

Thesis: The Critical Importance of Rare Earth Minerals in the Production of Quantum Processors

Abstract Quantum computing represents a paradigm shift in computational power, with quantum processors at its core. These processors rely on advanced materials, including rare earth minerals (REMs), to achieve the precision, stability, and functionality required for quantum operations. REMs, such as neodymium, dysprosium, yttrium, and erbium, are integral to the fabrication of superconducting circuits, cryogenic systems, and photonics components in quantum processors. However, the global supply of REMs is constrained by geopolitical, environmental, and economic factors, posing significant risks to the quantum computing industry. This thesis argues that REMs are indispensable to quantum processor production, and securing a stable, sustainable supply chain is critical to advancing quantum computing technologies and maintaining technological leadership.

Chapter 1: Introduction

Quantum computing promises to solve problems intractable for classical computers, from cryptography to materials simulation. At the heart of quantum computers are quantum processors, which manipulate qubits using principles of superposition, entanglement, and quantum coherence. These processors require highly specialized materials to operate at near-absolute zero temperatures, maintain quantum states, and integrate with photonic or electronic systems. Rare earth minerals, a group of 17 elements including the lanthanides, scandium, and yttrium, are critical to these functions due to their unique magnetic, optical, and electronic properties.

The importance of REMs stems from their role in enabling key components of quantum processors, such as superconducting qubits, cryogenic cooling systems, and optical interfaces for quantum communication. However, REM extraction and processing are concentrated in a few countries, notably China, which controls approximately 60-70% of global production and 85-90% of refining capacity as of 2025. This dependency, coupled with environmental challenges and increasing demand, underscores the strategic importance of REMs. This thesis explores the technical necessity of REMs in quantum processor production, evaluates supply chain vulnerabilities, and proposes strategies to mitigate risks.

Chapter 2: The Role of Rare Earth Minerals in Quantum Processors

Quantum processors rely on materials that can operate in extreme conditions, such as millikelvin temperatures, while maintaining precise control over quantum states. REMs are critical in several areas:

2.1 Superconducting Qubits

Superconducting qubits, used in quantum processors by companies like IBM and Google, require materials with high magnetic and electrical performance. Neodymium and dysprosium are used in the production of high-strength permanent magnets for electromagnetic shielding and stabilization in superconducting circuits. These magnets protect qubits from external magnetic noise, which can disrupt quantum coherence. For example, neodymium-iron-boron (NdFeB) magnets are prized for their high magnetic field strength, essential for maintaining stable qubit environments.

2.2 Cryogenic Systems

Quantum processors operate at temperatures near absolute zero (e.g., 15 millikelvin) to minimize thermal noise. Cryogenic systems, such as dilution refrigerators, use REM-based materials like gadolinium and cerium in magnetic cooling stages. Gadolinium-based compounds, such as gadolinium gallium garnet (GGG), exhibit strong magnetocaloric effects, enabling efficient cooling to sub-Kelvin temperatures. Without these materials, achieving and maintaining the ultra-low temperatures required for quantum coherence would be infeasible.

2.3 Photonics and Quantum Interfaces

Quantum processors often integrate with photonic systems for quantum communication or networking. REMs like erbium and yttrium are critical in photonics. Erbium-doped optical fibers amplify signals at the 1.55-micron wavelength, ideal for long-distance quantum communication. Yttrium is used in yttrium aluminum garnet (YAG) crystals, which serve as substrates for lasers and optical amplifiers in quantum systems. These components enable the transfer of quantum information between processors or across quantum networks.

2.4 Substrates and Thin Films

REMs are also used in the deposition of thin films and substrates for quantum circuits. For instance, lanthanum-based compounds, such as lanthanum aluminate (LaAlO_3), are used as substrates for superconducting thin films due to their lattice compatibility and low dielectric loss. These substrates support the high-precision fabrication of qubits, ensuring minimal energy dissipation and prolonged coherence times.

Chapter 3: Supply Chain Challenges for Rare Earth Minerals

The critical role of REMs in quantum processors is overshadowed by supply chain vulnerabilities, which pose risks to the quantum computing industry.

3.1 Geopolitical Concentration

As of 2025, China dominates the REM market, producing approximately 60-70% of raw REMs and controlling 85-90% of global refining capacity. This concentration creates risks for quantum computing companies, particularly in the United States and Europe, where domestic REM production is limited. Trade restrictions, export quotas, or geopolitical tensions could disrupt supply chains, delaying quantum processor development.

3.2 Environmental and Economic Barriers

REM mining and refining are environmentally intensive, producing significant waste, including radioactive tailings from thorium and uranium byproducts. Stringent environmental regulations in Western countries have slowed domestic production, increasing reliance on foreign suppliers. Additionally, REMs are often mined as byproducts of other minerals, making supply inelastic and subject to market fluctuations. The high cost of establishing new mining and refining facilities further complicates efforts to diversify supply.

3.3 Competing Demand

Quantum computing is not the only industry reliant on REMs. Electric vehicles, wind turbines, and consumer electronics also demand neodymium, dysprosium, and other REMs, driving competition. For example, a single electric vehicle motor requires 1-2 kg of neodymium, while quantum processors, though requiring smaller quantities, demand ultra-high-purity REMs, which are costlier to produce. As global demand for REMs is projected to grow by 5-10% annually through 2030, securing supply for quantum computing will become increasingly challenging.

Chapter 4: Strategic Implications and Solutions

The reliance on REMs for quantum processors has profound implications for technological innovation, national security, and economic competitiveness. Addressing supply chain risks requires a multifaceted approach.

4.1 Diversifying Supply Chains

Governments and industries must invest in alternative REM sources. Australia, Canada, and the United States have significant REM deposits but lack refining capacity. Public-private partnerships could accelerate the development of domestic refining infrastructure. For example, the U.S. Department of Defense has funded projects like the Lynas Rare Earths facility in Texas, which aims to process REMs by 2026. Similar initiatives in Europe and Japan could reduce reliance on Chinese supply.

4.2 Recycling and Substitution

Recycling REMs from end-of-life electronics and industrial equipment could supplement supply. Current recycling rates are low (less than 1% globally), but advances in hydrometallurgical and pyrometallurgical processes could improve efficiency. Additionally, research into REM substitutes, such as non-rare-earth magnets or alternative cooling materials, could reduce dependency. However, substitutes often compromise performance, limiting their applicability to quantum processors.

4.3 International Cooperation

Global cooperation is essential to stabilize REM supply chains. Multilateral agreements could prevent export bans and promote sustainable mining practices. Organizations like the International Energy Agency or the World Trade Organization could facilitate frameworks for equitable REM distribution, ensuring access for quantum computing and other critical industries.

4.4 Investment in Quantum Materials Research

Advances in materials science could reduce the quantum computing industry's reliance on REMs. For example, developing high-temperature superconductors or novel photonic materials could minimize the need for REM-based components. Funding for interdisciplinary research, combining quantum physics, materials science, and engineering, is crucial to achieving these breakthroughs.

Chapter 5: Conclusion

Rare earth minerals are the backbone of quantum processor production, enabling the superconducting, cryogenic, and photonic systems that power quantum computing. Their unique properties make them irreplaceable in the near term, but their supply is fraught with geopolitical, environmental, and economic challenges. The quantum computing industry, poised to transform fields from cryptography to drug discovery, cannot afford disruptions in REM supply. Strategic investments in diversified supply chains, recycling, substitution, and

materials research are essential to ensure the continued development of quantum processors.

Securing a stable REM supply is not merely a technical necessity but a matter of global technological leadership. As nations race to achieve quantum supremacy, those that control REM supply chains will hold a significant advantage. By addressing these challenges proactively, governments, industries, and researchers can safeguard the future of quantum computing and unlock its transformative potential.

References (Note: A formal thesis would include a detailed reference list. Below are indicative sources based on general knowledge and trends as of 2025.)

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