge in rare earth production from 1988 to 1990 due to the recession both in China and worldwide during this period. However, production resumed and grew extremely quickly in the early 1990s, with an increase of over 90 percent from 1990 to 1995. During the 1990s, China’s rare earth exports grew so significantly that rare earth prices worldwide plunged. This change either drove many producers out of business (particularly in the U.S.), or significantly reduced their production. As Wang and Dou stated in 1996, “China’s abrupt rise in its status as a major producer, consumer and supplier of the rare earths and rare earth products is the most important event of the 1980s in terms of development of rare earths.” [171]

In 1992, Chinese leader Deng Xiaoping made a now famous statement during a tour in Jiangxi province: “The Middle East has oil; China has rare earth.” [172] In the same year, the Chinese State Council (CSC) approved the creation of the Baotou Rare Earth Hi-Tech Industrial Development Zone. In 1999, Chinese president Jiang Zemin wrote, “improve the development and application of rare earth, and change the resource advantage into economic superiority” [173].

China’s rare earth industry continued to grow throughout the 2000s, and Table 4.2 summarizes the country’s rare earth consumption and lists quotas for both export and production for 2000 through 2011. Production and export quotas began to reflect the Chinese government's attempts to control the country's growing rare earths industry, and a discussion of Chinese quota policies can be found in Section 4.3.

Most of China's rare earth enterprises are located in the vicinity of the larger rare earth mines, such as Baotou in Inner Mongolia, Mianning in Sichuan province and Ganzhou in Jiangxi province. As of 2009 it was reported that there were 24 enterprises for rare earth concentrate production and approximately 100 rare earth enterprises for smelting separation production in China [174]. China's 2009–2015 "Plans for Developing the Rare Earth Industry" simplified China's rare earth resource management by designating large districts [175]. These are the northern, western, and southern districts, as seen in Figure 4.3 (see color insert). The northern rare earth district includes Inner Mongolia and Shandong, processing raw materials from Baotou, with a separation capacity of approximately 80,000 metric tons. The western district refers to Sichuan, processing raw materials (bastnaesite concentrate) from Mianning city in Sichuan province, with a separation capacity of approximately 30,000 metric tons. The southern district includes Jiangxi, Guangdong, Fujian, Hunan, and Guangxi, processing raw materials from the seven provinces in the south of China, mainly from Ganzhou in Jiangxi province, with a separation capacity of approximately 60,000 metric tons [177]. Further discussion of each of China's rare earth districts follows Table 4.2.

The rare earth industry in China has also been divided into two rare earth production systems (northern and southern). The northern production system produces mainly light rare earth products, including rare earth concentrates, alloys, mixed rare earth compounds, metals and single rare earth compounds, and other more advanced products, such as polishing powder, permanent magnetic materials, and hydrogen storage alloys. The southern production system produces mainly middle and heavy rare earth products, including various high-purity single rare earth compounds and metals, concentrates, mixed metals, and alloys [178].

Northern District – Inner Mongolia Rare Earth Group

In the northern district, there were approximately sixty rare earth smelting and separation enterprises as of 2009, mainly located in Baotou. Among these enterprises, two have a concentrate separation capacity of greater than 10,000 metric tons, five have a concentrate separation capacity greater than 5,000 metric tons, twelve have a concentrate separation capacity greater than 2,000 metric tons, and the rest have a concentrate separation capacity of less than 2,000 metric tons [179].

Table 4.2: China's Rare Earth Production, Consumption, and Export Quotas for 2000-2011 [180]

(In metric tons of REO equivalent except as described in Footnote 1. Abbreviations: est=estimated; MIIT=China Ministry of Industry and Information Technology; MLR=China Ministry of Land and Resources; NA=not available. All numbers represent metric tons of REOs.)

Year	Production Quota (MIIT)	Production Quota (MLR)	Production (est.)	Consumption (est.)	Export Quota (Domestic (1))	Export Quota (Sino-foreign(1))
2000		55,000	73,000	19,000	47,000	NA
2001		NA	81,000	20,000	45,000	NA
2002		NA	88,000	22,000	NA	NA
2003		NA	92,000	30,000	40,000	NA
2004		NA	98,000	34,000	45,000	NA
2005		NA	119,000	52,000	48,010	17,570
2006		86,620	133,000	63,000	45,000	16,070
2007		87,020	120,000	73,000	43,574	16,070
2008	119,500	90,180	125,000	67,700	34,156	15,834
2009	110,700	87,620	129,000	73,000	31,310	15,845
2010	89,200	89,200	120,000	77,000	22,512(2)	7,746(4)
2011	93,800 (5)	NA	NA	NA	14,446 (3)	

(1) Export quotas are in gross weight rather than REO content for domestic and Sino-foreign producers in 2005 and years after.

(2) Total export quota for 22 domestic producers and traders.

(3) Export quota for 2011 is only for the first of two rounds for 31 domestic and Sino-foreign producers.

(4) Total export quota for Sino-foreign producers.

(5) Additional source, Xinhua, 2011 [181]

Inner Mongolia Rare Earth Group, established in 1999, is the largest rare earth smelting and separating company in China. It is a subsidiary organization of Baotou Iron & Steel (Group) Company (Baogang), which is a modern iron and steel production base, the largest rare earth industrial base in China and the biggest industrial enterprise in Inner Mongolia [182]. It was established in 1954 and reorganized in 1998 as two companies, Baogang Share and Baogang Rare Earth. The Inner Mongolia Rare Earth Group is headquartered in Hexi Industrial Zone, Baotou, Inner Mongolia, with total assets of US$8.7 billion as of the end of 2007 [183]. According to Lin, there were nine subsidiary companies in the Group as of 2006, including:

- Inner Mongolia Baogang Rare-Earth Hi-Tech Co., Ltd
- Baotou Research Institute of Rare Earths
- Baotou Tianjiao Seimi Polishing Powder Co., Ltd
- Zhongshan Tianjiao Rare Earth Materials Company
- Sanfeng Rare Earth Co., Ltd
- Ming Research Institute of Baogang
- Steel Ball Plant
- Baogang Baiyun Iron Ore BoYu Company
- The Comprehensive Factory of the Initial Third Rare Earth Plant

The Baotou Research Institute of Rare Earths, a subsidiary of the Inner Mongolia Rare Earth Group, has been conducting research and development into NdFeB products since the 1980s and built the first domestic pilot NdFeB magnet production line in 1987. The research center achieved a world-record 52.2 MGOe in 1990, and in 2003 the Institute met the project goals of the National Development and Reform Commission that required "300 tons annual output of high-performance NdFeB magnet industrialization demonstration projects" [184]. Inner Mongolia Baotou Steel Rare Earth Magnetic Material Co., Ltd was set up for this purpose, and as a wholly owned subsidiary company of Inner Mongolia Baotou Steel Rare-earth Hi-Tech Co., Ltd had registered capital of US$26.9 million as of 2011 [185]. The company’s facilities include a production line producing 15,000 metric tons of NdFeB strip cast alloy and 2,000 metric tons of NdFeB magnets per year.

The Inner Mongolia Rare Earth Group has formed a vertically integrated rare earth industrial system, covering production, R&D, and applications of rare earths, including dressing, smelting and separation, manufacturing, and application. According to the group, it has adopted protective mining methods for the exploitation of Bayan Obo's rare earth deposits, with strict technical procedures being employed in ore mining and processing including separation of products and processes. In 2005, Baotou Iron & Steel (Group) Company produced a total of 49,000 metric tons of rare earth concentrate [186], and as of 2006, 714 of the group's 5,713 employees were technical engineers [187].

As of 2006, there were more than 20 rare earth companies using rare earth concentrate from Baotou to produce mixed rare earth carbonates and rare earth chlorides, including Rare Earth Hi-Tech, Huamei Hi-tech, Hefa Rare Earth, Baotou Rhodia, Shanxi Suohuang Rare Earth, Gansu Rare Earth, and Baiyin Lan'ao. The combined rare earth concentrate processing capacity of these companies in 2006 was estimated at 169,000 metric tons, with the Inner Mongolia Rare Earth Group's capacity at 72,000 metric tons, accounting for 44.4 percent of the total capacity in China [188].

Major rare earth products of the Group include mischmetals; the metals of La, Pr-Nd, Ce, Nd (annual production of 3,000 metric tons as of 2006); and individual rare earth metals such as Tb, Dy, Sm, and Dy-Fe alloy. Due to the level of integration in the group, from processing raw rare earth materials to value-added rare earth products, the Inner Mongolia Rare Earth Group has become the largest and most successful group of companies in China's rare earth industry. Table 4.3 presents the main rare earth products from the Group's subsidiary companies.

Southern District – Seven Provinces in the South of China

The rare earth industry in the seven provinces in the south of China has also set up vertically integrated operations, consisting of mine exploitation, metallurgy, research and development, scientific applications and foreign trade. The rich ion adsorption deposit in Ganzhou, in Jiangxi province, plays a major role in the region as the center of rare earth operations. As of 2006, Ganzhou's rare earth output capacity was more than 10,000 metric tons per year, accounting for 60 percent of the total Chinese output of ion adsorption-type rare earths [189]. The rare earth smelting and separation capacity in Ganzhou has previously been estimated at approximately 20,000 metric tons per year, processed in major companies such as Ganxian Hongjin Rare Earth Co., Ltd, Longnan Wanbao Rare Earth Co., Ltd, and Dingnan Southern Rare Earth Co., Ltd.. As of 2006 Ganzhou produced 10,000 metric tons per year of mischmetal and single rare earth metals, which have experienced a significant increase in demand due to their application in nickel-hydrogen batteries and rare earth permanent magnets. Local companies Ganzhou Qiandong Rare Earth Metal Smelting Co., Ltd; Southern Rare Earth High-tech Co., Ltd.; and Chenguang Rare Earth Materials Co., Ltd. are among the largest companies in China producing rare earth metals, and Ganzhou also produces rare earth cast iron, rare earth alloys, magnets, and luminescent materials [190].

Table 4.3: Inner Mongolia Rare Earth Group Main Products [191]

Company	Main Products	
Baogang Rare Earth Hi-Tech Co., Ltd.	Primary rare earth products	mixed concentrate of bastnaesite & monazite (produces but does not sell), mixed rare earth chloride, mixed rare earth carbonate, less-Nd rare earth carbonate, Sm-Eu-Gd concentrate, La-Nd rare earth carbonate
	Individual rare earth deposit	lanthanum oxide, cerium oxide, praseodymium oxide, neodymium oxide, europium oxide, gadolinium oxide, lanthanum chloride, cerium chloride, lanthanum carbonate, cerium carbonate, praseodymium carbonate, cerium acetate, lanthanum acetate, cerium nitrate, lanthanum hydroxide, cerium hydroxide, neodymium fluoride.
	Mixed rare earth metal	mixed rare earth metal, less-Zn, Mg mixed metal
	Individual rare earth metal	neodymium metal, lanthanum metal, cerium metal
	Cylinder-shaped high-power Ni-MH battery	C-type battery and D-type battery
Rare Earth Research Institute Co., Ltd	REO	europium oxide, rare earth hydroxide, rare earth nitrate, rare earth acetate, rare earths for agriculture
	NdFeB products	33H, N38, N40, N42, N45, NdFeB
	Sm-Co products	Sm_2-Co_{17}, Sm-Co_5
	Rare earth metal powder	samarium powder, alloy powder
	Rare earth metal and alloy	neodymium metal, alloy of lanthanum and neodymium
	Rare earth application products	rare earth permanent magnet iron remover, rare earth permanent water magnetizer, magnet dressing machine
Tianjiao Qingmei Rare Earth Polishing Powder Co., Ltd.	Rare earth polishing powder	TE-98, H-500, LCE-600, H-401, H-502, H-900 polishing powder

Western Rare Earth District – Mianning in Sichuan Province

Following the 1986 discovery of rare earth mines in the region of Maoniuping, Mianning, the first rare earth (bastnaesite concentrate) processing plant began production in Chengdu in 1993. Today, the Sichuan rare earth industry covers the following main areas:

(1) The Mianning and Xichang areas in Liangshan autonomous prefecture – main products in this area are rare earth minerals, rare earth ferrosilicon, rare earth chloride, chlorinated rare earth mixtures, rare-earth oxides, and metals.

(2) The Leshan, Emei and Wutongqiao area – products in this region include chlorinated rare earth mixtures, lanthanum-rich chlorinated rare earth mixtures, rare earth carbonate, rare earth nitrate, polishing powder, oxides and metals.

(3) Chengdu and its neighboring areas – companies in this area focus on advanced processing, high-technology and high-value-added products and applications [192].

4.3 Rare Earth Policies in China

Many different government agencies play a role in setting up rare earth policies in China, due to the strategic importance of rare earths to the development of the Chinese economy. These agencies include:

- The Ministry of Land and Resources (MLR)
- The State Development and Planning Commission (SDPC) (formerly the State Planning Commission [SPC])
- The Ministry of Commerce (MOC)
- The Ministry of Foreign Trade and Economic Cooperation (MOFTEC)
- The State Economic and Trade Commission (SETC)
- The Ministry of Industry and Information Technology (MIIT).

These agencies regularly cooperate in the process of managing and regulating the rare earth industry, although at times there has been a lack of communication among agencies. Following is an examination of policies introduced by the preceding agencies to control the rare earth industry in China, covering production and export quotas and export taxes.

China's Rare Earth Production Quota Policies

The Chinese government regulates overall production quotas to prevent over-exploitation and unsustainable mining practices. From the early 1990s to 2008, the MLR was in charge of developing production plans for China's strategic commodities, including rare earths. The strategic commodity production plan included not only overall nationwide production quotas, but also quotas for individual provinces and/or autonomous regions. Provincial governments were then able to allocate production quotas to individual mining companies within their regions. However, the actual production output of rare earths has been found to be much higher than the specified governmental quota due to the high demand in the rare earth market. In addition, this demand has led to a significant amount of rare earths being produced by illegal mining practices. According to estimates from the CSRE, output exceeded government quotas by 40 percent in 2010 [193].

In 2008 the MIIT started issuing rare earth production quotas after the Rare Earth Office was transferred to the MIIT. At the same time, the MLR continued to issue its production quotas. Due to a lack of communication between the two agencies in 2008 and 2009, the production quotas issued by MIIT and MLR were not consistent, with MIIT quotas set higher than those from MLR (Table 4.2). In 2010, the two agencies came to an agreement and set the same rare earth quotas for the country [194]. Production quotas have stayed reasonably stable from 2006 to 2011, rising from 86,620 metric tons to 93,800 metric tons. According to China's "Rare-Earth Industry Development Plan of 2009–2015," annual rare earth production quotas may be limited to between 130-140,000 metric tons (REO) during the plan's seven year period [195].

According to a USGS report, rare earths were declared as protected and strategic minerals by the Chinese government in 1990. Subsequently, foreign investors were not allowed to mine rare earths in China and have been prohibited from participating in rare earth smelting and separation practices, except in joint ventures with Chinese companies. All rare earth smelting and separation projects must obtain approval from the Rare Earth Office, a division of the SDPC. Prior to 2003, the MOFTEC was in charge of approving rare earth Sino-foreign joint ventures. Beginning in 2011, Sino-foreign ventures needed to be approved by both SDPC and MOC [196].

China's Rare Earth Export Quota Policies

Prior to 2003, rare earth export quotas were set by the SDPC and distributed by the SETC, and then MOFTEC issued the licenses. To improve management efficiency, MOC took over all responsibilities in 2003 and has been in charge of issuing and distributing export licenses since then [197]. Table 4.4 illustrates the decreasing number of domestic rare earth producers and traders approved to deal in export trades in China, with a 51% reduction from 2006 to 2009.

Table 4.4: Export Approved Rare Earth Producers and Traders in China, 2006-2011 [198]

Year	Domestic Producer	Sino-foreign Joint Venture
2006	47	12
2009	23	11
2010	22	10
2011	22	9

Due to dramatically rising demand in the domestic market, the Chinese government has continued to reduce export quotas, as previously seen in Table 4.2. Figure 4.4 shows a downward trend in China's rare earth material export quotas from 2005 to 2012, and of particular note is the rare earth export quota for 2010, reduced by almost 40 percent from the previous year.

Chinese rare earth export quotas were reduced by a further 11 percent for the first half of 2011, compared to first half 2010 levels [199]. However, the MOC set the rare earth quota for the second half of 2011 at 15,738 metric tons, meaning that the full-year quota was 30,184 metric tons, almost unchanged from 2010's 30,258 metric tons [200]. The announcement was made two weeks after a WTO expert panel ruled that "China's export restrictions on nine raw materials were inconsistent with its WTO obligations" [201], even though rare earths were not included in the raw materials cited in the WTO ruling. According to Wang Caifeng, a former official at the MIIT, the export quota is in line with China's production plan, which included an increase in the country's production quota of 5 percent [202].

Due to a combination of skyrocketing market prices for materials in early 2011, a subsequent global drop in demand, and decreased production due to a Chinese government crackdown on domestic rare earth producers, an estimated 51% of China's 2011 export quota went unused [203]. Some companies may have also been skirting official government export quotas due to their use of rare earth “ribbons” – this is material comprised of 30-40% rare earth elements typically used to make magnets, and it can be sold overseas without government restrictions. According to an official from Ganzho Zhaori Rare Earth New Materials in China, as of 2012 there were almost 100 companies producing rare earth ribbons in China, and his own company had an annual production capacity of 2,000 metric tons. Baotou Steel Rare Earth, a major Chinese rare earths producer, announced in November 2011 that it would build a production line for rare earth ribbons in Ningbo, with an annual capacity of 5,000 metric tons. This followed a previously announced plan to build a similar ribbon project with an annual capacity of 4,000 metric tons [204].

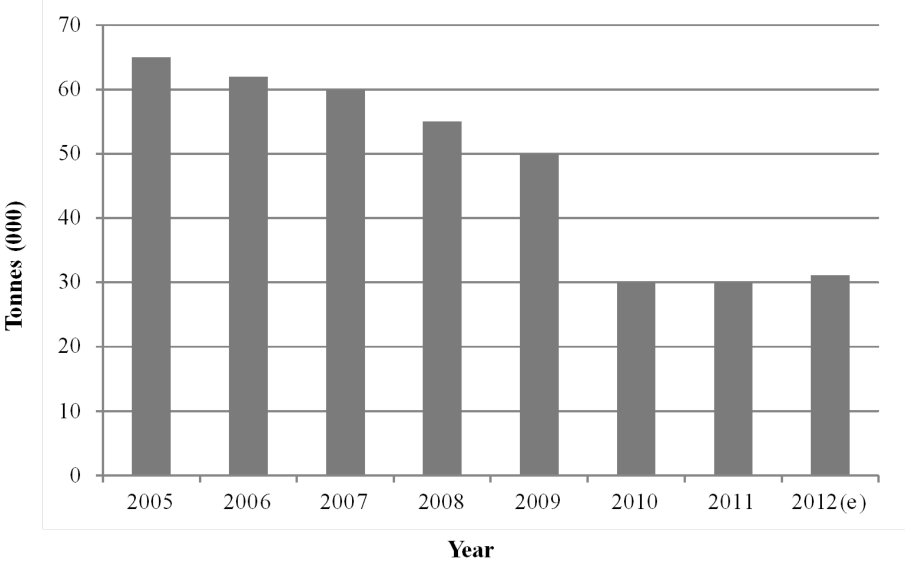


Figure 4.4: The Historical Decline of China’s REO Export Quota [205, 206]

(Note: (e) denotes estimated total)

On December 27, 2011, the Chinese Ministry of Commerce announced initial 2012 rare earth material export quotas at 24,904 metric tons. For the first time, the quota was separated between heavy and light rare earths, with an allowance of 21,700 metric tons for light rare earths and 3,204 metric tons for medium/heavy rare earths. Also for the first time, the MOC communicated their intent for the full year quota and stated that it would remain unchanged from the levels seen in 2010 and

2011, with the initial quota representing 80% of the total for the year [207].

According to data from the MOC in 2011, Sino-Foreign ventures represented roughly 10% of total export quota allowances, while 90% were awarded to Chinese-owned producers and traders. Rare earth enterprises operated by Neo Material Technologies (Zibo Jiahua Advanced Material Resources Company and Jiangyin Jiahua Advanced Material Resources Company) and Rhodia (Baotou Rhodia Rare Earth Company and Liyang Rhodia Rare Earth New Materials Company) received the bulk of quota allocations for Sino-foreign joint ventures operating in China [208].

Table 4.5: China's Rare Earth Export Quotas, 2009-2011 [209]

	2009		**2010**		**2011**	
Sub-group	**H1 (t)**	**H2 (t)**	**H1 (t)**	**H2 (t)**	**H1 (t)**	**H2 (t)**
Domestic	15,043	18,257	16,304	6,208	10,762	12,221
Foreign-owned	6,685	10,160	5,978	1,768	3,746	3,517
Sub-Total	21,728	28,417	22,282	7,976	14,508	15,738
TOTAL	**50,145**		**30,258**		**30,246**	

(Note: H1 = First half of year, H2 = Second half of year, t = metric tons**)**

Ruidow Rare Earth Monthly compiled rare earth product export data for January to June 2011 (based on their destination countries), as shown in Table 4.6. The data illustrates the significant scale of China's rare earth export market.

China's total rare-earth export value between January and June of 2011 surged to US$1.54 billion, an increase of 930 percent over the same period of last year, according to statistics from the Nonferrous Metals Society of China [210].

China's Rare Earth Export Tax Policies

In addition to issuing production and export quotas, the Chinese government applies taxes on mineral production as part of its efforts to regulate the rare earth industry. During the early developmental stages of its rare earth industry, China refunded the value-added tax that producers paid on exported products in an effort to encourage enterprises to export their products. A combination of this rebate and significant investment in

Table 4.6: Rare Earth Products Export Data to Foreign Countries (First Half of 2011) [211]

Products	Customs	Quantity (Kg)	Value (US$)
Cerium Oxide	Thailand	50,000	6,218,507
	Vietnam	50,000	6,217,807
	Germany	21,250	2,287,588
	South Korea	12,830	771,865
	The Netherlands	8,175	892,070
	Japan	7,480	921,583
	United States	3,060	348,435
	Canada	1,000	126,000
	Hong Kong	200	14,016
Yttrium Oxide	Japan	381,728	45,249,394
	Hong Kong	90,100	12,554,183
	United States	71,735	8,166,482
	South Korea	52,200	6,021,331
	Italy	25,000	3,259,998
	Taiwan	12,660	1,303,500
	Austria	12,000	1,618,000
	France	9,000	1,375,500
	The Netherlands	8,524	1,167,194
	England	6,500	808,538
	Germany	1,400	122,100
	Singapore	2	301
Lanthanum Oxide	United States	801,000	91,803,643
	Japan	691,830	71,628,617
	Hong Kong	297,010	28,171,120
	Germany	149,500	17,401,018
	Italy	138,000	16,230,294
	France	60,020	7,929,950
	Brazil	60,000	3,900,000
	The Netherlands	15,000	1,858,800
	Canada	10,000	1,470,000
	South Korea	7,000	510,930
	India	5,000	540,000
	Taiwan		276
Neodymium Oxide	Japan	230,107	49,383,123
	France	42,000	8,616,000
	The Netherlands	32,000	5,454,620
	United States	22,645	5,332,555
	South Korea	21,600	3,082,041
	Taiwan	13,000	2,670,000
	South Africa	12,000	2,682,386
	Hong Kong	5,305	1,144,725
	England	5,001	435,222
	Mexico	4,460	848,000

	Germany	4,100	707,939
	Canada	1,000	229,000
	Argentine	540	123,660
Europium Oxide	Japan	11,400	10,906,406
	Germany	1,500	1,349,616
	United States	1,500	1,537,684
	The Netherlands	900	972,494
	South Korea	750	662,544
	Austria	75	63,750
	Taiwan	50	33,470
	England	1	1,360
Dysprosium Oxide	Japan	43,000	25,642,070
	South Korea	16,780	13,000,311
	Taiwan	1,080	612,513
	The Netherlands	950	650,637
	United States	200	152,033
	Germany	100	87,923
	Hong Kong	50	22,000
	England	1	783
Terbium Oxide	Japan	10,000	7,865,983
	France	2,000	1,280,000
	Germany	1,400	1,467,568
	South Korea	1,010	1,111,330
	Hong Kong	1,000	1,459,000
	The Netherlands	50	34,192
	Austria	50	43,250
	Commonwealth of Independent States (Former Soviet Union)	50	74,350
	England	1	1,360
Nd, un-mixed/fused	Japan	83,000	17,602,733
	Germany	33,000	5,689,658
	The Netherland	24,500	2,450,000
	Hong Kong	3,500	358,410
	South Korea	500	50,900
Battery-grade Sc and Y, mixed/fused	Japan	14,000	16,470,870
Cerium Carbonate	Japan	545,800	50,541,107
	United States	188,300	15,028,182
	Hong Kong	48,050	3,843,700
	South Korea	46,200	2,702,398
	England	36,000	4,305,040
	France	5,000	230,600
Lanthanum Carbonate	United States	99,000	9,033,710
	France	11,200	966,448
	Japan	1	196

the rare earths industry quickly led to China’s dominance in global rare earth supply.

In the early 2000s, the government reduced the export rebate for rare earths due to increasing domestic demand. In 2005, the rebate on rare earth exports was eliminated entirely, and trade on rare earth concentrates was banned for the year, to again meet domestic demand and to discourage the export of rare earth raw materials. In 2007, China introduced an export duty on rare earth products to further restrict exports.

As shown in Table 4.7, Chinese export duty rates have increased for all rare earth export goods since their introduction. The commodities with the highest export duty rate (25 percent) since 2008 include yttrium oxide; lanthanum oxide; europium and its oxide; terbium and its oxide, chloride, and carbonate; dysprosium oxide, chloride, and carbonate; mixed rare earth; yttrium and scandium compounds; and metals (including battery grade). Additionally, lanthanum, cerium and dysprosium metals and other mixed metals have the highest export duty rate, due to increased demand in the global market. While export duties and quotas are inconsistent with WTO global trading rules, China has stated publicly it is ready to defend these policies and believes them to be necessary as part of its future plan for management of domestic resources [212].

The significant price delta between exported and domestic rare earths is sending a clear message to rare earth consumers outside China that moving their operations into the country will result in significant fiscal benefits. According to Michael Silver, Chief Executive of American Elements, a global rare earth material supply company, “there is roughly a 40 percent difference in the cost of rare earths if you're buying on an export basis, due to the cost of the quota and the export tax….A company that moves here gets an incredible benefit." [213]

4.4 Academic Research in China

China showed significant interest in rare earths, particularly in R&D, even in the early years of the country’s development of its resources. In 1952, Beijing’s General Research Institute for Nonferrous Metals (GRINM) was established, becoming the largest institution in China in the field of nonferrous metals. Prior to the 1990s China's main focus was on applied research, in particular the separation of rare earths, and this resulted in weakness in the area of fundamental research. In an effort to become a world leader in high-tech innovation, China has implemented two national programs: National High Technology Research and Development Program 863 (known simply as Program 863) and National

High Technology Research and Development Program 973 (known as Program 973).

Table 4.7: China's Rare Earth Export Duty Rates [214]

Commodity	Export Duty Rate (percent)				
	2007	2008	2009	2010	2011
Yttrium oxide	10	25	25	25	25
Lanthanum oxide	10	25	25	25	25
Cerium oxide, hydroxide, carbonate, and others	10	15	15	15	15
Neodymium oxide	10	15	15	15	15
Europium and its oxide	10	25	25	25	25
Terbium and its oxide, chloride, and carbonate	10	25	25	25	25
Dysprosium oxide, chloride, and carbonate	10	25	25	25	25
Other REOs	10	15	15	15	15
Mixed rare earth chlorides and fluorides	10	15	15	15	15
Mixed rare earth carbonates	10	15	15	15	15
Mixed rare earth, yttrium and scandium compounds and metals (including battery grade)	10	25	25	25	25
Non-mixed rare earth carbonates	10	15	15	15	15
Rare earth ores	10	10	15	15	15
Lanthanum metal	NA	NA	NA	NA	25
Cerium metal	NA	NA	NA	NA	25
Neodymium metal	10	15	15	15	15
Dysprosium metal	NA	NA	NA	25	25
Other mixed metals	NA	NA	NA	25	25

(Note: NA=not available.)

Program 863 was proposed by four Chinese scientists to accelerate China's high technology development, and it was approved by the government in March 1986. The objectives of the program include (1) gaining a foothold in high-tech fields globally, (2) achieving breakthroughs in key technical fields that have a significant influence on the national economy and security, and (3) achieving "leapfrog" development in key high-tech fields in which China has a relative advantage, or should take strategic positions in to support the implementation of its process of modernization [215]. Rare earths are considered to be one of the important resources in which China has an advantage, due to its considerable reserves and successful mining and processing industry. The major areas of focus for Program 863 were biotechnology, space, information, laser, automation, energy, and new materials, and rare earths are routinely used in each of these areas [216].

In March 1997, China's Ministry of Science and Technology launched Program 973, and it became the largest fundamental research program in the country. Research projects funded by Program 973 generally receive the equivalent of millions of U.S. dollars and last for up to five years. An example of rare earth work funded by the program is seen in the paper *Effect of annealing process on magnetic properties of* $Sm(Co_{0.6}\,Fe_{0.27}\,Cu_{0.1}\,Zr_{0.03})_{7.5}$ *ribbons* [217], examining the effect of heat treatment on the magnetic properties of melt-spun Sm(Co, Fe, Cu, Zr) ribbons.

Two state laboratories in China now focus their efforts on fundamental rare earths research and have made significant contributions to rare earth technologies: the State Key Laboratory of Rare Earth Materials Chemistry and Applications at Peking University, and the State Key Laboratory of Rare Earth on Advanced Materials and Valuable Utilization of Resources at the Changchun Institute of Applied Chemistry under the Chinese Academy of Sciences (CAS).

China also hosts the only two technical journals worldwide that are exclusively dedicated to rare earths: the *Journal of Rare Earths* and the *China Rare Earth Information Journal* (CREI). Both were launched by the Chinese Society of Rare Earths (CSRE), a major science and technology research organization founded in 1980 in China [218]. The CSRE also hosts the International Conference on Rare Earth Development and Application (ICRE), last held in 2010 [219].

The following sections provide details on the academic research performed in key Chinese rare earth research laboratories, along with a brief introduction of the functions of the CSRE in China.

Baotou Research Institute of Rare Earths (BRIRE)

The Baotou Research Institute of Rare Earths (BRIRE), established in 1963, is now the largest rare earth R&D institute in the world and consists of the North China Rare Earth Industry Productivity Promotion Center and the Ruike National Engineering Center of Rare Earth Metallurgy and Function Materials. BRIRE has nearly 500 employees, 50% of whom are technicians, along with 100 professorial senior engineers and 200 engineers, 40 of whom have doctorate and master's degrees. The center focuses on the comprehensive exploitation and utilization of rare earth resources and research on rare earth metallurgy, environmental protection, new rare earth functional materials, and rare earth applications. Specific research subjects at BRIRE include the following [220]:

- Rare earth mineral decomposition, separation, and purification
- Disposal of rare earth hydrometallurgy waste
- Rare earth compound powder materials
- Rare earth permanent magnet materials
- Rare earth catalysis materials
- Rare earth fine chemicals and rare earth assistants
- Rare earth metals and alloy powder, wire, strip, and abnormally-shaped materials
- Magnetic refrigeration materials
- Phosphor materials
- Hydrogen storage materials
- Evaporation and film-coating materials
- Heating materials
- Analysis and testing methods

Over the past 40 years BRIRE has: undertaken 1,600 national projects, including first-class local and Program 863 projects; gained 248 science and technology achievements; won 180 awards, including National Inventions Awards and Scientific and Technology Advance Awards; and obtained 35 patents. BRIRE's China Rare Earth Information Centre publishes two rare earth magazines – *Chinese Rare Earth* and *Rare Earth Information* (Chinese and English versions) – and the institute also publishes the Chinese language *Rare Earth Database* and *Chinese Rare Earth* website (http://www.cre.net), providing up-to-date online information on the rare earths industry. BRIRE has set up two research centers at the provincial level, including the Inner Mongolian Xiyuan Functional Materials Engineering Research Center and the Inner Mongolia Rare Earth Industry Productivity Promotion Center. In addition, the analysis and testing center at BRIRE is authorized to undertake analysis of both imported and exported rare earth products [221].

BRIRE provided the permanent magnet material for the AMS-01 alpha magnetic spectrograph carried on the U.S. space shuttle *Discovery* in 1998, as well as important magnetic material for China's *Shenzhou* space aircraft and *Chang'e 1* carrier rocket. In terms of scientific development, BRIRE has partnered successfully with many domestic and foreign research institutes and universities in the U.S., Italy, Japan, Germany, and France [222].

The State Key Laboratory of Rare Earth Materials Chemistry and Applications

The development of the State Key Laboratory of Rare Earth Materials Chemistry and Applications was approved by the State Commission of Planning and Development of China in 1991, with initial financing provided by the World Bank. The laboratory has been formally open to the public since 1995 and has 29 researchers on staff, including 3 Chinese Academy of Sciences (CAS) members, 13 professors and 3 senior engineers [223].

The laboratory performs both fundamental and applied research, emphasizing the theory and technology of rare earth separation in high and ultrahigh purity, and the design synthesis and characterization of new functional materials containing rare earth elements. The laboratory's three major research areas are: (1) the development of rare earth separation chemistry, (2) solid state chemistry, and (3) coordination chemistry and physical chemistry. These research areas have the following goals [224]:

- To further develop a generalized multi-component counter-current extraction theory, especially applicable for the efficient and optimized separation of heavy rare earths for both high purity and high yield.
- To study the correlation between structural and functional properties of optical, electric, and magnetic solid materials containing rare earth elements, and to explore new methods of preparing materials with controlled size, especially in the nanometer range, and morphology.
- To design and synthesize novel rare earth coordination compounds and functional molecule-based materials in membrane forms and composite devices, and to study their applications.
- To develop highly accurate computational methods based on relativistic density-functional theory, to study the electronic structure of rare earth compounds, to explain the behaviors of rare earth functional materials, and to aid the computer design of synthesis.

- To investigate the microstructure and reaction process for compounds containing rare earth elements by various spectroscopic methods and to provide explanations for the extraction mechanism and basis of molecular design.

The laboratory has made significant progress in the separation of rare earth elements, and their major achievements have included the following [225]:

- Establishment of a multi-component counter-current extraction theory and solutions to existing problems in rare earth separation technology, as well as construction of a large separation plant of heavy rare earths for high purity and high yield in Jiangsu Province. This work has received significant national recognition, with a number of national Science and Technology prizes during the 1990s.
- Development of a new method for preparation of the efficient X-ray-stimulated luminescent material $BaFBr:Eu^{2+}$, for which the laboratory was awarded a Second Grade Prize of Science and Technology Progress by China's Ministry of Education in 1995.
- Preparation of a series of molecule-based optoelectronic functional LB membranes and electroluminescent devices containing Eu or Tb complexes, with high brightness and stability. Published studies on these subjects in 1997 were awarded Ministry of Education prizes, and a study in 2003 was awarded a National Prize of Natural Sciences.
- Significant progress on fundamental research on molecular spectroscopy and applications. A study on infrared spectroscopy was awarded the 9th Chinese Publication Prize in 1995, and a second study on vibrational spectroscopy was awarded a Beijing Municipal Government prize in 2001.
- Development of highly accurate algorithms based on relativistic density functional theory, and creation of a related software package, BDF (Beijing Density Functional). The software can provide the most accurate results currently possible for four component relativistic density functional calculations of molecules containing rare earths and other heavy elements.

The laboratory has also participated in extensive successful academic exchanges and established collaborations with scientific institutes and universities both in China and abroad. These include the following [226]:

- University of Texas Medical Branch at Galveston (U.S.)
- Department of Chemical Engineering, Auburn University (U.S.)
- Department of Chemistry, Cornell University (U.S.)
- Department of Chemistry, McGill University (Canada)
- Molecular Materials Center, University of Sheffield (U.K.)
- Department of Hydrocarbon Chemistry, Kyoto University (Japan)
- Joint laboratory with the University of Hong Kong on Rare Earth Materials and Bio-medicinal Chemistry in 1999 (Hong Kong)

Extensive collaboration with both domestic and overseas organizations has enabled the laboratory to achieve international recognition in the field of rare earth materials.

State Key Laboratory of Rare Earth on Advanced Materials and Valuable Utilization of Resources

Originally titled the "Open Laboratory of Rare Earth Chemistry and Physics," the State Key Laboratory of Rare Earth on Advanced Materials and Valuable Utilization of Resources at the Chang Chun Institute of Applied Chemistry was founded in 1987 under the Chinese Academy of Sciences (CAS). As of 2012 there were 32 faculty members in the laboratory, including two members of CAS. The National Science Fund selected four faculty members as Distinguished Young Scholars, and seven were recruited into the CAS Hundred Talents program. Between 1999 and 2005, the laboratory received a Second Grade Award of Natural Science from the CAS and published 842 research papers, 51 in journals with an SCI impact factor larger than 3.0. Fifty-two patents have been granted to the institution as of 2012, six of which are international patents [227]. The laboratory primarily focuses on the following research fields [228]:

- Rare earth solid-state chemistry and physics: rare earth material defects, rare earth luminescence and molecular engineering, thin films and interfaces, material simulation and design, rare earth light alloys, nano-coatings, and microstructures.
- Bioinorganic chemistry and the chemical biology of rare earths: specific recognition between rare earth compounds and biomolecules, protein expression and nucleic acids chemistry, and the modulation of biomolecular confirmation and function.

- Rare earth separation chemistry: clean techniques for rare earth separation, and chemical and environmental issues with rare earth separation.

The Chinese Society of Rare Earths (CSRE)

There are more than 100,000 registered experts in the CSRE, making it the world's largest rare earth-focused academic community. It serves the Chinese government and the country's researchers in the science and technology of rare earths and provides the ability for scientists to explore technical ideas for fundamental and applied research. The CSRE also plays an important role in the international rare earth community, organizing the International Conference on Rare Earth Development and Application once every three years, and a biennial CSRE meeting. As previously noted, the CSRE publishes two technical journals dedicated to rare earths, one in Chinese, and the other in both Chinese and English [229].

The CSRE describes itself as "the most important social force in developing the rare earth science and technology in China." There are fifteen sub-committees in the CSRE, covering almost every R&D field in rare earth development [230]:

- Rare Earth Geochemistry and Ore Dressing
- Rare Earth Chemistry and Hydrometallurgy
- Rare Earth Magnetic Materials and Magnetism
- Rare Earth New Materials
- Rare Earth Catalytic Materials
- Application of Rare Earths in Iron and Steel
- Application of Rare Earth in Casting
- Rare Earth Analytical Chemistry
- Application of Rare Earth in Ceramic and Glass
- Rare Earth Refining
- Environmental Protection on Rare Earth Industry
- Rare Earth Phosphor and Luminescence
- Application of Rare Earths in Agriculture
- Rare Earth Information
- Technique and Economy of Rare Earth Enterprises

4.5 Rare Earth Issues China Faces

Despite its success, the rare earths industry in China has been rife with unrestrained mine development and poor resource management practices. Chinese leaders have expressed their concern that the country’s future demand for rare earths may not be met if existing mining practices are allowed to continue without further regulation. In 2011, China's State Council announced a new set of national guidelines for the rare earth industry, identifying a wide range of problems affecting the industry as a result of its rapid development. These issues included the illegal mining and export of rare earths, the severe environmental damage to areas in which rare earths are mined and processed, and the challenge of ensuring the country's domestic supply needs. In addition, the level of China’s downstream rare earth application industries falls far behind international levels, and therefore China shows great interest in both developing and attracting companies with the technologies needed to create significant growth in the sector.

Rare Earth Illegal Mining and Export

As discussed in Section 4.3, China has been regulating rare earth production quotas over the past decade to prevent over-exploitation and unsustainable mining practices. However, due to increased demand, rare earths have become the most sought-after industrial metals in China. This has led to widespread illegal mining, particularly in the southern seven provinces. For example, the official annual production quota for Ganzhou in Jiangxi Province in 2011 was only 10,000 metric tons, yet the city has over one hundred rare earth processing companies with a processing capacity of 40,000 metric tons, four times the allocated production quota [231]. County governments are believed to have supported illegal mining operations even in the face of production quotas, particularly during periods such as early 2011 when significant profits could be made by continued mining. In order to maximize their profits, these operations can often use obsolete processes and technology, causing more damage to the environment than otherwise necessary.

Due to both the growing level of international demand and escalating material prices, many buyers have resorted to purchasing illegally produced rare earths that have been smuggled out of China. In 2008, China legally exported 39,500 metric tons of REOs. However, it is believed that approximately 20,000 additional metric tons were illegally exported during the same time period [232]. In other words, illegal exports accounted for one-third of the total rare earth oxides leaving

China, many under the guise of being other minerals. On July 25, 2011, Shanghai customs caught a case of illegal rare earth exportation, with the material's total value at US$2.67 million [233]. The trading company, Nanjing Hanzhihai Trade Co., Ltd, attempted to smuggle lanthanum oxide out of the country, reporting it as strontium carbonate in order to avoid export taxes and quotas.

The illegal export of rare earth materials adversely affects the industry in China by reducing profits for legal producers and depleting the country's rare earth resources at an unsustainable rate. High levels of illegal exports have resulted in greater industry regulation, including the MIIT's "Rare-Earth Industry Development Plan of 2009–2015." One of the plan's goals, among others, is to curb illegal exports by introducing regulations and policies to punish offenders [234]. Illegal mining has also flourished due to geographical reasons – China's rare earth resources are distributed across multiple provinces and regions throughout the country, making enforcement of unauthorized mining and processing more difficult than it would be for more centralized operations.

Severe Environmental Damage from Mining and Processing

The environmental impact of rare earth mining operations is a major issue wherever mining occurs, for those both inside and outside the industry. According to the CSRE, "Every ton of rare earth produced, generates approximately 8.5 kilograms (18.7 lbs) of fluorine and 13 kilograms (28.7 lbs) of dust; and using concentrated sulfuric acid high temperature calcination techniques to produce approximately one ton of calcined rare earth ore generates 9,600 to 12,000 cubic meters (339,021 to 423,776 cubic feet) of waste gas containing dust concentrate, hydrofluoric acid, sulfur dioxide, and sulfuric acid, approximately 75 cubic meters (2,649 cubic feet) of acidic wastewater, and about one ton of radioactive waste residue (containing water)" [235].

Another study conducted within Baotou claims that "'all the rare earth enterprises in the Baotou region produce approximately ten million tons of all varieties of wastewater every year' and most of that waste water is 'discharged without being effectively treated, which not only contaminates potable water for daily living, but also contaminates the surrounding water environment and irrigated farmlands.'" [236]. Hurst noted in 2010 that "according to Wang Caifeng, China's Deputy Director-General of the Materials Department of the Ministry of Industry and Information, producing one metric ton of rare earths can generate 2,000 metric tons of mine tailings" [237]. China's rare earth production in 2009 was 120,000 metric tons, implying that 240 million metric tons of mine tailings were produced in 2009.

The environment in China suffers greatly due to the extraction of rare earths – Figure 4.5 (see color insert) illustrates the heavy environmental damage from the Baotou mining operation, showing a very large scale polluted sludge lake formed by rare earth mine wastewater. Illegal mining is often much worse, as the extraction process can be as archaic and dangerous as simply drilling holes in the ground a few feet deep, inserting pipes, and pumping a mix of chemicals into the clay to leach out rare earths. As a result, there have been both crop and water supply contamination and landslides in the areas in which this type of illegal mining has occurred.[239]

A number of factors contribute to poor mining practices in China's rare earth mines. Most importantly, the country has traditionally lacked a mechanism to effectively enforce environmental regulations and policies. Secondly, in China, land belongs to the government, rather than to the companies who use the land. If a rare earth producer invests a large sum of capital in environmentally friendly machinery and processes to comply with regulations, this investment could potentially be lost at any time, as the government can reclaim the land for any reason. In order to maximize profit, many producers opt to keep their costs to a minimum by implementing less environmentally friendly processes. For example, due to outdated equipment and technology and a lack of oversight, waste from ore processing at Baotou often finds its way into the Yellow River [240]. This is the second-longest river in China and the sixth longest in the world, and serves as the primary water source for about 140 million people [241].

Occupational safety standards are also seriously lacking in China's rare earth mining industry. As of 2009, in Baotou, near the Bayan Obo Mining District, 5,387 residents suffered from pneumoconiosis, otherwise known as black lung [242]. Producers have no financial incentive to follow health and safety regulations, and the government in China has historically been unsuccessful in enforcing these regulations. As a result, the health of workers in mining and processing districts has been seriously compromised.

Another example of the environmental damage that can be caused by poor rare earth mining practices can be seen in the town of Papan, in the northern region of peninsular Malaysia. In 1979, a collaboration between local businessmen and Mitsubishi Chemicals named Asia Rare Earth (ARE) set up a mining factory in nearby Bukit Merah. During the mine's operation in the 1980s, radioactive waste was transported into Papan, creating a permanent radioactive waste dumpsite, unbeknownst to the town's residents. In 1992 ARE closed the factory, due to growing public protests and pressure of a boycott against Mitsubishi for its involvement in the project, but by that time they had created radioactive sites, both in open ground areas in Papan and in the town of Bukit Merah. To this day, exceptionally high levels of radiation are seen in both towns, as truckloads of radioactive waste continue to be buried under a granite slab in Papan [243].

China's Growing Domestic Need for Rare Earths

The Chinese government is now clearly aware of the strategic importance of the country's rare earth deposits and is actively taking steps to protect supplies for domestic consumption. Government export quotas decreased annually beginning in 2003 and then stabilized from 2010 to 2011, while rare earth production continued to increase to cope with internal demand.

In a February 2012 presentation at the Technology Metals Summit, in Toronto, Canada, industry expert Dudley Kingsnorth profiled China's growing needs for rare earths. He indicated that Chinese demand from 2008 to 2011 was as follows, with an estimate for 2012-2016 demand ('kt' denotes 1000 metric tons) [244]:

- 2008: Global demand 124kt, China consumes 68kt (55%), China export quota is 56kt.
- 2009: Global demand 85kt, China consumes 60kt (71%), China export quota is 50kt.
- 2010: Global demand 120kt, China consumes 71kt (59%), China export quota is 30kt.
- 2011: Global demand 105kt, China consumes 70kt (67%), China export quota is 30kt.
- 2012: Global demand 123kt, China consumes 80kt (64%), Chinese export quota is 30kt – estimated.
- 2011-2016: Global demand will rise to 160kt, China's demand will grow from 70kt to 105kt, Chinese exports will stabilize at 20-25 kt.

The increasing use of neodymium magnets in cell phones is helping to drive China's increasing domestic demand for rare earths. In 2009, China had 600 million cell phone users [245], and by November 2011 that number had grown to 952 million [246]. Not only does this make China the country with the largest number of cell phone users in the world by a sizable margin, but it also illustrates 63% growth over two years, a rate that is not predicted to decrease. Domestic demand for cell phones is estimated at 300-400 million units per year, and according to an industry expert speaking about local production, “there are 1 billion mobile phone units coming out of Shenzhen and its immediate surroundings every year. That is out of the estimated 1.7 billion to 1.8 billion units worldwide annually” [247].

Another example of China’s growing domestic demand for rare earths is seen in the exponential increase in the implementation of solar and wind power generators. The country utilizes four types of wind power generators [248]:

- Stall-regulated wind generators, a mature technology and the primary type until 2007.
- Variable-speed constant-frequency double-fed wind generators, an advanced and mature technology that is now the most common type in China.
- Direct-driven permanent magnet wind generators, which eliminate the need for a gearbox and have a greater adaptability to power grid generators, with improved efficiency and reduced maintenance needs.
- Hybrid-driven wind generators, which combine the direct-driven wind generator and double-fed wind generator.

Due to the increase in direct-driven permanent magnet wind power in China, the need for NdFeB has increased significantly, particularly from 2009 to 2010, and is expected to continue to increase, as demonstrated in Table 4.8.

According to the August 2011 *China Securities Journal*, the country "aims to have 100 gigawatts (GW) of on-grid wind power generating capacity by the end of 2015 and to generate 190 billion kilowatt hours (kWh) of wind power annually" [249]. During 2010, China produced 50.1 billion kWh of wind power, which grew to an estimated 70 billion kWh in 2011, in increase of approximately 40 percent [250]. With NdFeB magnets being a critical component in large permanent magnet generators for wind-power turbines, rare earths will continue to be in great demand. As Mark Smith, CEO of Molycorp, noted in a 2009 interview regarding wind power, “if the permanent magnet weighs two tonnes, then 28 percent of that, or 560 lbs, is neodymium.” [251]

4.6 China’s Rare Earth Development Future

Xu Guangxian, considered the father of rare earths chemistry in China, called for protective measures in 2005, warning that rare earth and thorium resources at Bayan Obo were in “urgent need of protection and rational utilization" [252]. Over 250 million metric tons of ore have been mined since 1958, and the remaining ore volume has been estimated to be 350 million metric tons. Assuming the rate of ore removal remained constant from 2005 onwards at 10 million metric tons per year, the mine's total rare earth resources would be depleted in 35 years. However, at the 2012 Technology Metals Summit, industry expert Dudley Kingsnorth predicted that China's supply of heavy rare earths may be limited to as short as 8-12 years at current rates of exploitation [253].

Table 4.8: NdFeB Demand in China's Wind Power Industry [254]

	2008	**2009**	**2010**	**2011E**	**2012E**	**2013E**	**2014E**
Newly-increased installed capacity (MW)	6298	7790	12472	15000-20000(1)	15000	17000	20000
Newly-increased installed capacity of direct-driven permanent magnet wind power (MW)	629.8	1558	4988	6750	7500	9350	12000
Consumption of rare earth permanent magnet materials (metric tons)	503.8	1246.4	3991	5400	6000	7480	9600
Consumption of Nd (metric tons)	151.2	373.9	1197.3	1620	1800	2244	2880

(1) Output in 2011 originally estimated at 15,000 MW, believed by Xinhua in January 2012 to be 20,000 MW [255]

The Chinese government has realized the importance of maintaining control of rare earth resources and as a result has placed a tighter grip on the industry, announcing a "Rare Earth Development Plan for 2009-2015" in 2009, and publishing a 22-item State Council advisory on sustainable rare earth development policy in May 2011. It has begun to implement various measures to address the issues covered in the previous section, including restricting export quotas on rare earths, implementing production quotas, closing down illegal rare earth operations, consolidating smaller operations into a few larger ones for better control, practicing greater enforcement of new environmental regulations, and setting up a rare earth industry association.

Restriction of Export Quotas

The Chinese government has put in place rare earth material export quotas in order to both satisfy domestic demand and to build a stronger vertical supply chain, particularly in the area of finished products. These restrictive policies have helped raise international prices for rare earths, particularly for the more expensive ones, such as terbium, europium and dysprosium.

In October 2010, as the result of a separate dispute, the Chinese government began blocking the shipment to Japan of rare earth materials used in the production of electronics, alternative energy equipment, electric and hybrid electric vehicle batteries, and other high tech industries vital to Japan's economy. The restriction was removed a few weeks later and replaced with new customs procedures, requiring thorough inspections of all shipments and the submission of paperwork in Chinese. In addition, a Chinese ministry official stated that "restrictions on the excavation, production and export of rare earth metals will continue in order to protect limited natural resources and ensure sustainable development. These measures do not violate rules set by the World Trade Organization" [256]. China's action triggered Japan to ramp-up efforts to improve rare earth recycling, make greater mining investments, enter into agreements with processing companies outside of China, and expend significant effort in attempting to reduce rare earth usage within the country.

Export and production quotas for 2011 and 2012 remained stable amid market turmoil caused by extreme price fluctuations during 2011 as a result of global supply concerns. A further discussion of Chinese rare earth quotas and policies can be found in Section 4.3.

China is continuing to build a stronger vertical supply chain in the rare earth industry and is encouraging the export of finished products by creating export limits for not just REE oxides and metals, but also semi-finished REE products. Chen Fucai, a government planner working at Baotou's high-tech industrial park, illustrates China's level of interest in developing the capability to create such products. Chen notes in an interview that he "has already proposed to a Bosch executive that the company develop a plant to produce electric motors in the Inner

Mongolian city. The wages there are unbeatably low, there are generous tax abatements, and land can be had for next to nothing.” [257] He also notes that "anyone who builds a factory in our high-tech park will receive a 5-10 percent discount on the raw materials." [258]

Rational Exploitation and Utilization of Rare Earth Resources

In 1991, China’s State Council listed rare earths as a specially designated ore type for “national-level protective extraction” [259]. In 2008, China began to implement regulations to gain greater control over the rare earth industry. The MLR announced a regulation in 2009 that would “protect and make rational use of China’s superior natural resources,” in particular, antimony, tungsten and rare earth ores [260]. According to China’s “Rare-Earth Industry Development Plan of 2009–2015,” annual rare earth production quotas may be limited to between 130-140,000 metric tons (REO) during the plan’s seven year period [261] (See Section 4.3 for a further discussion of China’s production quota policies).

Following the introduction of the new 2009 to 2015 regulations in 2009, China suspended any applications nationwide for mining surveys and/or mining licenses for rare earth ores until June 30th, 2010. In addition, the Government would not approve any separation projects before 2015. The government’s goal is “to prevent over-exploitation and blind competition and to advance effective protection and scientific, rational use of these superior mineral resources” [262]. In February 2011, Chinese officials announced that supplies of REOs would be controlled by implementation of “reasonable quotas according to both domestic and international pressures” [263]. The Chinese State Council stated that it would take five years to “establish a sustainable and healthy setting for the rare earths industry with reasonable mining, orderly production, efficient usage, advanced technology and intensive development” [264].

Closing Illegal Operations and Industry Consolidation

China is putting significant effort into closing down illegal operations and consolidating small operations into larger ones, measures intended to help the Chinese government ultimately gain complete control over the industry. In 2010 the MIIT stated it planned to establish an expert board for rare earth extraction to oversee the industry as a whole. The board would make impromptu onsite visits to mines and inspect operations to ensure that national directives are being implemented and executed appropriately [265].

According to the plan, “Rare-Earth Industry Development Plan of 2009–2015,” 120 mining companies were to be merged into fewer than 20, and 73 processing firms were to be merged into approximately 20 by 2015 [266]. In the first week of July 2010, authorities in China announced a number of changes affecting the rare earth sector, one of which was their plan to consolidate the disparate companies into 3-5 conglomerates. Also, according to the announcement, “rare earth prices would be set and published by the central government on a monthly basis, through a unified pricing structure covering the main provinces responsible for rare earth production” [267].

As a result of the Chinese government’s initial consolidation efforts, Baotou Steel Rare Earth set up the Inner Mongolia Baotou Steel Rare Earth High-Tech Co., a state-owned sole-proprietor company in the northern rare earth production area high-tech zone. It is an eight-party, US$102.5 million joint venture that includes Baotou Huamei Rare Earth High-Tech Co., Zibo Baogang Lingzhi Rare Earth High-Tech Co., Inner Mongolia Baogang, and the Rare Earth Development Co. [268]. A national guideline issued by China’s State Council on May 20, 2011, did not require industrial consolidation among producers in northern China, as the consolidation of rare earth enterprises in the region had been completed. It did, however, state that the State Council “aims to concentrate 80% of southern China’s heavy rare earth mining assets in the hands of the three biggest companies in the next one to two years” [269].

Ganzhou, within the southern rare earth production district, previously contained 88 separate rare earth producers. As of 2011, 90 percent have ceased operations [270]. According to Shanghai Securities News, the six largest companies include: China Minmetals Corp (Minmetals), Aluminum Corporation of China (Chinalco), China Non-Ferrous Metal Industry's Foreign Engineering and Construction Co. Ltd, Guangdong Rising Nonferrous Metals Group Co. Ltd., Xiamen Tungsten Co. Ltd. and Ganzhou Rare Earth Mineral Industry Co. Ltd [271].

In 2008, Dingnan Dahua New Materials Co. Ltd., Ganxian Hongjin Rare Earth Co. Ltd., and Minmetals Nonferrous Metals Co. Ltd. formed a joint-venture company, Minmetals Ganzhou Rare Earth Co. Ltd., to process ion-adsorption rare earths in Ganzhou. Minmetals Ganzhou Rare Earth had a rare earth separation capacity of 8,500 metric tons/year at the time, and planned to expand their separation capacity to 13,500 metric tons/year within a five-year period [272]. With an effort to acquire rare earth resources in Guangdong and Hunan, and a focus on value-added rare earth products, Minmetals Ganzhou Rare Earth has quickly become one of the leading producers in the country.

Chinalco is another major Chinese rare earth company located in Jiangxi province. Backed by the Jiangxi government, Chinalco captured 51 percent of the shares of Jiangxi Rare Earth and Rare Metals Tungsten Group Co. Ltd. (JXTC, a leading producer of rare earths in the province), to manufacture nickel-cobalt products. China Nonferrous Metal Industry's Foreign Engineering Construction Company Limited (NFC), a subsidiary of the state-owned China Nonferrous Metal Mining (Group) Co. Ltd. (CNMC), established a rare earths joint venture with privately owned Yixing Xinwei Group Company Limited (Xinwei Group) in July 2011. The partnership was intended to improve CNMC's chances of being chosen as one of the three companies to lead southern China's rare earths industry. NFC Rare Earths Company Limited (the name given to the joint venture) will be based in Guangdong's provincial capital of Guangzhou and focus on rare earths separation [273]. Minmetals, Chinalco and NFC Rare Earth Company Limited are likely choices to be the three major producers chosen by the government to compete for southern China’s rare earth resources.

A top official from the country’s MIIT group spoke on the subject of rare earth industry consolidation during a March 2012 meeting of the Fifth Session of the 11th National People’s Congress in China. He reaffirmed that China will establish three or four single large enterprises as a result of government-driven consolidation efforts, referencing the fact that the first enterprise, Baotou Steel Rare-Earth Hi-Tech Co., had completed efforts to absorb 14 related companies [274]. It is also of note that the Chinese government has provided sizeable loans to four major companies to further boost consolidation efforts by allowing them to purchase smaller operations. A major concern for the rest of the world, however, is that the oligopoly created from this process may give the Chinese government the ability to limit exports without the need for official export quotas, putting them out of the WTO’s regulatory reach [275].

In an effort to speed industry consolidation efforts, on April 8th, 2012, the Chinese government set up a rare earths industry association reporting to the MIIT, dubbed the Association of China Rare Earth Industry (ACREI). The association will have 155 members throughout the supply chain, including major industry players such as Baotou Steel Rare Earth, China Minmetals, and Aluminum Corporation of China. The association was created to “actively provide support and services for relevant departments and local governments, help maintain order in the sector, facilitate exchange and cooperation between enterprises to spur innovation, and coordinate efforts to cope with international trade frictions and disputes.” [276] It will be led by Gan Yong, the current president of the CSRE and an academician with the Chinese Academy of Engineering.

Environmental Protection Regulation Enforcement

China has traditionally had very lax environmental regulations for its rare earth mining and processing industries, helping lower costs of operation and falling far short of global standards. In October 2011 the Ministry of Environmental Protection (MEP) put into effect their new "Emission Standards of Pollutants from Rare Earths Industry" restrictions [277]. The MEP standards regulate six atmospheric and fourteen water pollutants and are divided into two categories: those for existing enterprises and those for new enterprises. However, issues such as self-checking by rare earth companies, unannounced penalty rules, and a lack of any standards for pollutant discharge techniques threaten to derail the process, even as it begins. In the words of one Chinese news source, “the measure barely poses a threat to those companies that have no plan to expand production or go public” [278].

There have been additional concerns with the new standards, as it was estimated by Hurst in 2010 that the additional yearly cost associated with water pollutant treatment would add roughly US$145-220 to every metric ton of rare earths. China has been able to run its rare earth industry at approximately one-third the cost of other countries, partially due to its loose environmental regulations, and the higher cost could lead to a decrease in production. It could potentially hurt China’s industry-leading status if higher costs allowed other global sources were to successfully ramp up production and compete on price. According to industry expert Dudley Kingsnorth, speaking in reference to China’s environmental regulations, “I think it will be at least 10 years before China will match our standards.” [279]

China’s Quest for Dominance in the Global Rare Earth Industry

China’s drive to become an industrial power in the rare earth industry can be demonstrated by an examination of the history of production and supply of NdFeB. In 1986 General Motors commercialized their 1982 discovery of NdFeB permanent magnet material by forming a company called Magnequench in Anderson, Indiana. In 1995 two Chinese companies successfully acquired Magnequench, and according to the terms of the deal for the next five years, NdFeB production remained in Indiana, and a technology center was opened in North Carolina. In 2001, after the contractual terms were met, production at the Indiana ceased, and all production moved to a plant in Tianjin, China. In 2004, the North Carolina technology center was moved to Singapore, and the U.S. was no longer a leader in NdFeB magnet technology [280].

According to John Burba, Executive Vice President and Chief Technology Officer at Molycorp, Inc., as of 1998 ninety percent of the world's magnet production was located in the U.S., Europe, and Japan. 70-80 percent of global fully sintered magnet production was in the Japan, while the U.S. and Europe produced the remaining 20–30 percent. In addition, the U.S. produced approximately 80 percent of rapidly solidified magnets, with the remaining 20% being produced in Europe. By 2007, China had approximately 130 large sintered NdFeB magnet manufacturing enterprises, with an annual capacity of over 80,000 metric tons, covering 80% of global production [281].

China has also attempted to gain control of rare earth mine resources worldwide. In 2005, the China National Offshore Oil Corporation (CNOOC) submitted a US$18.5 billion offer for Union Oil Company of California (UNOCAL), which had previously purchased the original Molycorp company, owners of the Mountain Pass mine in California. If the deal had gone through, a Chinese company would have controlled the U.S.'s best hope for domestic rare earth supplies [282].

China has also targeted Australia's significant rare earth resources. In 2009, a Chinese government entity, Jiangsu Eastern China Non-Ferrous Metals Investment Holding Co., successfully gained a 25 percent stake in Arafura Resources Ltd, a rare earth company in control of the Nolans Bore project in Australia [283]. In 2009, Lynas Corporation, an Australian mining company, suspended construction at its Mount Weld mine due to financial problems. China Non-Ferrous Metal Mining Group Co. Ltd. (CNMC) proposed an investment of US$252 million in return for a 51.6 percent share in Lynas and four of eight seats on the company board. The Australian Foreign Investment Review Board (FIRB) approved the deal conditional on several changes, including a reduction of stake to less than 50 percent and fewer board seats. However, CNMC pulled out of the deal as a result of the new requirements [284].

Chapter 5

Rare Earth Industry Outlook

The future of the rare earth industry requires careful analysis and monitoring, particularly in light of the volatile environment of the past two years. Countries throughout the world are concerned about potential threats to continued access to rare earths and their intermediate products, due to their importance within future technologies. A projected outlook of the global demand and supply for the rare earth industry is provided in this chapter, and it includes a discussion of the industrial impact of rare earth supply issues.

5.1 Rare Earth Supply and Demand Outlook

As seen in Figure 5.1 (see color insert), industry expert Dr. Dudley Kingsnorth of Curtin University, Western Australia has prepared a popular chart commonly known as the "Dudley Chart," illustrating demand and supply trends over time for rare earth oxides for China and the rest of the world (ROW). According to Kingsnorth's 2012 estimates ROW supply is predicted to grow to fully accommodate total global demand in 2014 but for 2012/13 shows a significant near-term supply gap for rare earths. Increased ROW production or increased Chinese export quotas, neither of which has yet occurred, would normally be expected to make up this shortfall.

According to the USGS, there are sufficient exploitable reserves of rare earths around the world to meet estimated needs for a long time. The challenges lie in the difficulty of discovering rich deposits and processing them in a way that is economically viable, while minimizing the resulting damage to the environment. China, as traditionally almost the sole producer in terms of the global market, will continue to dominate the rare earth industry in the near future. In 2004, China produced approximately 90–100,000 metric tons of REOs; in 2010 Kingsnorth predicted this production level would increase to 160–170,000 metric tons by 2014 (Table 5.1). Since global demand was estimated to be over 170-190,000 metric tons by 2014 (Table 5.2), approximately 20,000 metric tons in global production would need to be provided by ROW producers. Kingsnorth also estimated in 2010 that three rare earth elements will be in short supply by 2015: neodymium, terbium and dysprosium [286].

In 2009 however, demand for rare earth oxides fell to 85,000 metric tons following the global financial crisis, skewing the forecast in Table 5.2. Newer projections from Kingsnorth in 2012, as seen in Figure 5.1 (see color insert), show the level of global demand forecast to now be only 150,000 metric tons in 2015. This still represents a shortfall of approximately 20,000 metric tons required from ROW producers. However, Kingsnorth's projection now shows ROW production growing to approximately 70,000 metric tons to effectively cover the shortfall.

Table 5.1: Chinese Production of Rare Earth Chemical Concentrates 2004–2014 (tpa REO ±10%) [287]

Year	Bayan Obo Bastnaesite	Sichuan Bastnaesite	Ion Adsorption Clays	Monazite	Total	NDRC Quotas
2004	42–48,000	20–24,000	28–32,000		90–100,000	n/a
2006	45–55,000	22–26,000	40–50,000	8–12,000	125–140,000	n/a
2008	60–70,000	10–15,000	45–55,000	8–12,000	125–140,000	127,280
2010	55–65,000	10–15,000	35–45,000	4–8,000	110–130,000	122,000
2014e	80–100,000	20–40,000	40–50,000	8–12,000	160–170,000	140–160,000

Note: Illegal or uncontrolled mining and processing are not included. This has been estimated at 10–20,000 tpa REO over the last 3–5 years.

China expects that it will become a net importer of rare earths within the next five years and has stated it is not going to increase production, according to Zhanheng Chen, a director at the CSRE. "There are early signs that China is moving from a sell side to a buy side. China is the largest user of rare earths in the world and it will become a new market opportunity for producers outside of China and there will be other opportunities to sell other products to China related to the rare earth industry," said Chen. He added that from 2011 to 2015, the export quota should be 32,000 to 35,000 metric tons, and the demand balance should be 18,000 to 50,000 metric tons. "This is a return to a rational development that was started in 2006 and China is now a growing consumer," he said. He forecast that China's supply will dwindle to 87,000 metric tons, or 65 percent of global supply by 2013, and that this trend will continue to 36 percent after 2015, with supply at 100,000 metric tons and the rest of the world at 64 percent at 178,000 metric tons a year. He also said that there will be reduced production and exports from China over the next few years and China's growing clean-tech and high-tech industries will be buyers of rare earths. "The 10,381 tonnes of rare earth concentrate imported by China (in 2009) is likely to increase," he said. John Kaiser, an analyst at Kaiser Research, said that "China is expecting the rest of the world by 2015 to be doing as it does now (in terms of rare earth exports) and it is not going to increase production. I see a serious shortage happening if China restricts output, and a serious crisis needs to be solved." [288]

Table 5.2: Global Rare Earths Demand in 2008 and 2014 (Forecast) [289]

Application	**Consumption REO (metric tons per annum: tpa) ±15 Percent**		**Market Share 2014 (percent)**
	2008	**2014f**	
Catalysts	25,000	30–33,000	17
Glass	12,000	12–13,000	7
Polishing	15,000	19–21,000	11
Metal Alloys	22,250	42–48,000	25
Magnets	26,250	38–42,000	22
Phosphors & pigments	9,000	11–13,000	7
Ceramics	7,000	8–10,000	5
Other	7,500	9–12,000	6
Totals	124,000	170–190,000	100

In December 2010 (with a follow-up in 2011), the DoE conducted an analysis of the role of rare earths and other strategic materials in clean energy, combining the importance of a material to the clean energy economy with supply risk to create a measure of criticality. Of the materials analyzed, five rare earth metals (dysprosium, neodymium, terbium, europium, and yttrium) are assessed as most critical in the short term, as demonstrated in Figure 5.2 (see color insert). The same five materials remain critical in the medium term (Figure 5.3 – see color insert). Cerium and lanthanum are near critical in the short term, but their status drops to not critical over the medium term (5 to 15 years).

Various countries worldwide are looking to secure alternative sources of rare earths, particular those with industries that rely on rare earth materials. Japan is a prime example, with sensitive Sino-Japanese relations and a strong high tech manufacturing industry, where a steady supply of rare earth materials is key.

5.2 Potential Rare Earth Suppliers

The following section discusses potential rare earth suppliers and related mine projects, both within the U.S. and globally. International investments and cooperative agreements to further procure rare earth resources are also examined.

North America

There are a number of rare earth mines outside of China that show promise as sources of additional global supply. Table 5.3 summarizes the major rare earth projects in North America**.**

Mountain Pass, California, United States - Molycorp

California's Mountain Pass operation is perhaps the most promising, due to its previous status as a fully functioning mine, operating until 2002. The site was reopened in 2007, and Molycorp Minerals (owners of Mountain Pass) now operate a separation plant and sell rare earth concentrates and refined products from previously mined ore [292]. Molycorp embarked on a US$781 million expansion and modernization project, entitled “Project Phoenix,” in January 2011, as part of an effort to compete with China by implementing newly developed low cost processing technologies. On February 21st, 2012, Molycorp began the sequential startup of their Project Phoenix manufacturing facility, and the company stated it would “achieve its full Phase 1 annual production rate of 19,050 mt of rare earth oxide equivalent by the end of the third quarter of 2012” [293]. The company plans to expand production of rare earths to approximately 40,000 metric tons per year by the end of 2013. Output at this level is predicted to put the U.S. in a position to dominate non-Chinese supply [294].

One caveat, however, is that the Mountain Pass deposit contains relatively high percentages of cerium and lanthanum, the most abundant rare earths, and relatively small percentages of the less abundant heavy rare earths, such as europium, terbium, dysprosium, and yttrium.

Table 5.3: Potential North American Rare Earth Suppliers [295]

Project	Developer	REO resource (metric tons, grade)	Production Date
Mountain Pass (USA)	Molycorp Inc.	1.4m tons at 6.63% TREO (Indicated)	2012
Hoidas Lake (Canada)	Great Western Minerals Group	1.6m tons at 2.35% TREO (Indicated)	2015/2016 (estimate)
Nechalacho at Thor Lake (Canada)	Avalon Ventures Ltd.	88m tons at 1.53% TREO (Indicated)	2016 (estimate)
Bear Lodge (USA)	Rare Element Resources Ltd.	4.3m tons at 3.67 TREO (Indicated)	2015 (estimate)
Strange Lake (Canada)	Quest Rare Minerals Ltd.	140m tons at 0.93% TREO (Indicated)	2016 (estimate)

Furthermore, these materials are not currently converted into rare earth metals in large quantities in the U.S. Instead, they are exported to Japan for conversion [296]. Mountain Pass may able to produce enough rare earths to meet most U.S. domestic needs but is not projected to produce enough in the near term to challenge China for control of the majority of the world’s supplies.

Hoidas Lake, Canada - Great Western Minerals Group

According to energy policy analyst Marc Humphries, in a report for Congress entitled “Rare Earth Elements: The Global Supply Chain,” some Canadian deposits contain heavy rare earths, such as dysprosium, terbium and europium, sufficient for magnet production. As shown in Table 5.3, the Great Western Minerals Group (GWMG) has a deposit at Hoidas Lake with an estimated heavy rare earth content of up to 2.4 percent. A refinery is planned near the mine, and along with the magnet alloy production facility the company owns in the U.K., this could be GWMG's biggest advantage in establishing a vertically integrated operation [297]. As of February 2012, the last phase of metallurgical testing in China was nearing completion, with the project planned to subsequently follow feasibility stages and possibly move to production in 2015/16 [298].

Nechalacho, Thor Lake, Canada – Avalon Rare Metals Inc.

Avalon Rare Metals Inc., a Toronto-based company, is currently developing the Nechalacho project at Thor Lake, in the Northwest Territories of Canada. Some in the industry believe Thor Lake contains one of the largest rare earth deposits in the world, with the potential to produce heavy rare earths. Drilling was initiated in January 2010, and as of May 2012, "85,240 metres of drilling has been completed in exploring and developing the property," at a cost of over US$56 million [299]. Avalon stated that the resource estimate for its Nechalacho deposit in Canada has more than doubled following completion of the prefeasibility process, and in 2012 stood at 57.4 million metric tons at 1.56% TREO [300]. However, Avalon said the increase "would not necessarily influence its previous decision on the production rate at the mine, which will ultimately be determined by sales volumes estimates rather than resource size" [301]. The company's plans indicate that at a sustained exploitation rate of 2,000 metric tons per day, the mine life would be approximately 20 years, with production estimated to begin in 2016.

Bear Lodge, Wyoming, United States – Rare Element Resources Ltd.

The Bear Lodge property in northeast Wyoming is currently being developed by Canadian mining company Rare Element Resources Ltd. As of February 2012, updated mineral resource estimates of rare earth deposits showed an indicated resource of 4.3 million tons at 3.67% REO [302]. The company released a positive pre-feasibility study on March 1st, 2012 and has estimated that production may occur as soon as 2015 [303].

Ytterby project, Quebec, Canada - JOGMEC/Midland Exploration Inc.

The Japan Oil, Gas, and Metals National Corporation (JOGMEC) signed an agreement with Midland Exploration Inc. for development of an ytterby project in Quebec, Canada. As of August 2011, first drilling efforts had begun on the site to test samples from various locations [304]. JOGMEC is under the authority of the Japanese Ministry of Economy, Trade and Industry and has a mandate to invest in projects worldwide to secure stable supplies of natural resources for Japan.

Strange Lake, Quebec, Canada – Quest Rare Minerals

The Strange Lake project, in Quebec, Canada is being developed by Quest Rare Minerals, a Canadian-based minerals exploration company. The site contains a promising ratio of heavy to light rare earths, with an indicated resource estimate of 140 million metric tons at 0.93% total REO. As of February 2012, pre-feasibility work was underway at the location's B-zone REE deposit, with a pre-feasibility study to be completed by mid-2012 and startup of a pilot plant planned for second quarter 2012 [305]. The company has forecast that production at the site may begin in 2016 [306].

Pea Ridge, Missouri, United States

The Pea Ridge Mine in Washington County, Missouri, may soon reopen for iron ore mining after shutting down in 2001 [307]. The mine was previously operated by Bethlehem Steel only to harvest iron ore, but mine documentation showed there may be as much as US$3 billion worth of heavy rare earths at the site. The Pea Ridge deposit is small, yet its heavy rare earth concentrations may be greater than anywhere else in the world. However, as of February 2012, the deposit may remain untapped for now. After months of legal issues, the mine was sold in January 2012, and the new owners are more focused on mining the location's iron resources, with no mention of its rare earth deposit [308].

Outside North America

As of April 30, 2012, the Advanced Rare Earth Projects Index, created by market analysis company Technology Metals Research. consists of 36 rare earth projects in 13 countries. A selection of major active projects are profiled in the following section.

Mount Weld, Australia – Lynas Corp.

Table 5.4 shows a listing of potential rare earth suppliers outside of North America. One particularly promising mine is Mount Weld, located in an isolated region in the southwest of Australia and developed by Lynas Corp. Mount Weld is particularly promising due to its combination of high-grade rare earth ore and easy access to the ores. An initial mining phase was completed in June 2008, with Lynas Corp successfully mining 773,300 metric tons of ore, at an average concentration of 15.4% REO [309]. While Lynas Corp. is currently processing the stockpiled ore, it is also in the process of expanding its onsite concentration plant to 22,000 metric tons/year of processing capacity. The concentrated materials will then be sent to the company's Advanced Materials Plant in Kuantan, Malaysia, construction of which was 98% complete as of March 31st, 2012, despite protests and court challenges from local residents [310].

Table 5.4: Other Potential Rare Earth Suppliers Outside of North America [312]

Project	Developer	REO Resource (metric tons, grade)	Production Date
Mount Weld (Australia)	Lynas Corp.	6.9m tons at 8.1% TREO (Indicated)	2012 (estimate)
Steenkampskraal, (South Africa)	Rareco, a division of Great Western Mining Group	19,670 tons at 16.74% TREO (hist. ore, current exploration underway)	2013 (estimate)
Kvanefjeld (Greenland)	Greenland Minerals and Energy Ltd.	437m tons at 1.09% TREO (Indicated)	2016 (estimate)
Dubbo Zirconia Project (Australia)	Alkane Resources Ltd.	35.7m tons at 0.89% TREO (Indicated)	2013-2014 (estimate)
Nolans Bore (Australia)	Arafura Resources Ltd.	21m tons at 2.53% TREO (Indicated)	2014 (estimate)
Wigu Hill (Tanzania)	Montero Mining and Exploration Ltd.	3.3m tons at 2.59% TREO (Inferred)	2014 (estimate)

The company has signed agreements with Japan's Sojitz and an unnamed European rare earths consumer, and expects to announce further contracts with potential customers in the U.S., Europe, and Japan.

Phase 1 of its project is on schedule to reach full capacity of 11,000 metric tons/year in 2012 [311]. If production increases to 22,000 metric tons/year in 2013, output will be equivalent to about 15 percent of the estimated 2013 global REO supply.

Steenkampskraal, South Africa – Rareco/GWMG

Steenkampskraal (owned by Rareco, a division of Great Western Mining Group) is located in South Africa and is another potential supplier in the near future, with the company looking to begin first production in 2013 [313]. The site is another formerly operational rare earth mine that was restarted in 2010, and as of January 2012 the first phase of an exploration program at the site had been completed successfully [314]. GWMG has also entered into an agreement with China's Ganzhou Qiandong Rare Earth Group to begin construction of a rare earth separation plant in South Africa.

Kvanefjeld, Greenland – Greenland Minerals and Energy

Greenland Minerals and Energy's Kvanefjeld project contains both light and heavy REEs, and the site has been in initial development since the 1950s with a focus on possible uranium production. The Danish government decided to cease investigative work at the site in 1983 and work resumed in 2007 to explore for rare earth elements. Full access to existing drill cores and US$50 million worth of historical development work has resulted in the project quickly moving to the pre-feasibility stage. According to Technology Metals Research's Advanced Rare Earth Projects Index, as of February 2012, the company had estimated that initial production could begin as soon as 2016 [315].

Dubbo Zirconia Project, Australia – Alkane Resources

Australian company Alkane Resources's Dubbo Zirconia mine project is located in New South Wales, in the southeast region of Australia. The mine's deposit contains zirconium, niobium, and rare earths with light to heavy REEs at a 3:1 ratio, and with measured resources of 35.7 million metric tons at 0.89% total REO [316]. A pilot plant has been successfully running at the site since 2008, and published estimates from the company are for production to begin in Q3 2014 [317].

Nolans Project, Australia – Arafura Resources

Arafura Resources' Nolans project in Australia is comprised of the Nolans Bore mine in the Northern Territory and the Whyalla Rare Earths Complex processing facility in South Australia. The mine site's deposit is graded at 21 million metric tons at 2.53% rare earth oxides, primarily cerium, neodymium, and lanthanum. A feasibility study is underway as of February 2012, with production projected by the company to begin in 2014, at an estimated 20,000 metric tons per year of rare earth [318].

With the exception of Nolans Bore, Dubbo, Steenkampskraal, Mt Weld and Mountain Pass, most potential REE projects are in the initial stage of the production process, as shown in the chart of processes that potential suppliers are following (Figure 5.4). It will often take years, hundreds of millions of dollars, and favorable economic conditions – in the global economy and in the rare earth industry – before even initial production is possible.

International Efforts to Develop Alternative Rare Earth Suppliers

Beyond the potential suppliers summarized in Table 5.3 and Table 5.4, Japan, South Korea, India and Germany are also actively seeking and developing additional sources for rare earths. South Korea revealed in January 2011 that it would develop rare earth supplies in Australia, Vietnam, Kyrgyzstan, and South Africa, and would begin cooperation with Japan for overseas development efforts. This comes after a previous statement that it "would seek to nearly quadruple combined self-sufficiency rates of rare earths and lithium to 26 per cent by 2019 from 7.3 percent in 2009 as part of a broader move to improve self-sufficiency." [319]

The Korean government-owned mining company Korea Resources Corporation (KORES) announced in December 2011 that it had formed a strategic partnership with Frontier Rare Earths, a mineral exploration company in South Africa. Frontier Rare Earths has completed its preliminary economic assessment for its Zankopsdrift project in South Africa, and KORES along with a consortium of Korean companies have invested in accelerated development of the project. The agreement secures rights to KORES for 31% of future mine production, with a further option of an additional 21% of future production with a further investment [320].

Figure 5.4: Rare Earth Mine Development Progress as of June 2011 [323]

Note: As of February 2012, Mountain Pass, CA began Phase 1 production startup.

Japan has also accelerated its search for new supplies after China's temporary ban on rare earth sales to the country late in 2010. Its annual demand for rare earths is more than 30,000 metric tons as of 2011, and it depends on China for about 90 percent of its supply [321]. The Nikkei business daily reported that Japan would increase its efforts in searching for undersea mineral reserves in the Pacific, with surveys near Minamitorishima, an isolated island 2,000 kilometers southeast of Tokyo. Japanese scientists believe metals such as platinum, cobalt, nickel, manganese, and neodymium lie beneath the seabed near the island [322].

In November 2011, Vietnamese Prime Minister Nguyen Tan Dung entered into a cooperative agreement with the Japanese Prime Minister, Yoshihiko Noda, regarding Japan's exploration, mining and processing of rare earths in Vietnam [324]. As a result, Japan's Toyota Tsusho (a subsidiary of Japan-based Toyota Motor Corporation) and Sojitz corporations have entered into a joint venture with the state-run Vietnamese mining company Lavreco to develop the Dong Pao deposit in Vietnam, with plans for annual production of 2-3000 metric tons of rare earth oxides by the summer of 2012 [325]. The company believes that if successful, the project may be scaled up to an annual supply of 7,000 metric tons per year by as early as 2014 [326].

Japan is also reaching out to Australia for rare earth supplies. "Japanese Trade Minister Banri Kaieda made it clear after talks with his Australian counterpart in Sydney that he wanted Australia to become a reliable, long-term alternative supplier." [327] Japan's Sojitz Corporation forged an agreement with Australia's Lynas mining company in late 2010 to finance the company's Mount Weld site expansion and Malaysian Advanced Materials Plant, in return for a 10 year guaranteed supply of 8,500 metric tons per year of rare earths to Japan [328].

Toyota Tsusho Corporation is looking to refine rare earths from the slag output that results from tin refinery operations on the Western Indonesian island of Bangka. The company plans to build a refinement plant to recover dysprosium and neodymium, although as of February 2012 there had been no published production target dates [329]. The company also signed a memorandum in December 2011 with Canadian mining company Matamec Explorations Inc. to form a joint venture in which Toyota Tsusho will input US$17.5 million, and buy all of the output of the company's Kipawa rare earth mine.

Toyota Tsusho Corporation is also setting up a rare earth processing plant in Vishakapatnam, on India's southeast coast, under its Indian subsidiary Toyotsu Rare Earths India (TREI). The plant began construction in July 2011, with production to begin in April 2012, and will process mixed rare earth chloride sourced from an Indian Rare

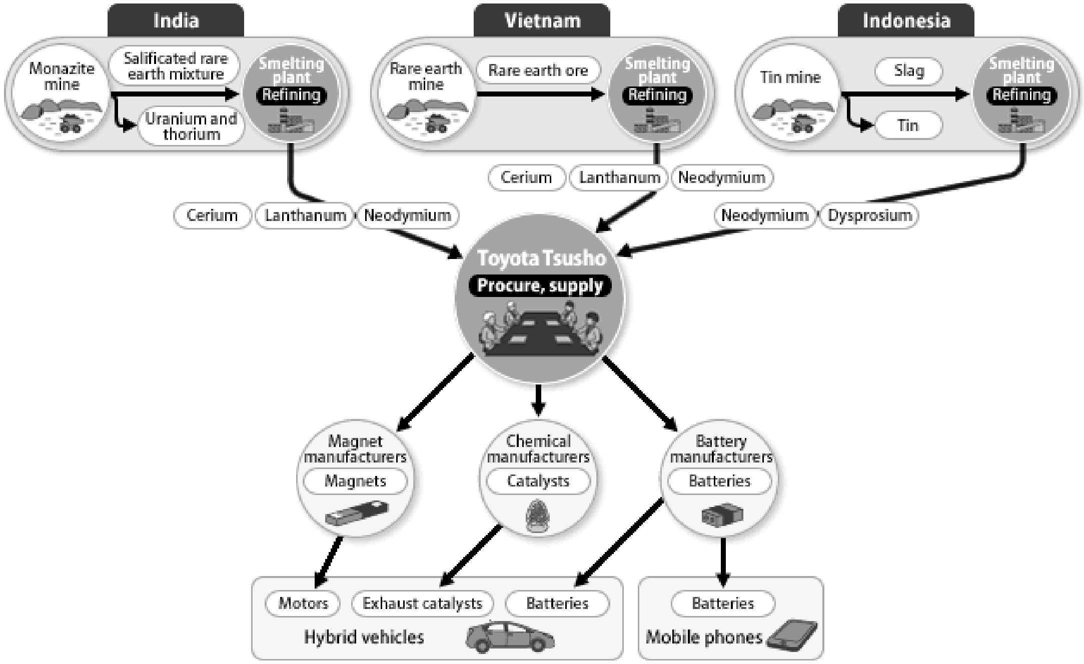


Figure 5.5: **Toyota Tsusho's Growing Rare Earth Value Chain [332]**

Earths Limited plant (mentioned below) at an anticipated rate of 3-4,000 metric tons per year [330].

India is also planning to restart mining and production of rare earths to bolster global supply. Indian Rare Earths Limited (IREL), a state-run producer of rare earths, stopped production in 2004 due to Chinese competition. The company is now spending US$31.9 million to bring a plant online with a 5,000 metric tons/year capacity, and plans are for it to be producing rare earth chloride material by 2012 [331].

In February 2012, German Chancellor Angela Merkel and President Nursultan Nazarbayev of Kazakhstan entered into a strategic partnership valued at US$4 billion, guaranteeing "German companies the right to search for and mine rare earths and other raw materials in Kazakhstan in exchange for technological and other investments." [333] This followed a similar commodity partnership agreement between the German Chancellor and Mongolian Prime Minister Sukhbaatar Batbold in October 2011, ensuring that Germany has unlimited access to raw materials from Mongolia, and that Mongolia will be able to process those materials locally with German processes and technology [334]. German mining and exploration company Tantalus Rare Earths AG has also entered into an agreement with France's Rhodia as of April 2012, in order to process 15,000 metric tons per year of rare earths from ionic clay deposits in northwestern Madagascar [335].

Russian rare earth reserves are believed to be quite large, at 16.7% of global commercially exploitable reserves as estimated by the USGS. However, there are no active mine development projects in place as of February 2012. As noted by Jack Lifton of industry analysis firm Technology Metals Research, "I would say if they start now you would see that at the end of this decade they could be producing … we are not looking for production to happen anytime soon." [336]. Russia has only one active rare earths mine, Lovoversky GOK, producing light rare earths from loparite concentrate. Output from the mine was estimated at 12,000 metric tons of rare earth concentrate in 2011.

The DoE in 2011 estimated production of rare earth elements from new mines projected to be online by 2015, and the results are summarized in Table 5.5. Australia's Mount Weld mine came online in 2011, and California's Mountain Pass mine is projected to be in full Phase 1 production in the fourth quarter of 2012.

Figure 5.6 illustrates the locations of the deposits listed in Table 5.5, as well as some promising deposits that could be candidates for development in the medium term. However, it is worth noting that these alternative sources may struggle to compete with China, due to three factors: the cost and time involved in developing rare earth production facilities, the fact that a significant portion of Chinese rare earths is

Table 5.5: Current and Projected Future Rare Earth Supply by Element [338]

	2010 Production	**Potential Sources of Additional Production between 2010 and 1025**									**Total 2015 Production Capacity**
		United States		Australia			Vietnam	South Africa	Russia and Kazakhstan	India	
		Mt. Pass Phase I	Mt. Pass Phase II	Mt. Weld	NolansBore	Dubbo Zirconia	Dong Pao	Steenkampskraal			
La	31000	5800	6800	5600	2000	510	970	1100	140	560	54000
Ce	42000	8300	9800	10300	4800	960	1500	2300	290	1200	81000
Pr	5900	710	840	1200	590	110	120	250	20	140	9900
Nd	20000	2000	2300	4100	2200	370	320	830	44	460	33000
Sm	2800	130	160	510	240	56	27	125	5	68	4000
Eu	370	22	26	88	40	2		4	1		550
Gd	2400	36	42	176	100	56		83	1	30	3000
Tb	320	5	6	22	10	8		4	0.4		370
Dy	1600	9	10	22	30	53		34	1		1700
Y	10500			66		410	21	250			11300
Others	2000	73	86			75	25	12	3	25	2300
Total	120000	17000	20000	22000	10000	2600	3000	5000	500	2500	200000

(1) Molycorp, (2) Lynas, (3) Indian Rare Earths/Toyota Tsusho/Shin-Etsu, (4) Kazatomprom/Sumitomo, (5) Great Western Minerals, (6) Vietnamese Govt/Toyota Tsusho/Sojitz, (7) Stans Energy, (8) Alkane Resources, (9) Arafura Resources, (10) Greenland Minerals and Energy, (11) Great Western Minerals, (12) Avalon Rare Metals, (13) Rare Element Resources, (14) Pele Mountain Resources, (15) Quest Rare Minerals, (16) Ucore Uranium, (17) US Rare Earths, (18) Matamec Explorations, (19) Tasman Metals, (20) Montero Mining/Korea Resources, (21) Namibia Rare Earths, (22) Frontier Resources/Korea Resources, (23) Hudson Resources, (24) AMR Resources, (25) Neo Material Technologies.

Figure 5.6: Current and Projected Rare Earth Projects Outside China [339]

mined as by-product of other materials, and the fact that China's ion adsorption clay deposits are cheaper and easier to process [337].

5.3 Impacted Industries

The following section explores the impact of possible future rare earth shortages and price fluctuation on the production of goods where rare earths are used.

Figure 5.1 (see color insert) shows that the global market for rare earths grew to approximately 120,000 metric tons in 2010, and demand is predicted to reach approximately 140,000 metric tons by 2014. Steady growth in the global market has been predicted out to 2016 and 2020, with metal alloys and magnets for HEVs responsible for most of the growth [340, 341]. As seen in Table 5.6, industry expert Dudley Kingsnorth has estimated that a number of rare earths – europium, yttrium, terbium, and dysprosium – may be in short supply by 2016, and as also seen in Figure 5.1 (see color insert), total global supply shortages may occur in both 2012 and 2013. In a study conducted for the German Economics Ministry, scientists, looking out to the longer-term view, examined rates of increase in the consumption ofrare metals and concluded that the level of demand for neodymium will increase by a factor of 3.8 by 2030 [342].

Table 5.6: Demand and Supply Projections for 2016 [343]

	Demand (metric tons)	Supply (metric tons)	Projected Shortfall (metric tons)
Cerium	60,000-70,000	75,000-80,000	none
Neodymium	25,000-30,000	30,000-35,000	none
Europium	625-725	450-550	75-275
Dysprosium	1,500-1,800	1,300-1,600	100-500
Terbium	450-550	300-400	150-250
Yttrium	12,000-14,000	9,000-11,000	1,000-5,000

Stratfor, a geopolitical analysis company, divided manufactured goods into the following six categories based on their corresponding level of production impact, in an attempt to illustrate to what level industries will be affected by increasing rare earth costs.

The first of these categories involves goods and services using cerium. This rare earth element is heavily used in the petroleum refining industry to “crack” oil, and in automotive catalytic converters. With stricter global standards for air pollution, use of cerium in catalytic converters is predicted to continue to increase. However, cathode-ray tubes used a lot of cerium, so their gradual phase out frees up a significant amount of the material for other purposes, and the result has been that cerium is being stockpiled globally. Even though the automotive and petroleum industries are heavy users of cerium, stockpiles are ensuring that prices stay reasonably low and availability is not threatened, with cerium being the second to lowest priced rare earth as of February 2012 [344].

The second category covers goods with inelastic demand that utilize rare earths other than cerium, typically luxury and irreplaceable items. Examples include lanthanum in iPhone camera lenses, scandium in movie studio lighting, europium in LED televisions, and yttrium in satellite communication systems. However, while these goods do use rare earths, the small amount used means that the cost is minimal as a percentage of the total cost of the item, so even larger price fluctuations have a minimal effect [345].

The third category includes defense goods, another area where demand is inelastic in the short to medium term. Defense systems and components using rare earths will be built and maintained almost regardless of cost, due to both strategic importance and long development cycles. It is another area in which the cost of rare earth materials as a percentage of the total budget for the component or system is very minimal, and thus often has little or no effect on the decision to use the material or not. Night vision, heads up displays in fighter jets, and even nuclear threat detection systems use rare earths, and these systems will continue to be built using them almost regardless of any additional material cost [346].

The fourth category covers goods where rare earths are critical but also where the industry involved has a history of effectively adapting to price changes by adapting technologies to use substitute materials or methodologies. Toyota is an appropriate example, as due to rare earth material price hikes in 2011, it is working quickly towards replacing rare earth materials completely in its popular hybrid electric vehicles, switching instead to less expensive materials for the motor and battery systems [347].

The fifth category includes goods where pricing is the greatest force affecting the industry, and where an item simply will not be manufactured or will see low sales if the price rises too high, as demand will be too weak to sustain continued production. These are also industries where acceptable product substitutes exist, such as LED televisions (europium) and compact fluorescent light bulbs (terbium) [348].

The sixth and final category is comprised of goods where demand is already high and rising rapidly, and material stockpiles are low and supply chains are not in place to meet the demand. Miniaturized consumer electronic goods such as cell phones require neodymium and do not have a viable alternative material. They are in a growing state of demand, and non-China sources of neodymium are currently very limited. While cheaper production costs and cost efficiencies elsewhere in these devices can help offset the limitation to some degree, this will likely not be the case for windmill turbines, currently using as much as a metric ton of NdFeB magnets per windmill and having no workable alternative. These industries will clearly suffer greatly from price changes, and the only solutions will be to either bolster production of the rare earths used, or find alternative materials or technologies [349].

5.4 Rare Earth Stockpiles

Given the high demand for rare earths and export restrictions imposed by the Chinese government, it is logical that some government policy makers and industry leaders would advocate establishing a government-run economic stockpile and/or private-sector stockpiles that would contain supplies as needed for commercial and military applications. However, creating a stockpile carries an element of risk, considering that pricing and technology changes may alter rare earth demand in the future. A critical question for stockpile development would be, “What materials along the supply chain should be stockpiled?” [350] For example, should the stockpile contain REOs or alloyed magnets? The following section examines rare earth stockpiles and policies both in the U.S. and abroad.

China’s “Father of Chinese Rare Earths Chemistry,” Xu Guangxian, has alleged that Japanese industry has already stockpiled sufficient rare earth inventories for the next 20 years [351]. Even if his estimates are high, it may be unlikely that Japan faces a pressing supply problem, except at the hands of Japanese rare earth traders, who could manipulate market inventory in anticipation of even higher prices. JOGMEC officially announced on its website in March 2012 that the country’s national stockpile has “42 days of standard consumption in Japan (70% of stockpile target),” while private industry has “18 days of standard consumption in Japan (30% of stockpile target)” [352].

In addition to legal exports from China, it has been estimated that approximately 20% of the rare earth oxides imported into Japan were smuggled from China, presumably through trading companies willing to falsify export declarations, for instance, by labeling rare earth oxides as other mineral products [353]. It is of particular note that only approximately half of the allocation under China's official export quota for 2011 was utilized, and the likely major cause was the skyrocketing high price for many of these materials. As a result, Japanese companies (among others) are believed to have utilized materials from their own stockpiles to avoid paying higher prices.

China has been building a strategic stockpile of rare earths with a focus on concentrates, in addition to the stockpile already being gathered by China's top rare earth producer, Baotou Steel Rare-Earth High-Tech Co. The firm produced about 55,000 metric tons of REOs in 2010, but the regional government of Inner Mongolia enforced a market quota of just 50,000 metric tons as part of the country's effort to manage resource usage. The company likely reserved 5,000 tons from production output during 2010 to add to existing stockpiles. Although Baotou Steel Rare-Earth did not confirm that it was building a stockpile, the company did confirm that the Baotou city government gave them approval in February 2010 to build facilities to store up to 200,000 metric tons of REOs [354]. Furthermore, the Chinese government was also studying whether to strengthen state rare earth stocks, and if approved by the State Council, the State Reserves Bureau would have the ability to purchase part or all of Baotou Steel Rare-Earth's stocks. With more than US$2 trillion in foreign currency reserves, Beijing certainly would have more than enough money to fill its stockpiles [355]. As noted at the time by Niu Jingkao, the Deputy Secretary General of the CSRE, "stockpiling is a responsible measure for macro control given the strategic importance of rare earths." [356]

National guidelines issued by China's State Council in May 2011 acknowledged rare earths as a key part of national strategic reserves. According to the guidelines, China will set up a strategic stockpile for rare earth metals in addition to its existing REO stockpile, giving the country guaranteed supplies and the ability to manipulate domestic and international supply conditions and market pricing as necessary. The guidelines also stated that the government would plan the further exploration of heavy rare earths in Southern China and light rare earths in Northern China, and mark certain mining areas as strategic reserves unavailable for exploration without the state's permission [357].

In the U.S., the DoD (with the assistance of the USGS) is in charge of examining which rare earths are necessary for a National Defense Stockpile (NDS). Decisions as to which materials to store are generally based on a three-year war scenario. The Defense Logistics Agency Strategic Materials (DLASM), previously the Defense National Stockpile

Center (DNSC), has stated that DLASM stockpiling is not solely for military needs. In fact, the group specifically mentions the fact that the stockpile “is intended for all essential civilian and military uses in times of emergencies” [358]. As of early 2012, there were no rare earth materials in the national stockpile, according to a DLASM materials report [359]. The DoD had stockpiled some yttrium in the past but has since sold it [360].

According to a 2010 GAO report, "a 2009 National Defense Stockpile configuration report identified lanthanum, cerium, europium, and gadolinium as having already caused some kind of weapon system production delay and recommended further study to determine the severity of the delays" [361]. To this end, on January 28, 2011, U.S. Senators Mark Begich and Lisa Murkowski and Congressman Mike Coffman wrote to the Secretary of Defense to propose that the DoD "establish a limited stockpile of rare earth alloys that are in danger of supply interruption to ensure security of supply of both metals and magnets" [362]. The senators noted that in 2010, DoD Industrial Policy director Brett Lambert said that although he was also concerned about the rare earth supply situation, he argued that market forces would produce new supply sources, saying the U.S. only has to “survive a few more years of Beijing’s dominance over rare earths mineral supply and pricing, then American and key allies should be able to turn the tables” [363]. The senators noted specifically, “the components needed for our defense systems are virtually non-existent in the U.S. today and to our knowledge, no prime contractor has long-term supply agreements to ensure access in a fully secure supply chain. Given the dwindling domestic supply chain and struggle to accurately identify DoD consumption of rare earth elements, we respectfully disagree with director Lambert’s initial assessment.” [364] The politicians suggested that the DoD require contractors to detail which rare earths are used in their weapons systems and compile a criticality list for those materials.

As noted in Section 3.4, as of 2012, the importance of investigating a U.S. stockpile of rare earths was officially recognized with newly introduced legislation. In H.R. 1540, (the National Defense Authorization Act for Fiscal Year 2012), signed into law by President Obama in December 2011, Section 853 directs that the “Administrator of the Defense Logistics Agency Strategic Materials shall submit to the Secretary of Defense an assessment of the feasibility and advisability of establishing an inventory of rare earth materials” [365]. The specifics of Section 853 required the following steps from the DLA Strategic Materials office:

- Identify steps necessary to create an inventory of rare earths
- Provide a detailed cost-benefit analysis
- Provide analysis of potential market effects (pricing/commercial availability)
- Identify and explain mechanisms involved in making inventory accessible for purchase
- Provide a detailed explanation of ability of the Administrator to authorize sale of excess materials
- Analyze potential revision of DLA Strategic Materials annual plan for FY2012 and beyond
- Identify steps involved to develop a multi-source supply chain
- Identify and describe reliable supply sources, including production capabilities of sources and security of upstream supply
- Include any other considerations or recommendations as necessary to support establishment of inventory

The Secretary of Defense is then required to describe any actions to be taken in response to the above analysis, including “any recommendations for legislative or regulatory changes to ensure the long-term availability of such rare earth materials” [366].

A National Research Council (NRC) report on minerals critical to the U.S. economy defined critical minerals as those that “are both essential in use (difficult to substitute for) and prone to supply restrictions” [367]. Based on several availability criteria used to rank minerals for criticality (geological, technical, environmental, social, political, and economic), rare earths were determined to be critical materials at a high supply risk, with the possibility of severe impact if supplies were ever restricted. Of course, as mentioned, some rare earths are assessed as being more important than others (e.g. lanthanum, neodymium, and europium), and some are at greater supply risk than others (e.g., neodymium, terbium, and dysprosium). In general, heavy rare earths are at greater risk than light rare earths, as substitutes are unavailable or not as effective [368].

In the private sector, stockpiles are more critical, due to the need for both protection from price changes and continuous availability for production lines. The DoE's 2010 Critical Materials Strategy report suggests that the "DoE can encourage industry to increase private stocks and inventories, to the extent practicable and possible, in order to maintain resiliency in case of future supply disruptions. Private sector stocks of critical materials can then be traded between market participants to help balance supply and demand." [369]

As an example of private stockpiles, rare earths investment group Dacha Strategic Metals, an investment company with offices in Canada and China focused on acquisition, storage, and trading of strategic metals, reported the acquisition of 12 metric tons of dysprosium iron metal on December 29, 2010. The company has established its strategic stockpile of rare earths in a London Metal Exchange-approved metals facility in Pusan, Korea. On February 1, 2011, Dacha announced an equity offering for proceeds up to US$100 million in physical rare earth metals [370].

5.5 Rare Earth Substitutes and Recycling

Due to a cheap, plentiful supply of rare earths from China over the past decade, there has been little incentive to develop substitutes or effectively recycle materials. However, with rapidly rising prices and growing concerns about supply insecurity, the DoE has proposed to identify appropriate substitutes and improve recycling, reuse, and more efficient use of critical rare earth materials [371].

Rare Earth Substitutes

Rare earth substitutes are generally either unknown or provide inferior performance due to the specific functions of rare earths. When there are substitutes available, they are often more expensive materials, such as platinum-group elements that can be used to replace cheaper light rare earths in petroleum cracking and automotive catalysts [372]. Additionally, there has been no success during the past 20 years of research to find alternatives for NdFeB magnet material with a similar energy product. Similarly, europium, the most expensive rare earth element, used in millions computer monitors worldwide, currently has no substitute [373].

Some rare earth substitutions may be possible where specific magnetic and metallurgical properties are required, as summarized by Gupta and Krishnamurthy in Table 5.7. However, the more specific the properties required, the less likely the possibility of substitution becomes. As a result, rare earths are still required in certain applications, including magnets, optical glass components, X-ray pigments, phosphors, polishing applications, catalysts, and magnets [374].

Table 5.7: Alternatives to Rare Earths in Limited Applications [375]

Application	Rare Earth Material	Substitute
Nodular iron	Mischmetal	Magnesium
Steel	Rare earth silicate	Calcium
Control rod in nuclear energy	Europium	Hafnium
Hydrogen storage	Lanthanum	Iron titanium alloy
Glass polishing	Cerium oxide	Plate glass (Pilkington) process
Glazed ceramic tiles	Cerium	Tin zirconium

Systems and components are now beginning to be redesigned to either make less use of rare earths or remove them completely. The following are examples of active research projects and products where the use of rare earths is either minimized or removed, with the aim of functionality similar to existing technologies:

- Hitachi has unveiled a midsize industrial electric motor that delivers comparable performance to a motor utilizing rare earths, and also at a lower price. It will go into commercial production in 2014 [376].
- Daikin Industries and Osaka Prefecture University have been working together to develop an iron and ferrite magnet motor component for use in vehicles [377].
- NovaTorque in California sells ferrite motors that do not utilize rare earths [378].
- Toyota is developing electric induction motors that do not use rare earths for their vehicles, and "could bring the technology to market in two years if the price of rare earths does not come down" according to Japan's Koyodo News. A Toyota spokeswoman noted the company has no specific timeframe for commercialization [379].
- Associate Professor Nobukazu Hoshi at the Tokyo University of Science has demonstrated a functional electric vehicle with a switched reluctance motor, which is completely free of rare earths [380].
- Continental AG of Germany has developed an REE-free electric vehicle motor, used in two Renault vehicles in 2012 [381].

- U.S. rare earths supplier Molycorp Corp. has invested in Boulder Wind Power, a company using permanent magnets that do not require dysprosium in their wind turbines [382].
- Enercon, a German wind turbine manufacturer, has begun using an electrical system to generate the necessary magnetic field required by its generators in place of a rare earth permanent magnet [383].

Development of REE-free battery technology has been primarily focused on batteries used in hybrid and electric vehicles, due to the amount of rare earths used in each battery and the growing level of production of these vehicles. Li-ion battery technology has been in a development race with Ni-MH battery technology over recent years, and in many cases can be an effective substitute for Ni-MH while requiring little to no rare earths. With concerns over the price and supply of rare earth materials, research and development into more advanced Li-ion batteries and other alternative battery technologies is expected to grow. U.S. government program funding has been provided by the DoE to identify alternative vehicle battery technologies under ARPA-E's Batteries for Electrical Energy Storage in Transportation (BEEST) program. While not specifically targeted at replacing rare earths, if successful, many of the projects would enable REE-free battery technology at energy densities previously unreachable [384]. As previously mentioned in Section 3.5, ARPA-E has provided funding in past years to develop REE-free technologies, and in 2011 under their REACT program funded 14 research projects at a total value of US$31.6 million.

Rare Earth Recycling

With China's rare earths supply and production dominance, export quotas and taxes, preference for its domestic market, and rising prices, resulting perceived threats to industry and national security have reignited interest in R&D for cost-effective reclamation of rare earths from EOL electronics. Before China temporarily cut off its rare earth supply to Japan in October of 2010, the recycling of electronic waste (e-waste) was a concept just beginning to gain traction in the U.S. and Western Europe, mainly as a source of noble and precious metals. Only for these metals do cost-effective reclamation processes exist, due to their high initial production cost, and the fact that prices had been so low for a number of years for rare earths that they could not be recovered cost-effectively.

Rare earth recycling, recently labeled “urban mining,” has recently grown in popularity and refers to “the process of reclaiming compounds and elements from products, buildings, waste” [385]. The United Nations conducted a study of eleven countries in 2009 and noted the following barriers for the development of sustainable e-waste recycling technologies: policy and legislation, technology and skills, and business and financing [386]. In the rare earth industry, the incentive to develop processes for reclaiming rare earths from end-of-life (EOL) electronics was virtually non-existent until recently, and so far Japan has achieved the greatest global progress in developing recycling processes and technology.

Japanese companies are looking to exports of advanced green energy technologies, in addition to Toyota’s hybrid electric vehicle technology, for future economic growth. Major electronics companies such as Panasonic are moving out of low-margin, competitive industries such as the television market and into the development of next-generation batteries for electric cars [387]. With rare earths critical to the success of these industries, Japan’s incentive to develop its recycling industry is being spurred on by government policy. In July 2009, Japan’s Ministry for Economy, Trade, and Investment (METI) emphasized recycling as the second of four key pillars in its “Strategy for Ensuring Stable Supplies of Rare Metals” [388]. In October 2010, the Japanese Cabinet allocated US$1.25 billion in its supplementary budget for an overall rare earths strategy. Approximately US$525 million was earmarked for recycling initiatives in 2010 to establish the country as a global center for rare earth recycling [389].

METI announced in February 2012 that it has earmarked US$65 million for the current fiscal year in subsidies for companies to help reduce reliance on rare earths and to develop new REE recycling methods and REE-free technologies. Utilizing processes and technologies funded under this program, METI is aiming to recover 13 metric tons of dysprosium and 69 metric tons of neodymium annually by 2016 [390]. A rare earth recycling bill has been drafted by the Japanese government, requiring businesses and consumers to recycle used electronics or face fines of up to US$3,750. The government stated in early 2012 that “the annual amount of used electronic products disposed of in Japan stands at 650,000 tons, from which 280,000 tons of rare earth and other metal resources worth 84.4 billion yen could potentially be recycled.” [391]

As of early 2012, the only metals being recovered on a large scale in Japan are the more expensive ones, such as copper, gold, and indium. The estimated cost of recovering rare earth metals through recycling was reportedly more than US$24/kg in 2010, and while in that year the only metals with a market price close to or exceeding this amount were limited to Nd, Y, Dy, and In, as of February 2012 all rare earths were above this price threshold. A financial success story in rare earth recycling is reported to be the Dowa recycling facility in Kosaka, Japan, where "the factory processes 300 tons of materials a day, but each ton yields only about 150 grams of rare metals … after a year of operating at low capacity, the factory now turns a profit." [392]

Other Japanese companies are also heavily involved in developing novel rare earth recycling processes. Hitachi announced in 2010 that the company had developed machinery and accompanying processes to dismantle hard drives and compressors, extracting rare earth magnet material from both. Neodymium and dysprosium alloys are then separated from the magnet's other materials utilizing a dry method, unlike usual acid leaching methods. The company hopes to begin full volume recycling operations by 2013 [393]. Mitsubishi Electric Corp. announced in February 2012 that the company is developing a project that allows rare earth elements to be recycled from used household air conditioners. According to the company, their device can "automatically take apart air-conditioner compressors and separate neodymium magnets from their rotors," and will begin operation in April, 2012 [394]. Honda Motor Company announced in late April 2012 that it has reached a breakthrough in rare earth recycling as the result of a partnership with Japan Metals & Chemicals Co. Ltd., and is planning to recycle Ni-MH HEV/EV batteries on a mass production basis. The company claims it will recover 80% of the rare earths present in used batteries collected from hybrid vehicles inside and outside Japan [395].

In the U.S., although the EPA promotes and has documented electronics recycling from an environmental protection viewpoint, there is no evidence of viable domestic material reclamation activities, mainly due to the lack of government policy. Even the Institute of Scrap Recycling Industries Inc. (ISRI) tacitly admits to the lack of an economically viable electronics recycling market. There is, however, some rare earth recycling currently being performed in the U.S. - a novel process for the recovery of rare earths from Ni-MH batteries in the U.S. has been developed as a result of a partnership between two companies, Umicore and Rhodia. In September 2011, Umicore's New Jersey recycling plant began operation, putting batteries through a proprietary ultra high temperature treatment process to separate them from iron and nickel before further processing the resulting rare earths into a high-grade concentrate. The concentrate is then shipped to Rhodia's plant in France, where it is refined and formulated into rare earth materials. According to Umicore, "a typical NiMH battery will contain some 7% of rare earth elements, including cerium, lanthanum, neodymium and praseodymium" [396].

China produces rare earth metals from denuded ore, while not traditionally being overly concerned about environmental measures. As a result, advanced countries have been able to obtain such metals cheaply from China. Australia and the U.S. also have large deposits of rare earth metals, but they prefer not to produce metals in their countries since refining causes major environmental problems (see Section 5.2). Thus, metals refined in advanced countries will continue to be very expensive. Although the concentration of rare earth metals from recycling is not high, particularly for REEs such as Nd and Dy, the recycling process does not have serious environmental problems. Thus, rare earth metal production via recycling has merit in view of its lower environmental cost, independent of other considerations such as politics or strategy.

Chapter 6

Recommendations and Conclusions

It is by now clear that a complete rare earth supply chain is currently lacking in the U.S., and it must be further developed, either nationally or in conjunction with our allies. Unfortunately, however, this is an expensive, difficult and time-consuming endeavor that will not provide near-term relief to concerns surrounding Chinese control of the rare earth market.

Rare earth mining and processing is simply a dirty business to be in, as the economics of rebuilding the supply chain domestically are either financially prohibitive or environmentally unacceptable. We should therefore be looking to build our diversified supply chain within "friendly" nations. Even Molycorp's goal of 40,000 metric tons of REE output per year from Mountain Pass in California will not satisfy U.S. demand for rare earth elements. Japan's Toyota Tsusho is a prime example of a motivated private company aggressively diversifying its supply chain across the globe, and it exemplifies a model to be emulated within the U.S.

An aggressive R&D agenda is recommended for REE alternatives, reduction strategies, processing optimization, new applications, alternative REE-free technologies and REE recycling. We should better quantify our dependence on REEs as catalysts, as well as examine other usage areas where REEs are currently considered essential. In considering REE alternatives, emphasis should be placed on utilizing existing and/or novel nanomaterials, i.e. carbon nanotubes, carbon buckyballs and graphene, in search of desired functional material goals. We also need to emphasize research to decrease the quantity of REEx used in product design, and in the process decrease the total domestic consumption of REEs. Rare earth ore processing requires a large amount of both water and acid, and aside from special handling associated with radioactive elements often found with REEs, the development of improved refining/processing techniques that encourage water and acid reduction and/or reuse is a key technical and environmental challenge. We should direct universities to work with rare earth materials to create new applications, such as the use of REE additives to increase power density in batteries. In the future, the U.S., China or another country may find new and even more critical uses for REEs, and we should strive to be first to develop a competitive advantage. While the U.S. does not currently recycle significant amounts of rare earths, greater efforts are underway globally, particularly in Japan, and we should direct similar research efforts towards developing effective recovery processes so more material would be available to be directed to new high impact applications.

The development of a serious research agenda in REEs would have the added benefit of creating an intellectual component to a resurrected domestic supply chain. As the industry dwindled during the 1990s and focus shifted to procuring rare earths from China's rapidly growing supply chain, scientists and engineers moved on to other fields or retired. The current lack of a strong intellectual component to supply chain rebuilding efforts will seriously hamper U.S. efforts to regain in-house rare earth industrial capabilities, and in order to have an adequate supply of S&Ts going into the field and repopulating the supply chain, this issue must be addressed as quickly as possible.

Our analysis clearly indicates that rare earth materials have a significant impact on the national economy, rather than on the DoD alone, as the authors originally anticipated. Nevertheless, it is imperative that DoD supplies be assured in case of an unanticipated emergency. For the DoD to effectively maintain a state of readiness and capability appropriate for the nation's defense, a stockpile of the most critical materials should be created in the form of a public/private (government/industry) partnership. This would ensure that national defense capabilities are not compromised, even in further downstream application industries that supply defense needs.

There is, however, no sense of urgency to this issue from the perspective of the DoD and the U.S. Government. The DoD believes that by 2015 the domestic supply of rare earth materials and downstream products will have grown, additional reliable foreign sources of supply will have been established, and the resulting market will be capable of meeting future demand. It also bears consideration that a large percentage of REE usage is for non-essential purposes, and it may not be unreasonable to consider that the public could live without catalytic converters, LED televisions, and even the entire green energy industry if necessary – these are essentially ‘bonus’ capabilities afforded by the current level of availability of REEs.

The future risk/impact of rare earth element availability will depend on a host of factors, such as life cycle costs and geopolitical considerations, that are hard to predict. It is the opinion of the authors that this risk will rise significantly over the next decade. Supply uncertainties and disruptions in product sustainment are anticipated, and these will be felt throughout the entire supply chain. We conclude that this is a critical issue but not yet a crisis. Thus, a call to action at the national level is required in order to galvanize and create the sense of urgency needed to appropriately address this issue.

In spite of all the Congressional studies, government platitudes, industrial hand-wringing, lofty studies and the usual recommendations of monitoring, stockpiling, leveraging and so on, the fact remains that both national security and economic growth from emerging technologies are dependent upon the steady availability of rare earth elements, which will be supplied in the foreseeable future primarily by a single, potentially hostile supplier. Is a billion dollars too much to have an adequate insurance policy for the military and civilian rare earths consumer? If it is, then “ultimately, they’ll have to put their money on the table if they want to see this happen. Talk is cheap. Some of these projects have a price tag of around $1 billion. There are very few people [however] that have the longer-term confidence in prices and demand.” [397] Our challenge is to address this issue head on and in an imaginative way.

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