Securing the Future: Critical Materials Policies for the US Energy Transition

by

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ABSTRACT

As the U.S. pushes forward industrial policies to support its energy transition with policies like the Inflation Reduction Act (IRA) to develop domestic green-tech supply chains, it overlooks the crucial need for a sustainable and secure supply of critical materials. This oversight threatens the success of the nation's sustainable transition due to limited resilience and dependencies on geopolitically, environmentally, and socially sensitive international sourcing, particularly from China.

This thesis examines the key considerations for the US to secure a sustainable supply of these materials, hypothesizing that a comprehensive policy framework integrating sustainable practices, domestic production incentives, and international cooperation can effectively reduce risks and externalities. Methods include empirical and case studies that highlight specific challenges such as permitting delays and dependency on foreign minerals, alongside economic models analyzing the impacts of these dependencies and market dynamics. Industry roundtables provide insights into prospective innovations and recent trends in the industry. Findings indicate significant market outlook uncertainty, critical dependence on imports, and significant limitations and inertia for new domestic resources development.

The thesis proposes a policy framework aimed at addressing these deficiencies to support the U.S. in leading the global transition to sustainable technologies. Recommendations focus on enabling domestic production increase through better regulation and innovation, adopting sustainable practices, and diversifying supply chains to enhance resilience. This framework is crucial for policymakers, industry stakeholders, and academics involved in shaping a resilient U.S. energy strategy.

Thesis supervisor: Christopher R. Knittel
Title: George P. Shultz Professor of Energy Economics

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Introduction

The Paris Agreement that resulted from the COP21 marked a turning point in the fight against global warming in 2015 [1]. It commits all the signing countries to keep average global warming below 2°C compared to the pre-industrial era. According to the Intergovernmental Panel on Climate Change, achieving this target requires significant reductions in greenhouse gas (GHG) emissions [2]. Among the leading emissions contributors, the United States plays a crucial role due to its substantial industrial base and high per-capita emissions. Transportation and power generation are the two largest sectors in terms of GHG emissions contributions with 28% and 25% respective shares of total U.S. emissions [3].

The U.S. strategy for meeting its emission reduction targets is tied to the decarbonization of these sectors: shifting from traditional fossil fuel-based vehicles to electric vehicles (EVs) and transitioning the power sector towards clean energy sources. These strategies are the backbone of most scenarios developed at domestic [4] and global levels [5], and are expected to transform deeply the economic structure of our world, particularly the production infrastructure dynamics. Traditionally, the world's energy supply has relied heavily on hydrocarbons—dense and readily exploitable energy sources, operating on light capital infrastructure. In contrast to this marginal system, clean technologies typically harness energy from more diffuse and leverage less dense sources. Consequently, to deliver equivalent services, these technologies demand greater resource input for the development of production capital, reflecting in increased material and energetic consumption [4].

Transitioning from a marginal energy use paradigm to a more capitalistic infrastructure underlines the strategic importance of dominating future technology supply chains, critical commodities, and key manufacturing sectors. The heightened interest in industrial policies and national sovereignty can be viewed as a strategic response to these shifts, especially pertinent in the context of the U.S.'s competition with China in securing a leadership position in clean technology [6]. The U.S., recognizing the strategic and economic imperatives, has intensified its focus on developing robust domestic supply chains for critical materials essential for clean energy technologies. This is evident in legislative efforts such as the Inflation Reduction Act, which aims to bolster domestic industries and reduce dependency on foreign materials, positioning the U.S. as a leader in the global shift towards sustainable energy practices [7].

Despite the Inflation Reduction Act (IRA) implementing domestic content requirements to promote the use of U.S.-sourced materials through tax credits and financial incentives, significant strategic gaps remain, particularly in the upstream segments of the supply chain such as mining, processing, and recycling of critical materials. Although these measures aim to bolster domestic industries, several mining companies indicated that the U.S. currently lacks the necessary domestic mining and processing capacity to meet these requirements competitively both in terms of scale and cost [8]. Recent infrastructure developments have lagged behind global developments due to regulatory, environmental, and economic hurdles [9], meaning that the U.S. is inadequately equipped to meet the growing demand driven by the clean technology sector [10]. This disconnection between policy aspirations and industrial capabilities, could lead to supply chain bottlenecks, escalating costs, and delaying the deployment of clean technologies [11].

Without a comprehensive strategy to enhance these upstream sectors, the U.S. remains at risk of continued reliance on foreign imports for essential materials. The manufacturing of green technologies heavily relies on a few elements that present strategic challenges in supply security and economic competitiveness for the U.S. [12]. Challenges are intensified by underdeveloped global supply chains and geopolitical dependencies, especially given China's dominance of critical materials supply chains [13], potentially exposing the U.S. to supply disruptions or geopolitical manipulations [12].

Consequently, the absence of a comprehensive and detailed strategy for developing the critical materials sector significantly undermines the effectiveness of the IRA and other policies intended to develop a domestic cleantech industry. Without substantial investment and advancement in mining, processing, and recycling infrastructure, the U.S. faces ongoing reliance on imports from geopolitical rivals, which could compromise national security, economic independence, and the long-term success and sustainability of its clean energy transition.

The research objective of this thesis is to investigate the need and potential of policy interventions aimed at securing a sustainable and resilient supply of critical materials to support the U.S. energy transition. This thesis aims at developing a rigorous framework of policy recommendations based on a thorough examination the challenges that the US critical materials supply faces.

The hypothesis proposed is that a comprehensive policy framework that integrates sustainable mining practices, incentives for domestic production, and strategic international collaboration, can effectively ensure resilient and sustainable supply chains. Such actions would reduce dependence on sources that pose geopolitical, environmental, and social risks, thereby enhancing security, resilience and supporting the domestic energy transition needs.

The thesis begins by presenting the motivation background and defining the problem statement. It then details the research methodology, describing the investigative techniques employed to characterize the challenges and issues, and presents the empirical results obtained. The study concludes with a set of detailed policy recommendations and strategic actions. This structure ensures the development of actionable, well-substantiated policy solutions to support the broad ambitions of the U.S. to lead in clean technologies while strengthening economic competitiveness and national security.

Chapter 1

Motivation

1.1 Critical Materials and the Energy Transition

As the global energy transition accelerates, there is a marked shift from traditional hydrocarbons to an increased reliance on critical minerals necessary for energy production. This transformation is driven by the worldwide adoption of green technologies and a concerted effort to reduce greenhouse gas emissions in line with international climate goals, such as those outlined in the Paris Agreement. As countries strive to decarbonize their economies, the demand for minerals like lithium, cobalt, nickel, and rare earth elements—essential for electric vehicles, renewable energy systems, and other green technologies—is expected to surge. This global demand increase represents a significant shift in resource consumption patterns, highlighting the challenge that tense critical materials supply now poses to securing a sustainable energy future.

1.1.1 Green Technologies Global Adoption

Key strategies to achieve decarbonization goals involve enhancing energy efficiency and transitioning major sectors like power and transportation to cleaner energy sources. This shift is crucial in reducing the carbon intensity of these sectors, with renewable energy and electric vehicles playing pivotal roles supported by advancements in technology and policy incentives.

Reducing GHG Intensity of Economies to Combat Climate Change

The Paris Agreement, ratified in 2015 under the United Nations Framework Convention on Climate Change (UNFCCC), epitomizes a global consensus on the imperative need to combat climate change. It uniquely commits signatory countries to limit global warming to well below 2°C above pre-industrial levels, aiming for a more stringent cap of 1.5°C to mitigate adverse environmental impacts [14]. The agreement underscores the dual necessity of fostering economic development while significantly reducing greenhouse gas (GHG) emissions in accordance to the IPCC findings [2], thereby avoiding detrimental effects on population stability and global development.

Central to the Paris Agreement is the concept of "Nationally Determined Contributions" (NDCs), which are individualized commitments by countries to reduce national emissions to mitigate climate change. The overarching goal is to create a decarbonized global economy by the second half of the century, which is crucial to staving off severe climate disruptions [15]. This target implies not merely a reduction in absolute emissions but also a profound decrease in the GHG intensity of economic activities to enable economic development. Reducing this intensity effectively decouples economic growth from environmental degradation (from a GHG perspective), allowing for a sustainable development without the corresponding rise in emissions. The United Nations' Sustainable Development Goals (SDGs) underscore this balance, particularly SDG 13, which calls for urgent action to combat climate change and its impacts [16]. This approach aligns with the broader goals of the Paris Agreement, aiming to implement resilient and adaptive strategies to foster economic stability and growth without the detrimental environmental impacts traditionally associated with such development.

The reduction of GHG intensity involves enhancing energy efficiency and transitioning to cleaner energy sources [17]. The primary strategies employed globally to reduce emissions focus significantly on transitioning the power sector to clean energy sources and electrifying the transportation sector. These strategies are pivotal because they address the sectors with the highest CO2 emissions and offer proven and cost-effective abatement options [17]. According to the International Energy Agency (IEA), the power sector[1] is the largest contributor to global CO2 emissions, accounting for about 40% of total global emissions, with the transport sector contributing approximately 22% in 2022 [18], with almost 3/4 of these emissions coming from road transportation. This substantial share underscores the critical need for strategic interventions in these areas, and why most governments focus on these two sectors for achieving their decarbonization goals [4].

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[1] Electricity and heat

The Role of Green Technologies in Mitigating Climate Change

The power and transportation sectors, being the most significant contributors to global CO2 emissions due to its heavy reliance on fossil fuels, is thus a primary focus for interventions aimed at reducing GHG intensity [4], [19], [20]. Improvements in energy efficiency and shifts towards intermittent renewable energy sources such as wind and solar power are seen as pivotal strategies in this transition, made possible by the continuous reduction in costs these technologies faced in the last decades [21]. For instance, solar and wind power have reached and in some cases undercut the cost competitiveness of traditional fossil fuels, making them a preferred choice for new power generation capacity [17], [21]. This economic viability, coupled with strong policy support, has led to a substantial increase in their adoption, with renewables forming 30% of the world's electricity in 2023 [4], [22].

Simultaneously, the transportation sector is witnessing a significant shift with the proliferation of electric vehicles. EVs are recognized for their efficiency and lower emissions compared to conventional vehicles. With advancements in battery technology reducing costs and extending driving ranges, EVs are set to play the main role in reducing the sector's carbon footprint compared to other more costly alternatives [5], including on the long term for the united states [23]. Policy measures such as purchase incentives, tax rebates, and investments in charging infrastructure further facilitate the transition towards electric mobility. The Global EV Outlook suggests that there could be as many as 240 millions in 2030 in the Stated Policies Scenario (STEPS), and about 380 millions in 2030 for the Net Zero Emissions by 2050 (NZE) scenario [24]. In the NZE Scenario, this number is expected to surpass 1.6 billion in 2050 [5], significantly reducing emissions from the transportation sector.

In terms of renewable energy, the annual global capacity additions for renewable energy are expected to exceed 1 200 GW by 2030 to reach a total of approximately 11 000 GW in 2030 and 26 000 GW in 2050, with renewables reaching over 60% of total 2030 generation in the updated targets of IEA NZE scenario [5], [22], [25]. By 2050, wind and solar combined are projected to constitute more than 75% of the global power generation capacity, reflecting an aggressive shift from fossil fuels to renewable sources [22].

The United States is aligning with these global trends, emphasizing both EV adoption and renewable energy expansion. By 2030 and 2050, the U.S. is expected to have around 10 and 40 million EVs respectively in operation, supported by federal incentives and robust infrastructure developments [26]. US wind and solar installations are expected to constitute around 630 and 1100GW of capacity, (90% of total renewable installed capacity) in 2030 and 2050 respectively [26].

Figures 1.1 and 1.2 are the graphical illustrations of the projections in IEA NZE.

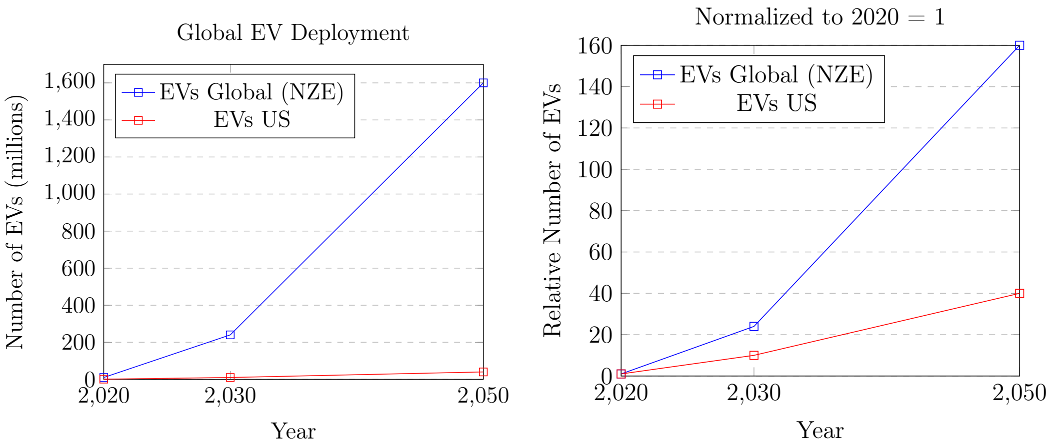

Figure 1.1: Projected global and US EV deployment from 2020 to 2050. Data sourced from the IEA Global EV Outlook 2023 [24] and U.S. EIA projections [26].

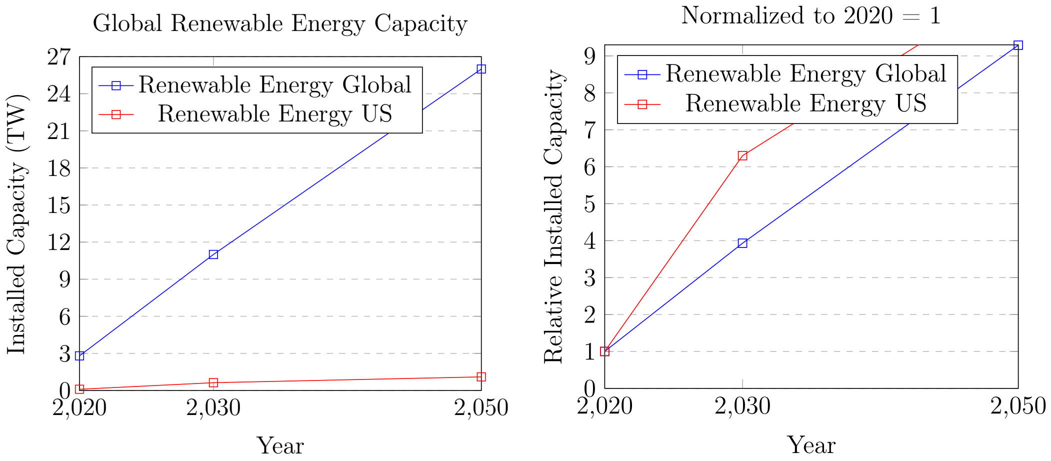

Figure 1.2: Projected global and US renewable energy capacity from 2020 to 2050. Data sourced from the IEA World Energy Outlook 2022 [25], IEA 2023 Renewables Report [22], and U.S. Energy Information Administration [26].

1.1.2 Increased Materials Intensities

As we advance towards a sustainable energy future, the shift from traditional energy sources like hydrocarbons to green technologies such as electric vehicles (EVs) and renewable energy systems introduces new dynamics in material demands. Unlike hydrocarbons, which are energy-dense and straightforward to store and transport, energy from electricity is more complex to store and renewable sources such as solar and wind harness more diffuse and intermittently available energy. To compensate for these characteristics, renewable technologies and EVs rely significantly on advanced material technologies [27], larger infrastructures and more complex logistic systems to guarantee high efficiencies and compensate from less dense production or storage factors. Thereby, they necessitate a larger quantity of critical materials per unit of capacity compared to their fossil-fueled counterparts: for the same service delivered, electrified technologies require more resources to be implemented [28].

Energy Density and Material Demand

Renewable energy sources like wind and solar, and storage technologies such as batteries for electric vehicles, face challenges due to their lower energy density. Energy density refers to the amount of energy stored in a given system or space per unit volume. Traditional fuels like gasoline have high energy density, making them highly efficient for storage and transport. In contrast, the energy captured and stored from renewable sources requires more infrastructure—solar panels, wind turbines, and batteries—which inherently increases the material footprint. For example, to produce the same amount of energy, a solar farm requires a significantly larger physical area compared to a gas-fired power plant, and a much larger and more robust grid infrastructure to support them [29]. Similarly, the batteries needed to store energy for consistent supply or for use in electric vehicles require materials like lithium, cobalt, and nickel, which are critical for their operation due to their ability to enhance energy density and battery longevity.

The material footprint of renewable technologies and the underlying grid requirements is substantially higher than that of traditional technologies. According to recent studies [28], [30], the shift to low-carbon energies necessitates a higher consumption of materials to build the capital equipment needed for these technologies. This is due to the need to compensate for the lower operational energy use with more substantial material input during the manufacturing phase. For instance, manufacturing an electric vehicle or constructing a wind turbine involves a significant amount of rare earth elements and other critical materials, which are required in larger quantities compared to traditional car manufacturing or power generation methods. Compared to traditional technologies, the materials intensity of renewable technologies installations is on average 4 to 10 times greater per unit of energy produced [28], while EVs weight on average 20 to 30% more than traditional internal combustion vehicles [31]. The factors are even greater when restricting to key critical materials since they are more prevalent in green technologies (share of critical materials in the overall material intensity) [28].

By critical material, the literature often refers to a mineral or element that is essential for various industries and applications but is subject to potential supply chain risks or significant economic and strategic implications. The designation of a material as critical is determined by factors such as its importance in key industries, scarcity or limited availability, geopolitical considerations, and the potential impacts of its supply disruptions. Critical materials typically possess unique properties that make them indispensable for specific technologies or sectors. They may be essential components in advanced electronic devices, renewable energy systems, defense technologies, or other critical applications. The criticality of a material is determined not only by its economic value but also by the level of difficulty in finding substitutes or alternatives. The concept of critical materials emphasizes the need for a secure and sustainable supply chain to mitigate risks associated with market volatility, geopolitical tensions, trade restrictions, or inadequate production capacity. It highlights the importance of diversifying sources, developing recycling and substitution options, and promoting responsible mining practices to ensure a reliable and resilient supply of these materials for continued technological advancement and economic growth. There is no common definition or classification of critical materials that is unanimous and emerged from a consensus. Which minerals are critical depends by sector, institution, and region, reflecting different economic, geopolitical, and technological contexts.

Key Elements Impacted

From a global perspective, each application demands specific materials due to their unique properties and roles in technology. Out of them, some are more critical according to the different definitions mentioned in the previous paragraph:

Electric Vehicles (EVs) Electric vehicles are pivotal in reducing greenhouse gas emissions from the transportation sector. They rely heavily on advanced battery technologies, primarily lithium-ion batteries, which utilize several critical materials [24]:

- Lithium: Lithium's light weight and high electrochemical potential make it ideal for use in batteries, providing high energy density which translates to longer driving ranges for EVs.
- Cobalt: Cobalt is used in lithium-ion batteries to increase energy density and battery life. It stabilizes battery chemistry and improves safety by preventing thermal runaway during charging.

- Nickel: Used in the cathodes of lithium-ion batteries, nickel increases energy storage capacity, thereby enhancing the energy density and overall performance of the battery.
- Manganese: Often used in lithium-ion battery cathodes, manganese improves the battery's thermal management, contributing to safer and more stable battery operations.

Renewable Energy Systems Renewable energy technologies such as wind turbines and solar panels also depend on a range of critical materials that enable their efficient operation [30], [28]:

- Rare Earth Elements (REEs): Elements like neodymium and dysprosium are critical for permanent magnets in wind turbine generators. These magnets are crucial for converting kinetic energy from wind into electrical energy efficiently.
- Silver: Used in solar panels, silver paste is applied to photovoltaic cells to collect and transport electrons generated when sunlight stimulates the silicon in the cells, enhancing the electrical conductivity and efficiency of solar panels.
- Copper: Extensively used in both wind and solar technologies, copper is a key component in coils and conductors due to its excellent electrical conductivity. It is essential for the transmission of electricity from renewable sources to the grid.
- Silicon: The primary material for most photovoltaic solar cells, high-purity silicon is used to convert solar energy into electricity. Its semiconductor properties are critical for effective energy conversion.

Grid Infrastructure As the penetration of renewable energy increases, the electrical grid must evolve to handle intermittent renewable energies and ensure reliable energy supply. Critical materials play essential roles in grid infrastructure [32]:

- Copper and Aluminum: These metals are crucial for electrical cables and wires due to their high conductivity. Copper is particularly valued for its reliability and efficiency in conducting electricity, while aluminum offers a lightweight and cost-effective alternative.
- Zinc: Used for galvanizing steel and iron components in the grid infrastructure, zinc protects against corrosion, thereby extending the life of these components.

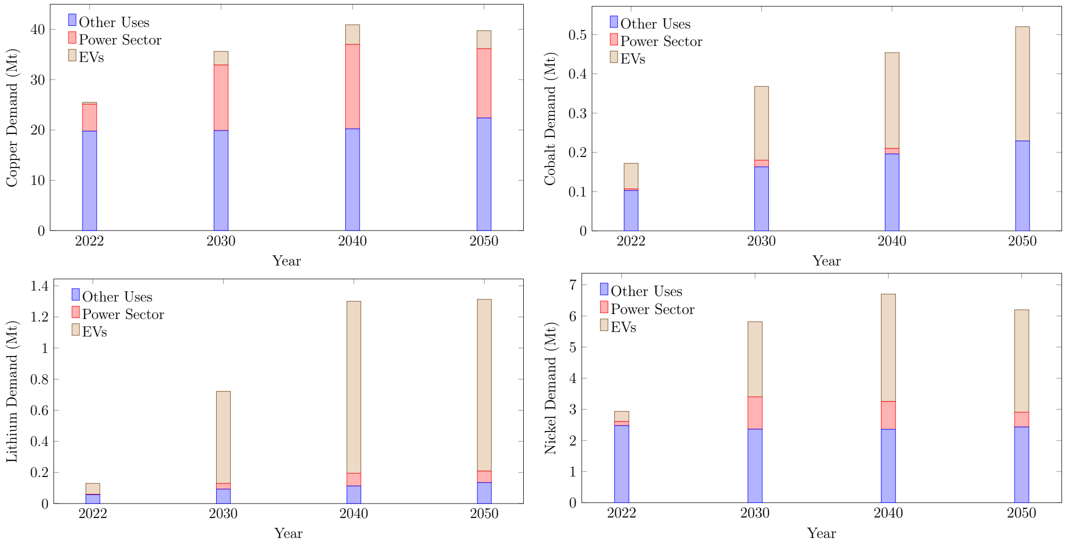

Figure 1.3: IEA demand estimations for Cobalt, Copper, Lithium and Nickel under the reference NZE scenario [5].

- Lead: Despite its environmental concerns, lead is used in some backup batteries and protective sheaths for underground cables, contributing to grid reliability and safety.

1.1.3 Exploiding Demand Growth

The burgeoning boom of materials-intensive green technologies is poised to drive an unprecedented surge in demand for critical materials. Out of the different critical materials, the IEA has estimated global projections from the demand induced by a net-zero transition, as illustrated in Figure 1.3 page 24. By 2040, clean technologies are set to compose more than half the global annual demand for copper (by 2035, mainly driven by the grid 30% and E.V.s, 20%) and cobalt (by 2030, mostly by E.V.s), and about 60% and 80% by 2030 respectively for nickel (incl. 50% for E.V.s) and lithium (E.V.s mostly). These technologies are hence responsible for most of the demand increase. A global deployment is therefore set to induce substantial pressure the extractive systems in place in order to provide the necessary minerals for their manufacturing. In 20 years from now, the global expansion requires extraction expansion in large magnitudes: multiplying by 10 the extraction of lithium, more than doubling cobalt and nickel supply volumes and increasing by 60% copper mining outputs.

The global critical materials demand increase derived from clean technologies adoption is a significant pressure and break from traditional global growth trends the industry experienced in the last 30 years. The sheer magnitude of this upsurge in demand is unprecedented when compared to the gradual and relatively predictable increase in demand driven by China's economic development over the past few decades.

The rapid escalation of demand imposes significant pressures and uncertainties on mining operators. The sector faces questions about whether it can ramp up production sufficiently to meet the surging demand. For example, the production of lithium is projected to need a quadruple increase from 490 kt in 2021 to 2 Mt by 2030 to meet the growing demand. Without the development of new mining projects, a significant market deficit is anticipated, suggesting potential supply shortages. Furthermore, to address a projected copper market deficit of nearly 4.7 million tonnes by 2030, close to $100 billion in investment is estimated to be required to bridge this gap [33].

This situation presents a complex challenge for the sector operators across the world and places scrutiny over whether the world extractive system can meet the additional demand from clean energy technologies.

1.2 US Domestic Amplification Factors

The United States is intensifying its focus on establishing a robust domestic clean technology industrial base, a move driven by a confluence of strategic imperatives. These include enhancing energy security by reducing reliance on imported fossil fuels, spurring economic growth and job creation across various sectors of the economy, and reinforcing national security. This national shift is not only about achieving energy independence or economic benefits but also about positioning the U.S. as a global leader in the emerging high-tech, environmentally sustainable industries. As the U.S. accelerated to develop its domestic capabilities in green technologies with policies like the Inflation Reduction Act (IRA), this is expected to significantly amplify the domestic need for critical materials in order to support a thriving clean tech manufacturing sector. Hence, if the demand for critical materials is set to surge at the global level, the dynamic in north America could be even more significant for both domestically sourced metals as well as imports.

1.2.1 US Domestic Clean Tech Industrial Base Aspirations

The United States has identified the clean technology sector as a pivotal element of its future economic and environmental strategy. This recognition is underpinned by the dual goals of achieving environmental sustainability and establishing global leadership in emerging high-tech industries. The pursuit of a robust domestic clean tech industrial base is motivated by several strategic imperatives. Indeed, developing a domestic clean tech industrial base allows for greater control over its decarbonization strategies and the ability to set ambitious emission reduction targets, but also yields significant co-benefits:

Energy Independence and Security

The drive towards a domestic clean tech industrial base is largely fueled by concerns over energy independence and national security [34]. The United States has historically been dependent on imported oil, which has subjected the economy to fluctuations in global oil prices and political instability in oil-rich regions. This dependency has been a significant national security concern, driving energy policy decisions for decades. Even if the hydrocarbons trade balance has been inverted since fracking, the development of domestic renewable energy sources and the deployment of EVs reduce this dependence by reducing volatility and uncertainty in the future: they give a fixed and stable perspective of energy supply. Additionally, they free volumes for additional exports that have positive impacts on the trade balance. By investing in these technologies, the U.S. can produce its own energy sources, thereby diminishing the influence of external geopolitical factors on its energy prices and availability [35].

Diversifying energy sources is essential for enhancing energy security. Renewable energy sources offer diversification in energy supply chains by spreading production across various technologies and geographical locations. This diversification helps mitigate risks such as natural disasters, terrorist attacks, or other disruptions that can affect more centralized and less varied energy production methods. The domestic production of renewable energy also ensures a consistent and reliable energy supply that is less susceptible to international shipping delays and trade disputes [36]. Recent global events like the blockage of the Suez canal or post-COVID19 disruptions have underscored the importance of resilient supply chains. By localizing the production of critical clean tech components, the US aims to safeguard against supply chain disruptions that could impede its ability to meet renewable energy targets. This strategy is vital for ensuring the availability of essential materials and components necessary for the rapid deployment of clean technologies.

Economic Growth and Job Creation

The clean tech industry in the United States is not just a pivotal sector for achieving environmental goals but also a significant driver of economic growth and job creation.

Investments in this sector catalyze wide-ranging benefits across various dimensions of the economy, from increasing employment opportunities to fostering sustainable economic development.

First, the clean tech sector encompasses a diverse range of activities across the value chain, each contributing to job creation, across all segments of the workforce: high skills in extraction, manufacturing, R&D and other technical functions, as well as lower skilled jobs related to construction, installation, maintenance, etc. However, the clean tech sector's impact on the economy extends beyond direct job creation. It has strong economic multipliers in local and national economies. For example, construction of a new wind farm or solar facility boosts local businesses ranging from materials suppliers to hospitality. Moreover, workers employed in these projects spend their earnings in the local economy, further enhancing economic growth. Clean technologies industries is a rapidly growing field that attracts significant domestic and foreign investment.

Innovations in this sector, such as advancements in solar energy efficiency or battery storage solutions, draw large investments as well as venture capital that can lead to the growth of entirely new industries or securing a large stake in the global clean energy market [37]. Indeed, in the dynamic landscape of U.S.-China relations, green technology also emerges as both a field of competition, plotting a race for technological superiority and domination of future key value chains and associated economic outcomes [38]. The United States has a long-standing reputation as a leader in technological innovation. Therefore, it aims to maintain and extend this leadership into the new realms of renewable energy, battery storage, and other green technologies, which is seen as crucial for maintaining competitive advantages in a global economy increasingly driven by innovation [34].

These strategic imperatives underscore the US government's rationale for fostering a domestic clean tech industry. This approach is expected to yield dividends not only in terms of economic and employment growth but also in enhancing national security, positioning the US at the forefront of global efforts to combat climate change, and ensuring that the nation remains a leader in technological innovation. As the world transitions to a greener economy, the US's focus on building its domestic capabilities in clean technology is a clear indication of its commitment to being a leader in the energy sectors of the future [39].

1.2.2 IRA Pressure on Demand

The COVID-19 pandemic and ensuing supply chain disruptions have significantly highlighted the strategic importance of critical materials, propelling them into the forefront of political and policy discourse worldwide. The pandemic exposed the fragility of global supply chains, particularly the risks associated with concentrated production of critical materials in specific regions, impacting industries like electronics, renewable energy, and automotive. In response, governments have initiated various policy actions to mitigate these risks and reduce dependency on foreign sources and non-resilient supply chains. While the subject was already on the table for the reasons exposed in the previous section, there has been a significant acceleration in the last couple of years. Yet, if action is currently undertaken, it remains at national levels, and no global consensus or unified approach appears as the silver bullet for that.

The integration of critical minerals as a central topic in the Inflation Reduction Act (IRA) is the best indication that these materials have become a central focus in contemporary industrial policymaking. The IRA's provisions related to critical minerals underscore their growing importance in the global shift towards sustainable energy and the electrification of the economy. There are several key rationales behind implementing the Inflation Reduction Act (IRA) and the focus on domestic content requirements within the cleantech industry. The main aim is to accelerate the development of a robust and sustainable cleantech industry within the country, thereby positioning the United States as a leader in the global race for clean technology and energy transition [7]. From that perspective, the IRA seeks to build integrated domestic supply chains by offering tax credit incentives to E.V. manufacturers based on U.S. soil and matching domestic mining and processing requirements. It is a slimmed-down version of the Build Back Better bill and was voted in Aug 2022 but still makes the largest investment in combating climate change in U.S. history. It has several components (IRS, prescription drug price reform, corporate minimum tax, ACA extension) but mainly includes energy security and climate change investments ($369 Bn out of $433 Bn): tax credits for households to offset energy costs, investments in clean energy production and tax credits aimed at reducing carbon emissions.

The IRA will impact directly and indirectly the national critical materials demand, both from domestic and international sourcing. Indeed, the support for clean energy and national E.V. manufacturing using nationally sourced elements will increase the demand for both U.S. and globally sourced minerals (market pull) and direct push through subsidies and production incentives (Minerals Security Partnership, Infrastructure Law). These include:

- New "advanced manufacturing" tax credit for domestic production of critical minerals
- $500 million appropriation for "enhanced" use of the Defense Production Act
- Revised E.V.s tax credit to require regional sourcing of critical minerals used in E.V. batteries
- New authorization for $40 billion in loan guarantees which could be used to support development of manufacturing capacities for CM-consuming technologies and CM mining projects.

All these incentives directly and indirectly impact the mining and processing sector, and their effects can be classified as a dual push/pull dynamic:

Direct Minerals Production Support:

Tax Credit Incentives The IRA directly supports the mining industry with tax credit incentives for production. It names 50 "applicable critical minerals" for the energy transition in section 45X(c)(6), for which mining companies excavating them will be able to seek production credit equal to 10% of production costs. The extracted minerals must meet defined purity thresholds to qualify for the credit, as the act outlines. The list includes battery metals such as cobalt and lithium and several other s-block metals such as cesium and beryllium. The list also specifies almost all rare earth metals, including neodymium and other metals used in clean energy technologies like aluminum, tin, nickel, graphite, and chromium. The new tax credit would apply to several downstream products as well, including solar energy components, wind energy components, power inverters, and battery components. For these downstream products, the tax credit would begin to phase out in 2030 and would phase out completely by 2033. However, the tax credit for producing critical minerals would not be subject to a phase-out. The sponsors of the IRA estimate that this tax credit will result in tax expenditures of approximately $30 billion.

Direct Governmental Funding The IRA would appropriate $500 million for "enhanced use" of the Defense Production Act, concerning critical minerals to increase federal support for "domestic mining, beneficiation, and value-added processing of strategic and critical materials for the production of large-capacity batteries," including materials "such as lithium, nickel, cobalt, graphite, and manganese". This enables the Department of Defense ("DOD") to use DPA funds to encourage domestic mining and processing of such materials to support:

- Feasibility studies for mature mining, beneficiation, and value-added processing projects;
- By-product and co-product production at existing mining, mine waste reclamation, and other industrial facilities;
- Mining, beneficiation, and value-added processing modernization to increase productivity, environmental sustainability, and workforce safety.

Clean Energy-induced Market Pull

Subsidies Incentives for Domestically Sourced E.V.s Other tax incentives in the IRA are expected to position many clean energy technologies for deployment and spur investment in domestic supply chains. Most notable is consumer tax credits for electric vehicle (E.V.) purchases. The credits aim to make E.V.s more affordable, but their greatest impact lies in their requirement that a proportion of the battery minerals in qualifying vehicles must have been extracted or processed in the United States or free trade partner countries. More precisely, vehicles are only eligible for the $7500 credit if final assembly occurs within North America and no critical minerals are sourced from a "foreign entity of concern," including China and Russia. The tax credit is then split in half based on two further conditions:

1. A percentage of battery metal value must be extracted or processed in the United States or a partner country with a free trade agreement (FTA) or sourced from material recycled in North America (from 40% currently to 80% by 2027).
2. A proportion of battery components must be manufactured in North America (before 2024, at least 50% of the value of a US-made battery's components must come from North America. This rises to 60% in 2024 and 2025, 70% in 2026, and 10% more each year until reaching 100% in 2029).

E.V. consumer tax credits will increase producer demand for new sources of battery metals to capitalize on the provision. The Inflation Reduction Act, therefore, provides a needed investment signal for the diversification of critical materials supply chains (primarily for lithium, cobalt, nickel, manganese, and graphite) through its E.V. consumer tax credit mechanism. This market pull thus not only increases the overall demand for E.V.s by subsiding the price of E.V. vehicles, raising the overall demand for minerals but also indirectly subsidizes the domestic mining industry through U.S. sourcing requirements.

Support for Minerals-intensive Clean Energy Technologies The IRA will indirectly impact the mining industry through four key clean energy-related programs based on new Loan Programs Office (LPO, part of the DoE) provisions. The LPO finances large-scale, all-of-the-above energy infrastructure projects in the United States. LPO administers three distinct loan programs, but each offers a similar value to borrowers:

- LPO can provide first-of-a-kind projects and other high-impact energy-related ventures with access to debt capital that private lenders cannot or will not provide;
- LPO can provide flexible, custom financing that helps to meet the specific needs of individual borrowers;
- LPO encourages early engagement and is a valuable partner to applicants throughout the entire lifetime of a project.

More precisely, those loans usually cover several sectors, ranging from innovative fossil projects and clean energy projects to nuclear projects, all at commercial scale. They are structured around three vehicles:

- Energy Infrastructure Reinvestment (EIR) loans targetting projects that retool, repower, repurpose, or replace energy infrastructure that has ceased operations or enable operating energy infrastructure to run more cleanly. It provides also loan guarantees and grants to deploy carbon dioxide transportation infrastructure.
- Direct loans and partial loan guarantees for tribal energy development projects (TELGP);
- Direct loans to support U.S. manufacturing of fuel-efficient, advanced technology vehicles and qualifying components (ATMV).

Given the high material content of these technologies, this will significantly increase demand (through financial incentives and facilitation of projects) for minerals used in the associated manufacturing sectors.

1.3 Addressing Supply Challenges in the Clean Tech Transition

The transition to a clean technology economy presents a formidable challenge for the United States, underscored by a surging demand for critical materials essential for domestic renewable energy systems and electric vehicle manufacturing. These materials serve as the cornerstone for technologies that will define the future economy and are crucial for the U.S. to achieve its ambitious climate goals. The urgency is amplified by a strategic competition, particularly with China, which has integrated these materials into its national strategy to dominate future economic sectors. This context underscores the critical need for a comprehensive and integrated approach to manage critical materials supply chain effectively. Such strategies must not only address domestic imperatives for economic security, environmental sustainability, and national defense but also position the U.S. to maintain its leadership against a backdrop of intense global competition. However, current attempts in the public and private sectors to draw a comprehensive picture remain either superficial, or do not cover all aspects of the issue. This significant gap that contrast with the stakes highlights the need for further research work.

1.3.1 The Need for a Coordinated Strategy

The accelerating global shift towards green technologies underlines a critical challenge for the United States: a surge in demand for critical materials necessary for domestic renewable energy systems and electric vehicles manufacturing. These materials are the linchpins in the array of technologies that will power the future economy and are essential for the U.S. to meet its ambitious climate goals. Additionally, the context of a systematic race for leadership with China that has a tremendous edge in the sector makes the issue too important to be left out of main energy or industrial policies. It is therefore imperative for the United States to develop comprehensive and integrated strategies to manage its critical materials supply.

Domestic Imperatives for Integrated Strategies

The domestic need for an integrated strategy to manage critical materials stems from multiple imperatives that underpin the United States' transition to a green economy. As industries such as renewable energy and electric vehicles become central to economic growth, the availability and control of essential materials like lithium, cobalt, and rare earth elements become crucial.

- **Economic Security:** A stable supply of critical materials is fundamental for the health and expansion of key sectors driving future economic growth [40]. Without a secure and sustainable supply chain, the U.S. risks falling behind in global markets and losing economic competitiveness.
- **Environmental Goals:** Meeting the targets set under international agreements like the Paris Agreement requires effective deployment of clean technologies that rely heavily on critical materials [32]. Integrated strategies ensure that environmental goals are met through sustainable practices that do not shift the burden from carbon emissions to mining-related ecological damage.
- **National Security:** Reliance on critical materials from geopolitically sensitive regions introduces vulnerabilities for key defence, economic and energy applications [41]. By developing robust domestic capabilities, the U.S. can reduce these risks and enhance its geopolitical stability.

A comprehensive, integrated strategy would align exploration, extraction, processing, and recycling of critical materials, ensuring that these processes support the U.S.'s economic goals while adhering to environmental standards. This requires a collaborative framework involving government agencies, industry leaders, and academic institutions to foster innovation, regulatory reform, and infrastructure development.

Global Competition and Strategic Imperatives

The global competition for dominance in the critical materials market, particularly with China, underscores the necessity for the U.S. to enhance its strategic posture. China's strategic integration of these materials into its national policies is aimed at dominating the supply chains that will fuel future economies [42] and weakens American leadership.

- **China's Strategic Momentum:** China has strategically maneuvered to dominate the global supply chain of critical materials through heavy investments in mining and processing capabilities, which is part of its broader industrial strategy to lead in future technologies.
- **Block Logic:** In response, the U.S. must develop a cohesive strategy that not only strengthens domestic production capabilities but also leverages international

alliances to diversify sources and reduce dependency on single points of failure [9].

- **Technological and Economic Leadership:** The U.S. must assert its leadership in the development and deployment of clean technologies by spearheading international collaborations and setting global standards [43]. This would not only secure critical supply chains but also position the U.S. at the forefront of the global economic transition towards sustainability.

To maintain technological and economic leadership in the global clean tech industry, the U.S. must adopt proactive strategies that integrate domestic needs with global dynamics, and address the current shortcomings in the sector.

1.3.2 Preliminary Mapping of Issues

The United States, poised at the frontier of the green technology revolution, faces a strategic imperative to secure a stable supply of critical materials necessary for the widespread adoption of renewable energy technologies and electric vehicles. There have been a few attempts to map the challenges faced by the sector across different type of stakeholders. These key findings from academic studies, industry reports, and government documents constitute a good first proxy for mapping the existing challenges and potential recommendations to address these shortcomings in the critical materials sector.

Government Reports and Strategic Documents

Government strategic documents such as the "Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals" (2020) [44] highlight the vulnerability of the U.S. supply chain for critical minerals such as lithium, cobalt, and rare earth elements. These reports underscore the national security risks associated with heavy reliance on foreign sources, particularly from geopolitically sensitive regions like China [41]. The U.S. Department of Defense (DoD) and the Department of Energy (DoE) have pointed out the necessity for enhancing domestic mining capacities and processing facilities to reduce import dependency and mitigate supply chain disruptions [9], [45].

Academic and Industry Analysis

Articles and industry analyses provide a granular understanding of the challenges at various stages of the critical material supply chain. For instance, studies by researchers such as [27] and [30] discuss the technological and economic barriers to substituting critical materials and improving recycling rates. Most of the studies often criticize the lack of comprehensive policy frameworks that integrate mining, processing, and end-of-life management of critical materials. They also point the need for adopting more efficient and responsible practices to meet demand needs [46].

Market Dynamics and Economic Implications

The International Energy Agency (IEA) and various economic forecasts emphasize the growing demand for critical materials driven by the global push towards decarbonization [24], [32], [47]. They often contain projections about market demand and supply scenarios up to 2050, illustrating potential shortages if current production capacities are not expanded. These documents also point out the economic implications of price volatility in critical materials markets, which could undermine the affordability and scaling up of green technologies.

Policy Recommendations

To address these challenges, several policy recommendations have been put forward:

- **Enhanced Federal Investment:** Calls for increased government investment in research and development (R&D) to innovate more efficient recycling technologies and less material-intensive clean technologies [40].

- **Strategic Alliances and Partnerships:** Advocating for stronger international cooperation with countries that have significant reserves of critical materials, such as Canada and Australia, to diversify supply sources [32], [47].

- **Regulatory Reforms:** Recommendations for streamlining permitting processes for new mining and processing projects to reduce lead times and increase production capacity [44], [48].

- **Economic Incentives:** Proposals for subsidies, tax incentives, and financial support for domestic producers of critical materials to encourage investment in this sector [9], [44], [45], [48].

The existing literature and strategic documents reveals a clear consensus on the need for a multi-faceted approach to secure the critical materials supply chain in the United States. While significant strides have been made in identifying the core issues, there remains a substantial gap in implementing cohesive strategies that align national security, economic, and environmental objectives. According to this preliminary mapping, future research and policy efforts must focus on bridging these gaps, with a particular emphasis on fostering innovation, enhancing supply chain resilience, and promoting sustainable mining practices.

1.3.3 Absence of a Comprehensive, Detailed Global Plan

Despite the acknowledged urgency and strategic necessity of securing critical material supplies for the United States' clean technology industries, there remains a conspicuous absence of comprehensive, integrated planning and policy-making. This gap is evident in both the academic literature and government strategic documents, which often provide fragmented insights without a cohesive strategy or highlight specific challenges as highlighted in the previous section.

Lack of Detailed US-specific Analysis and Comprehensive Planning

Current strategic publications reveals a significant deficiency in detailed, actionable plans that encompass the entire supply chain of critical materials. Academic studies and industry reports frequently discuss the potential risks and solutions in segments such as mining or recycling but fall short of addressing the full spectrum of challenges and opportunities in a unified and cohesive framework.

- Fragmented Policy Approaches: Most governmental and industry strategies are narrowly focused on specific aspects such as increasing domestic production like the *Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals* [44], enhancing recycling capabilities, or solely identify criticality points like the Department of Defense [41]. There is a notable lack of a unified strategy that ties together mining, processing, manufacturing, usage, and end-of-life management of critical materials, even in non-governmental work such as reports from McKinsey & Company [40] and Brookings Institution [49] or even the International Renewable Energy Agency (IRENA) [12] that restrains the analysis to geopolitical considerations.

- Insufficient Depth in Strategic Analyses: Even comprehensive reports from major agencies often lack depth in their strategic analysis, offering broad guidelines without delving into the specifics necessary for actionable policy formulation [9] or not focusing on the scope of the US [32], [47].

Insufficient Policy Action and Guidance

Current policy frameworks and guidance documents from key governmental bodies do not adequately address the multifaceted nature of the critical materials challenge. While there are numerous initiatives aimed at securing critical materials, they typically do not provide the detailed, sector-specific pathways needed for a coordinated and effective response.

- Lack of Sector-Specific Roadmaps: There is a critical need for detailed, sector-specific roadmaps that lay out clear, step-by-step actions to achieve the strategic objectives related to critical materials. If some offer direct guidance on policy action like the U.S. Government [44], they however fail to provide supporting analysis to justify prioritisation or encompass only one sub-category of action. Current policies often lack these detailed roadmaps, resulting in piecemeal efforts with limited overall effectiveness [42].
- Policy Silos and Lack of Coordination: Efforts to secure critical materials frequently suffer from a lack of coordination among various government departments and between the public and private sectors. This results in disjointed initiatives that fail to leverage synergies across different segments of the supply chain [43].

1.3.4 Future Research Needs

Given the strategic gaps identified current approaches to CM policy frameworks, there is an emerging consensus on the need for comprehensive research and nuanced policy-making that addresses the entire lifecycle and supply chain of critical materials. First, future research should aim at providing a comprehensive analysis of supply chain vulnerabilities and opportunities from mining to recycling. This research should include evaluating the economic, environmental, and social impacts of various strategies [50]. Additionally, there is a need for integrated policy development that considers the interdependencies of the issues that resulted of the analysis, and their projection in the next decades given potential policy action. This approach would ensure that policies are not only reactive but also proactive, addressing potential future challenges and leveraging emerging opportunities [49].

The absence of comprehensive, detailed planning and adequate policy guidance for managing the U.S.'s critical material needs poses a significant risk to the country's clean technology ambitions. Addressing these gaps through cohesive, informed, and proactive strategies will be crucial and is the principal aim set for this thesis.

Chapter 2

Methods

The pressing need for a comprehensive and coordinated strategy to manage the critical materials is essential for powering the United States' clean technology ambitions. This thesis aims to bridge the identified gaps in current strategies by developing actionable policy recommendations informed by mapping the sector's challenges across the entire supply chain of critical materials thanks to a diverse range of methods. This chapter outlines the methodological approach, which combines qualitative and quantitative analyses to assess the economic, environmental, and technological aspects of critical material supply chains. Through this multi-faceted investigation, the thesis aim to develop a robust framework that not only addresses current deficiencies but also anticipates future demands and challenges in the critical materials sector. The principal aim there is to provide the necessary elements for articulating a complete policy action strategy.

2.1 Scope

First to be defined for the methodology is the scope of the thesis. It encompasses several dimensions including geographic focus, temporal range, and the specific materials and technologies under examination. By clearly defining these parameters, the thesis aims to provide a structured and targeted analysis, ensuring that the findings are relevant, precise, and actionable. This section outlines these aspects in detail, setting the stage for a comprehensive exploration of the challenges, opportunities, and strategic imperatives.

2.1.1 Critical Materials selection

The U.S. Department of the Interior, through the U.S. Geological Survey (USGS), periodically publishes a list of critical minerals. This list often includes minerals like lithium, cobalt, rare earth elements, vanadium, and uranium, which are selected if essential for various industries, including technology, defense, and energy. The European Commission also publishes its list of critical raw materials (CRMs), updated every few years. These materials are considered crucial for the E.U.'s economy and have a high risk associated with their supply. Finally, the IEA, particularly in the context of energy transition and renewable energy technologies, identifies several minerals as critical for achieving the energy transition. These include lithium, cobalt, nickel, copper, and rare earth elements, vital for batteries, wind turbines, and solar panels. Other countries, like Canada, Australia, and Japan, also have their lists of critical minerals, often overlapping with the U.S. and E.U. lists but tailored to their specific economic and strategic interests.

In that regard, four main minerals were selected as they were prevailing globally and do not have significant technology alternatives to reduce reliance: they can be considered critical (both in terms of clean technology applications and risk) and systemic.

- Cobalt is a key element in the energy transition, mainly due to its critical role in producing lithium-ion batteries, which power electric vehicles (E.V.s) and energy storage systems. These batteries rely on cobalt for their longevity, energy density, and recharge capabilities. As the world increasingly adopts renewable energy and E.V.s, the demand for cobalt is expected to rise significantly. However, cobalt mining is heavily concentrated in the Democratic Republic of Congo, which raises concerns about supply stability, ethical sourcing, and political risks. Although efforts are underway to reduce cobalt content in batteries, currently, limited substitutes offer the same performance characteristics, making cobalt a systemic material with limited alternatives.

- Copper's significance in the energy transition stems from its crucial use in renewable energy systems, such as wind turbines and solar panels, the needed increase in transmission to connect those renewables to demand sources, and its extensive application in E.V.s, particularly in electric motors and batteries. It also plays a vital role in the broader electrification of energy systems. The demand for copper is anticipated to increase sharply, driven by its indispensable role in these technologies. Copper production, however, faces geopolitical and supply chain vulnerabilities as it is concentrated in a few countries. This, coupled with the fact that there are few effective substitutes for copper, especially considering its superior electrical and thermal conductivity, underscores its criticality in the energy transition.

- Lithium stands out as a critical component in the shift to sustainable energy, primarily due to its use in lithium-ion batteries, which are essential for E.V.s and energy storage systems. The accelerated adoption of E.V.s is expected to surge the demand for lithium. The production and processing of lithium are concentrated in a few countries, potentially leading to supply bottlenecks. Currently, no viable alternatives can match the energy density and efficiency of lithium-ion batteries, making lithium a systemic material with significant implications for the energy transition.
- Nickel is vital for the energy transition, especially for its use in lithium-ion batteries, contributing to their energy density and overall performance. It is particularly important in high-nickel cathode chemistries such as nickel-cobalt-aluminum (NCA) and nickel-manganese-cobalt (NMC), used in E.V. batteries. With the shift towards these high-nickel battery chemistries in E.V.s, the demand for nickel is expected to increase significantly. Nickel mining and processing are concentrated in specific regions, posing supply disruption risks. Current efforts to find alternative battery chemistries have yet to yield substitutes for nickel in high-energy-density batteries, emphasizing its critical role in the energy transition.

The main drivers for the increased demand for cobalt, copper, lithium, and nickel are closely linked to the global transition towards sustainable energy. In particular, as governments worldwide push for stricter regulations on vehicle emissions and aim to accelerate the adoption of clean transportation like the U.S. with a 50% E.V. share of sales by 2030 and the conventional car ban in Europe in 2035, the demand for these minerals is set to surge. Cobalt's demand is primarily fueled by its essential role in lithium-ion batteries used in E.V.s and energy storage systems, where it enhances energy density and battery longevity. Copper's surge in demand stems from its extensive use in renewable energy systems like wind turbines and solar panels and its crucial role in the electrification of energy systems, including its use for power transmission and distribution (i.e., the grid). Lithium's growing demand is directly tied to the burgeoning E.V. market, as it is a key component in lithium-ion batteries, which are also vital for stationary energy storage systems integral to renewable energy. Similarly, the increased demand for nickel is predominantly driven by its use in high-energy-density lithium-ion batteries, especially in E.V.s, where it contributes to enhanced battery performance and energy density.

2.1.2 Geographic Scope

The United States has been selected as the primary focus of this study, and the North American continent as a secondary geographical scope. Choosing the US as the primer choice is due to its significant role in the global clean technology market and its ambitious national goals for energy transition. As a leader in technological innovation and policy development, the U.S. sets precedents that influence global trends in renewable energy and electric vehicle (EV) adoption. Furthermore, the U.S. government's recent legislative actions, notably the Inflation Reduction Act (IRA), demonstrate a strong commitment to reshaping the country's energy infrastructure, which significantly impacts the demand for critical materials. The strategic emphasis on establishing a robust domestic clean technology industrial base underscores the critical need for a sustainable and secure supply chain of critical materials, making the U.S. an essential case study for addressing broader issues in critical materials management in other jurisdictions like the EU.

The considering Canada partially in the geographic scope of this study is justified by the strong economic and geopolitical ties between Canada and the United States, particularly in the context of critical materials and clean technologies. Canada is not only a major trading partner but also a key ally in securing North American energy independence and economic security. The country's vast reserves of critical minerals, especially nickel, are vital for the U.S. clean technology sector, and its advanced mining capabilities make it a strategic partner in the North American critical materials supply chain.

Canada's inclusion is also strategic from the perspective of developing a comprehensive North American critical materials strategy as most exploited resources are sitting on the border. This approach aligns with both nations' goals to enhance their manufacturing capacities and reduce reliance on geopolitically sensitive regions for raw materials, and is coherent given the Free-Trade provisions of the IRA [7]. By considering Canada closely in this study, we can explore potential regional synergies and collaborative opportunities that could benefit the entire North American region in terms of supply chain resilience, technological innovation, and sustainable mining practices.

Moreover, both the United States and Canada have similar environmental standards but different regulatory frameworks, which yield comparative insights on effective strategies for sustainable mining and materials processing. Given the relative proximity of the US with Canada compared to Mexico (economic, regulatory and industrial similarities), the US-Canada scope appears as the most relevant for the thesis goals. Indeed, exploring the environmental policies and practices of both countries provides valuable insights into how similar standards and challenges can be managed within a unified framework, thus offering a model for other regions with less integrated policies.

This geographic focus not only reflects the current economic realities but also positions the research to have practical impacts in enhancing regional competitiveness and environmental sustainability.

2.1.3 Time Scope

In this study, the temporal scope extends from historical perspectives to projections up to the year 2050. This extensive time frame is essential for several reasons. First, examining the past enables us to understand the evolution of critical materials' roles in technology and industry, offering insights into how past challenges were managed and how policies have shaped the current landscape. This historical analysis helps identify trends and cycles in material demand, production capacities, and technological advancements, which are crucial for grounding future projections in empirical data.

The current situation provides a snapshot of ongoing developments in technology, market dynamics, policy environments, and geopolitical scenarios. It allows us to assess the immediate impacts of recent policy decisions, such as the U.S. Inflation Reduction Act, and to understand current challenges and opportunities within the critical materials supply chain. This analysis is vital for identifying leverage points for policy interventions and for benchmarking the U.S. and Canada's positions within the global context.

Looking forward to 2050 is critical given the long lead times for developing mining capacities, processing facilities, and full-scale commercial deployment of clean technologies. Projections until 2050 enable us to align with the long-term goals set by major international agreements like the Paris Agreement and anticipate the future needs of the clean technology sectors, including renewable energy and electric vehicles. This coincides with most of the current projections for technology deployments as well as the current time horizon of policy action employed by governments for integrative energy and industrial policies. This forward-looking perspective is crucial for crafting strategies that ensure a sustainable and resilient supply of critical materials, capable of supporting the anticipated massive expansion of green technologies.

2.2 Quantitative Methods

In this thesis, we employed two quantitative economic models to model the dynamics of critical materials supply. The first model is a macroeconomic model used to quantify the impacts of critical materials on the economy, while the second model aims at characterizing the dynamics of investments and expansion of this extractive industry.

2.2.1 Macroeconomic Model

To characterize the impact of materials price shocks on the US economy, this thesis adopts a macroeconomic model to compare long term effects of oil and materials price disruptions.

Introduction

Global economies have traditionally been tethered to the oil and natural gas sectors, rendering them susceptible to fluctuations in commodity prices. Oil shocks, characterized by abrupt spikes in prices, have historically yielded profound macroeconomic repercussions, including but not limited to inflation, unemployment, and even recession [51], [52]. Such shocks perturb consumer spending patterns, trigger sectoral declines, and can induce significant fiscal and monetary policy shifts [53]. However, the global landscape is undergoing a tectonic shift towards a new paradigm of energy systems that are less reliant on consumable commodities and more dependent on material capital like lithium, cobalt, and rare earth elements [54]. This transformation alters the economic dynamics of energy markets, as it emphasizes upfront investments in materials and technologies that, once deployed, have relatively low marginal running costs [55]. As economies grow more reliant on these concentrated material assets, concerns regarding commodity price shocks have surfaced across the public and political debate.

However, these concerns might manifest differently than traditional oil shocks. Unlike oil, where price fluctuations impact the cost of using existing capital, mineral price shocks principally affect the cost of new capital [56], including final goods (infrastructure, consumer goods) but not their direct use. This inherent difference in capital nature mitigates their immediate macroeconomic impact, as companies and economies at large can opt to delay investments in new capital, thereby circumventing immediate disruptions [56], but slows adoption of new processes and infrastructure, leading to a "technological and consumption advancement delay".

The study of commodity shocks, particularly those emanating from oil and mineral markets, has produced a wealth of economic models seeking to capture their nuances and implications. These models range from those that integrate oil price shocks into macroeconomic frameworks to more specialized models that focus on the unique aspects of mineral markets. For instance, Blanchard and Gali [57] demonstrate how oil price increases lead to stagflation, Krugman [58] and Baumeister and Kilian [59] on how it affects the exchange rate and creates a wealth transfer from oil-importing to oil-exporting countries and Jorgenson [60] argues that it forces an economy to operate below its potential (production efficiency). While models of oil price shocks are well-established, those for mineral price shocks are less developed, reflecting the emerging significance of these commodities. Mathieux, Ardente, Bobba, *et al.* [61] quantifies supply chain risks due to concentration. Bui, Mayer, and Zignago [62] suggests that firms may defer investment in new projects in response to mineral price volatility, which contrasts with the more immediate consumption-based impacts of oil price shocks while Maxwell [63] predicts that price shocks could eventually lead to technological stagnation and economic decline if alternative sources or substitutes for these minerals are not found. Aghion, Dechezleprêtre, Hémous, *et al.* [64] add to this by examining how carbon taxes and directed technical change in response to mineral price shocks can influence long-term economic competitiveness and growth. As the literature suggests that oil and commodities shocks are very different in how they impact the economy, this thesis develops a comparative model to asses how they would vary which is key to adapting classic oil policy measures to critical materials.

The model builds off the work of Schubert and Turnovsky [65] who study the impact of oil price shocks on the economy. The goal is to extend this analysis to be able to study the impact of critical mineral price shocks. The main modeling hypothesis is derived from the literature for the foundation of the model: an oil price shock affects the cost of using existing capital (e.g., cars) while a critical mineral price shock affects the cost of building new capital (e.g., EVs) but does not affect the price of using existing capital.

Model Structure

To represent this dynamic, the model considers a one-sector economy with production function $Y = F(K, L, Z)$.

The representative agent maximizes the present value of utility derived from consumption C and leisure l, with the utility function given by:

$$\int_0^\infty \frac{1}{\gamma}[Cl^\theta]^\gamma e^{-\beta t} dt$$

where:

- C is consumption.
- l is leisure, with $l \equiv 1 - L$ where L is labor.
- γ, θ, and β are parameters of the utility function.

Constraints

The optimization is subject to two primary constraints: the capital evolution constraint and the budget constraint.

Capital Evolution Constraint The change in capital stock over time is determined by investment I minus the depreciation and dilution due to population growth:

$$\dot{K} = I - (n + \delta)K$$

where:

- n is the population growth rate.
- δ is the depreciation rate of capital.

The shadow cost variable associated with that constraint is k.

Budget Constraint The change in the representative agent's bond holdings reflects the balance of income sources and expenditures:

$$\dot{B} = (r - n)B + C + pZ + (1 - m + mw)I + h\frac{(I)^2}{2K} - F(K, L, Z)$$

The shadow cost variable associated with that constraint is λ.
where:

- r is the real interest rate, equal to $r^* + e^{\eta \cdot \frac{B}{qK}} - 1$, with q being the cost of equity equal to the value of capital in terms of bonds $\frac{k}{\lambda}$. The agent takes it as given.
- B represents the bond holdings.

- pZ reflects the cost of oil imports.
- $(1 - m + mw)I + h\frac{(I)^2}{2K} = \Phi(I, K)$ is the total cost of investment, including costs related to capital adjustments.
- mw is the impact of minerals prices on investments costs, with w being the aggregated price of minerals and m the weight of materials in the economy.
- $F(K, L, Z)$ is the production function, representing the output of the economy: $Y = F(K, L, Z) = A[\alpha_K K^{-\rho} + \alpha_L L^{-\rho} + \alpha_Z Z^{-\rho}]^{-1/\rho}$, where $\alpha_K + \alpha_L + \alpha_Z = 1$.

Optimization Problem

The representative agent maximizes their utility at each time, subject to the capital evolution constraint and the budget constraint. The utility maximization problem is expressed as:

$$\max_{C,l,K,Z,B,I} \frac{1}{\gamma}[Cl^\theta]^\gamma \tag{2.1}$$

at each time t.

subject to:

$$\dot{K} = I - (n + \delta)K, \tag{2.2}$$

$$\dot{B} = (r - n)B + C + pZ + \Phi(I, K) - F(K, L, Z). \tag{2.3}$$

First-Order Conditions

The Hamiltonian H incorporating the objective function and the constraints with their respective shadow prices (ψ for capital and λ for the budget) is:

$$H = \frac{1}{\gamma}[Cl^\theta]^\gamma + k[I - (n + \delta)K] - \lambda[(r - n)B + C + pZ + \Phi(I, K) - F(K, L, Z)] \tag{2.4}$$

Where k is the shadow price of capital and λ is the shadow price of the budget or the wealth.

To maximize utility, we need to find the conditions where the derivative of the Hamiltonian with respect to each control variable is zero. For our model, the control variables are C, l, K, Z, B and I. We'll also need to derive the conditions for the evolution of the shadow prices (k and λ) and their ratio $q = \frac{k}{\lambda}$.

FOCs for Control Variables:

1. **Consumption** (C)**:** The first-order condition for consumption is given by:

$$\frac{\partial H}{\partial C} = [Cl^{\theta}]^{\gamma-1}l^{\theta} - \lambda = 0 \tag{2.5}$$

   This leads to the consumption rule:

$$C^{\gamma-1}l^{\theta\gamma} = \lambda \tag{2.6}$$

2. **Leisure** (l)**:** The first-order condition for leisure is:

$$\frac{\partial H}{\partial l} = \theta C^{\gamma}l^{\theta\gamma-1} - \lambda F_L = 0 \tag{2.7}$$

   Which simplifies to:

$$\theta\frac{C}{l} = F_L \tag{2.8}$$

3. **Investment** (I)**:** The first-order condition for investment is:

$$\frac{\partial H}{\partial I} = k + \lambda\left(1 - m + mw + h\frac{I}{K}\right) = 0 \tag{2.9}$$

   Which simplifies to:

$$q = 1 - m + mw + h\frac{I}{K} \tag{2.10}$$

4. **Oil** (Z)**:** The first-order condition for Oil is:

$$\frac{\partial H}{\partial Z} = -\lambda(p - F_Z) = 0 \tag{2.11}$$

   Which simplifies to the following equation:

$$p = F_Z \tag{2.12}$$

FOCs for State Variables (applying the maximum principle):

1. **Debt** (B)**:** Given that the agents take the interest rates as given, the first-order

condition for Debt is:

$$\frac{\partial H}{\partial B} = -\lambda(r-n) \tag{2.13}$$

For the shadow price of the budget or wealth λ, the evolution is:

$$\frac{\dot{\lambda}}{\lambda} = \beta - (r-n) \tag{2.14}$$

2. **Capital** (K)**:** Similarly, the first-order condition for Capital is:

$$\frac{\partial H}{\partial K} = k(n+\delta) + \lambda\frac{\partial F}{\partial K} - \lambda\frac{\partial \Phi(I,K)}{\partial K} \tag{2.15}$$

For the shadow price of capital k, the evolution is given by:

$$\dot{k} = -\frac{\partial H}{\partial K} = -\left(k(n+\delta) - \lambda\frac{\partial F}{\partial K} + \lambda\frac{\partial \Phi(I,K)}{\partial K}\right) \tag{2.16}$$

Hence:

$$\frac{\dot{k}}{k} = (n+\delta) - \frac{F_K}{q} - h\frac{I^2}{2qK^2} \tag{2.17}$$

Which is equivalent to:

$$\frac{\dot{q}}{q} = r + \delta - \frac{F_K}{q} - \frac{hI^2}{2qK^2} \tag{2.18}$$

Note: here I would expect $r + delta - \beta$. Justification: consistency with the principles guiding the dynamics of q that reflects the ratio of shadow prices and its dynamics should intuitively capture the net effect of economic forces on capital valuation relative to the budgetary valuation)

Dynamic equations:

- **Budget function:**

  From the FOC for oil and Labor, we can substitute Z and C from the marginal condition:

$$Z(p,K,L) = \omega^Z(p,K,L)$$

Where $\omega^Z(p,K,L)$ is solved numerically from the expression $p = F_Z(K,L,Z)$

$$C(l, K, Z) = \omega^C(l, K, \omega^Z) = \frac{1}{\theta} l F_L(K, L, Z) = \frac{1}{\theta} l F_L(K, L, Z(p, K, L)) = \omega^C(K, l)$$

$$I(q, K) = K \frac{q - (1 + m(w-1))}{h}$$

Given that

$$\Phi(I, K) = I + \frac{h(I)^2}{2K}$$

and

$$F(K, L, Z) = A\left[\alpha_K K^{-\rho} + \alpha_L L^{-\rho} + \alpha_Z Z^{-\rho}\right]^{-1/\rho},$$

we can now substitute the expressions for Z, C, and I into the equation for $\dot{B}$. First, let's rewrite the equation for $\dot{B}$ for clarity:

$$\dot{B} = (r - n)B + C + pZ + \Phi(I, K) - F(K, L, Z)$$

Substituting the expressions for C, Z, and I, we get:

$$\begin{aligned}\dot{B} &= (r - n)B + C + pZ + \Phi(I, K) - F(K, L, Z) \\ &= (r - n)B + \omega^C(l, K, \omega^Z) + p\omega^Z(p, K, L) + K\frac{(q - m(w-1))^2}{2h} \\ &- A\left[\alpha_K K^{-\rho} + \alpha_L L^{-\rho} + \alpha_Z \omega^Z\right]^{-1/\rho}\end{aligned}$$

This equation now only depends on K, L, Z, and B.

- **Capital function:**

  By substituting the investment FOC expression to the capital accumulation constraint we can obtain:

$$\frac{\dot{K}}{K} = \frac{q - 1 - m(w-1)}{h} - (n + \delta) \tag{2.19}$$

- **Arbitrage condition:**

  From the Capital FOC, we substitute I:

$$\frac{\dot{q}}{q} = r + \delta - \frac{F_K(K, l, \omega^Z)}{q} - \frac{(q - 1 - m(w-1))^2}{2hq} \tag{2.20}$$

- **Leisure function:**

  From deriving the log of the Consumption FOC we obtain:

  $$(\gamma - 1)\frac{\dot{C}}{C} + \theta\gamma\frac{\dot{l}}{l} = \beta - (r - \delta)$$

  We couple it with the time derivative of the log of $C = \omega^C(K, l)$ that yields

  $$\frac{\dot{C}}{C} = K\frac{\frac{\partial\omega^C(K,l)}{\partial K}}{\omega^C(K,l)}(\frac{\dot{K}}{K}) + l\frac{\frac{\partial\omega^C(K,l)}{\partial l}}{\omega^C(K,l)}(\frac{\dot{l}}{l})$$

  and obtain:

  $$\frac{\dot{l}}{l} = \frac{r - (\beta + n) - K(1-\gamma)\frac{\omega^C_K(K,l)}{\omega^C(K,l)}\left(\frac{q-1-m(w-1)}{h} - (n+\delta)\right)}{(1-\gamma)l\frac{\omega^C_l(K,l)}{\omega^C(K,l)} - \theta\gamma} \tag{2.21}$$

Steady state equilibrium By zeroing every time derivatives in the dynamic equations, we obtain the following equations for the 10 endogenous variables (W, K, B, C, L, l, Z, Y, I, r, q):

1. $W_0 = \frac{1}{\gamma\beta}C_0^{\gamma}l_0^{\gamma\theta}$
2. $r_0 = \beta + n$
3. $r_0 = r^* + e^{\frac{\eta B_0}{q_0 K_0}} - 1$
4. $q_0 = (n + \delta)h + 1 + m(w - 1)$
5. $l_0 + L_0 = 1$
6. $Y_0 = F(K_0, L_0, Z_0)$
7. $F_Z(K_0, L_0, Z_0) = p$
8. $C_0 = \frac{1}{\theta}l_0 F_L(K_0, L_0, Z_0)$
9. $\beta + n + \delta = \frac{F_K(K_0,L_0,Z_0)}{q_0} + \frac{(q-1-m(w-1))^2}{2hq}$
10. $\beta B_0 + C_0 + pZ_0 + K_0(n + \delta + h(n+\delta)^2) = Y_0$
11. $I_0 = (n + \delta)K_0$

Numerical simulation

List of Parameters To calibrate the model for the simulations, benchmark values from the literature and initial paper were used. They are represented in the Table 2.1.

Table 2.1: Parameters of the macroeconomic model

Parameter	Description	Value
γ	Relative risk aversion	-1.5
β	Time discount rate	0.04
θ	Leisure preference parameter	1.75
A	Total factor productivity	1
δ	Depreciation rate of capital	0.05
$\alpha_1, \alpha_2, \alpha_3$	Production function parameters	0.35, 0.6, 0.05
σ	Elasticity of substitution	1.5
m	Contribution share of investment in capital	0.14
h	Investment cost dependency rate	12
r^*	World interest rate	0.045
η	Borrowing premium parameter	0.1
n	Population growth rate	0.015
p, w	Initial prices of oil and capital	1 at t_0 (doubles for $t > 0$)

Simulations Because finding exact analytic solutions for each variable is very challenging, a numerical approximation solver is employed to compute the Steady State Equilibrium. For the dynamic equilibrium, we solve for the systems of dynamic equations with the new values of price and set the initial sate values as the steady state equilibrium with initial prices.

2.2.2 Microeconomic Model

To characterize the extraction dynamics of mine operations, this thesis adopts a microeconomic model to examine mining operations, leveraging the conceptual framework of Hotelling's classic model coupled with a realistic operational extraction mechanism.

Introduction

Hotelling's theory of exhaustible resource extraction posits that forward-looking resource owners maximize wealth by balancing extraction today against future extraction, a principle applicable across various resource extraction industries including mining, that supposedly gives ground to future extraction decisions by individual mines given exogenous prices. Despite the elegance and theoretical appeal of the initial model [66], its empirical integration within the mining sector, much like in energy economics, has been limited and often inconclusive due to the unique operational and economic realities of mining. The literature on resource economics offers numerous alternatives to

Hotelling's model, from prey-predator models [67] to real options considerations [68] to integrate more realistic factors such as technological change, regulatory environments, and market dynamics which are critical for realistic modeling of mining operations. These studies underscore the necessity of adapting classical economic theories to reflect the complexities and specificities of modern mining operations, including the variable costs and the finite nature of mineral resources, but nevertheless none considers both the operational reality of mining and the underlying macro behaviour of market prices described in the original Hotelling paper, mostly because of poor empirical evidence supporting it [69].

To reconcile this, this thesis employs a model adapted from Anderson, Kellogg, and Salant [70] to mining. The proposed model is designed to address the above mentioned complexities by characterizing the operations of a single mining site, which simplifies the analysis but allows for a detailed exploration of economic and geological factors at a micro level, and then aggregates the production sites for an integral coverage. This site-specific approach enables the application of Hotelling's rules in a controlled environment, facilitating the analysis of how pressures like market fluctuations and resource depletion impact mining economics. The objective is to deliver clearly identifiable Hotelling rules at the extensive and intensive margins to account for both mine production and capacity expansion dynamics of the mining industry.

Key to this model is the introduction of an 'extractive constraint,' which adapts Hotelling's framework to the mining context where resource depletion significantly impacts extraction rates and costs over time. This constraint reflects the diminishing ore grades and the increasing difficulty of extraction within a site, aspects that are often overlooked in traditional models but are critical in mining.

Model Structure

We consider the production of a single material, which can be adjusted to response to market price signals through the extensive (increase of the production capacity) and intensive (increase of the assets utilization) marginal outputs with a pressure constraint that represents the statistic resource depletion rate.

The unit scale of the model corresponds to a single mining site. The characterization of the mine's economics doesn't follow a classic rule as its specificities encompass several geological, engineering and location aspects that are often complex, singular for each mineral extracted and are often studied case-by-case. For instance, the location of the mine can impact both the fixed and variable costs[1]. The geological characteristics

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[1] For example, mines in remote or difficult-to-access areas may require higher transportation costs

of the deposit, such as the depth of the ore body and the presence of impurities, can also impact the economics and business decisions as great depth requires more energy and equipment to extract, as well as different mining methods[2] that have a significant impact on the heterogeneity of the mining economics. If mines sites are often characterized by evolving ore grades distributions (decrease with time, increase with exploration), we assume in this model that a mine is characterized by a single value that represents the average quality of the resource, and hence it's accessibility (costs).

We consider here that mining operations consist in two main processes that can be separated: the opening of a new mine, represented by an upfront cost, and the exploitation, where marginal costs represent the larger share of the costs (labor, energy, storage mostly[3]). Mine costs are affected by the unit cost of capital r, labor w and energy e, and their needed quantity depend on geologic quality and accessibility of the site. We quantify this variation through the ore grade γ of the geological deposit (basin) and neglect other aspects such as depth or other significant factors: $c = cf(\gamma, r, w, e)$ and $mc = mcf(\gamma, r, w, e)$ as we assume that total labor $L(\gamma)$, capital $C(\gamma)$, and energy $E(\gamma)$ requirements only depend on γ. We consider capital r, labor w and energy e prices exogenous and constant within the scope of the US where mining operation requirements are defined by a certain ore grade.

We assume that the discount rate is equal to the cost of capital (capital depreciation rate) as it is often the practice in extractive industries with WACC-centric business models. Here we assume one unique costs of capital across the region studied and neglect variations across geographies (here considered within the scope of the US).

By first approximation, we neglect fixed extraction costs and assume constant marginal costs to scale. Similarly, opening costs are assumed constant to scale. They are associated with the development and construction of open-pit and underground mines. We also suppose a time granularity that is large enough to consider labor and services as variable costs as they are adjusted to match production expectations from one period to the other. We do not initially account for delays and inertia in initial mining openings, neither we account for fixed costs of closing/maintaining new

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for equipment and supplies, while mines in areas with high labor costs may require higher wages for workers.

[2] For example, open-pit mining may require less energy and equipment than underground mining, but it may also require more land and have a greater impact on the environment.

[3] According to Aguirregabiria and Luengo [71], the biggest contributors to production costs for copper are the storage costs, which accounted for roughly 33%, on average. Labor costs are the second most important component in production costs (24%) while other costs such as fuel and electricity make most of the remaining costs.

capacity.

Regarding the operations of the mine, we consider each mine to operate at a given ore grade level that remains constant throughout the exploitation of the mine, which is not observed in reality as average ore grades diminish with exploitation and increase with capacity increases in a single mine unit.

The main approximations to real operations can be summarised as such:

- Inertia is neglected, along with lead times and frictions for both operations (labor mobility for instance) and openings (no delays between mining investment and operational capacity expansion readiness). This hypothesis can hold only if the considered time-frame granularity is large (years), but also has other considerations over costs currently not included (fixed costs of operations are then considered variable as they adjust to the output over the long term) which is potentially in contradiction with the operational reality of sites (opening-closing cycle and its associated costs).

- Depletion of resources impact on capacity is linear and homogeneous across units, with a mine reserves corresponding to a specific capacity-years ratio of extraction capabilities. This is not representative of the exploitation of a mine but at the aggregated level, it corresponds to a statistical rate of depletion if ratios of capacities/reserves are homogeneous across the region.

- Exploitation and exploration of sites do not influence the ore grade of the resource exploited - considered constant in time at a defined site. This hypothesis can hold partially at the aggregated level under short periods of time, but not at the operational level of a site or basin.

- Storage in final state is not accounted and we only consider shadow storage by retention of reserves. This implies that there is no decoupling possible between the time of production and time of financial interaction with the market (selling the commodity).

We distinct each endogenous variable by capitalized letters. At a time t, the profit generated by the production units operating at a given ore grade γ is:

$$\pi(t,\gamma) = (p_t - mc_{t,\gamma})Q(t,\gamma) - c_{t,\gamma}S_{open}(t,\gamma) \tag{2.22}$$

With the exogenous variables:

- p_t the exogenous price of the commodity in the market

- $mc_{t,\gamma}$ the marginal cost of extraction of one unit of the mineral
- $c_{t,\gamma}$ the fixed costs of opening one new unit of extraction capacity

And the endogenous variables, which combination is chosen by the mining operator (planner) to maximize its utility: profits (π):

- $Q(t,\gamma)$ the total production of the mine
- $S_{open}(t,\gamma)$ the opening rate of new mining productive sites in capacity terms

Across time t, his goal is to maximize the sum of discounted profits π:

$$\max_{Q(t,\gamma),S_{open}(t,\gamma)} \int_{t=0}^{\infty} e^{-rt}\pi(t,\gamma)\,dt = \max_{Q(t,\gamma),S_{open}(t,\gamma)} \int_{t=0}^{\infty} e^{-rt}((p_t - mc_{t,\gamma})Q(t,\gamma) - c_{t,\gamma}S_{open}(t,\gamma))\,dt \tag{2.23}$$

Constraints

This maximization is done under the constraint of not exceeding the production capacity $C(t,\gamma)$ (reserves in exploitation) and non-exhaustion of both capacity of non-exploited resources in the mining site $US(t,\gamma)$ as well as total remaining reserves $R(t,\gamma)$:

$$0 \leq Q(t,\gamma) \leq C(t,\gamma) \tag{2.24}$$
$$S_{open}(t,\gamma) \geq 0 \tag{2.25}$$
$$R(t,\gamma) \geq 0 \tag{2.26}$$
$$C(t,\gamma) \geq 0 \tag{2.27}$$
$$\dot{U}S(t,\gamma) = -S_{open}(t,\gamma) \tag{2.28}$$
$$\dot{C}(t,\gamma) = S_{open}(t,\gamma) - F(C(t,\gamma), Q(t,\gamma)) \tag{2.29}$$
$$\dot{R}(t,\gamma) = -Q(t,\gamma) \tag{2.30}$$

Where F is the function that quantifies the impact of depletion of reserves on capacity of extraction. If F is assumed homotetic, it is equivalent to view mining operations as accessing the same resource with total accessibility of the same resource from all sites operations. Indeed, this might be true for liquids and gaz extraction as wells access the same resource, but it is not the case in the mining industry. It therefore requires to consider that extraction capabilities are entirely mobile across sites.

Therefore if $F(C(t,\gamma), Q(t,\gamma)) = \alpha Q(t,\gamma)$, α is approximated by ratio of $\frac{C_{ref}(t_0,\gamma)}{R_{ref}(t_0,\gamma)}$ of one reference mine site at the opening, equal to the inverse of the numbers of potential years of reserves at current production capacity, which appears to be almost constant over time and across materials (close to 2% or 50 years of production). This approximation is coherent with operations from a statistical point of view as at equilibrium with stable additions, capacities decrease at this average rate. Under that assumption, $\alpha R(t_0,\gamma) = US(t_0,\gamma)$ while $R(t_0,\gamma)$ is defined exogenously by the ore tonage $\tau(\gamma)$ available for production. This implies an indirect constraint on the sign of $US(t_0,\gamma)$: $US(t_0,\gamma) \geq 0$

Optimization Problem

The mine operators chose their production and expansion rates to maximize their utility (discounted sum of profits).

In the case of a homotetic function F, the current-value Hamiltonian-Lagrangian of the planner's maximization problem is given by:

$$H = e^{-rt}\pi(t,\gamma) + \theta(t,\gamma)(S_{open}(t,\gamma) - \alpha Q(t,\gamma)) + \phi(t,\gamma)(C(t,\gamma) - Q(t,\gamma)) + \psi(t,\gamma)(-S_{open}(t,\gamma)) \tag{2.31}$$

Where θ is the costate variable on the capacity, ψ on the reserves and ϕ is the shadow cost of the mining production constraint.

Additional necessary conditions of the maximization problem are:

$$For \quad Q(t,\gamma) \geq 0, \quad (p_t - mc_{t,\gamma}) - \alpha\theta(t,\gamma) - \phi(t,\gamma) \leq 0 \tag{2.32}$$

$$For \quad \phi(t,\gamma) \geq 0, \quad C(t,\gamma) - Q(t,\gamma) \geq 0 \tag{2.33}$$

$$For \quad S_{open}(t,\gamma) \geq 0, \quad \phi(t,\gamma) - \psi(t,\gamma) - c_t S_{open}(t,\gamma) \leq 0 \tag{2.34}$$

$$\dot{\psi}(t,\gamma) = r\psi(t,\gamma) \tag{2.35}$$

$$\dot{\theta}(t,\gamma) = r\theta(t,\gamma) - \phi(t,\gamma) \tag{2.36}$$

$$\lim_{t\to 0} C(t,\gamma)\theta(t,\gamma)e^{-rt} = 0 \tag{2.37}$$

$$\lim_{t\to 0} UR(t,\gamma)\psi(t,\gamma)e^{-rt} = 0 \tag{2.38}$$

Under dynamic exogenous prices (i.e. the US production remains relatively small compared to the world production - relatively low supply and demand price elasticity) and perfect competition assumptions, the aggregated level of production is given by:

$$Q_{total}(t) = \int_{\gamma_{min}}^{\gamma_{max}} Q(\gamma, t), d\gamma \tag{2.39}$$

Where $Q(\gamma, t)$ is the production output of the mine operating at the ore grade γ at t given by maximizing the profit in (10).

When profits are negative, the mine can still operate if the opportunity cost of closing the mine is higher than the sum of negative revenues over the period. The closing condition of a mine operating at the ore grade γ over a period of negative profits of of any duration Δ can be written as:

$$Cost_{closing} + Cost_{reopening} \leq \int_{t=t_0}^{t=t_0+\Delta} \pi(\gamma, t), dt \tag{2.40}$$

Hence over that period, $Q = 0$. Note that under the assumption of marginal costs for production (no fixed costs as labor, etc. can be considered as marginal over a long period), production will always lead to zero but the mine will remain open. Accounting for closing decisions therefore does not affect the equilibrium computed from (10) and can lead to a separate decision conditions once the optimal production path has been decided. With (19) we can thus identify each period where the mine will be effectively closed (production) and adjust the path consequently.

Extension

Out of the different assumptions, the most simplifying is the large time-frame setup that induces no fixed costs (salaries and storage costs are adjusted periods over periods) and no lead time for the mines capacities. However, they are characteristic of mining operations and expansions: the inertia is often presented as the main factor of risk for satisfying in time the increased needs for critical metals that are required for the energy transition. Accounting for this requires to switch from a uni-temporal model (static) to a multi-temporal model.

The equations (1) to (9) are impacted through (i) the profit $\pi(t)$ now encompasses fixed costs:

$$\pi(t, \gamma) = (p_t - mc_{t,\gamma})Q(t, \gamma) - fc_{t,\gamma}^{fixed}C(t, \gamma) - oc_{t,\gamma}S_{open}(t, \gamma) \tag{2.41}$$

With the exogenous cost variables that depend on γ, r, w and e:

- mc_t the marginal costs of extracting one unit of the considered mineral (energy and consumables costs mostly)
- fc_t the fixed costs of maintaining one unit of capacity (labor and storage costs mostly)
- oc_t the fixed costs of opening one new unit of extraction capacity

and (ii) the capacity constraint now integrates a lag δ_{lag} that corresponds to the lead time of setting up a new mining capacity:

$$\dot{C}(t,\gamma) = S_{open}(t-\delta_{lag},\gamma) - \alpha Q(t,\gamma) \tag{2.42}$$

With the amount of capacity at γ in preparation given by:

$$C_{developping}(t,\gamma) = \int_{t-\delta_{lag}}^{t} S_{open}(u,\gamma)du \tag{2.43}$$

With the introduction of lags in the capacity deployment, the maximization problem is equivalent as there is a perfect foresight of price levels: the lag can be written as an equivalent discounted cost correction applied to the cost of opening a new unit of capacity $oc_{t,\gamma}$ in the present:

$$\max_{Q(t,\gamma),S_{open}(t,\gamma)} \int_{t=0}^{\infty} e^{-rt}(p_t - mc_{t,\gamma})Q(t,\gamma) - fc_{t,\gamma}^{fixed}C(t,\gamma) - oc_{t,\gamma}^{lag}S_{open}^{lag}(t,\gamma)\,dt \tag{2.44}$$

With:

- $oc_{t,\gamma}^{lag} = oc_{t-\delta_{lag},\gamma}$
- $S_{open}^{lag}(t,\gamma) = S_{open}(t-\delta_{lag},\gamma)$

The problem can therefore be rewritten as the following objective-constraints equations set:

$$\max_{Q(t,\gamma),S_{open}(t,\gamma)} \int_{t=0}^{\infty} e^{-rt}[(p_t - mc_{t,\gamma})Q(t,\gamma) - fc_{t,\gamma}^{fixed}C(t,\gamma) - oc_{t,\gamma}^{lag}S_{open}^{lag}(t,\gamma)], dt \tag{2.45}$$

$$\dot{R}(t,\gamma) = Q(t,\gamma) \tag{2.46}$$

$$\dot{C}(t,\gamma) = S_{open}(t - \delta_{lag},\gamma) - \alpha Q(t,\gamma) \tag{2.47}$$

$$C(t,\gamma) = C_{developing}(t,\gamma) + \int_{t-\delta_{lag}}^{t} S_{open}(u,\gamma), du \tag{2.48}$$

$$R(0,\gamma) = R_0(\gamma) \tag{2.49}$$

$$C(t,\gamma) \leq C_{max}(\gamma) \tag{2.50}$$

$$S_{open}(t,\gamma) \geq 0 \tag{2.51}$$

$$Q(t,\gamma) \geq 0 \tag{2.52}$$

$$\int_{0}^{\infty} Q(t,\gamma), dt \leq R_{max}(\gamma) \tag{2.53}$$

$$oc_{t,\gamma}^{lag} = oc_{t-\delta_{lag},\gamma}^{lag} \tag{2.54}$$

$$S_{open}^{lag}(t,\gamma) = S_{open}^{lag}(t - \delta_{lag},\gamma) \tag{2.55}$$

where $oc_{t,\gamma}^{lag}$ represents the lagged open cost and $S_{open}^{lag}(t,\gamma)$ is the lagged open capacity, both with a lag of δ_{lag}.

The Hamiltonian for this problem is given by:

$$\begin{aligned} H(t,\gamma,Q,S,C,\lambda_Q,\lambda_S,\lambda_C) =& e^{-rt}(p_t - mc_{t,\gamma})Q - fc_{t,\gamma}^{fixed}C - oc^{lag}t,\gamma S^{lag}open \\ &+ \lambda_Q(\dot{Q} - Q_{prev} - \frac{1}{\gamma}S(t-\delta_{lag},\gamma)Q(t,\gamma)) \\ &+ \lambda_S(\dot{S} - S_{prev} + S^{lag}open(t - \delta lag,\gamma) - S(t,\gamma)) \\ &+ \lambda_C(\dot{C} - S(t-\delta_{lag},\gamma) + \alpha Q(t,\gamma)) \end{aligned} \tag{2.56}$$

Where Q_{prev} and S_{prev} are the values of Q and S at time $t - \Delta t$, and the dot notation denotes time derivatives. Here, the first line represents the immediate revenue and costs, the second line represents the inventory carrying and the third line represents the setup and running costs of extraction capacity. The following three lines represent the constraints in the problem, where λ_Q, λ_S, and λ_C are the Lagrange multipliers associated with the respective constraints.

We can simplify the expression of the problem by substituting the capacity constraint in the profit function.

Using the capacity constraint $\dot{C}(t,\gamma) = S_{open}(t-\delta_{lag},\gamma) - \alpha Q(t,\gamma)$, we can write $C(t,\gamma)$ as:

$$C(t,\gamma) = C_0(\gamma) + \int_0^t S_{open}(u-\delta_{lag},\gamma)du - \alpha \int_0^t Q(u,\gamma)du \tag{2.57}$$

where $C_0(\gamma)$ is the initial capacity at γ.

Substituting this expression of $C(t,\gamma)$ in the profit function, we get:

$$\begin{aligned}\pi(t,\gamma) = (p_t - mc_{t,\gamma})Q(t,\gamma)\\ -fc^{fixed}_{t,\gamma}\left[C_0(\gamma) + \int_0^t S_{open}(u-\delta_{lag},\gamma)du - \alpha \int_0^t Q(u,\gamma)du\right]\\ -oc_{t,\gamma}S_{open}(t,\gamma)\end{aligned} \tag{2.58}$$

The problem can now be expressed as:

$$\begin{aligned}\max_{Q(t,\gamma),S_{open}(t,\gamma)} \int_{t=0}^{\infty} e^{-rt}[(p_t - mc_{t,\gamma})Q(t,\gamma)\\ -fc^{fixed}_{t,\gamma}\left[C_0(\gamma) + \int_0^t S_{open}(u-\delta_{lag},\gamma)du - \alpha \int_0^t Q(u,\gamma)du\right]\\ -oc_{t,\gamma}S_{open}(t,\gamma)], dt\end{aligned} \tag{2.59}$$

with the constraint on $Q(t,\gamma)$ and $S_{open}(t,\gamma)$ being the same as before.

The Hamiltonian for the simplified problem with the capacity constraint replaced by the relationship $C(t,\gamma) = \int_{t-\delta_{lag}}^{t} S_{open}(u,\gamma)du$ is:

$$\begin{aligned}H = (p_t - mc_{t,\gamma})Q(t,\gamma) - fc^{fixed}_{t,\gamma}\int_{t-\delta_{lag}}^{t} S_{open}(u,\gamma)du - oc_{t-\delta_{lag},\gamma}S_{open}(t-\delta_{lag},\gamma)\\ +\lambda_t\Big(\dot{Q}(t,\gamma) - rQ(t,\gamma) + \alpha\lambda_t Q(t,\gamma) - \alpha C(t,\gamma)\Big)\\ +\mu_t\Big(\dot{S}_{open}(t,\gamma) - \gamma_t S_{open}(t,\gamma)\Big)\end{aligned} \tag{2.60}$$

where λ_t and μ_t are the costate variables associated with the quantity and opening rate constraints, respectively.

Since oc_t is given exogenously, the change of variable doesn't affect the maximization problem under certainty because of perfect foresight (deterministic model). In the case of constant fixed costs to capacity levels ($fc_{t,\gamma}^{fixed}C(t,\gamma)$ constant) the problem and first order conditions remain identical to the ones obtained in the first section.

First-Order Conditions

The conditions given by the hamiltonian (2.32, page 57) can be structurally interpreted as this:

- Condition (32) relates to the exploitation incentives. It signifies that if production is always non null, $\theta(t,\gamma)$ is the marginal value of an addition to capacity at time t and equals the additional stream of discounted revenues from the additional production capacity at a rate $r+\alpha$ which is the aggregation of both the financial discounting as well as a shadow physical discounting related to the aggregated exhaustion of the reserves (at a rate α, related to production). If it is optimal to shut in and thereby defer production to some future interval, doing so must generate even greater wealth than the discounted sum of future revenues. Increasing production at time t exhausts reserves (mining capacity) and hence tightens the constraint on future production at the rate α. α can therefore be interpreted as a rate of infra-marginal exhaustion of resources. Thus, $\alpha\theta(t,\gamma)$ captures the opportunity cost of a marginal increase in production at t in terms of forgone future revenue. This marginal cost is independent of the rate of current production, while the marginal benefit decreases in $Q(t,\gamma)$. If the marginal revenue is greater than the opportunity cost, the production constraint is saturated (production at the capacity constraint), while if its lower, then production stops. The interior point where the production is non null but remains unconstrained (i.e. not operating at capacity) is characterized with $\dot{\theta}(t,\gamma) = r\theta(t,\gamma)$ and the marginal utility rises in percentage terms at the discount rate as in the standard Hotelling model with zero extraction costs. As detailed in the original paper, this dynamic could explain why mines could still operate at full capacity even if the commodity price will (temporarily) rise faster than r, since the deferred production can't be completely recovered at the future instant in which it is most valuable due to the capacity constraints, but instead must be recovered over the full remaining life of the mine, including both the time period when the commodity price is higher than the current price in present value and the period when the commodity price is lower than the current price in present value.

- Condition (34) relates to the incentives for exploration. $\theta(t)$ is the value of one additional mining capacity, while ψ is the shadow value of the marginal undeveloped production capacity at time t, which increases at a rate r (condition 35): Intuitively, for someone to hold undeveloped sites instead of some other asset, its value must rise by at least the discount rate and can rise no faster, or else arbitrage would incentives untapped reserves ownership. Thus, when expansion occurs ($S_{open}(t,\gamma) > 0$), the marginal return ($\theta(t,\gamma) - c_{t,\gamma} S_{open}(t,\gamma)$) to adding a new unit of capacity must rise at the rate r. This is a classic Hotelling rule in its formulation, but that applies to marginal capacity additions value: constrained to a fixed mining potential (in reserves and therefore in extraction capacity or mining sites), the planner should expand so that the net marginal value of increasing its production capacity rises at the rate of interest. Thus, every mine in capacity terms yields the same net payoff in present-value terms and should be valued equally - at a given production cost level context (ore grade and access conditions).

- During a time while expansion is happening, production may be either at the constraint or below it even with no inertia for the mine openings. Such a plan can be optimal if more capacity in the future is desirable (expected increases of prices due to demand increases) and if, because mine expansion costs are increasing, it costs more to build that capacity over a short future interval when it will be fully utilized than over a longer period before it is utilized (indeed, it is not possible to instantaneously increase mining capacity without raising the cost of mine openings as there are limited availability of factors which reallocation is marked by inertia and scarcity frictions, be it capital through specialized machinery, specialized workforce, etc).

- Finally, the combination of the two constraints can be interpreted as following: whenever mines open while production is below capacity, the marginal cost of increasing mining capacity must rise at the rate of interest; and whenever mines open while production is capacity constrained, the marginal cost of drilling must rise at less than the rate of interest. In the case of affine fixed costs of mining capacity openings (rather than strictly convex), one can infer a standard Hotelling rule for an extraction model with a constant marginal extraction cost of $(r + \alpha) mc_{t,\gamma}$.

2.3 Qualitative Methods

In addition to the insights gleaned from economic modeling and qualitative analysis of the sector current dynamics, conducting in-depth case studies and facilitating industry roundtables offer unique advantages that significantly enhance our understanding of critical minerals issues. These methods provide granular, specific insights that are often unattainable through generalized quantification or open-source information. Case studies delve into the nuanced operational, environmental, and socio-economic dynamics of individual mining projects, revealing the intricate interplay of factors that drive success or failure. Meanwhile, industry roundtables bring together diverse stakeholders, fostering a rich dialogue that surfaces real-time challenges, innovative solutions, and strategic partnerships directly from those at the forefront of the industry. Together, these approaches complement and enrich our methodology, ensuring a comprehensive and relevant assessment of the sector and enabling the formulation of effective, informed recommendations. This multifaceted approach not only broadens this thesis perspective but also deepens its insights, making it indispensable for crafting policies that are both practical and impactful.

2.3.1 Case Studies

The selection process for case studies involved a rigorous methodology designed to ensure comprehensive coverage of the critical materials sector's complexities. Case studies were selected and developed by Abigail Randal based on several criteria: relevance to the energy transition, diversity in geographical and geopolitical contexts, and significance in the supply chain from mining to market. It strategically focuses on contrasting scenarios in the mine permitting process to provide a comprehensive view of the challenges and innovations within the industry. The Stillwater and East Boulder mines and the Twin Metals case were selected based on their distinct experiences and outcomes in navigating the permitting process, which encapsulates both success and contention. Here, we will only exploit their conclusions, as the attribution for the work remains to the Olivetti Group team. Two cases were selected:

Stillwater and East Boulder Mines

These cases exemplify successful application of best practices through the establishment of the Good Neighbor Agreement (GNA), the first of its kind in the United States. This agreement has proven effective in fostering long-term cooperative relationships between mining companies and local communities, ensuring ongoing compliance with environmental standards, and facilitating adaptive management practices that respond to emerging challenges.

Twin Metals Case

In stark contrast, the Twin Metals project illustrates the complexities and uncertainties inherent in the permitting process influenced by political and environmental dynamics. This case highlights the challenges faced when mining proposals become entangled in broader political and environmental debates, demonstrating the high degree of uncertainty and risk that can impede project development. These case studies were chosen to highlight the spectrum of potential outcomes in the mine permitting process and to provide insights into the factors that contribute to both successful and challenged project developments. The contrast between these cases offers valuable lessons on the impacts of community engagement, legal strategies, and regulatory environments.

2.3.2 Industry Roundtables

Industry roundtables form a critical component of the qualitative methodology, serving as platforms for direct engagement with key stakeholders in the critical materials sector. These roundtables are organized to gather insights from a wide array of participants, including industry leaders, technical experts, policymakers, and academia. The discussions are structured around several core themes: technological trends, market dynamics, regulatory challenges, and sustainability practices. This methodology facilitates a holistic understanding of the sector by collecting at the source diverse points of views, enhancing the relevance and applicability of the research findings.

The methodology for gathering industry perspectives was centered around the "Reimagining Resource Stewardship" (R2S) Roundtable, hosted at MIT. This event was meticulously planned to foster innovative thinking and collaborative problem-solving among industry leaders, academics, and policymakers. The roundtable aimed to transcend traditional boundaries and address the pressing challenges of the mining industry through a series of structured discussions and brainstorming sessions.

The insights garnered from the roundtable are instrumental in shaping our policy recommendations. The discussions facilitated an in-depth understanding of industry needs, technological advancements, and the socio-economic impacts of mining operations. Key areas of focus included:

- Innovative Practices: Discussions on tailings management, water use, and land use provided fresh perspectives on sustainable mining practices and innovative technologies that could significantly reduce environmental footprints.

- Regulatory Frameworks: The roundtable highlighted the need for adaptive regulatory frameworks that can accommodate new technologies and sustainable practices without stifling innovation.
- Community Engagement: Insights into effective community engagement strategies underscored the importance of building trust and mutual benefits, which are crucial for securing social license to operate.

The roundtable's collaborative environment allowed for a dynamic exchange of ideas, helping to identify viable solutions and partnerships that could be implemented to advance sustainability and efficiency in mining operations.

In addition to the main roundtable, stakeholder insights were complemented with a set of interviews with a major automotive manufacturer. The main objective was to gather EV manufacturers experience on how critical materials markets expectations impact their investment and technology choices, that in return affect future demand.

Chapter 3

Findings

3.1 Critical Materials Market Uncertainty

The relationship between critical materials and technology choices forms a dynamic two-way system where technology decisions by firms significantly impact the demand for critical materials. Conversely, firms act strategically based on future materials' price expectations. This interaction creates a substantial degree of uncertainty, particularly for industries like electric vehicle (E.V.) manufacturing, where investments are both high in value and long-term. Therefore, the sector requires coordination between actors to reduce risks over the long term.

3.1.1 Technology Arbitrages and Critical Materials Demand

The relationship between critical materials and technology choices forms a dynamic, interdependent system. Technological advancements significantly influence the demand for critical materials, which in turn, shape market dynamics and influence future technology choices. This is even more the case with battery chemistries choices as they are the main source of variation in potential future demand due to the volumes involved. The global demand for batteries, particularly for clean transportation, increased substantially in the last five years [24]. In the face of this increased demand, car manufacturers, are at the forefront of responding to technology shifts driven by relative prices and the need for risk mitigation related to their large-capacity batteries needs. These manufacturers are constantly evaluating and adapting to changes in the cost and availability of battery materials and advancements in battery technology. Their choices significantly affect the entire battery supply chain, from sourcing raw materials to manufacturing and recycling.

For instance, the transition to nickel-rich cathodes in lithium-ion batteries, such as NMC and NCA, has drastically increased the demand for lithium, nickel, and cobalt, influencing their market prices. The recent increases of prices and supply chains concerns led to the exploration of options that could alleviate supply constraints and offer cheaper alternatives if prices for these key minerals were to surge.

As highlighted during the industry roundtables, the volatility of material prices and the risks associated with supply chain disruptions encourage firms to diversify their sourcing strategies, engage with multiple suppliers, or secure long-term contracts to mitigate these risks. But most importantly, firms adapt their technology strategies in response to high material prices or supply uncertainties, often shifting to alternative technologies that utilize more abundantly available materials [24]. The most recent trends in battery technology are particularly evident in the choices of cathode chemistries. There's a noticeable bifurcation towards two main types of chemistries: High-nickel cathodes, such as nickel-manganese-cobalt (NMC) and nickel-cobalt-aluminum (NCA), and lithium iron phosphate (LFP) technologies. So far, high-nickel batteries were favored for their high energy density, which is particularly beneficial for extending the range of electric vehicles, but LFP cathodes are gaining popularity as a more cost-effective and stable alternative along Sodium-Ion technologies. The recent exploration of solid-state batteries by General Motors and Volkswagen also represents a major technological leap, opening up new avenues for battery composition. These batteries promise higher energy density, faster charging times, and enhanced safety, while significantly reducing the dependence on traditional critical materials.

The strategic choices made by manufacturers are profoundly influenced by relative commodity prices, anticipated supply and demand imbalances, and associated supply risks. These factors are crucial in determining the adoption and development of various battery chemistries.

In an ideal market setting, multiple technologies would coexist, each competing to offer similar costs at equilibrium, influenced by market elasticities. However, the reality of the battery market, which is still maturing and is dominated by a few large players, complicates this scenario. Current investments in future battery capacity are heavily based on market expectations and anticipated strategies of competitors. Manufacturers project different relative prices for raw materials based on the aggregated demand influenced by these choices, which then guides their technology adoption strategy. For instance, if a significant number of manufacturers opt for nickel-rich cathode technologies like nickel-manganese-cobalt (NMC) due to their higher energy density and efficiency, this aggregated preference could lead to a surge in nickel demand. Such a surge, in turn, impacts nickel prices, potentially making these technologies less economically attractive in the long run due to increased material costs. This phenomenon is detailed in studies such as those by Benchmark Mineral Intelligence (2021), which track the fluctuating costs of battery metals and their impact on technology choices.

This is the rationale behind automakers exploration of alternative battery technologies like LFP to reduce exposure on cobalt and nickel prices, or sodium-ion batteries that circumvent lithium potential price explosions. These strategic diversifications are supported by research indicating that LFP and sodium-ion batteries could provide competitive performance metrics for specific applications. For example, the IEA highlights the increasing adoption of these technologies in stationary storage and less range-critical EV segments, where energy density is a less critical factor compared to cost and stability [24].

This strategic approach, where manufacturers anticipate and respond to market forces by diversifying their technology portfolios, illustrates a sophisticated application of game theory in the industrial setting. Each player's decision-making is influenced not only by current market conditions but also by forecasts of how these conditions will evolve based on the collective impact of the industry's technology choices. Such dynamics underscore the need for ongoing research and development, coordination between actors, as well as agile supply chain strategies to adapt to an ever-changing technological landscape.

Another component of the decisions is related to supply risks. Geographic concentration and potential disruptions in the supply chains for critical materials can introduce significant risks for E.V. manufacturers, outside of the coordination dilemna they face. For instance, the supply chains for cobalt, nickel, and manganese used in NMC and NCA batteries are more geographically concentrated and prone to disruptions compared to the materials used in LFP batteries. However, LFP batteries also have their own supply chain concerns, such as the potential for conflicting demands for phosphorus between battery manufacturing and the agriculture sector and the geographic concentration of phosphate rock resources. This is verified empirically since NMC are currently chemistries are being phased out in favor of high-nickel/low-cobalt chemistries like NMC 721 and NMC 811 to reduce costs and exposure to unreliable congo-sourced supplies.

3.1.2 Impact on Investment and Mining Developments

The electric vehicle (EV) sector is characterized by a volatile market environment where fluctuating prices and supply risks significantly affect investment and mining developments. As firms navigate this landscape, they employ diverse strategies to mitigate these risks, including diversifying sourcing strategies, engaging multiple suppliers, and entering into long-term contracts. These strategies are vital in stabilizing operations amidst the fluctuating prices of critical materials such as lithium, cobalt, and nickel, which are essential for battery production. Despite these efforts, the high stakes and long-term nature of investments in EV technology present a significant dilemma for automakers. The critical decision to choose the right technology and secure the necessary materials must be made in the context of considerable market uncertainty. Predicting future market conditions for these materials is indeed challenging not only for the reasons mentioned previously but also, complicated by factors like rapid technological advancements, regulatory changes, and supply shifts. This uncertainty is highlighted in industry analyses, such as those from the IEA, which note the difficulties in projecting long-term material demand due to these dynamic factors [24]. This lack of foresight on future minerals prices could yield to lower EV and batteries manufacturing investments or inefficient market outcomes.

The inherent unpredictability of these factors makes it also difficult for companies to commit to long-term investments in mining operations needed to extract these critical materials. Mining projects require extensive capital investments and have long lead times, often spanning several decades. The misalignment between the rapid pace of change in technology and market preferences in the EV sector and the slow pace of mining development exacerbates the investment risks: this disconnect leads to cautious under-investment strategies in the mining sector, potentially resulting in future shortages if demand for certain materials unexpectedly increases.

Given these challenges, the industry requires action to address the coordination problem between actors and providing projections for market outlooks.

3.2 Imports Dependency and Vulnerability

The United States heavily relies on imports to meet its domestic demand for critical minerals, with production concentrated among a few global players, including China. This concentration significantly heightens the US's vulnerability to market shocks and supply chain disruptions. To mitigate these risks, it is imperative for the US to implement policies that promote diversification of supply sources and enhance resilience. Additionally, reducing dependence on unreliable partners is crucial to securing a stable supply of essential minerals.

3.2.1 US Dependency on Critical Materials Imports

Recent decline of the US mining industry, attributed to factors including decreasing resource quality, stringent environmental regulations, and under-investment, has led the US to rely on imports to meet it's demand. In contrast, China has significantly increased its control over these critical minerals through heavy investment in domestic production and foreign resources, becoming dominant in the processing of these minerals for global markets. Hence, the US relies on very concentrated market to meet its needs.

Historical Production Decrease

Over the last fifty years, the US mining industry has experienced a notable decline in its competitiveness and market share in key transition minerals, such as copper, lithium, nickel, and cobalt. This shift is due to several factors, including high labor costs, stringent environmental regulations, decreased domestic demand due to a shift from manufacturing to services, technological advancements leading to material substitutes, and increased environmental activism. These elements combined have not only reduced the industry's profitability but also its attractiveness to investors compared to countries with less stringent regulations like China, who's control over these critical minerals has grown in parallel to its economic development, reflecting the shifting economic power dynamics since its entry in the WTO in 2001. [72], [73].

Historically, the US led global production of these materials. For instance, in the 1970s, the US was responsible for over 20% of the world's copper output [74]. However, 50 years later, its market share had dwindled to about 7% [72], with Chile and Peru now dominating the market. Similarly, US production of lithium, nickel, and cobalt has significantly declined, with the country relying almost entirely on imports for nickel and cobalt [72]. In stark contrast, China has dramatically increased its influence and control over these markets, investing heavily in both domestic production and foreign resources, leading to its dominance in processing critical minerals for global markets [75], [76]. Though not a significant producer, China leveraged its large internal market and its first place as a global consumer of commodities to invest, innovate, and develop a tremendous monopoly over the processing of key elements, either on its soil or in foreign countries through acquisitions and foreign developments. This trend emerged in the early 00s and accelerated over the past ten years. For instance, it's accounting for over 50% of global copper consumption by the 2010s [75]. Its influence on the lithium market is even more prominent. Ten years later, China controlled over 60% of the global lithium production [72], and it's the leading global producer of lithium chemicals necessary for battery production [76]. China also dominates the cobalt market. China's nickel consumption follows a similar trajectory, and it is the largest consumer, with 56% of global refined nickel use in 2019 [77], mostly due to its stainless steel industry and growing demand for EV batteries.

The decline of the US mining sector can largely be attributed to the high costs of adhering to environmental laws such as the Clean Air Act and the Clean Water Act, which have significantly increased operational costs [78]. Additionally, the US faces higher labor costs compared to other countries [79], [80], and the evolution of the US economy towards services has reduced the domestic demand for raw materials [81], sending a strong market signal for disinvestment. The development of material substitutes has also decreased dependence on traditional mining outputs. Moreover, the growth of environmental activism, exemplified by opposition to projects like the Keystone XL Pipeline, has further hindered the initiation of new mining projects [73]. Meanwhile, countries like Chile and Peru have seen their mining industries thrive due to less stringent regulations and lower operational costs, allowing them to increase their market shares significantly [75].

Concentration of Overseas Markets

The decrease in domestic mining output in the US over recent decades has led to a growing reliance on imports for essential minerals and metals, placing the country in a precarious position regarding its supply chain risk exposure. As domestic production dwindled due to the competitive disadvantages discussed earlier, the gap between the nation's demand for various raw materials and its internal production capabilities widened, especially for critical materials whose demand remained increasing despite overall loss of domestic manufacturing because of their technological content. The Department of Energy has highlighted this dependence as a critical vulnerability, especially considering the strategic importance of these materials in emerging technologies and green energy solutions [45]. Currently, the us imports 76% of its cobalt needs, and has an imports reliance over 56% for nickel, 34% for copper and 25% for lithium.

For copper, the US is heavily dependent on imports primarily from Chile and Peru, with these countries not only being leading producers globally but also key trade part-

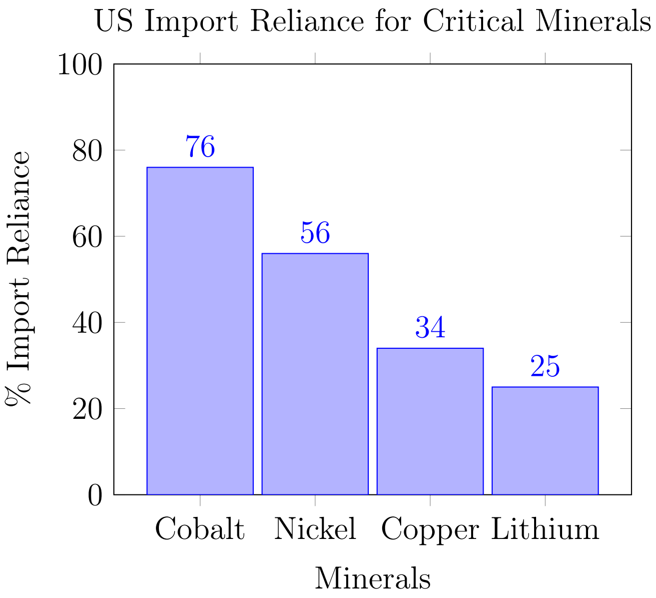

Figure 3.1: US Import Reliance for Critical Minerals (2022) [13].

ners of the US Despite stable trade relations, neither country is a NATO ally. Nickel imports present a different dynamic. Canada is the primary source of US nickel imports, offering a relatively secure and stable supply chain, while the global leader in nickel production is Indonesia, a country with which the US maintains good economic relations. Lithium dependency also highlights the complexity of US import sources. The US imports lithium primarily from Argentina, a significant trading partner with generally favorable bilateral relations, despite having significant reserves on it's soil. While the leading producer, Australia, shares a strong alliance with the US, the majority of global lithium reserves are concentrated outside of traditional US allies, in countries like Chile and China. Cobalt imports underscore perhaps the most significant challenge. While Norway, a stable NATO ally, is a primary source of US cobalt imports, the dominant producer globally is the Democratic Republic of the Congo (DRC). The DRC's production involves significant ethical and humanitarian concerns, alongside the geopolitical risks inherent in its political instability.

This reliance is accentuated by a combination of diminished domestic mining capabilities and the highly concentrated nature of global mineral supply chains. Given the future growing demand expectations, this dependence might increase even more.

Indeed, mining activities for these critical minerals are heavily concentrated in a few geographic locations worldwide due to the specific geological presence of these resources (see Figure 3.2 page 74). For instance, significant copper mining operations are clustered in Chile's Atacama Desert and Peru's Andes Mountains, while Indonesia and the

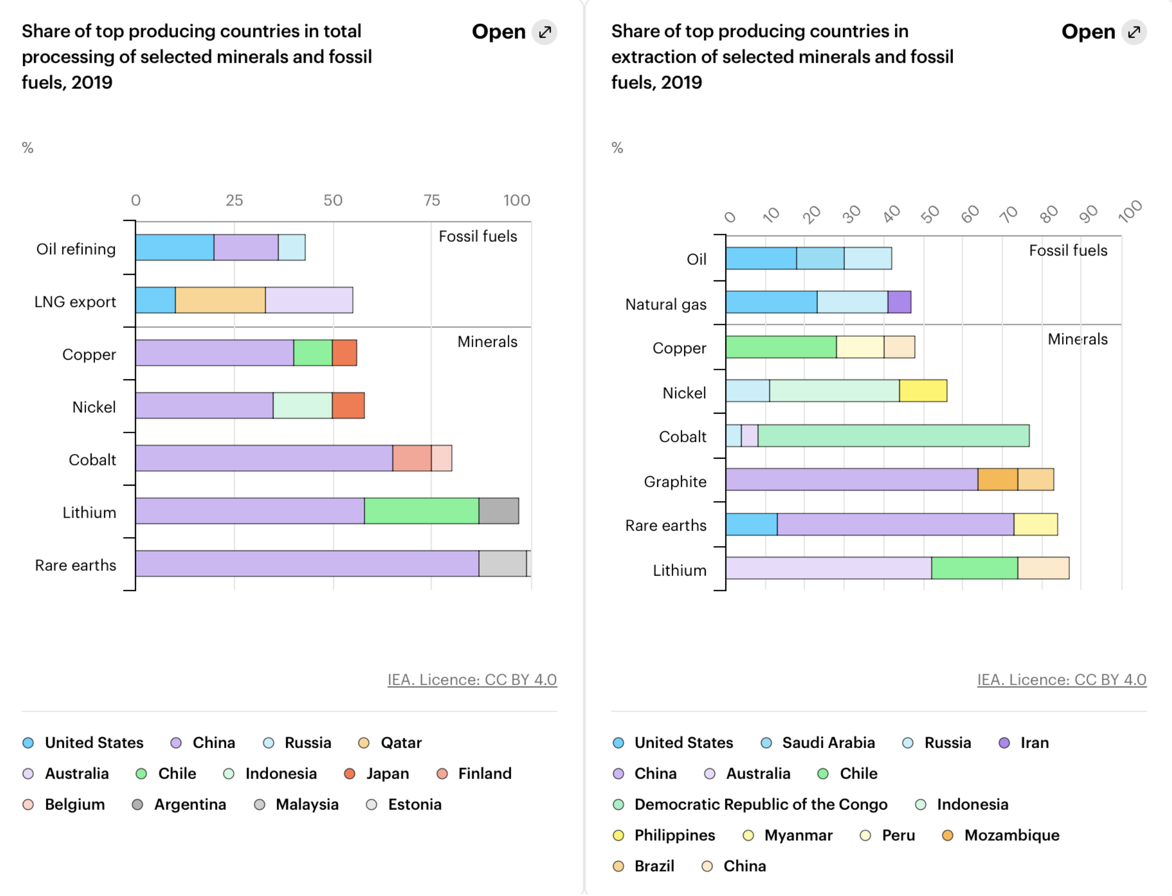

Figure 3.2: Concentration of processing and mining reported by the IEA [32].

Philippines are noted for their abundant laterite deposits crucial for nickel extraction. Similarly, lithium production is predominantly located in Australia's Greenbushes region and Chile's Salar de Atacama. The Democratic Republic of the Congo (DRC) is pivotal for cobalt, hosting the majority of global production within its Katanga Copperbelt. Such geographical concentration not only highlights the natural scarcity and localized abundance of these minerals but also underscores a critical vulnerability in achieving diverse sourcing of elements.

Indeed, the concentration of reserves of critical minerals in a few countries inherently leads to a concentrated market for mining these resources. This geographical centralization of natural mineral deposits dictates where mining operations can feasibly occur, subsequently shaping the global mining landscape. For example, Chile, Peru, and China collectively account for a substantial share of global copper production (see Figure 3.2 page 74). This concentration is quantitatively expressed through the Herfindahl-Hirschman Index (HHI), where the combined HHI for these top three copper-producing nations stands at 903, while Nickel and Lithium markets exhibit similar concentration risks. Indonesia, the Philippines, and Russia, the top nickel producers, have a combined Top-3 HHI of 1710, reflecting a high market concentration that could translate into significant market power for these countries over global nickel prices and supply chains. The lithium market, which is dominated by Australia, Chile, and China and has an Top-3 HHI of 3554, faces risks from operational, environmental, or political challenges in these key producing regions. Moreover, the cobalt market, with an Top-3 HHI of 5219, is extremely concentrated, primarily due to the DRC's dominance in global production. For reference, oil production HHI for the Top-3 producers sits at 612.

Even more pronounced than the mining sector is the concentration found within the processing market, particularly where China plays a dominant role (see Figure 3.2 page 74). The processing of these critical minerals—transforming raw extracted materials into usable forms—is significantly more concentrated than the mining sector itself. China's dominance in the processing capabilities across virtually every critical mineral underscores a strategic leverage and control over the entire supply chain. This monopolistic dominance in processing is alarming as it not only poses supply chain risks but also endows China with the capability to influence global markets and foreign policy through resource allocation.

Beyond the geographical concentration of mining operations in resource-rich countries and China's dominance in the processing sector, the ownership of these critical mineral activities is also highly concentrated. This concentration of ownership often manifests in a few large corporations controlling significant shares of global production capacities. For instance, in the cobalt market, Glencore alone is responsible for over a quarter of the world's cobalt production, mainly from the Democratic Republic of the Congo. This concentration not only places significant control of cobalt supplies in the hands of a single company but also subjects the market to the operational and strategic decisions of that company, as well as to the political and economic conditions in the DRC. Similarly, in the lithium market, the top three producers (Albemarle Corporation, Sociedad Química y Minera de Chile (SQM), and Tianqi Lithium) collectively control a substantial portion of global production (24%, 21% and 7% market shares respectively). Moreover, in the nickel sector, the concentration of production is evident with companies like Norilsk Nickel in Russia (7%), Vale in Brazil (6%), and the Chinese firm Tsingshan Holding Group (3%) dominating the market. These companies not only control large portions of global nickel production but also have significant stakes in the processing facilities that convert raw nickel into market-ready forms.

However, ownership concentration is even higher since one of the cornerstone tactics of China's strategy is the acquisition of stakes in foreign mining projects. This approach allows China to control raw material sources directly, thereby securing the supply needed for its domestic industries while exerting influence over global production. For example, Chinese companies like Tianqi Lithium have invested billions in acquiring stakes in Australian lithium mines, and in SQM, a major Chilean lithium producer. In addition to direct investments in mining, China has formed numerous partnerships with local and international companies to bolster its supply chain from extraction to processing. These partnerships often come with terms that benefit Chinese interests, such as agreements on supply quotas or joint ventures in processing facilities. An example of this is the partnership between Chinese cobalt companies and the Democratic Republic of the Congo's mining firms. China's CMOC Group, for instance, operates one of the largest cobalt mines in the DRC and has partnerships with local mining operations to ensure preferential access to cobalt resources. China has also extended its influence by financing and developing infrastructure in countries rich in mineral resources through initiatives like the Belt and Road Initiative (BRI). This not only strengthens China's diplomatic ties but also often grants Chinese companies preferential treatment in mining rights and operations.

3.2.2 Dependence Risks and Challenges

Considering these factors, the United States is likely to become increasingly reliant on imports for these critical minerals. With a growing demand, limited domestic production capabilities and global markets largely dominated by a select few foreign nations, this dependency on imports poses substantial economic and strategic risks. The danger is particularly acute due to the high concentration of production in these markets; a single disruption in one of these dominant producing countries could significantly impact the entire market due to their large market shares. This situation exposes the US to severe vulnerabilities, where geopolitical or logistical issues in just one or two countries could lead to widespread supply chain disruptions.

Supply Shocks

First, the United States' reliance on imports for critical materials significantly exposes it to the global market price fluctuations. As these materials are essential (relative demand inelasticity), any disruption in these supply lines have immediate consequences of the price these commodities trade.

The landscape of global energy has been frequently and profoundly altered by oil price shocks, events that have left indelible marks on the economies and policies of nations worldwide [51]:

1. **The 1973 Oil Crisis:**
   The 1973 oil crisis is often cited as the quintessential price shock that reshaped the global economy. Triggered by the Yom Kippur War and the subsequent OPEC oil embargo against the United States and other countries, the price of oil quadrupled in a short period. This shock not only led to immediate economic turmoil, characterized by high inflation and a stock market crash, but also instigated a long-term shift towards energy conservation and fuel efficiency in the affected economies. The crisis underscored the vulnerability of oil-dependent nations and set in motion a search for alternative energy sources and policies aimed at reducing dependence on OPEC oil.

2. **The 1980s Oil Glut:**
   In stark contrast to the shortages of the 1970s, the 1980s experienced an oil glut. The Iranian Revolution of 1979 had initially caused another price surge, but the subsequent Iran-Iraq War saw a decrease in demand coupled with increased production from other OPEC members and new players such as Norway and

Mexico. The result was a steep decline in oil prices, with the cost of a barrel falling by more than half in the span of four years. The oil glut had complex economic effects: it provided a reprieve from inflation for consumer nations but caused severe fiscal strains in producer countries, highlighting the double-edged nature of oil price volatility.

3. **The 2000s and the Commodities Boom:**
   The turn of the millennium saw a resurgence of oil prices. Several factors contributed to this rise, including increased demand from emerging economies like China and India, geopolitical tensions in major oil-producing regions, and market speculation. Prices peaked dramatically in 2008, touching record highs that significantly influenced global economic conditions, contributing to the onset of a global recession. This era illustrated the intricate connections between energy markets and the broader financial system, emphasizing the need for vigilant economic policies to manage the risks associated with oil market volatility.

Each of these episodes of oil price shocks had cascading effects on the global economy, influencing not only immediate consumption patterns but also longer-term strategic decisions in both the public and private sectors. The shocks impacted inflation rates, trade balances, and even the pace and focus of technological innovation. For instance, the 1973 crisis spurred significant investment in alternative energy and fuel-efficient technologies, whereas the 2000s boom underscored the importance of financial markets and derivatives in commodity pricing [82].

The US response to these shocks has evolved over time, shaped by both the changing nature of the global oil market and domestic policy shifts. Initially, the US responded with measures such as the Strategic Petroleum Reserve to buffer against future supply disruptions. Later, policy emphasis shifted towards increasing domestic production and achieving energy independence, which has been realized to a significant extent with the shale oil revolution [83].

On the other side, commodity shocks, while less immediately dramatic than oil price swings, have nonetheless exerted considerable influence over economic conditions and policy decisions:

1. **The 1970s and '80s Metal Price Shocks:**
   In the aftermath of the oil crises of the 1970s, the prices of metals and minerals also experienced significant volatility. The heightened oil prices increased production costs for mining and metal production, which, in turn, were passed on

to a wide range of industrial and consumer products. This period saw a substantial increase in the prices of commodities like gold, driven by inflationary fears and a turn towards safe-haven assets. However, the economic recession of the early 1980s, combined with a strong US dollar, led to a collapse in many commodity prices. The volatile movement in metal prices during this period not only impacted mining companies and commodity-dependent economies but also prompted a reconsideration of resource management and strategic stockpiling practices [84].

2. **The 2000s Commodity Boom:**
   The early 21st century was marked by a significant rise in commodity prices, often referred to as the commodities boom. This period was driven by robust demand from rapidly industrializing countries, particularly China, which embarked on massive urbanization and infrastructure projects. Metals such as copper, iron ore, and nickel saw prices soar, greatly benefiting export-oriented economies but also leading to increased costs for manufacturing and construction globally. This boom highlighted the importance of resource-rich countries in the global economic hierarchy and the susceptibility of global supply chains to demand-side pressures [85].

3. **The COVID-19 Pandemic Impact:**
   The recent COVID-19 pandemic has caused unprecedented disruptions in the commodity markets, with initial sharp declines in demand and prices due to lockdowns and economic slowdowns. However, certain commodities, especially those critical for technology and renewable energy, such as lithium and cobalt, have seen price surges due to supply chain constraints and a rapid pivot towards green technologies. The pandemic has underscored the fragility of global supply chains and the need for robust and resilient resource management strategies.

Oil price shocks have been a recurring economic phenomenon with far-reaching consequences for both consumer behavior and macroeconomic stability. An immediate consequence of an increase in oil prices is the short term inflationary pressure it exerts on consumer goods, particularly energy-intensive products. High energy costs lead to reduced discretionary spending, precipitating declines across various economic sectors [57], which under certain conditions, result in a broader economic downturn when prices are sticky and adjustments are not immediate [86]. Historically, when the US was a net importer of oil, an increase in oil prices effectively resulted in a transfer of wealth overseas, negatively impacting the GDP [58]. However, since the fracking revolution, increase in oil prices results in an uptick in employment and economic output [59].

While oil price shocks have been well-studied, mineral price shocks related to key components like lithium and cobalt are comparatively under-researched, despite their increasing significance in the global economy. Unlike oil, where fluctuations in price affect existing operational costs, the primary impact of mineral price shocks is on capital expenditure for new projects. Companies might choose to delay or reevaluate these new capital-intensive initiatives, mitigating immediate macroeconomic impacts [62]. Given that these minerals are used predominantly for new capital, as opposed to running existing capital, the macroeconomic repercussions of a mineral price shock are inherently more contained, at least in the short term. Businesses can defer new projects, and there are generally fewer spillover effects on other sectors of the economy [63], but longer-term effects could include reduced technological innovation and progress. In the long run, it could impact productivity growth rates and economic competitiveness [64].

Long Term Dynamic Impact

Results from the model indicate that the long term impact of mineral price shocks is significant for long term Capital and Investment levels (see Figure 3.3), while the energy trade balance is more affected by oil prices. The capital variable decreases as the price shock in both minerals and oil increases. This suggests that higher input costs lead to a reduction in capital accumulation and investment in the economy. The decrease is more pronounced in the case of mineral price shocks, indicating that it might have a more substantial influence on capital-intensive industries, like clean tech manufacturing. Labor also shows a decreasing trend with increasing price shocks, though the impact is less steep compared to capital. This might suggest that labor markets adjust more slowly or are less sensitive to immediate changes in input prices. Consumption decreases with price shocks, mirroring the trends seen in wealth. As input prices rise, disposable income likely decreases, leading to reduced consumption. The relatively flatter slope for minerals suggests that the direct consumption impact of minerals is less immediate or severe than that of oil.

This impact should be particularly pronounced in capital-intensive industries that rely heavily on minerals like EV manufacturing. As mineral prices increase, companies may delay or scale back capital-intensive projects, which, while mitigating immediate economic shocks, suggests a long-term reduction in technological innovation and progress (long term capital accumulation and investment levels), which is less apparent for oil disruptions. Similarly, the model shows that labor markets adjust more

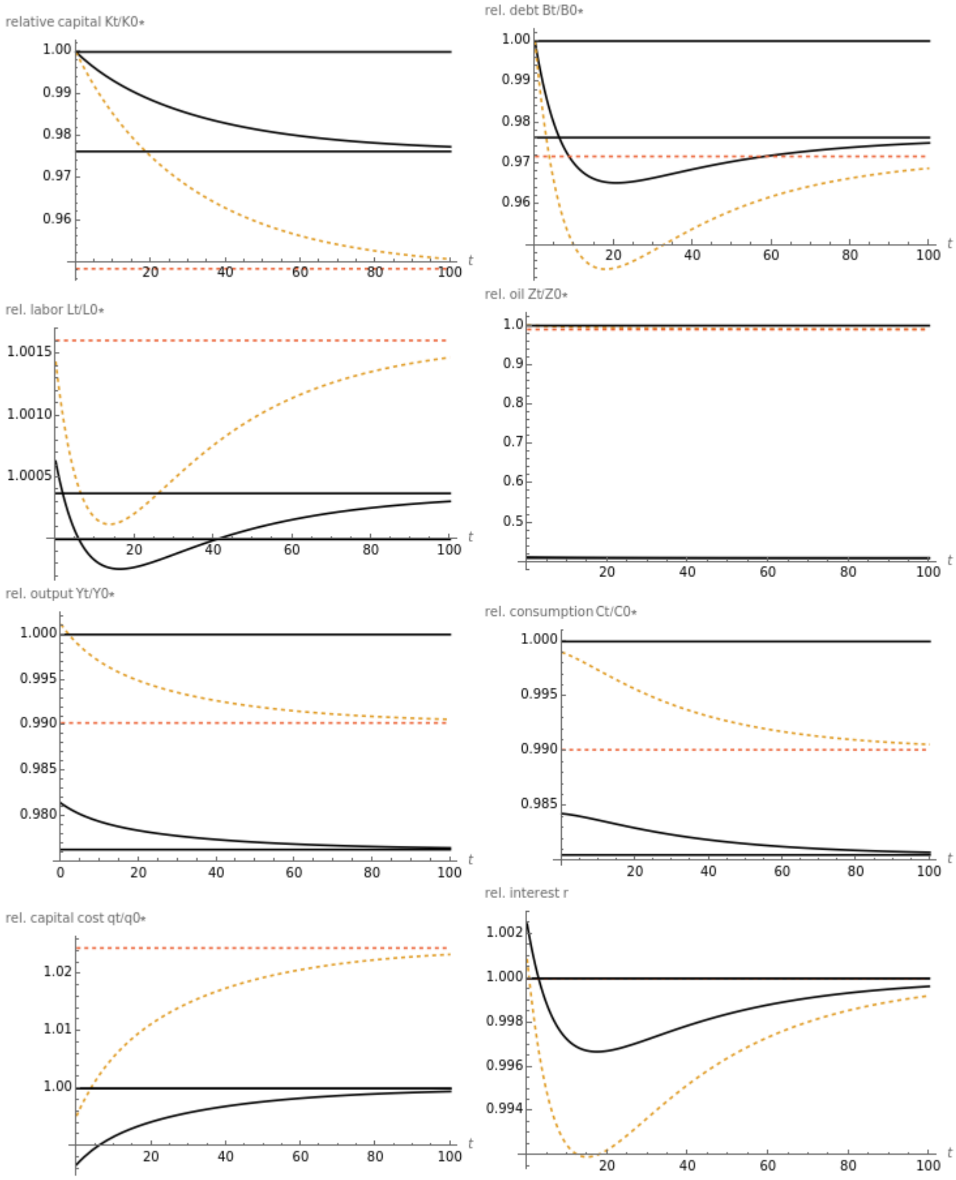

Figure 3.3: Example of comparison of short term response to long term price disruptions (orange line corresponds do double mineral prices, black to oil).

slowly to these shocks, with a less steep decline compared to capital, indicating a gradual adaptation rather than immediate displacement. Additionally, the consumption patterns depicted in the model align with expected economic behavior, where rising input costs lead to decreased disposable income and subsequent reductions in consumer spending and short term economic activity, especially for oil shocks. This indicates that materials-intensive burgeoning industries will face significant difficulty to scale up and attract investment in the US if market prices explode. The implications of this scenario are multifaceted and particularly relevant in the context of the Inflation Reduction Act (IRA), which aims to foster domestic production and reduce reliance on imported materials through various incentives and investments.

Indeed, as mineral prices increase, the cost of capital-intensive projects in industries such as renewable energy, electric vehicles, and advanced battery manufacturing will rise. This could lead to delayed or canceled projects, reducing the overall pace of innovation and technological advancement in these sectors. The IRA's focus on boosting domestic production may be undermined if the cost of essential raw materials makes projects financially unviable. The US's ability to compete in the global market for clean technologies could also be compromised. High costs of critical minerals might make US products more expensive compared to those produced in regions with cheaper or more controlled resource costs. This could lead to a loss of market share in rapidly growing industries that are crucial for future economic growth. Investment slowdowns in materials-intensive industries due to high mineral prices could lead to reduced job creation in these sectors. The IRA aims to create high-paying, secure jobs in clean energy and technology sectors, but these goals may be at risk if the underlying economics are disrupted by soaring input costs. Such a dynamic of shocks indicates that the policy response to these shocks should be oriented towards the long run and investment (through subsidies), rather than consumer relief, and highlights the fact that short term market variations are less relevant than long term average prices levels for the industry choices.

The Chinese Risk Factor

The heightened risks tied to the limited diversity in supply, potential price fluctuations, and the strategic geopolitical dependencies on critical materials are particularly significant given China's influential global position and the escalating battle for global supremacy. China's pivotal role in both the production and processing of critical materials has increased the vulnerabilities in global supply chains. As China continues to pursue economic and technological supremacy, this dominance represents a significant leverage. In today's context of intensified global competition, often conceptualized as the "Thucydides Trap"—a theory suggesting that conflict is likely when a rising power threatens to displace a dominant one—the resilience of critical material supply chains becomes not just an economic priority but a strategic imperative. This is especially crucial for nations like the United States and its allies, as the secure and stable access to these materials directly influences national security and global geopolitical standing. Given the strategic importance of these resources and China's substantial role in their processing, the ongoing competition for global dominance increasingly centers on economic and technological prowess, heightening the strategic value of these materials.

Indeed, countries that control critical materials may use this control as geopolitical leverage. For instance, China's command over the rare earth elements market provides it significant influence over global industries that rely on these materials for manufacturing everything from consumer electronics to advanced military equipment like the F-35. The F-35, which utilizes rare earth elements in its sophisticated electrical systems and precision-guided munitions, could face production and maintenance challenges if China were to limit exports amid rising geopolitical tensions, considering the minimal stockpiling of these materials. China's strategic manipulation of rare earth exports was notably demonstrated in 2010 during its territorial dispute with Japan over the Senkaku/Diaoyu Islands when it sharply curtailed its rare earth export quotas. At that time, China controlled approximately 95% of the global supply of these materials. This reduction severely disrupted the global supply chain for high-value Japanese electronic products, underlining the critical nature of these resources.

Similarly, the US's reliance on critical materials from non-allied nations can significantly affect its foreign policy and diplomatic engagements. This dependency is akin to Germany's reliance on Russian natural gas, which has sometimes restrained Germany's diplomatic actions in response to Russian geopolitical maneuvers, such as the annexation of Crimea. China's potential to restrict exports could similarly compel dependent nations to moderate their foreign policy positions, particularly in disputes involving minor territorial conflicts like those in the South China Sea. Countries heavily reliant on China for critical domestic industries, such as the US in its electric vehicle and high-tech sectors, may find their foreign policy options particularly constrained.

China has strategically positioned itself not only as a dominant player in the processing sector but is also proactively expanding its influence in the extraction of critical materials. This broad and aggressive approach includes significant investments in lithium production, particularly in South America, where Chinese companies like Tianqi Lithium have acquired substantial shares in top lithium producers [87]. Beyond mere mining, China has asserted control over more than 90% of the global processing capabilities in the rare earth sector, a critical stage that involves complex and technologically advanced processes compared to extraction alone.

China's strategy extends to employing resource diplomacy through initiatives such as the Belt and Road Initiative, which helps it dominate access to essential minerals in resource-rich countries. In Africa, especially in the Democratic Republic of Congo, Chinese firms have gained significant stakes in cobalt mining, cementing China's influential role in the supply chains of these vital materials. Moreover, China uses development financing strategies to deepen its mining influence. For instance, in 2007, the Export-Import Bank of China provided substantial funding for infrastructure and development in the DRC, including \$6 billion for infrastructure and \$3 billion to develop copper and cobalt mines under a State-Owned Enterprise model. This investment has given China control over a significant portion of the DRC's mining operations, encompassing more than half of the largest 18 mine projects by 2019. For lithium, China has rapidly expanded its influence; within just six years, it has secured control or influence over 59 percent of the world's lithium resources. This expansion includes financial stakes in Latin American lithium extractors, such as acquiring a 24 percent stake in Chile's Sociedad Química y Minera (SQM), the world's second-largest lithium producer. Furthermore, by restricting foreign investment in its considerable domestic market, China has crafted an industrial strategy that enhances its strategic and technical dominance over certain minerals technologies: the US also faces risks from the monopolization of crucial technological knowledge in materials processing. While the US possesses its copper reserves, superior processing technologies developed in countries like Chile and China could place the US at a technological disadvantage. Innovations in mining and smelting abroad suggest that the US may become dependent on foreign technologies for effective copper processing. Additionally, advancements in nickel processing, particularly through the High-Pressure Acid Leaching (HPAL) method, have been significantly refined in countries like Indonesia. This method is crucial for extracting nickel from laterite ores under high-pressure and high-temperature acidic conditions, which could lead to further US dependencies on international technological developments in nickel processing.

Therefore, the strategic landscape characterized by China's ascendancy in the control and processing of critical materials presents a profound vulnerability for the United States, amplifying the risks associated with supply chain disruptions. China's consolidation of influence in both the technology, mining and processing stages heightens the global market's susceptibility to price shocks and supply constraints. The fact that

China not only leads in the processing of these materials but also actively extends its reach into their extraction and global distribution underscores a dual risk. This risk is not just from potential direct supply disruptions but also from China's ability to impose price controls or export restrictions, thereby wielding considerable geopolitical leverage.

Such a scenario places the US and its allies in a precarious position, given their dependence on these critical materials for key industries, including defense, technology, or clean energy. The situation mirrors the global commodity market's dynamics, where China's restrictions or policy shifts can lead to significant and immediate impacts on global prices and availability.

3.3 Inertia of Domestic Capacity Extention

The US urgently needs to expand its mining capacity through new projects to secure domestic supply, but faces significant hurdles due to an excessively lengthy permitting process. This slow process is largely due to prolonged review times and substantial community opposition, which together threaten to stifle ambitions for increasing domestic supply. To overcome these challenges, it is critical to streamline the permitting process and align with best practices from top-performing countries, ensuring faster and more efficient project approvals.

3.3.1 Fast Mining Expansion Needs

The us reliance on imports is partially explained by limited reserves, but there is definitely untapped potential for extraction. In the United States, cobalt resources are estimated at about 1 million tons, found across several states [13]. Lithium resources are about 12 million tons, primarily located in Nevada, North Carolina, and California, with Nevada being a major production site. Nickel production is very minor due to limited economic reserves (340kt) centered around the Eagle Mine in Michigan, supplemented by production in Montana and Missouri and a developing nickel beneficiation project in North Dakota. The US produced 1.3 million tons of recoverable copper in 2022, predominantly in Arizona, but also in Michigan, Missouri, Montana, Nevada, New Mexico, and Utah, for 44Mt of recoverable reserves. In Canada, cobalt reserves are notable (220kt), especially in Ontario and Quebec, where they are often found alongside nickel and copper ores. Canada's lithium resources, which are much less significant (1Mt) than the US and found in Quebec, Manitoba, and Ontario, contribute to the country's growing mining sector. Canada is a leading global producer of nickel, with extensive reserves in Ontario, Manitoba, Newfoundland and Labrador, and Quebec. Nickel reserves are very large (about 2Mt of recoverable material). Canadian copper reserves (10Mt) are predominantly in British Columbia, Ontario, Quebec, Newfoundland, and Labrador. These reserves are complementary, with the US concentrating large copper and lithium deposits with around 20 and more than 300 years of respective reserves as years of consumption. On the other side, the lack of nickel occurrence (2 years) is compensated by the vast reserves found in Canada.

When looking at the current market conditions and the modelled operations dynamics, there is a strong indication that the US has an incentive to open new mines rather than increasing production from exploited sites:

- Domestic demand boom: according to the model, increased demand leads to higher market prices p_t, which, in turn, increase the potential revenues from mining operations. This scenario aligns with the Hotelling rule that the value of extracted resources $\pi(t, \gamma)$ should be maximized over time. Given the assumption of rising prices due to heightened demand mostly propelled by domestic content requirements of the IRA and expansion of clean manufacturing, the present value of future mining outputs justifies the earlier upfront investment in new capacities, even if existing assets are not fully depleted. This is because investing in the additional capacity can capture higher market prices sooner, offsetting the opportunity cost of untapped production capacity.

- High shadow cost rates: in the model, the discount rate r plays a critical role in determining the present value of future profits from mining operations. Increased interest rates would typically discourage investment due to the higher cost of capital. However, since future prices of minerals are expected to rise significantly (due to the demand boom), the potential future revenues could outweigh the increased discount rates. This makes investments in new capacities economically viable as the net present value of these investments remains positive, particularly when considering the $r + \alpha$ rate, which accounts for both financial and physical depletion costs. This higher rate signals that delaying investment into new capacities becomes more costly, as the opportunity cost of unexploited resources grows: given that physical depletion (exhaustion of reserves) raises the cost of continued production over time, mining firms will find it economically rational to open new mines with fresher, more accessible reserves, rather than solely relying on older, increasingly costly to exploit reserves.

- Slowing inflation: inflation impacts both the cost structure ($mc_{t,\gamma}$ and $fc_{t,\gamma}$) and the pricing of output commodities in your model. While inflation generally increases operational costs, it also tends to increase the prices of commodities, particularly critical minerals whose markets are characterized by limited supply and surging demand. The model suggests that if commodity prices rise at a rate that compensates for or exceeds the rate of inflation and cost increases, then continued investment in mining horizontal expansion can remain profitable. This is particularly relevant in scenarios where inflation drives commodity prices higher at a faster rate than operational costs, enhancing the relative profitability $\pi(t, \gamma)$ of new mining projects. In addition, the model posits that if the costs of expansion (including the cost of opening new mines) increase, potentially due to scarcity of inputs or technological challenges, at a rate slower than or in line with r, then expanding capacity is more profitable. This is particularly pertinent under scenarios where the costs of expanding existing operations exceed those of establishing new ones due to logistical, geological, or regulatory complexities.

According to the model results, there is a clear indication that mining expansion in the US is expected to pick up (economically attractive given market conditions), but also that accelerating the deployment of new capacity is primordial. First, the increase in domestic demand (subsidies pass-through effect) enhances the profitability of mining operations, making the expansion of mining capacities economically attractive. According to the model, higher future prices, anticipated due to this increased demand, justify significant upfront investments in new mining capacities. The model also indicates that the marginal revenue from new mining projects, factoring in rising prices, will likely exceed the increased costs due to high interest rates and inflation, making these projects economically viable. Then, the resource depletion rate α adds more pressure to early decision-making and investment, suggesting that delays in expanding capacity could lead to significantly higher costs later, both in terms of lost revenue opportunities and higher extraction costs as resources become harder to access and prohibitively expensive to extract. When α is significant (scarce resources), it underscores the importance of quickly developing new mining operations to capitalize on high commodity prices and demand. Quick investment and deployment can indeed help minimize the opportunity costs associated with leaving potential mining sites undeveloped. As the rate $r + \alpha$ indicates, the longer new capacities are left undeveloped, the greater the potential revenue lost that could have been earned from these resources.

Thus, the model not only supports the economic rationale behind expanding US mining operations given the prevailing market conditions but also strategically underscores the importance of hastening the deployment of new capacities to optimize returns and secure a competitive stance in the global market.

3.3.2 Mining Externalities

Mining operations, while critical for the global supply of minerals essential for modern technologies and industries, impose severe negative externalities on both the environment and human health. These impacts manifest in diverse ways, ranging from local ecological disturbances to widespread social repercussions, affecting communities far beyond the immediate area of the mining sites.

Local impacts include groundwater and soil pollution, plant growth inhibition, and the physical disturbances from mine workings—particularly in open pits—and associated waste rock disposal areas. The oxidation of sulfide minerals such as pyrite, when exposed to air and water, produces sulfuric acid, leading to acid mine drainage (AMD) that can severely affect soil acidity and plant life [88]. This drainage not only lowers the pH of local water systems but also introduces heavy metals that can accumulate in aquatic ecosystems, posing significant risks to both wildlife and human populations [88].

Regional impacts encompass infrastructure developments like roads, ports, railway tracks, and power lines that disrupt migratory routes and contribute to habitat fragmentation. Studies have shown how mining operations can alter the geographic distribution of species and fragment habitats across large areas [89]–[91]. Additionally, pollutants from mining activities can travel long distances, affecting air quality and leading to phenomena such as acid rain, which deteriorates soil quality and inhibits vegetation growth. The deposition of these pollutants into lakes and rivers extends the environmental impact, harming aquatic life and even affecting human health through the consumption of contaminated water and food sources.

The intensive use of water in the processing phase presents another critical issue, especially in water-scarce regions. Not only does this phase use large amounts of water, but it also risks contaminating water sources with acids and metals, complicating their use for drinking or irrigation.

These environmental impacts are closely linked to social effects, particularly on the health and well-being of miners and those living in mining-intensive regions. The comprehensive understanding of these implications is crucial for developing effective mitigation strategies and sustainable mining practices. The health implications of mining and processing, particularly concerning critical minerals, pose risks to both workers and surrounding communities. These impacts are influenced by the resource type, mining phase, and related operations, including excavation, grinding, and metallurgical processing. The nature of mineral waste, dependent on the mineral and extraction technologies, significantly affects the type and extent of environmental contamination [92].

Mining operations release large amounts of dust and aerosols, mobilizing toxic elements like arsenic, cadmium, lead, mercury, and uranium. These pollutants, particularly heavy metals from polymetallic mines, pose serious health risks. The exposure pathways include inhalation, ingestion of contaminated particles, and direct skin contact. Mining environments, especially confined underground spaces with poor ventilation, significantly increase the risk of respiratory diseases and cancers [93], [94]. Mining also releases a variety of contaminants, each with specific health implications. Particulate matter, often comprised of dust and aerosols from mining processes, is a primary concern as it can lead to respiratory diseases and gastrointestinal issues. Fine particulate matter (PM10 and smaller), easily transported by air currents, can penetrate deep into lung tissue and enter the bloodstream, leading to systemic health issues [88]. Heavy metals such as lead, arsenic, and mercury, common byproducts of mining operations, pose severe risks. Exposure to heavy metals is particularly dangerous as it can cause chronic conditions, including neurological damage, kidney failure, and cancers [95].

Miners face numerous hazards, from pneumoconiosis (black lung disease) and silicosis to increased risks of lung cancer and autoimmune diseases due to exposure to radioactive materials like radon gas [96]. Non-environmental risks include accidents and stress from harsh working conditions. The surrounding communities are also affected through air, water, and soil contamination, leading to widespread health and social impacts.

Certain segments of the population are particularly vulnerable to mining-related environmental contamination. Children, for instance, are at significant risk due to their developing bodies and behaviors that increase their exposure, such as play activities that often involve soil. Studies have shown elevated levels of lead and arsenic in children living near mining sites, which correlate strongly with local soil contamination [97]. Pregnant women also face heightened risks. Research indicates that exposure to toxic elements like mercury, prevalent in gold mining areas, can lead to developmental issues in infants. These effects are exacerbated by co-exposure to multiple heavy metals, highlighting the complex nature of environmental health risks in mining areas [98].

It is essential to recognize the diversity in mining practices and the specific health risks associated with different minerals. For instance, cobalt and nickel mining involves significant exposure to toxic elements, while lithium mining presents risks related to water use and contamination. Each mineral and mining technique bears distinct environmental and health implications that must be assessed on a case-by-case basis [99], [100].

- Cobalt extraction is notably detrimental to health, potentially causing eye, skin, heart, and lung damage, and even cancer. These risks are exacerbated in artisanal mining, particularly prevalent in the Democratic Republic of Congo, where health and safety regulations are minimal, and child labor is widespread [101], [102]. By contrast, industrial mining operations in countries like the US and Canada, which follow stricter regulations, present lower health risks but still face significant challenges related to environmental and social impacts. The harmful effects of cobalt include radioactive emissions from the blasting process, which pose cancer risks [103]. These particles, when airborne, can be inhaled by workers and accumulate in the environment, leading to widespread contamination affecting both local ecosystems and human populations.

- The United States holds substantial reserves of lithium, primarily in the form of lithium brines. Extraction involves pumping brine to the surface and using evaporation ponds, which significantly impacts local water tables and ecosystems due to the extensive water required [104]. The evolving technology of Direct Lithium Extraction (DLE) promises greater efficiency but has yet to be proven at scale, with ongoing concerns about its potential environmental impacts [105].

- Nickel extraction varies significantly depending on the ore type. The processing of nickel laterites, which are becoming more prevalent due to the depletion of higher-grade nickel sulfides, requires energy-intensive methods like High-Pressure Acid Leaching (HPAL), leading to high carbon emissions [32]. Global policies, particularly in Indonesia, have shifted towards refining nickel domestically to capture more value from the energy transition, impacting global nickel markets and environmental standards.

- Copper mining is essential for modern technology and energy infrastructure but is challenged by decreasing ore grades, which increase the energy and water required for extraction. This exacerbates the environmental impacts, particularly in water-scarce regions like Chile [106], [107]. The comprehensive management of copper mining's environmental effects is crucial to mitigating its ecological footprint.

The health impacts on communities are not limited to chemical exposure; the physical disruption of landscapes and ecosystems can also have profound effects on community health and livelihoods. The degradation of land can limit agricultural productivity, while contamination of water sources can affect aquatic biodiversity, impacting food security and economic activities based on fishing [108].

The extent of these impacts often depends on the methods used in mining and the effectiveness of regulatory frameworks in place. For instance, surface mining and smelting operations can spread pollutants over large areas, affecting communities several kilometers away from the actual mining sites. In the United States and Canada, stringent regulations on mining operations help to mitigate some of these impacts. These countries have established comprehensive standards for environmental protection and community engagement, which are designed to ensure that mining practices do not adversely affect local communities [109].

In contrast, in regions like the Democratic Republic of the Congo, where governance issues and the enforcement of regulations are less stringent, the impacts can be more severe. Here, artisanal mining, often performed under hazardous conditions and without adequate safety measures, significantly affects community health and safety [109]: the extraction and processing of cobalt in the DRC have been linked to severe human rights abuses, including child labor and exploitation [110]. The lack of effective government oversight and the dominance of artisanal mining operations contribute to these issues, underscoring the need for more robust regulatory frameworks and international cooperation to address these challenges. The extraction of lithium, particularly in the Lithium Triangle of Argentina, Bolivia, and Chile, presents different challenges. These include significant water use and potential contamination, which can affect local communities' access to water and disrupt traditional livelihoods. Despite economic benefits, these activities have led to social conflicts and demands for greater community involvement in decision-making processes and equitable sharing of benefits and water quotas [111].

3.3.3 Challenges for New Developments

The extensive and sometimes detrimental impacts of mining on communities and the environment lead to substantial local opposition and rigorous regulatory assessments. These factors often introduce significant delays in the permitting processes, creating inertia that can extend the timeline for opening new mining operations.

Opening new mining operations in the United States can be a protracted process, typically ranging from 7 to 10 years and often extending to 15 years or more. The initial phase of exploration, lasting 1-3 years, involves geological surveys and drilling to ascertain the potential and size of the deposit, and is later complemented by feasibility studies (lasting 1-2 years) that evaluate the economic viability, environmental impact, and technical aspects of the project. If these two phases have the same requirements for most countries and cases, the permitting and legal process can be lengthy, often taking 5-10 years in the US, due to stringent environmental regulations and community negotiations. This is where most of the inertia lies, especially relative to other countries. The final phase of development, lasting 2-5 years, involves building the mine and related infrastructure and is specific to each site.

When compared internationally, the US permitting process is notably longer. Australia and Canada have more streamlined processes, generally resulting in shorter timelines for permit approvals. They achieve this through more integrated permitting processes and clearer guidelines that reduce the uncertainty and delays common in the US system. As a leading copper producer, Chile has optimized its permitting process to support its critical mining industry, often completing the process within two to three years.

In the US, examples abound of mining projects experiencing significant delays due to these factors:

- Pebble Mine, Alaska: One of the most controversial mining projects in the US, the Pebble Mine has seen decades of legal and regulatory battles over environmental concerns, particularly regarding the impact on the local salmon population and other ecological risks. In contrast, Canada's recent mining projects, like the Voisey's Bay nickel mine, also reflect significant timelines but with slightly swifter progress in the permitting phase. This highlights that new developments, eventually triggered by the infrastructure bill and IRA act, will have a limited impact in the short- to medium-term.

- Mountain Pass Rare Earth Mine, California: This mine, critical for rare earth elements, faced closure and bankruptcy in part due to environmental regulatory challenges before reopening under new ownership with revised environmental strategies.

Based on the cases studies and industrial experience gathered from mining operators through the Roosevelt project interviews and roundtables, there are two main reasons for the permitting problem in the US.

Community Opposition

Community opposition in mining refers to the resistance from local communities and stakeholders against mining projects due to potential negative impacts on their environment, health, and way of life. This opposition can stem from a variety of concerns including environmental degradation, health risks, disruption of local economies, and impacts on cultural heritage. Communities often oppose projects when they feel the risks outweigh the benefits, or when they perceive that their concerns are not adequately addressed by mining companies or regulatory bodies.

The Twin Metals Minnesota project illustrates a significant case of community opposition impacting the permitting process. Positioned near the Boundary Waters Canoe Area Wilderness (BWCAW), this project faced substantial resistance due to environmental concerns, particularly the risk of pollution in a sensitive and pristine ecosystem. The opposition was fueled by the project's proximity to a national forest and a popular recreational area, raising fears about potential damage to water quality and local wildlife habitats. The community's concerns were heightened by the fact that this area has a historical significance for conservation. The opposition contributed to a prolonged legal and regulatory battle, leading to repeated denials and reinstatements of mineral leases, influenced by changing political administrations. This case demonstrates how environmental concerns can galvanize community opposition, leading to significant delays and uncertainties in the permitting process.

In contrast, the Stillwater and East Boulder mines in Montana offer an example of how community opposition can be effectively managed through proactive engagement. Faced with potential adverse effects on local water bodies and quality of life, the community initially resisted the mine expansions. However, the implementation of a Good Neighbor Agreement (GNA) between the mining company and local community groups facilitated a collaborative approach. This agreement not only addressed environmental concerns through stringent water quality standards but also established a framework for ongoing communication and joint decision-making. By involving community members in the mine planning and operational decisions, the GNA helped mitigate opposition and foster a partnership that has endured for over two decades.

In both cases, the primary driver of community opposition was the potential environmental impact. For Twin Metals, the threat to a national wilderness area was a critical concern, while for the Stillwater and East Boulder mines, it was the impact on local water quality and the natural landscape. The proximity to ecologically sensitive and culturally important areas heightened community concerns, underscoring the importance of environmental stewardship in mining operations. For Twin Metals, the strong community and environmental opposition resulted in a protracted legal and regulatory process, with permits being repeatedly contested and rescinded. This not only delayed the project but also created a climate of uncertainty that can deter future investments. In contrast, the proactive engagement strategy employed by the Stillwater and East Boulder mines through the GNA resulted in a smoother permitting process. By addressing community concerns early and establishing a mechanism for ongoing involvement, the mines were able to avoid significant delays and build a stable operational framework.

The comparative analysis of these cases reveals several key lessons. First, early and proactive engagement with communities is crucial in identifying and addressing concerns that could lead to opposition. Second, establishing formal agreements that include community input and participation in decision-making processes can mitigate opposition and foster long-term partnerships. Third, transparency and clear communication about the environmental and economic impacts of mining projects can help build trust between mining companies and communities. Lastly, adapting project plans in response to community feedback, as seen in the Stillwater and East Boulder mines through environmental safeguards and community benefits, can lead to more sustainable and less contentious mining operations.

Complex Regulatory Assessments

In the United States, the regulatory assessment process for opening new mines is multifaceted, involving numerous federal, state, and local regulations designed to ensure that mining activities meet environmental, safety, and community standards. The process begins with the exploration phase, requiring initial permits for geological assessments. If viable deposits are found, the company proceeds to the feasibility and planning stages, which involve more detailed environmental and economic evaluations.

Environmental Impact Assessment (EIA) The Environmental Impact Assessment (EIA) is a foundational element in the regulatory process for mining operations in the United States, aiming to ensure that environmental considerations are integrated into the decision-making process. This assessment involves several critical steps:

- Preparation of an Environmental Impact Statement (EIS): The EIS is a comprehensive document that details the potential environmental effects of the proposed mining project. It evaluates both the direct and indirect impacts on the environment, including effects on water and air quality, wildlife habitats, vegetation, and the socio-economic impacts on local communities. The EIS must also propose mitigation strategies to minimize these impacts.

- Scoping Process: Before drafting the EIS, a scoping process is conducted, which identifies the key issues and concerns that need to be addressed. This involves consultations with federal, state, and local agencies, as well as public input, to determine the scope of the environmental analysis.

- Public Participation: Public hearings and consultations are crucial components of the EIA process. These sessions allow stakeholders, including local communities, environmental groups, and other interested parties, to provide feedback on the EIS. Public comments can influence the final decisions regarding the project's environmental acceptability and the mitigation measures proposed.

- Review and Revision: Based on the input received during the public consultation phase, the EIS may be revised to address the concerns and suggestions made by the public and regulatory agencies. This iterative process ensures that all significant environmental impacts are thoughtfully considered and addressed before any final decision is made.

- Decision Making: After the final EIS is published, a Record of Decision (RoD) is issued by the lead regulatory agency. This document outlines the decision regarding the proposed action, the alternatives considered, and the mitigation measures that will be implemented. The RoD marks the culmination of the EIA process and either approves the project, possibly with conditions, or denies it based on environmental concerns.

Permitting Process The permitting process involves securing all necessary local, state, and federal permits to proceed with mining operations. This multi-layered process is designed to ensure compliance with a broad range of environmental, safety, and community standards:

- Local Permits: These may include zoning permits, local land use approvals, and community health and safety permits. Local government agencies assess the project's compliance with municipal ordinances and regulations.

- State Permits: State-level permits typically address broader environmental impacts and include water allocation, protection and quality permits, air quality permits, and mining permits. State environmental protection agencies play a significant role in ensuring that mining operations comply with state environmental laws and regulations.

- Federal Permits: Key federal agencies involved in the permitting process include:
- Environmental Protection Agency (EPA): Issues permits related to air and water quality, including the National Pollutant Discharge Elimination System (NPDES) permits and air emission permits under the Clean Air Act.
- Bureau of Land Management (BLM) and US Forest Service (USFS): Grant access and operational permits for mining activities on federal lands, ensuring compliance with the National Environmental Policy Act (NEPA) and other federal land use policies.
- US Army Corps of Engineers (USACE): Issues permits for any impacts to wetlands or waterways under Section 404 of the Clean Water Act.
- Integrated Permit Reviews: To streamline the process, some states and federal agencies coordinate their reviews to reduce redundancy and speed up the permitting process. This integrated approach can lead to more efficient processing times and reduce the administrative burden on mining companies.

There are a couple of examples of delays in Regulatory Assessments. The Twin Metals project in Minnesota showcases the complexities and challenges of the regulatory assessment process in the US. The project, proposed near the Boundary Waters Canoe Area Wilderness, faced intense scrutiny due to its potential environmental impacts. Throughout its permitting journey, Twin Metals encountered several obstacles. First, the project's progress was significantly affected by changes in federal administration, which saw shifts in environmental policies and priorities that impacted the status of the mineral leases essential for the project. Then, the proximity to a protected wilderness area led to heightened environmental scrutiny, requiring extensive EIS procedures and public consultations, contributing to prolonged delays. Two additional factors impeded their success:

- Complexity of Environmental Reviews: Projects like Twin Metals, located near sensitive ecological zones, require more rigorous environmental assessments, which can significantly extend the permitting timeline.

- Stakeholder Engagement: Insufficient or ineffective stakeholder engagement can lead to opposition and legal challenges, as seen in the Twin Metals case, where fluctuating political support and environmental concerns led to ongoing legal disputes and permit revocations.

Conversely, the Stillwater and East Boulder mines demonstrate a more streamlined approach within the same regulatory framework. Through the establishment of a Good Neighbor Agreement (GNA), these mines managed to engage effectively with regulatory bodies and the local community, which facilitated a smoother permitting process. The GNA included detailed environmental monitoring and community engagement plans that aligned with regulatory requirements, helping to expedite the approval processes. The GNA in the Stillwater and East Boulder mines exemplifies proactive engagement, which helped align the mining operations with community and environmental expectations, thereby smoothing the regulatory path. By exceeding standard environmental requirements and integrating robust monitoring systems, companies can foster trust with regulatory bodies and expedite the permitting process.

This highlights the importance of fluctuations in policy due to political changes as they can destabilize the permitting process. A more consistent regulatory approach could reduce delays and uncertainty for mining projects. Engaging with all stakeholders—including local communities, environmental groups, and regulatory agencies—from the early stages of a project can minimize opposition and facilitate a smoother permitting process. Also, projects that proactively address environmental concerns and incorporate sustainable practices are more likely to navigate the regulatory landscape successfully.

Hence, the regulatory assessment process for mining in the US, while designed to protect environmental and community interests, can pose significant challenges and delays for mining projects if mining operators do not adopt best practices such as early stakeholder engagement, exceeding environmental standards, and do not foster stable regulatory relationships. This approach not only ensures compliance with stringent regulations but also builds positive relationships with communities and stakeholders, ultimately leading to more sustainable and profitable mining operations.

Chapter 4

Recommendations

4.1 Policy Actions

4.1.1 Increase Domestic Production

Accelerate Permitting Timelines

Require CBAs Community Benefit Agreements (CBAs) are essential in ensuring that mining projects align with the needs and expectations of local communities. By formally integrating community concerns and expectations into project planning, CBAs foster a cooperative relationship between mining companies and local residents. This process involves negotiations that include provisions for local employment, environmental protection, and community development, which are crucial for gaining community support and facilitating smoother project implementation.

Impact: CBAs help secure a resilient and sustainable supply chain by enhancing community relations and reducing potential conflicts that can delay or halt projects. These agreements are instrumental in achieving the U.S. goal of an equitable energy transition by ensuring that the benefits of mining projects are widely shared within the community, thereby supporting social sustainability alongside economic and environmental objectives.

Evidence: Successful implementation of CBAs in various U.S. mining projects has demonstrated their effectiveness in reducing community opposition and enhancing project acceptance. These agreements have been shown to result in more efficient permitting processes and long-term community development benefits, contributing to stable and productive mining operations.

Encourage Fast-41 Coverage Advancing mining projects to become FAST-41 covered projects is essential for streamlining permitting processes. The Fixing America's Surface Transportation (FAST) Act, through Title 41, sets a framework for a more efficient, transparent, and predictable federal environmental review and authorization process. By meeting specific criteria, mining projects can benefit from coordinated project reviews and faster decision timelines, which are crucial for timely project launches and operations.

Impact: The findings chapter highlights the critical barriers posed by complex regulatory frameworks that delay mining project starts. FAST-41 addresses these issues by reducing procedural redundancies and ensuring a consolidated review process across multiple federal agencies. This reform is vital for enhancing the efficiency of project approvals, thereby ensuring a more reliable and timely supply of critical minerals in the U.S.

Evidence: Although currently, only a limited number of mining projects are designated under FAST-41, those that have achieved this status have reported shorter and more predictable permitting timelines. Industry feedback suggests that expanding FAST-41 coverage could significantly benefit the mining sector by reducing delays and providing clearer timelines for project planning and execution.

Streamline the Review Process and Enforce Deadlines Enforcing strict deadlines on permit reviews are crucial steps toward enhancing the efficiency of the permitting system. This approach involves setting clear, enforceable timelines for each stage of the permit review, ensuring that agencies and stakeholders adhere to a predictable schedule. Currently, the US does not have maximums on how long a permit can sit with any agency for review. Such measures would compel federal agencies to review and respond to permit applications promptly, preventing unnecessary delays.

Impact: One of the significant impediments to efficient critical mineral production in the U.S. is the prolonged and often unpredictable permitting process. Streamlining these processes and imposing deadlines would mitigate this issue, leading to quicker project starts and less uncertainty in project timelines. This is vital for maintaining a continuous and secure supply of critical materials essential for national security and technological innovation.

Evidence: Looking at international best practices, countries like Canada have successfully implemented maximum review times, which have substantially shortened their mine permitting timelines compared to the U.S. This has not only improved the investment climate in Canada but also provided a more attractive environment for new mining initiatives, showcasing the potential benefits of such reforms.

Adopt and Promote Advanced Mining Technologies

Promote Digitalization and Automation Emphasizing the adoption of digitalization and automation in mining processes, including the integration of digital twins, predictive maintenance, and operational optimizations, is paramount. These technologies enhance mining operations by significantly improving output and recovery rates across various ore grades, while also reducing energy intensity. The shift towards automated and autonomous systems facilitates continuous operations, eliminates human error, and increases productivity. IoT devices provide real-time monitoring of equipment, leading to efficient predictive maintenance and fewer operational bottlenecks.

Impact: The adoption of these advanced technologies (see Appendix A) directly addresses several critical issues outlined in the findings chapter, such as operational inefficiencies and high energy consumption. By enhancing process efficiency and reducing energy usage, digitalization and automation support the U.S. mining industry's move towards greater economic competitiveness and environmental responsibility. This transition is crucial for maintaining a sustainable and secure supply of critical minerals, essential for the energy transition and technological advancement in the U.S.

Evidence: The effectiveness of these technologies is well-documented, with mining operations that have implemented automation and digitalization reporting significant gains. For instance, the application of machine learning and AI in mineral processing has not only improved decision-making and increased output but also enhanced mineral recovery rates, contributing to higher productivity and reduced waste. In Australia, mining giants like Rio Tinto and BHP have fully integrated autonomous haul trucks, leading to a significant increase in productivity. Chile's Codelco has successfully implemented digital twin technology to optimize its operations and maintenance. Studies, such as those from McKinsey [46], suggest that machine learning alone could increase metal recoveries by 2 to 4 percent and throughput by 5 to 15 percent, significantly boosting global production capacities from both existing and planned mining operations.

Adopt Advanced Process Innovation The implementation of advanced drilling and fragmentation techniques, such as directional drilling, automated drilling systems, and controlled blasting, is crucial for enhancing the precision and efficiency of mining operations. These innovations enable miners to target mineral deposits more accurately, minimize wastage, and maximize resource utilization. Similarly, adopting efficient haulage systems like conveyor belts, in-pit crushing and conveying (IPCC), and automated trucking systems revolutionizes material transportation within mining sites, reducing reliance on manual labor, decreasing wait times, and enhancing overall operational efficiency.

Impact: These advanced process innovations address some challenges identified, including high operational costs and environmental impacts associated with traditional mining practices. By improving drilling accuracy and optimizing material handling, these technologies reduce the environmental footprint of mining operations and enhance productivity. This contributes to a more sustainable and economically viable mining sector, crucial for ensuring a continuous supply of critical minerals.

Evidence: The effectiveness of these technologies has been demonstrated in various global mining operations. For instance, mines employing advanced drilling techniques have reported a significant reduction in drilling times and an increase in resource recovery rates. Similarly, mines that have integrated IPCC systems have seen a reduction in greenhouse gas emissions and operational costs, proving the substantial benefits of these advanced process innovations in promoting more efficient and sustainable mining practices.

Leverage New Resources

Explore Deep Sea Mining Deep sea mining is emerging as a significant frontier for the mining industry, leveraging advanced underwater technologies to access seabed resources rich in metals such as copper, nickel, and cobalt. The Clarion-Clipperton Fracture Zone (CCFZ) in the Pacific Ocean, for example, is believed to contain more nickel, cobalt, and manganese than all land-based reserves combined. Utilizing remotely operated vehicles (ROVs) and advanced drilling systems minimizes the ecological footprint traditionally associated with mining.

Impact: This method addresses the critical need for diversifying the sources of critical minerals to ensure a resilient supply chain. Deep sea mining can provide access to abundant resources with potentially lower environmental and social impacts than terrestrial mining, offering a strategic advantage in minimizing land use and community displacement.

Evidence: Studies by the International Seabed Authority have highlighted the vast quantities of critical minerals available from deep-sea nodules, with extraction methods that are less disruptive than traditional mining practices. The ongoing projects by companies like The Metals Company underscore the potential for commercial viability and reduced ecological impacts.

Assess Space Mining Space mining, although still in its nascent stages, presents a futuristic avenue for acquiring valuable extraterrestrial minerals such as nickel and cobalt. The technological advancements in space travel, robotics, and artificial intelligence are gradually overcoming the significant legal, economic, and technical barriers, making the mining of asteroids a conceivable option for future mineral extraction.

Impact: Leveraging space resources could drastically expand the available resource base beyond Earth, potentially stabilizing supply for critical materials and alleviating the pressures on terrestrial sources. This could be pivotal in meeting the burgeoning demand for these materials in various high-tech applications.

Evidence: The increasing interest and investment in aerospace technologies and preliminary missions aimed at assessing the feasibility of asteroid mining highlight the growing consideration of this method. Although still primarily theoretical, the potential for high concentrations of critical metals in asteroids offers a compelling case for continued research and development.

Explore Geothermal Lithium Brines The extraction of lithium from geothermal brines represents an innovative approach to meeting the increasing demand for this critical battery material. Projects like the Hell's Kitchen Lithium and Power project in California are pioneering the extraction of lithium from geothermal brines, utilizing advanced technologies such as selective lithium extraction. This method not only provides a source of lithium but also aligns with the environmental goals of reducing emissions.

Impact: This approach directly contributes to securing a sustainable and domestic supply of lithium, crucial for the burgeoning electric vehicle and renewable energy sectors. By tapping into geothermal brines, the U.S. can reduce its reliance on traditional hard rock mining and salt flats, which are more environmentally taxing and often located overseas.

Evidence: Supported projects in North America and Europe, along with endorsements from major OEM and automotive companies, demonstrate the growing confidence in the economic and technical feasibility of this extraction method. While not yet commercially proven, pilot projects indicate promising results that could transform lithium supply chains.

Exploit Tailings Reprocessing and Old Mines Waste Recuperation Reprocessing tailings and other mining wastes offers a sustainable method to recover valuable minerals that were not extracted in initial processing. This approach not only reduces the environmental impact associated with new mining activities but also turns existing waste liabilities into economic assets.

Impact: By reprocessing tailings, the mining industry can extend the life of mines and decrease the demand for new mining projects, aligning with sustainability objectives and addressing the environmental concerns identified. This method contributes to a more circular economy in the mining sector, reducing waste and maximizing resource utilization.

Evidence: Successful examples of tailings reprocessing, such as the Elikhulu tailings retreatment plant operated by Pan African Resources in South Africa, demonstrate the technical and economic viability of this process. These projects have shown that reprocessing can recover significant amounts of metals, making previously discarded materials valuable once more.

Focus on Processing

Expand Domestic Processing Capabilities Expanding domestic processing capabilities involves two critical strategies: banning the export of raw ores and significantly subsidizing the development of local processing facilities. This approach aims to reduce dependency on international processing hubs, particularly China, by enhancing local capacities through technological innovation and sustainability. By processing minerals domestically, the U.S. can add value within its borders, improving economic benefits and ensuring a secure supply chain.

Impact: The findings identified dependence on foreign processing capabilities as a significant vulnerability in the U.S. supply chain for critical materials. Enhancing domestic processing infrastructure would not only alleviate this dependence but also strengthen national security and economic independence. Sustainable processing technologies tailored to the U.S.'s specific geographic and resource context can significantly enhance the efficiency and environmental sustainability of these operations.

Evidence: Economic analyses and policy discussions suggest that strengthening domestic processing capabilities is essential for achieving mineral supply chain resilience. Countries with robust local processing facilities demonstrate greater control over their supply chains and are less susceptible to international disruptions. Moreover, investments in domestic processing can lead to job creation, technological advancements, and improved trade balances, further underpinning the strategic importance of expanding these capabilities.

Improve Process Efficiency Enhancing process efficiency in mining operations involves the adoption of various technologies aimed at increasing output and recovery rates while minimizing waste and addressing the issue of declining ore grades. Key technologies include Coarse Particle Recovery (CPR), which enhances the recovery of coarse particles typically lost in conventional processing; Flash Flotation, which targets the removal of high-grade particles from the grinding circuit; and High-Pressure Grinding Rolls (HPGR), which improve the efficiency of mineral recovery processes by increasing the surface area of crushed ores.

Impact: Implementing these technologies directly addresses competitiveness challenges, such as high energy consumption and low ore recovery rates. By improving recovery efficiency and reducing waste, these innovations contribute to more sustainable mining practices. They enhance the economic viability of mining operations by increasing throughput and reducing operational costs, thereby ensuring a more stable and efficient supply of critical minerals.

Evidence: The effectiveness of these technologies is demonstrated in various mining operations worldwide. For example, the implementation of CPR techniques has led to significant increases in recovery rates and reductions in waste production. Similarly, the use of HPGR has been shown to increase particle liberation, leading to better leach recovery rates. These advancements not only improve the environmental impact of mining operations but also bolster economic outcomes by optimizing resource use and reducing the need for new mining ventures.

4.1.2 Ensure Diversification, Cooperation and Resilience

Reduce Exposure to Imports and Supply Disruptions

Strengthen Partnerships with FTA and NATO Producing Countries Strengthening partnerships with countries that are part of Free Trade Agreements (FTAs) and NATO can significantly enhance the resilience and diversity of supply chains for critical minerals and clean energy components. This strategy involves building robust economic and trade relationships that facilitate access to critical materials, encourage joint ventures in mineral extraction and processing, and promote the adoption of shared environmental and social governance standards. Such partnerships may also lead to collaborative technological innovations and transfers.

Impact: Leveraging FTAs and strategic alliances helps mitigate the risks associated with geopolitical and market volatility, as identified in the thesis. These partnerships are essential for securing a stable supply of critical minerals, which are pivotal for the clean energy sector and national security. Enhanced cooperation can lead to more efficient resource utilization and a reduced dependency on single-source suppliers.

Evidence: The effectiveness of such partnerships is evidenced by historical parallels in other technology sectors, such as the semiconductor industry, where international collaboration has led to advancements in technology and stable supply chains. Similar strategies can be applied to the critical minerals sector, leveraging existing relationships and frameworks to strengthen supply chain resilience.

Create Strategic Reserves for Critical Materials Establishing and maintaining strategic reserves of essential critical minerals is a proactive measure to buffer against short-term disruptions in the supply chain due to geopolitical tensions, natural disasters, or market fluctuations. These reserves act as a safeguard, ensuring a continuous supply of materials crucial for key industries, including technology and renewable energy.

Impact: Strategic reserves enhance national security and stabilize material supply, thereby supporting the ongoing growth and sustainability of critical industries. This approach is particularly relevant in today's volatile global market, where sudden disruptions can severely impact national economies and the technological sector. These strategic reserves should be able to be contracted over the long term in cases of disruptions by the domestic players.

Evidence: The U.S. has successfully implemented strategic reserves for oil, which have historically mitigated the effects of supply disruptions and stabilized markets during crises. This model provides a proven framework for critical minerals, suggesting potential benefits in terms of economic stability and national security.

Encourage Supplier Diversification and Long Term Supply Agreements Encouraging diversification of suppliers and securing long-term supply agreements are strategic measures to stabilize the supply chain for critical minerals. By broadening the base of suppliers and committing to long-term partnerships, industries can mitigate risks associated with supply volatility and geopolitical tensions. These agreements not only ensure a consistent supply but also foster mutual trust and collaboration between suppliers and purchasers, which is crucial for long-term strategic planning.

Impact: Diversifying suppliers and establishing long-term agreements addresses key vulnerabilities in the supply chain. This strategy reduces dependency on any single source and enhances supply chain resilience, crucial for industries that are heavily reliant on specific minerals. It supports sustained industrial growth by providing stability in raw material availability, which is essential for sectors such as electronics, clean energy, and automotive manufacturing.

Evidence: The effectiveness of supplier diversification and long-term agreements is well-documented in industries like automotive and electronics, where supply chain disruptions can lead to significant financial losses. Companies that have adopted these strategies have experienced fewer disruptions and improved supply chain stability, which in turn supports continuous industrial operation and innovation.

Centralize Information and Promote International Cooperation

Improve Information Transparency Enhancing information transparency in the mineral supply chain is critical for addressing issues related to conflict minerals and broader supply chain risks. The Dodd–Frank Wall Street Reform and Consumer Protection Act has already set a precedent by requiring companies to track and report on conflict minerals. Expanding these regulations to include all minerals and applying them extraterritorially could provide a more comprehensive understanding of global supply risks and help mitigate them more effectively.

Impact: Improving transparency is essential for identifying and addressing vulnerabilities in the supply chain. A more transparent system would not only help in tracking the origins of minerals but also in enforcing responsible mining practices globally. This could lead to improved regulatory compliance and help prevent the exploitation associated with mineral extraction, particularly in conflict-affected areas.

Evidence: The initial success of the Dodd-Frank Act in increasing transparency around conflict minerals demonstrates the potential effectiveness of such measures. Companies have become more aware of their supply chains, leading to increased accountability and steps towards more ethical sourcing practices. Extending these obligations could further enhance these benefits across the broader mineral market.

Establish an International Minerals Agency within the OECD Proposing the creation of an International Minerals Agency within the OECD framework aims to standardize and harmonize global mining practices. This agency would focus on ensuring fair trade, promoting sustainable mining practices, and facilitating technology transfer and capacity building among member countries. It would particularly support emerging economies with significant mineral reserves, helping them to participate more fully and fairly in the global market.

Impact: An International Minerals Agency could address several critical issues identified, such as the unequal benefits derived from mineral resources and the environmental impact of mining practices. By fostering cooperation and setting global standards, the agency would help level the playing field between developed and developing nations, ensuring that mineral extraction is beneficial and sustainable for all stakeholders involved.

Evidence: The model of other international regulatory bodies, such as the International Energy Agency, shows how such an organization can successfully bring together diverse stakeholders to address global challenges. These agencies have been instrumental in setting international standards and policies that enhance both market stability and environmental protection. An equivalent agency for minerals could similarly facilitate more equitable and sustainable global mining practices.

Level the Playing Field Internationally

Send Market Signals for Clean Energy Investment It is crucial for the government to set and publicly commit to ambitious, long-term targets for clean energy adoption and emissions reduction. These targets, backed by consistent policy support, serve as powerful market signals that can mobilize substantial investment in clean energy technologies. By clearly articulating these goals, the government can reduce market uncertainty and coordinate efforts both domestically and internationally, encouraging other nations to participate in global clean energy initiatives.

Impact: This approach directly addresses the demand uncertainty and coordination challenges outlined in the findings. Establishing clear and ambitious targets demonstrates the government's commitment to transitioning to a sustainable energy economy, thereby boosting investor confidence and fostering industry growth. This strategic signaling is essential for attracting private and international investments into renewable energy, energy storage, and electric vehicles, which are pivotal for achieving these clean energy goals.

Evidence: The effectiveness of such market signals is well-documented in cases where government commitments have led to increased private sector investment and accelerated technological development. For example, countries that have set clear renewable energy targets have seen a significant uptick in renewable energy production capacity, driven by enhanced investor confidence and spurred by favorable regulatory environments.

Align Internationally Verifiable Environmental and Social Standards Establishing and enforcing a comprehensive set of verifiable environmental and social standards is critical for industries engaged in critical minerals and clean energy technologies.

These standards should encompass precise methods for the calculation and disclosure of environmental footprints, enhancing transparency and accountability. Such standards provide a clear benchmark for assessing environmental and social performance, motivating industries to adopt sustainable practices that align with global sustainability goals.

Impact: These verifiable standards address significant concerns about environmental degradation and social impacts associated with mining and manufacturing of critical minerals. They ensure that industries commit to measurable and sustainable practices, fostering trust among stakeholders, including consumers, investors, and regulatory bodies. This trust is crucial for maintaining a social license to operate and for promoting a sustainable global supply chain.

Evidence: The effectiveness of these standards in driving industry transformation is exemplified by companies like Newmont Corporation, which adheres to the International Cyanide Management Code. This adherence has led to notable improvements in environmental management and enhanced relationships with local communities. Such success stories illustrate the tangible benefits of implementing robust environmental and social standards, including improved environmental outcomes and strengthened industry credibility.

Adjust Trade Taxonomy to Sanction Environmental and Social Dumping Revising trade taxonomy and policies to identify and penalize environmental and social dumping is crucial for safeguarding domestic industries that adhere to stringent sustainability standards. This reform involves creating mechanisms similar to the Carbon Border Adjustment Mechanism (CBAM) used in the EU, which adjusts import duties based on carbon emissions associated with goods. By expanding these principles to include broader environmental and social metrics, the U.S. can protect domestic industries from unfair competition and foster a global marketplace that values sustainable practices.

Impact: Adjusting trade policies to sanction environmental and social dumping directly addresses the challenges outlined related to global trade inequalities and the environmental impact of imported goods. This strategic shift would level the playing field for U.S. companies investing in sustainable operations, mitigating the competitive advantage held by entities in countries with lax environmental and social regulations.

Evidence: The effectiveness of such measures is demonstrated by the EU's implementation of the CBAM, which has begun to alter trade dynamics by incentivizing lower carbon emissions in the production of imported goods. Aligning U.S. policies with similar international standards could enhance the effectiveness of these measures, promoting broader adoption of sustainable practices globally and reducing the market share of products produced with lower environmental and social oversight.

4.1.3 Reduce Externalities

Promote Demand Reduction and Recycling

Implement Demand Reduction and Substitution Initiatives To mitigate vulnerabilities in the critical mineral supply chain, it is essential to support research and development of high materials efficiency technologies and alternative materials. This strategic focus aims to decrease dependency on critical raw minerals such as lithium and cobalt, which are susceptible to market volatility, geopolitical tensions, and environmental constraints. Significant investments should be directed towards developing technologies like solid-state batteries and exploring alternative chemistries such as lithium iron phosphate (LFP) and sodium-based batteries. These initiatives will reduce the reliance on scarce minerals and foster innovation in energy storage and efficiency solutions.

Impact: By prioritizing demand reduction and substitution, the U.S. can enhance its leadership in sustainable technological innovation within the clean energy and transportation sectors. This approach not only ensures the resilience of the supply chain but also positions the U.S. at the cutting edge of global advancements. Substituting traditional battery chemistries with less resource-intensive alternatives and enhancing materials efficiency can significantly reduce environmental impacts and resource dependency.

Evidence: The effectiveness of demand reduction strategies is exemplified by the development of alternative battery technologies by several automakers, which have improved cost resilience and reduced reliance on volatile raw materials markets. Additionally, incentivizing materials efficiency, such as adjusting electric vehicle (EV) subsidies based on battery size, encourages manufacturers and consumers to consider more sustainable options, further reducing the demand for critical minerals.

In response to the escalating demand for critical materials in electric vehicles and renewable energy storage solutions, mining companies should intensify their efforts in battery recycling programs. These programs are essential for recovering valuable materials such as lithium, cobalt, and nickel from end-of-life batteries. Extending these recycling processes to include tailings reprocessing can further capitalize on existing technologies to recover additional resources from waste materials. This integrated approach not only secures a more sustainable material supply but also mitigates environmental impacts and reduces reliance on virgin material extraction. Electric vehicle manufacturers should aslo be urged to prioritize the design for recycling in their products to ensure that materials are easily recoverable at the end of the product's lifecycle. This approach involves designing products in such a way that their components can be easily disassembled and recycled, significantly reducing the demand for virgin materials and enhancing the environmental benefits. Addressing the challenge of collecting end-of-life products is also crucial for maximizing the potential of recycling programs. Enhanced regulatory frameworks, incentives for recycling, and improvements in the infrastructure for collecting and sorting waste are vital.

Impact: By expanding internal recycling programs, mining companies can enhance their resource efficiency and adapt to a changing market where sustainable practices are increasingly valued. Recycling critical battery materials reduces the environmental degradation associated with primary extraction and lowers carbon emissions. Furthermore, such initiatives strengthen the supply chain against fluctuations in raw material availability and price volatility. Implementing robust recycling systems also aligns with global environmental standards and regulations, supporting the transition to a circular economy.

Evidence: Programs like Umicore's Lithium-ion Battery Recycling Program have successfully demonstrated high recovery rates, often exceeding 90% of metals from recycled batteries. This high level of efficiency showcases the potential for widespread application across the industry. Additionally, automakers are increasingly incorporating design for recycling principles into their products, which has shown to improve the end-of-life recovery of materials. Renault's battery leasing model is an example of how design for recycling can be integrated into business models to enhance sustainability and customer engagement. Companies adopting recyling-centered design principles have reported up to 95% recyclability rates for their products, which not only supports environmental objectives but also boosts brand reputation and consumer loyalty. regarding recycling rates has proved to be achievable. For instance, the European Union's Waste Electrical and Electronic Equipment (WEEE) Directive provides a regulatory model that sets ambitious collection, recycling, and recovery targets for electrical goods, driving significant improvements in recycling rates across member states.

Promote Recycling Initiatives for Urban & Telecom Mining The U.S. government should take a proactive role in establishing and funding a national recycling initiative focused on urban and telecom mining to recover critical minerals from electronic waste and end-of-life telecommunications equipment. This initiative should also include significant investment in research and development for advanced recycling technologies. Urban mining capitalizes on the accumulation of valuable metals in electronic waste, which often contains higher concentrations of precious and critical minerals than traditional ore deposits. Advancements in recycling technologies for this purpose are crucial for maximizing the recovery of materials. Innovative processes being developed include the use of bacteria to extract metals from electronic waste, offering an environmentally friendly alternative to more harmful traditional mining techniques. Additionally, the identification and mapping of secondary sources such as old telecommunication lines and residential piping provides further opportunities to recover valuable metals like copper, enhancing resource efficiency and reducing environmental impacts.

Impact: By enhancing the recovery of critical minerals from urban waste streams, this initiative supports the reduction of reliance on virgin mineral resources, which are becoming increasingly scarce and environmentally costly to extract. A robust urban mining program can substantially contribute to the circular economy, reducing electronic waste and promoting sustainable resource use. This approach not only addresses the need for critical minerals but also mitigates environmental impacts associated with both mining and waste.

Evidence: The potential for urban mining has been demonstrated by companies like Umicore and Retriev Technologies, which have developed successful technologies to extract valuable materials from e-waste. For example, bioleaching and other hydrometallurgical methods have proven effective in recovering metals more sustainably. Additionally, studies have shown that the concentrations of critical minerals in e-waste, such as those from recycled copper phone networks in France, often exceed those found in conventional mines, underscoring the viability and necessity of these recycling initiatives.

Compensate Social Externalities

Improve Workers Protection Improving worker protection in the mining industry is crucial due to the distinct occupational hazards associated with mining activities. Workers in this sector are exposed to a variety of risks including hazardous substances like silica dust, heavy metals, and chemical reagents, as well as physical strain from operating heavy machinery. These hazards necessitate stringent health and safety measures tailored to the specific conditions of mining operations. Beyond the direct occupational hazards, mining activities can also have significant health impacts on nearby communities, primarily through environmental contamination such as water and air pollution. These can lead to a range of health issues, from respiratory problems to neurological and systemic conditions.

Impact: Implementing comprehensive health and safety protocols not only protects workers but also contributes to broader community health and well-being. Effective strategies include enhancing mine ventilation systems to reduce airborne contaminants, enforcing stringent use of personal protective equipment (PPE), and regular health monitoring of workers for early detection of occupational diseases. Additionally, improving the environmental management practices of mining operations can help mitigate the indirect health effects on surrounding communities by controlling emissions and managing waste materials responsibly.

Evidence: The effectiveness of improved health and safety measures is well-documented. For instance, the introduction of the Mine Improvement and New Emergency Response Act of 2006 (MINER Act) in the United States has significantly advanced safety protocols by establishing the Office of Mine Safety and Health Research. This office actively promotes safety through innovation, such as the development of new mining equipment and technologies that reduce exposure to hazardous conditions. Furthermore, advancements in mine ventilation and dust control technologies have shown to substantially decrease the incidence of respiratory diseases among miners, demonstrating the direct benefits of such health and safety investments.

Further Initiatives: Ongoing research and development are essential to continue advancing worker protection measures. The mining industry should focus on integrating more advanced health monitoring systems, such as wearable technology that can track exposure levels in real time. There is also a critical need for regular training and education programs to ensure that workers are well-informed about the risks and the protective measures available. Additionally, collaboration between mining companies, government agencies, and health organizations can lead to better health outcomes by ensuring that safety standards are consistently applied and updated based on the latest scientific findings.

Mining companies must also prioritize investments in community health initiatives, particularly in regions where mining is a significant economic activity. This can include funding local health clinics, providing community health education, and participating in environmental cleanup efforts. Such initiatives not only improve public health but also strengthen community relations and enhance the social license to operate, which is increasingly recognized as vital for the sustainable success of mining operations.

Manage Mining Transfers Transitioning from traditional coal mining to the extraction of critical materials like lithium, cobalt, and rare earth elements is reshaping the mining industry, impacting both the environment and local economies. This shift offers an opportunity to promote environmental justice and enhance community well-being through the provision of fair and meaningful employment in new mining sectors. It's vital to support and encourage equitable practices[1] that ensure the benefits of resource extraction are widely distributed, particularly in marginalized communities that have historically borne the environmental and social costs of mining operations.

Impact: By focusing on equitable economic development and sustainable mining practices, companies can support local economies, improve social inclusion, and mitigate the adverse impacts associated with mining. This approach is crucial in regions where critical material deposits are located, often distinct from traditional coal regions, which requires a thoughtful redistribution of resources and opportunities. Effective management of mining transfers is essential for ensuring that these communities benefit from new mining activities without experiencing disproportionate environmental or social burdens.

Evidence: The effectiveness of these strategies can be observed in preliminary initiatives where regions have begun transitioning away from coal. For example, some areas have successfully implemented retraining programs, leading to new employment opportunities in sectors such as technology and renewable energy. Moreover, case studies from regions like the Rust Belt in the U.S. and parts of Canada's mining belt

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[1] These could include:

- Workforce Retraining Programs: Develop comprehensive programs funded by both public and private sectors to retrain former coal miners and other workers in communities affected by the mining industry's transformation. These programs should focus on skills pertinent to mining critical materials, including advanced mining technologies and environmental management practices.
- Investment in Education and Research: Increase funding for educational institutions and research initiatives focused on sustainable mining and the processing of critical materials. This investment should aim to develop a new generation of mining professionals equipped with the knowledge and tools to operate sustainably.
- Community Engagement and Support: Implement robust community engagement strategies in declining regions like economic aid or placement support. These policies should be designed to support not just individuals transitioning to new jobs but also the broader community in adapting to economic changes.
- Public-Private Partnerships: Foster strong partnerships between governments, educational institutions, and the private sector to create comprehensive support systems for communities affected by the mining industry shift. These partnerships can facilitate the development of training programs, economic development initiatives, and sustainable mining technologies.

show that comprehensive community engagement and support initiatives can lead to revitalization and less economic disruption.

Share Benefits with Communities The relationship between mining operations and Indigenous communities is often fraught with challenges due to the profound impacts these activities can have on Indigenous lands, cultures, and environments. For example, the development of the Thacker Pass lithium mine in Nevada and the Voisey's Bay nickel mine in Labrador have highlighted conflicts arising from mining activities that threaten sacred sites and the local environment. These cases illustrate the broader issue of how mining can disrupt Indigenous ways of life. Addressing these concerns requires a comprehensive approach that respects the rights and well-being of Indigenous populations, ensuring they benefit fairly from local mineral wealth. This could include mandatory legal biding conscent from communities, integrating traditional Indigenous knowledge alongside scientific analyses for environmental impact assessments, or encouraging agreements that guarantee a fair distribution of mining benefits. Additionally, supporting and funding educational and training programs specifically designed for Indigenous communities to build capacity for engaging in negotiations, managing environmental assessments, and participating effectively in the mining industry. This is indeed relevant to educate stakeholders on the environmental standards and sustainability goals of mining projects, such as achieving Net-Zero emissions.

Impact: Implementing fair and equitable practices in mining developments is crucial for maintaining social license to operate and for fostering sustainable relationships between mining companies and local communities, especially Indigenous ones. By involving these communities in decision-making processes and ensuring they receive a fair share of the benefits, mining companies can mitigate conflict and enhance project acceptability. This approach not only aligns with ethical standards but also stabilizes operations by rooting them in community consent and support.

Evidence: The effectiveness of these strategies can be observed in various international contexts where mining companies have successfully engaged with Indigenous communities to create mutually beneficial outcomes. For instance, several mining projects in Australia now operate with agreements that provide substantial community benefits, including royalties, employment, and environmental protections, leading to sustained community support and smoother project operations.

Mitigate Environmental Impact

Here's the revised paragraph for "Revise Market Mechanisms for Environmental and Social Performance":

Revise Market Mechanisms for Environmental and Social Performance It is imperative to update and enhance existing market mechanisms, such as carbon pricing and renewable energy certificates, to more explicitly incentivize and reward strong environmental and social performance in the mining sector. This reform should include mechanisms to publicly display the environmental footprint of raw critical materials used in products, allowing consumers and stakeholders to compare the environmental impacts of different materials. Additionally, implementing strict penalties for non-compliance with these standards can further enforce these measures.

Impact: By revising these market mechanisms, the government can foster a competitive advantage for companies that are committed to environmental stewardship and social responsibility. This strategic approach not only encourages green innovation but also compels companies across various industries to adopt sustainable practices. Such regulatory adjustments can drive significant improvements in environmental and social outcomes by integrating sustainability into the core business strategies of companies.

Evidence: Historical precedents in the energy sector, where market-based emissions control mechanisms have led to significant reductions in pollutants and greenhouse gas emissions, demonstrate the effectiveness of this approach. For instance, the success of emissions trading schemes and carbon pricing has motivated energy companies to invest in cleaner technologies and practices. Similarly, applying these principles to the mining and production of critical materials could encourage widespread adoption of sustainable practices, thereby enhancing environmental and social performance industry-wide.

Additional Measures: Extending these mechanisms to include criteria such as material efficiency—for example, regulating the size and weight of vehicles based on their environmental impact—can further promote resource conservation and reduce the environmental footprint of manufacturing processes.

Adopt Low Impact Mining Practices Adopting low-impact mining practices is crucial for reducing the environmental and social impacts of mining operations. Innovations such as electrification of mining equipment, in-situ leaching, and precision mining are transformative techniques that reduce the physical footprint of mining activities, minimize ecological disturbances, and enhance resource efficiency. These practices not only mitigate the direct environmental impacts associated with traditional mining methods but also contribute to broader corporate sustainability goals. The main strategies comprise broad electrification, in-situ leaching, precision mining, and reusing mine waste (in addition to tailings and water management). In addition to mining proceeds, adopting comprehensive environmental impact assessments before project initiation and detailed closure and reclamation plans that ensure the site is returned to a natural state or repurposed in an environmentally beneficial manner can alleviate further the externalities.

Impact: Implementing these low-impact techniques can significantly improve the sustainability profile of mining operations, making them more compatible with environmental conservation standards and reducing conflicts with local communities and regulatory bodies. This shift can also lead to operational efficiencies, reduced cleanup costs, and improved stakeholder relations, particularly with investors increasingly focused on environmental, social, and governance (ESG) criteria. Moreover, these practices can enhance the resilience of mining operations against regulatory changes, such as those related to carbon emissions and environmental restoration requirements. in addition, after mining activities have ceased, strategies such as land reclamation, habitat restoration, and community redevelopment ensures that post-mining land use meets community needs and expectations.

Conclusion: Adopting low-impact mining practices is essential for modern mining operations aiming to align with global sustainability standards and community expectations. These practices not only reduce the environmental footprint of mining but also enhance social acceptance and economic efficiency. By integrating these advanced techniques, the mining industry can significantly contribute to sustainable development goals, fostering a more responsible stewardship of natural resources.

Reduce Sector Emissions Reducing emissions in the mining sector is critical for aligning with global climate goals and enhancing sustainability within the industry. According to McKinsey's "Creating the zero-carbon mine" (2021), several strategies and technologies are essential for significantly lowering both Scope 1 (direct) and Scope 2 (indirect) emissions. These include improving operational efficiency, utilizing sustainable fuels and drivetrains, and transitioning to green electricity sources. Operational efficiency can be enhanced through performance benchmarking, automation, and predictive maintenance, which collectively reduce the energy per unit of output and optimize resource use. The integration of sustainable fuels such as biofuels and synthetic fuels, alongside the electrification of mining equipment, provides a pathway to reduce dependency on fossil fuels. Moreover, adopting renewable energy sources for electricity needs minimizes carbon footprints and contributes to a sustainable operational environment.

Impact: Implementing these technologies and strategies has a profound impact on the mining industry's sustainability. It not only reduces greenhouse gas emissions but also positions mining companies as leaders in environmental stewardship, enhancing their attractiveness to investors focused on ESG criteria. Additionally, these measures can improve regulatory compliance and reduce the costs associated with environmental penalties and fossil fuel usage. The shift towards low-carbon technologies and practices also helps in future-proofing the mining operations against stricter environmental regulations expected to arise as global climate policies tighten. Further strategies include operational efficiency improvements like upgrading to more efficient machinery, optimizing processes through AI and data analytics, and regular maintenance to prevent energy wastage. Finally, transitioning to clean energy like biofuels, synthetic fuels, and electric vehicles reduces direct emissions from diesel-operated machinery and expanding the use of solar, wind, and other renewable energy sources directly at mining sites or through grid connections significantly cuts down Scope 1 and 2 emissions.

Evidence: The effectiveness of these emission reduction strategies is evidenced by several case studies and real-world implementations. For example, Rio Tinto's incorporation of autonomous haul trucks and trains in their "Mine of the Future" program has significantly reduced diesel consumption and associated emissions. Similarly, Boliden's use of electric vehicles in its operations and IAMGOLD's installation of a solar power facility at its Rosebel gold mine demonstrate the sector's shift towards renewable energy. These initiatives not only decrease carbon emissions but also lead to operational cost savings over time. Additionally, the adoption of small modular reactors (SMRs) and hybrid energy systems by companies like U-Battery and the DeGrussa mine illustrate innovative approaches to integrating clean energy solutions in remote and off-grid mining operations.

Further Strategies:

Operational Efficiency Improvements: Includes upgrading to more efficient machinery, optimizing processes through AI and data analytics, and regular maintenance to prevent energy wastage. Sustainable Fuels and Electrification: Transitioning to biofuels, synthetic fuels, and electric vehicles reduces direct emissions from diesel-operated machinery and supports the industry's move towards carbon neutrality. Green Electricity Utilization: Expanding the use of solar, wind, and other renewable energy sources directly at mining sites or through grid connections significantly cuts down Scope 2 emissions.

Minimize Chemical Pollution Minimizing chemical pollution in mining involves adopting methods and technologies that reduce the environmental footprint of mineral extraction and processing. Techniques like In-Situ Leaching (ISL), Precision Mining, and Mine Backfill are central to this strategy. ISL reduces the need for extensive physical mining operations by using a leaching solution to extract minerals directly from the ore body, which significantly lessens surface disturbance and the production of waste materials. Combining this process with bio-leaching, closed loop water management and advanced water treatments solutions further reduces chemical pollution. Precision Mining utilizes advanced data analytics and automation to optimize material extraction, thus preventing over-mining and reducing unnecessary waste and chemical use. Mine Backfill involves filling mined-out voids with tailings or waste rock, which stabilizes the mine structure and reduces the surface storage of potentially hazardous materials. Investing in these technologies also eases the permitting process.

Impact: These innovative practices contribute to significant reductions in chemical pollutants, crucial for protecting water quality and preventing soil contamination. By minimizing the environmental disturbances associated with traditional mining practices, these methods help preserve biodiversity and ensure the health of ecosystems surrounding mining sites. Furthermore, such practices enhance the sustainability of mining operations and improve their compliance with increasingly stringent environmental regulations.

Evidence: The effectiveness of these methods is demonstrated through various successful implementations across the mining industry. Cameco, a prominent player in the uranium mining industry, has effectively used ISL to extract uranium with minimal environmental impact. This method allows for the extraction of minerals without extensive physical mining, reducing both land use and the generation of mining waste. Technologies such as Caterpillar's MineStar Command not only improve the efficiency of mining operations but also reduce the overall environmental impact by optimizing resource use and reducing waste. This system provides precise control over mining equipment, enhancing the accuracy of operations and minimizing unnecessary disturbances. Finally, companies like Newmont Corporation and Barrick Gold utilize mine backfill practices to effectively manage tailings and waste rock, reducing their environmental liability and enhancing the stability of mining areas. This practice not only mitigates the risk of ground subsidence but also reduces the need for new waste disposal areas.

Enable Sustainable Processing Enabling sustainable processing in the mining sector involves integrating innovative technologies and practices that enhance the efficiency and environmental friendliness of mineral processing operations. This includes the adoption of automated mineral processing, high-pressure grinding rolls (HPGR), non-toxic leaching techniques, and dry processing methods. These technologies not only aim to reduce the environmental impact associated with traditional processing methods, such as high energy consumption and chemical pollution, but also enhance operational efficiency by reducing waste and optimizing material use.

Impact: The implementation of these sustainable processing technologies can significantly reduce both CO2 and non-CO2 emissions within the mining industry. For instance, electrification of processing operations and the utilization of renewable energy sources minimize carbon footprints. Automated systems improve precision and efficiency, reducing resource wastage and energy usage. Non-toxic leaching methods, such as the use of thiosulfate, eliminate the environmental hazards associated with cyanide, thereby safeguarding local ecosystems and community health. Moreover, dry processing techniques address water scarcity issues by eliminating the need for large volumes of water in mineral processing, which is critical in arid mining regions.

Evidence: Companies like Metso Outotec are leading in providing automation solutions that significantly enhance the efficiency of mineral processing plants. These systems allow for real-time monitoring and control, which optimizes performance and reduces energy consumption. The Boddington gold mine in Western Australia has successfully implemented High Pressure Grinding Rolls (HPGR) technology, which has been shown to reduce energy consumption by up to 40% compared to traditional milling methods. Barrick Gold's adoption of thiosulfate non-toxic Leaching at its Goldstrike mine in Nevada represents a shift towards safer chemical processes in gold extraction, demonstrating that non-toxic chemicals can effectively replace cyanide in certain contexts. Finally, Vale's S11D project in Brazil utilizes natural moisture processing (dry processing) techniques to eliminate water use in ore processing, significantly reducing the mine's water consumption and eliminating the need for tailings dams.

Additional Strategies: Using aqueous solutions to extract metals from ores and recycled materials often results in lower energy use and can enhance metal recovery rates compared to traditional smelting and refining processes (hydro-metallurgical processing). The use of bio-leaching and bio-oxidation processes employs microorganisms to extract metals from low-grade ores and mining wastes, offering a more environmentally friendly alternative to chemical leaching. Finally, implementing advanced water treatment and recycling systems can significantly reduce water withdrawals and pollution in mining operations. BHP and Anglo American, for instance, have implemented sophisticated water recycling technologies tailored to the mining industry's needs.

4.2 Discussion

4.2.1 Implementation

Successfully implementing the proposed recommendations for sustainable and responsible mining requires a strategic and comprehensive approach that encompasses regulatory adjustments, technology advancements, and enhanced stakeholder collaboration.

The cornerstone of effective policy implementation lies in establishing robust regulatory frameworks that not only mandate but also incentivize the adoption of sustainable mining practices. Governments should consider revising mining codes to include stringent environmental protection measures, mandatory use of low-impact mining technologies, and comprehensive social impact assessments. These regulations should be enforced through rigorous monitoring and backed by penalties for non-compliance. Additionally, financial incentives such as tax breaks, subsidies, or grants could be employed to encourage mining companies to invest in cleaner technologies and more sustainable operational practices.

The integration of advanced technologies is pivotal in transforming mining practices. This integration can be facilitated by government and industry-led research and development initiatives aimed at advancing mining technology with a focus on reducing environmental footprint and enhancing efficiency. Public-private partnerships can play a significant role here, providing a platform for sharing risks and benefits associated with new technologies. Initiatives might include funding for innovation hubs, collaborative research projects between universities and mining companies, and pilot programs to test new technologies in operational settings.

Implementing new technologies and practices requires a skilled workforce. Therefore, investing in education and training programs is essential to equip current employees with new skills and attract talented individuals to the mining sector. These programs should focus on automation, data analysis, environmental management, and other relevant areas. Furthermore, transition programs specifically designed for workers shifting from traditional roles to new positions within restructured mining operations can facilitate smoother transitions and reduce resistance from the workforce.

For sustainable mining practices to be truly effective, they must have the buy-in of all stakeholders, including local communities, Indigenous groups, environmental NGOs, and government agencies. Establishing ongoing communication channels and consultation processes can help align mining operations with community expectations and environmental standards. This engagement should be transparent and inclusive, offering stakeholders a role in monitoring and decision-making processes. Regular community meetings, impact reports, and open forums can foster a collaborative environment where concerns can be addressed proactively and collaboratively.

In the context of globalized supply chains and the international nature of environmental challenges, collaboration across borders is crucial. By aligning policies and standards with international best practices and participating in global mining initiatives, countries can ensure that their mining sectors are not only competitive but also responsible. This international cooperation can extend to sharing knowledge, research, and technology solutions that have been successful in other regions.

4.2.2 Evaluation

Effective evaluation and monitoring of implemented mining policies are foundational to ensuring they achieve their intended outcomes—enhancing sustainability and responsible mining practices. The process involves a nuanced and continuous assessment that integrates various methods to capture a comprehensive view of the policies' impacts.

At the heart of the evaluation process is the development and utilization of specific, measurable indicators. These indicators must reflect a range of impacts, from environmental to social and economic outcomes. For instance, metrics could look at reductions in water and energy usage, decreases in emissions, improvements in biodiversity around mining sites, the socioeconomic benefits for local communities, and the overall economic viability of sustainable practices. Establishing these metrics provides a baseline against which progress can be measured and evaluated.

Transparency in reporting these metrics is crucial. Regular data collection, analysis, and public dissemination of this information serve multiple purposes. They hold mining companies accountable to their commitments, provide stakeholders with trust in the processes, and offer regulatory bodies the information needed to enforce compliance. Annual sustainability reports and regular environmental audits become tools not just for accountability but also for communication with the broader community.

The credibility of the evaluation process is significantly enhanced by independent auditing and third-party verification. These external reviews ensure that the data reported by mining companies is accurate and that practices align with stated policies. Independent assessments help bridge any gaps between reported practices and actual on-ground performance, providing an unbiased perspective that can highlight areas needing attention.

Adopting real-time monitoring systems is another step forward in creating a responsive and dynamic evaluation framework. With advancements in technology, sensors and IoT devices can provide continuous streams of data on critical operational parameters such as air and water quality, energy consumption, and waste management. This immediacy not only allows for quick adjustments and mitigations but also supports a more agile management approach that can respond to issues as they arise, rather than through retrospective analyses.

Moreover, the inclusion of stakeholder feedback in the evaluation process enriches the understanding of the impacts of mining operations. Regular interactions with local communities, employees, and environmental groups through surveys, forums, and other feedback mechanisms provide qualitative insights that complement the quantitative data. This feedback is invaluable for highlighting concerns that may not be immediately apparent through metrics alone and can drive improvements in community relations and operational practices.

Lastly, the evaluation process must be iterative and adaptive. It is not sufficient to establish policies and metrics only once; rather, they should be continuously reviewed and adjusted in light of new data, changing environmental conditions, and evolving stakeholder expectations. This adaptive management approach ensures that mining policies remain relevant and effective over time, fostering a cycle of continuous improvement.

In summary, a robust evaluation and monitoring framework in the mining sector is not just about compliance and reporting—it's about creating a dialogue between all parties involved, leveraging technology for real-time management, and continuously refining practices to meet the highest standards of sustainability and responsibility.

4.2.3 Limitations and Further Developments

While the proposed recommendations for the mining sector are designed to drive significant improvements in sustainability and social responsibility, they are not without their limitations. These constraints stem from various systemic, operational, and socioeconomic challenges that can affect the feasibility and effectiveness of the policies.

One of the most significant limitations is the timeframe for implementation. Many of the recommended technologies and practices, such as advanced automation, sophisticated recycling processes, or comprehensive community engagement strategies, require substantial time to develop, test, and scale. This delay can be a critical factor, especially in regions where immediate action is needed to mitigate environmental degradation or community impacts. Moreover, the integration of these new technologies often necessitates substantial upfront investment and long-term commitment, which can be a deterrent, particularly for smaller mining operations or in countries with unstable economic conditions.

Another major challenge is the scope of ambition of these recommendations. While they aim to set a high standard for the mining sector, their ambitious nature may make them difficult to fully realize. Political and economic resistance from well-established mining corporations, many of which have entrenched interests in maintaining the status quo, can significantly slow down legislative and regulatory changes. Furthermore, the global nature of the mining industry, with its complex supply chains and diverse regulatory environments, adds an additional layer of complexity to enforcing these standards universally.

The influence of economic considerations cannot be underestimated. Implementing sustainable mining practices often comes with high costs, and the financial burden can be prohibitive, particularly in less economically developed regions. The need for significant investment in new technologies, training, and compliance can strain budgets and affect profitability, making it challenging to gain buy-in from stakeholders who prioritize short-term financial gains over long-term sustainability.

Additionally, there is a lack of quantified targets in many of the recommendations, which can complicate the evaluation of their effectiveness. Without clear, measurable objectives, it can be difficult for policymakers and industry leaders to assess progress and determine whether the adopted practices are yielding the desired outcomes. This absence of quantified goals can also lead to inconsistencies in implementation and enforcement, reducing the overall impact of the initiatives.

Despite these challenges, the recommendations provide a comprehensive framework for transforming the mining sector. Addressing these limitations requires a coordinated effort among governments, industry leaders, and communities to foster an environment that encourages innovation, supports economic and social development, and prioritizes environmental stewardship.

The conclusions of this thesis underscore the urgent need to advance the understanding and management of critical materials within the U.S. supply chain, especially given the rapid evolution of global demand and technological developments. Several further developments have been identified to enhance the effectiveness of the proposed recommendations and to solidify the foundation for future policies.

1. Labor Reallocation and Opportunities from Coal: As the energy sector transitions from coal to more sustainable sources, there exists a significant opportunity to reallocate skills and workforce. This transition requires not just retraining but

a comprehensive strategy that ensures these workers are integrated into the new energy economy. By investing in targeted education and training programs, the U.S. can leverage the existing workforce and mitigate unemployment risks in communities historically dependent on coal mining.

2. Quantifying Supply Curve Impacts through Advanced Modeling: To better understand the economic implications of the Inflation Reduction Act (IRA) and other policy measures, advanced economic modeling should be employed. Extending the Hotelling model to include detailed calibration that reflects current market dynamics can provide deeper insights into how these policies influence the supply curve of critical minerals. Such modeling could predict future price fluctuations and supply bottlenecks, offering a more robust tool for policymakers.

3. Comprehensive Cost-Benefit Analysis of Recommendations: To prioritize actions effectively, a detailed cost-benefit analysis of the recommendations is essential. This analysis should quantify the economic, environmental, and social impacts of each recommendation. By understanding the relative benefits and costs, policymakers can sequence and allocate resources to initiatives that offer the highest returns or most critical impacts on supply chain resilience.

4. Technology Development and Integration: Further research into new technologies that could reduce dependence on critical raw materials is crucial. This includes developing alternative materials, enhancing recycling technologies, and improving material efficiency in product design. Encouraging public-private partnerships to drive innovation in these areas could significantly reduce the pressure on critical material demands.

5. Policy and Regulation Enhancements: The dynamic nature of the critical materials market necessitates continuous adaptation of policies and regulations. Future developments should focus on creating flexible regulatory frameworks that can quickly respond to market changes and technological advancements. This includes the ability to adjust import tariffs, subsidies, and tax incentives that promote domestic production and recycling initiatives.

6. International Collaboration and Standard Setting: Given the global nature of mineral supply chains, the U.S. should strengthen international collaborations. These partnerships could focus on harmonizing standards for mining and recycling, securing supply chains, and fostering global markets for recycled materials.

Joint ventures and cooperative agreements with countries that have rich mineral deposits could also help diversify supply sources and reduce geopolitical risks.

Each of these developments not only supports the recommendations outlined in this thesis but also provides a roadmap for ensuring the United States can maintain its leadership role in the global transition to a sustainable and secure energy future. The integration of these advancements will enhance the resilience of the U.S. supply chain and support the broader goals of economic stability and environmental sustainability.

Conclusion

In examining the U.S. critical materials supply chain for clean technology manufacturing, this thesis has identified profound strategic gaps in current policies and industry practices that threaten the nation's ability to sustainably transition to a secure energy future. Reliance on geopolitically sensitive and environmentally unsustainable foreign sources for essential materials such as lithium, cobalt, nickel, and rare earth elements poses significant risks of supply disruption. These vulnerabilities, combined with limited capabilities for rapid domestic production ramp up expose the U.S. to competitive disadvantages in the rapidly growing global clean tech industry.

Driven by the urgent need for a more resilient supply chain, this research employed a comprehensive approach, integrating empirical data, case studies, and industry consultations. The methods applied not only helped to highlight the existing challenges but also to explore potential solutions that could foster a more sustainable and secure supply chain. This integrative approach enabled a deep understanding of the intricate dynamics between policy, environmental sustainability, and industrial needs, laying the groundwork for informed recommendations.

The findings of this research clearly indicate the necessity for the U.S. to bolster its domestic mining and processing capabilities. A multifaceted policy framework is crucial, promoting the adoption of best environmental technologies and practices which can accelerate production capacities by expediting permitting processes, thanks to their reduced environmental impact. Additionally, these technologies offer significant operational benefits by minimizing ecological damages and increasing existing sites production.

The recommendations put forth by this thesis advocate for enhanced federal support through financial incentives, regulatory reforms and investment. These measures aim to reduce the U.S.'s dependency on unstable foreign sources and encourage a shift towards more sustainable and ethically sourced materials. Moreover, strategic international alliances and investment in research and development for recycling technologies and alternative materials are suggested to diversify supply sources and reduce the demand on critical raw materials.

This thesis contributes to the field by mapping the challenges and offering a detailed strategic framework. It provides policymakers and industry leaders with actionable insights to strengthen the U.S.'s position in the global clean tech landscape.

However, the study is not without limitations. It relies heavily on the current geopolitical and economic conditions, which are inherently dynamic. Future research should thus focus on the impact of emerging technologies on critical materials demand as it remains uncertain, and quantify the propositions. Continued exploration in these areas will be vital for adapting the policy framework to meet the evolving needs of the U.S. clean tech sector, ensuring that the nation remains at the forefront of sustainable technological advancement.

In conclusion, this thesis emphasizes the critical role of sustainable practices and robust policy frameworks in securing the supply of critical materials necessary for the U.S. to maintain its leadership in global technology and energy markets. By addressing both the challenges and opportunities associated with critical mineral industries, the recommendations aim to foster a more sustainable and equitable future.

Appendix A

Technology options

A.1 Mining

Increasing mining outputs can be achieved through a combination of digital and non-digital solutions. Here are some key factors that can contribute to boosting mining operations:

A.1.1 Mining Performance

Digital solutions

- **Automated and Autonomous Systems:** These systems allow for 24/7 operations without the constraints of human-operated schedules, significantly increasing output. Machines can perform monotonous tasks faster and more accurately than humans, thereby enhancing productivity.

- **Internet of Things (IoT):** IoT devices are being deployed to monitor equipment performance and status. The real-time data generated allows for predictive maintenance, reducing downtimes, identifying and predicting bottlenecks, and thus increasing output. Digital fleet management systems also help provide real-time monitoring to streamline operations and improve fuel efficiency.

- **AI and Machine Learning:** These technologies are revolutionizing the industry by improving decision-making based on patterns, trends, and predictions. They can also optimize resource allocation and process control, leading to increased output. Using advanced data analytics can also drastically improve mineral recovery rates by analyzing process efficiency and identifying areas of improvement.

It also facilitates a more accurate understanding of mineral deposits and aids in exploration, reducing instances of unsuccessful drilling and resource wastage.

Overall, the digitalization of mining operations through the implementation of captors and digital twins paired with the application of machine learning to optimize and help streamline mineral processing, could add consistency and rigor to a traditionally human-controlled process. According to McKinsey, Machine Learning could potentially add 2 to 4% to metal recoveries and 5 to 15% to throughput, resulting in an increase in global production from existing and planned mines [46].

Traditional solutions

- **Advanced Drilling Techniques:** Innovations in drilling technologies, such as directional drilling and automated drilling systems, can improve the accuracy and efficiency of drilling operations. This enables more precise targeting of mineral deposits, reduces wastage, and increases overall mining productivity at a given operational level.
- **Improved Fragmentation Techniques:** Optimal rock fragmentation is crucial for efficient mining operations. Techniques such as controlled blasting, precision drilling, and automated rock breakers can help achieve desired fragmentation, facilitating easier extraction and reducing downtime for clearing blockages.
- **Efficient Haulage Systems:** Implementing advanced haulage systems, such as conveyor belts, in-pit crushing and conveying (IPCC), or automated trucking systems, can streamline material transportation within the mining site. These systems minimize the need for manual handling, reduce truck wait times, and improve overall efficiency, leading to increased mining outputs.

A.1.2 GHG Emissions

McKinsey & Company [40] outlined several key strategies and technologies that mining operations are considering or implementing to achieve better sustainability and reduce emissions. These solutions address both Scope 1 (direct operations mainly from diesel operated machinery) and Scope 2 (indirect, mainly from electricity used in the processing and milling operations onsite) emissions in the mining industry.

Improving Operational Efficiency (Scope 1 and 2, intensity reduction)

- **Performance Benchmarking:** By upgrading operational efficiency to top-quartile levels via improved processes and performance, mining companies can generate both emissions reductions through less energy use per unit of output as well as savings from the cash flow needed to invest in alternative drivetrains or operations modifications.

- **Automated Mining:** The use of automation in mining is rapidly gaining traction as companies seek to improve safety, enhance productivity, and reduce operational costs. It has the potential to drastically reduce emissions and contribute to sustainability in the sector by increasing efficiency and reducing waste. Autonomous Vehicles and Equipment involves the use of self-driving trucks, trains, drill rigs, and other machinery. Autonomous vehicles can optimize fuel consumption, leading to reduced CO_2 emissions. They can operate continuously without breaks, leading to higher productivity. For example, Rio Tinto's Mine of the Future program incorporates autonomous haul trucks and trains to reduce the need for human operators and increase efficiency. Rio Tinto is indeed a leader in this area. They have deployed a fleet of autonomous trucks in their iron ore mines in Western Australia. Their "AutoHaul" project is also the world's first fully autonomous heavy-haul, long-distance railway system. Automated Drilling and Blasting: Automation in drilling and blasting can increase accuracy, which minimizes the amount of energy used and waste produced. Automated drill rigs can provide more consistent and accurate drilling, which can improve blasting efficiency and reduce overbreak, leading to less waste and less energy used in material handling. Epiroc, a Swedish manufacturer of mining and infrastructure equipment, offers a range of autonomous and remote-controlled drilling systems. BHP Billiton has used automated drills at their Jimblebar iron ore mine in Australia to improve safety and efficiency.

- **Predictive Maintenance:** The use of automated systems to predict and schedule maintenance can lead to improved efficiency and increased equipment life. Sensors and AI systems can predict when a machine is likely to fail, allowing for maintenance to be performed before a failure occurs, which minimizes downtime and inefficient operations that engender an overconsumption of resources. This results in less material and energy waste. Goldcorp, a gold producer, partnered with IBM to use AI in their Red Lake, Ontario mine to predict maintenance of machinery. The predictive maintenance technology has been used to reduce the maintenance costs and unplanned repair works which has induced energy savings over the long term.

- **Data Analysis and AI:** Automated data analysis and artificial intelligence can help optimize operations and reduce waste. AI can analyze large amounts of data to identify inefficiencies and suggest improvements. It can also be used to predict market demand and adjust production accordingly, reducing the chance of overproduction and waste. It also allows for optimization of transport, hauling and conveying operations, which induces energy savings from diesel and electricity, resulting in emissions cuts.

Sustainable Fuels and Drivetrains (Scope 1 and 2, less carbon energy sources switch)

- **Sustainable Fuels:** Sustainable fuels (also known as green or renewable fuels) are derived from renewable resources. Two main types of sustainable fuels are being considered in the mining industry: biofuels and synthetic fuels. First, Biofuels, derived from biomass materials, such as plants or organic waste. Biofuels are considered carbon-neutral because the carbon dioxide they release when burned is offset by the carbon dioxide absorbed by the plants as they grow. In the context of mining, biofuels can be used in existing diesel engines, which can be a relatively cost-effective way of reducing emissions. Then, Synthetic Fuels (Synfuels), which are man-made fuels produced from chemical reactions involving carbon dioxide and hydrogen. Synfuels can be designed to burn cleaner than traditional fossil fuels, producing fewer pollutants and greenhouse gases. However, producing synfuels typically requires a significant amount of energy. The carbon footprint of synfuels therefore largely depends on the source of this energy. If it is renewable (for example, solar or wind), synfuels can be a low-carbon fuel source. Both these alternatives could decrease carbon emissions by over 70%, albeit with a slight increase in the total cost of ownership. By using biofuels, companies can decrease their reliance on fossil fuels and reduce their carbon footprint. In that case, renewable diesel options like hydrotreated vegetable oil or Power to X synfuels have the biggest economic, scalability and risk mitigation potential.

- **Electrification:** Long-term carbon neutrality can be achieved through the use of electric and hydrogen fuel cells in mining vehicles. In that case the battery option (including swapable ones) coupled with onsite RE generation or grid connectivity provides the most promising potential for competitive decarbonation, with potential negative cost per ton of CO_2. This shift in drivetrains is already in progress, with mining companies testing hybrid and fully electric vehicles for their operations. For instance, Boliden has a pantograph-charged hybrid at Aitik, Anglo American is developing a 300-metric-ton fuel cell electric vehicle (FCEV) haulage truck, and Newmont Goldcorp has the world's first fully electric mine at Borden. Companies like Sandvik and Epiroc are leading in this area, with their electric powered drilling rigs and loaders. Additionally, the biggest lever of decarbonization is converting Haulage into clean operations since it contributes to a significant portion of a mine's emissions. Short-term strategies involve the use of sustainable fuels, such as biofuels, while long-term solutions include the transition from diesel-powered trucks to battery electric vehicles (BEVs) or hydrogen fuel cell trucks. This change can significantly reduce both carbon emissions and costs, as maintenance and fuel costs for BEVs and FCEVs are lower than for diesel trucks.

Green Electricity (Scope 2)

- **Clean Energy Sources:** Transitioning to clean energy sources is crucial to address between 30 and 50 percent of current emissions output (see graph by McKinsey above). Mining operations are increasingly powered by renewable energy sources, such as solar farms and wind turbines. A notable example is Rio Tinto's Gudai-Darri mine, which will have 65% of its total electricity consumption supplied by solar farms and battery storage. Mining companies are increasingly adopting renewable energy solutions to power their operations due to cost-effectiveness, sustainability goals, and sometimes due to the remote location of their mines. Overall there are several options to achieve this:
  - Onsite Renewable Energy Use: The use of renewable energy sources like solar, wind, and hydropower has become more prevalent in the mining sector. For instance, IAMGOLD, a mid-tier mining company, installed a solar power facility at its Rosebel gold mine in Suriname. The solar plant, with a capacity of 5MW, complements the existing 28MW installed power generation from heavy fuel oil sources. Many mining operations are beginning to use renewable energy sources such as wind and solar power to reduce their CO_2 emissions. For example, Gold Fields, a global gold mining company, has committed to using renewable energy for all its operations by 2025.
  - Small Modular Reactors (SMRs): As a source of low-carbon power, SMRs

could provide a suitable energy solution for remote mines. They are not widespread yet due to regulatory, financial, and social acceptance challenges. However, companies like U-Battery are developing SMRs specifically for remote industrial applications like mining.

  - Grid Connection: Where possible, mining operations are switching from diesel generators to cleaner, more reliable grid electricity. An example is Gold Fields' Agnew gold mine in Western Australia, which commissioned a microgrid combining wind, solar, gas and battery storage. In another case, B2Gold in Namibia transitioned the Otjikoto gold mine from heavy fuel oil to a solar plant for its power needs, significantly reducing costs and emissions.
  - Hybrid Systems: Mining companies often adopt hybrid energy systems that combine renewable energy with conventional power generation methods and energy storage systems. This ensures reliable power supply that can adapt to variations in demand and renewable energy production. For example, the DeGrussa copper-gold mine in Western Australia uses a combination of a 10.6 MW solar array, a 6 MW battery, and a diesel generator to power the mine and the associated accommodation village.

A.1.3 Chemical Pollution

- **In-Situ Leaching (ISL):** In-situ leaching, also known as in-situ recovery (ISR), is a mining method that involves pumping a leaching solution—often weakly acidic, but non-toxic chemicals like oxygen, carbonate, or bicarbonate ions—into the ground to dissolve the target mineral, which is then pumped back to the surface for recovery. This method significantly reduces both waste and surface disturbance compared to traditional mining methods. An example of a company utilizing this method is Cameco, a Canadian company that uses ISL for uranium mining.

- **Precision Mining:** Precision mining is an approach that uses data, automation, and better equipment control to improve operations. This can lead to less over-mining (i.e., extracting too much material), which in turn can reduce the amount of waste generated and the associated environmental impacts. Caterpillar's MineStar Command, for example, uses advanced technologies for machine control, monitoring, automation, and health reporting, reducing the environmental footprint of the mining operation.

- **Mine Backfill:** Backfilling mine voids with waste rock or tailings can minimize the surface footprint of mines and reduce the quantity of waste that needs to be managed. This can also help stabilize the mine, reducing the risk of ground subsidence. Several mining companies, such as Newmont Corporation and Barrick Gold, employ this practice.

All of these initiatives, technologies, and innovations help achieve sustainability goals by either reducing emissions, reducing energy consumption, improving efficiency, or reusing and recycling materials. While each of these approaches has its own challenges and limitations, the combination of them can contribute significantly towards sustainable mining operations.

A.2 Processing

A.2.1 Processing Performance

Several technologies could help increase the output and recovery rate of mined ore. They are either focusing on minimizing waste or tackling the decreasing ore grade problem.

For Recovery Efficiency:

- **Coarse Particle Recovery (CPR):** The CPR process is an emerging innovation that allows for more efficient recovery of coarse particles that are generally lost in traditional processing methods. By capturing these particles, CPR can increase overall recovery rates and reduce the amount of waste produced. Two promising developments in that area are grind-circuit roughing and coarse particle scavenging. Grind-circuit roughing recovers particles directly from the grind circuit using a novel material acting as a 'copper sponge.' It attracts mineralized particles and has the potential to boost ball mill throughput by up to 20% without changing grind size (for copper). On the other hand, coarse particle scavenging extends the range of particle sizes recoverable during flotation. It combines the principles of density separation and flotation to prevent coarser particles from sinking, thus enhancing recovery chances. These technologies could not only augment operating concentrators to improve recoveries and throughput but also reduce water and energy consumption, reprocess old tailings facilities, and make brownfield expansions economical. Moreover, they offer opportunities to redesign greenfield mine design, saving on capital requirements and water and energy usage.

- **Flash Flotation:** Flash flotation is a process used in mining to recover minerals from ore deposits. It's designed to remove coarse, high-grade particles from the recirculating load in the grinding circuit, hence improving overall plant performance and reducing the potential for the loss of valuable minerals.

- **High-Pressure Grinding Rolls (HPGR):** This is a more energy-efficient grinding technology that can significantly improve the efficiency of mineral recovery processes. HPGR technology improves the efficiency of mineral recovery by applying high pressure to crush ores, which increases the surface area of the particles and enhances the leaching process.

- **Advanced Gravity Separation:** Techniques like centrifugal gravity concentrators are being refined to improve the recovery of fine particles. These systems use the principles of centrifugal force to separate particles based on density, allowing for the efficient recovery of valuable minerals.

- **Microwave Pretreatment:** This innovative technique uses microwave energy to weaken the structure of the ore before grinding, making the subsequent extraction process more efficient.

- **Froth Flotation Improvements:** Developments in froth flotation, such as novel reagents and more efficient aeration methods, continue to enhance this essential mineral separation process. Better understanding of the surface chemistry of minerals and the use of advanced frothers and collectors can improve recovery rates.

- **Artificial Intelligence (AI):** AI algorithms can be trained to sort through mineral and waste rocks more efficiently, thus improving mineral recovery rates. These technologies can also predict equipment failures before they happen, enabling preemptive maintenance and reducing downtime.

For Decreasing Ore Grades:

- **Ore Sorting Technology:** One of the ways to tackle decreasing ore grades is by improving the efficiency of ore sorting. Advanced sensor-based ore sorting technologies, such as X-Ray fluorescence (XRF) or X-Ray transmission (XRT) sorting, can help to separate low-grade ore early in the process. These technologies allow the separation of valuable mineral particles from the less valuable ones based on their physical or chemical properties, leading to higher overall processing efficiency and better utilization of low-grade ores.

- **Enhanced Leaching Techniques:** As ore grades decline, improving the efficiency of leaching processes becomes more important. Enhancements in leaching, including high-pressure and high-temperature leaching or bioleaching, can increase the extraction rate of valuable minerals from low-grade ores. For instance, in bioleaching, bacteria are used to break down the sulphide minerals to produce soluble compounds that can be further processed to recover the metals.
- **In-Situ Processing:** In-situ recovery (ISR), or in-situ leaching, is a mining process used predominantly for uranium and copper in which solutions are injected into an ore body to dissolve minerals. This approach can be more efficient than traditional mining methods for low-grade ores that are otherwise uneconomical to extract.
- **Use of Artificial Intelligence (AI) and Machine Learning (ML):** AI and ML can help predict and locate high-grade ores with greater accuracy. AI algorithms can analyze geological data and predict the location of high-grade ore bodies. In addition, machine learning algorithms can optimize the processing of low-grade ores by predicting the best operating conditions for maximum recovery.
- **Hydrometallurgical Techniques:** These methods use aqueous chemistry to recover metals from ores, including ion exchange, solvent extraction, and bioleaching. One of the advantages of hydrometallurgical methods over traditional smelting is that they allow for the recovery of metals from low-grade ores, which could significantly increase overall recovery rates. This includes heap Leaching that involves stacking crushed ore on a liner and applying a leaching solution to extract the valuable minerals. Advances in heap leaching methods, such as improvements in stacking techniques, leaching solutions, and recovery systems, can improve the economic viability of mining lower grade ores. For copper, sulfide leaching are used for processing primary-sulfide ore bodies, which are typically processed using flotation-based systems and can recover copper from material currently considered waste due to its below-grade copper levels.

In addition, new lithium production technologies could fuel the global increase in lithium hydroxide demand: Direct Lithium Extraction (DLE) and Direct Lithium to

Product (DLP). DLE and DLP technologies show promise in increasing lithium supply, reducing the industry's environmental footprint, and lowering costs. DLE involves allowing lithium-rich brines to flow through a lithium-bonding material using adsorption, ion-exchange, membrane-separation, or solvent-extraction processes. This technology offers several advantages, including a reduced footprint of evaporation ponds, decreased production times, increased recoveries, lower water usage, and improved product purity. DLE has been successfully implemented in Argentina and China and has the potential to boost existing capacities and improve sustainability in brine operations. DLP technology aims to contain only the lithium metal in a polymer, which is then transformed into a final lithium product. If successful, this process could have a significant impact on lithium supply. In addition, Direct Shipping Ore (DSO) provides a short-term solution to potential undersupply risks. It involves supplying low-grade spodumene concentrate to the market, which can be quickly brought to market with a short lead time, and then refined elsewhere. This enables to bypass refining capacity bottlenecks. Refining DSO is more challenging and costly but has been successfully done in the past. Chinese refineries imported spodumene concentrates below a certain lithium oxide percentage to meet market needs.

A.2.2 Processing Sustainability

In addition to the innovations mentioned above that could potentially have a significant impact on the efficiency of processing operations (such as electrification of processes + RE/clean energy use, AI and optimization, etc.), there are specific actions that could help achieve better sustainability for the processing of critical materials:

- **Automated Mineral Processing:** Automating the mineral processing and sorting stages can enhance efficiency and reduce waste. Robotic sorting systems can sort mineral ores based on certain characteristics, reducing the amount of waste produced. Automated grinding and pulverizing systems can improve energy efficiency by maintaining optimal grinding conditions. Metso Outotec, a Finnish company providing technologies for the mineral processing industry, offers automation solutions that control and optimize performance in real-time for maximum efficiency and improved decision-making.
- **High Pressure Grinding Rolls (HPGR):** This technology used in crushing and grinding operations can significantly reduce energy usage. The Boddington gold mine in Western Australia has adopted this technology.

For Non-CO2 Pollution:

- **Non-Toxic Leaching:** Traditional leaching methods often rely on cyanide to dissolve and separate precious metals like gold and silver from their ores. However, cyanide is highly toxic and poses serious environmental risks in case of spills or leaks. An alternative to cyanide is the use of thiosulfate, a non-toxic chemical, for leaching. Barrick Gold's Goldstrike operation in Nevada uses thiosulfate leaching for gold recovery in some of its ores. The thiosulfate solution is mixed with the ore, which dissolves the gold that can then be collected. This method eliminates the risks associated with cyanide, and the tailings are also easier and safer to manage. However, thiosulfate leaching is more complex and less well understood than cyanide leaching and may not be suitable for all types of ores. The development and deployment of non-toxic leaching methods have the potential to greatly reduce chemical pollution associated with mining operations and make the industry more sustainable.

- **Hydrometallurgical Processing:** Hydrometallurgical processing uses aqueous chemistry for the recovery of metals from ores, concentrates, and recycled or residual materials. Techniques can include leaching, solution concentration and purification, and metal recovery. This method often results in less energy use and can often recover metals more efficiently than traditional methods.

- **Use of Biotechnology:** New biotechnological processes use living organisms or their components to aid metal extraction, typically through bioleaching or biooxidation. These techniques can allow for the recovery of metals from low-grade ores and waste materials and can be more environmentally friendly than traditional processing methods.

- **Recycling and Reuse of Process Water:** Water is used extensively in mineral processing, and managing this use is critical for reducing the environmental impact of mining. Recycle and reuse of process water through new filtration and recovery systems can help mining operations decrease their water footprint and minimize the amount of wastewater that needs to be treated. Several mining companies, like BHP and Anglo American, have developed water recycling technologies specific to mining industry constraints as part of their sustainability initiatives.

Dry Processing

Traditional mineral processing methods use water to separate valuable minerals from waste rock, resulting in a slurry of water and tailings that need to be stored in tailing dams. The collapse of such dams, like the Vale disaster in Brazil in 2019, can have catastrophic environmental consequences. To address these issues, companies like Vale are developing and implementing dry processing techniques, which separate the minerals from the waste rock without the use of water. This not only eliminates the need for tailing dams and reduces the risk of dam failures but also significantly decreases water consumption, making the operation more sustainable, especially in water-scarce regions. Vale's S11D project in Brazil is a notable example of dry processing, which uses a technique called natural moisture or dry processing to extract iron ore and eliminates the use of water in the beneficiation process.

Both these initiatives help reduce chemical pollution and support sustainability goals in mining operations. However, they also require significant investment and technical expertise to implement effectively.

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