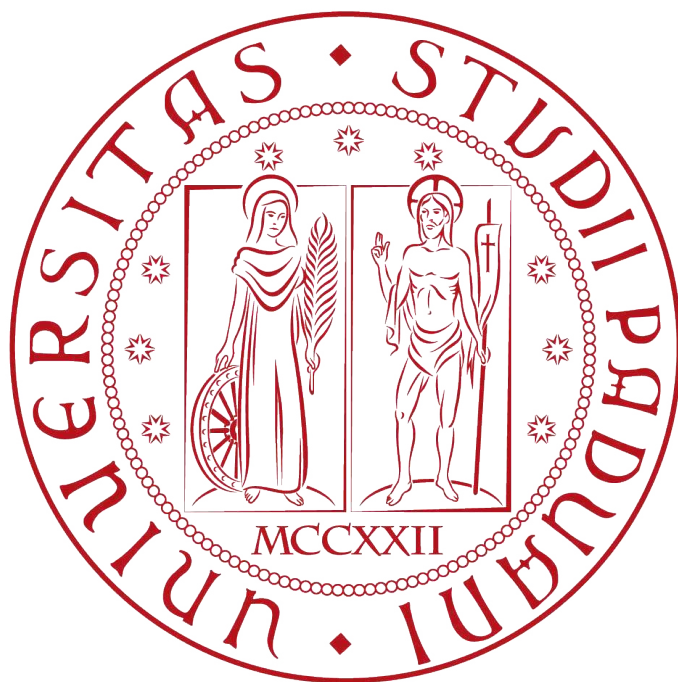




UNIVERSITY OF PADOVA

DEPARTMENT OF ECONOMY

ECONOMIC COMPLEXITY AND RAW MATERIALS

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2024-2025

APPENDIX

Declaration of Authenticity

(to be inserted in the thesis, after the cover page, on the first page of the Bachelor's degree or Msc degree thesis)

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Signature

Sefodil Mohammad ^{Su} Tekerabadi

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Literature Review

The literature on economic complexity and critical raw materials has evolved significantly over the past decades. Several strands of research have explored the intricate links between structural economic transformation and material input dependencies.

In recent years, the idea of economic complexity has become important in understanding how countries grow and develop. The Economic Complexity Index (ECI) measures how advanced a country's economy is by looking at what kinds of products it exports. Countries that export a wide range of complex products—such as advanced machinery, electronics, or chemicals—are usually seen as having more knowledge and stronger economic foundations.

At the same time, many of these complex products require special materials known as Critical Raw Materials (CRMs). These materials include rare earth elements and other inputs that are essential for modern industries, such as electronics, renewable energy, and digital technologies. Because of this, countries with more complex economies often depend more heavily on importing CRMs.

Several studies have looked at how technology and industrial development lead to greater demand for these critical materials. For example, Li et al. (2023) found that digital innovation increases the need for rare and strategic raw materials. This connection has also been highlighted in recent policy discussions in the European Union, such as the Critical Raw Materials Act, which aims to secure stable access to these important resources.

However, there is still a lack of detailed research that connects the ECI directly to the imports of CRMs. Most existing studies focus either on economic complexity or on raw material dependency, but few explore how these two areas are related over time. This is an important gap, especially now that supply chains are becoming more fragile due to global political and economic changes.

This thesis helps fill that gap by studying how economic complexity affects a country's need to import CRMs. Using recent economic data and statistical methods, it looks at whether countries with higher ECI scores also import more CRMs. The results of this analysis can help us understand not only how economies grow, but also what resources they rely on to support that growth.

Chapter

Introduction

The goal of this paper is to elaborate an empirical analysis of the relationship between Critical Raw Materials (CRMs) and Economic complexity (ECI).

Through the Stone Age to that of Bronze, Iron, and up to the modern times, technological progress has always been accompanied by tremendous shifts in the utilization of material resources. Especially after the emergence of Material Science in the 20th century, the development of modern technologies in a variety of fields has shown growing dependence on advancements in material usage, unveiling new properties of existing materials but also making their use more diversified in achieving specialized functionalities and meeting specific market demands. Indeed, material changes and evolving technologies have long been recognized as one key dimension in technological paradigm shifts[30]

CRMs include a broad range of raw inputs that are necessary for the production of intermediate and final goods, and that are deemed critical on account of both their strategic importance for multiple sectors of the economy and of issues concerning availability and limited substitutability. The European Commission (EC) published the first comprehensive list of CRMs in 2011[23] and updated it every three years. For the purposes of the present study we rely on an expanded version on the 2020 list[14]

Differently from major and base metals (e.g., copper, iron, and aluminium), RMs can be considered as industrial “vitamins” or “spices”—only used in very small quantities, but providing unique and essential chemical, electrical or mechanical properties, and leading to extensive applications in a variety of high-tech products, such as semiconductors, catalysts, engines, turbines, batteries, as well as medical equipment and weapons[1, 112]

While the importance of RMs for technological innovation is steadily expanding, they also face significant supply risks[25, 55, 94, 48].

Taken together, such supply conditions may constrain industrial development and influence the trajectory of modern technologies. For example, the solar energy industry and the corresponding technologies are seriously affected by fluctuations in the supply of gallium (Ga) and indium (In) [40]

Economic complexity offers a comprehensive framework for understanding the relationship between productive capabilities and economic development. Rooted in theories of knowledge division and specialization, this concept builds on the work of Adam Smith and later studies on economic systems as intricate networks of inputs and outputs.[? 38, 104]

The study of economic complexity gained prominence through the introduction of metrics that capture the diversity and sophistication of an economy’s productive capacities. Un-

like traditional economic measures, such as GDP, complexity metrics employ fine-grained data to assess how various factors of production-labor, capital, and technology-combine to generate outputs. These methods rely on techniques like dimensionality reduction (e.g., Singular Value Decomposition) to uncover patterns of specialization and diversification across geographies.[14, 23, 98]

The Economic Complexity Index (ECI), introduced by Hidalgo and Hausmann (2009), estimates a location's ability to produce complex goods by analyzing its export basket and the diversity of capabilities embedded within it. ECI has proven to be a strong predictor of economic growth, income inequality, and technological advancement.[? 14, 104]

A central aspect of economic complexity lies in its ability to explain the path-dependent nature of industrial specialization. The concept of "relatedness" highlights the affinity between a location's existing productive activities and its potential for diversification into new areas. Regions are more likely to specialize in activities closely related to their current capabilities, as these require less investment in new knowledge or infrastructure.[?] studies have demonstrated that economies diversifying into high-complexity activities experience greater income growth and resilience against external shocks. Moreover, this diversification often depends on strategic policies, such as industrial clusters and innovation hubs, which enhance knowledge spillovers and promote innovation.[30, 89, 29, 75, 39?]

Chapter

Economic Complexity

2.1 The Origin of Economic Complexity

Economic complexity is a concept that explores the diversity and sophistication of the productive capabilities within an economy, providing insights into the factors that drive economic development, diversification, and growth. The origins of this concept can be traced to interdisciplinary research that merges economics with complexity science, network theory, and development studies. Unlike traditional economic theories that focus solely on resource endowments, labor, or capital, economic complexity highlights the essential role of accumulated knowledge, capabilities, and technological innovation in shaping the trajectory of economic development.[51][49][52]

The foundation of economic complexity can be found in the intellectual movement that emerged in the late 1980s and early 1990s, largely facilitated by researchers at the Santa Fe Institute, a center for interdisciplinary study of complex systems.[7] Scholars such as W. Brian Arthur were pivotal in introducing the concept of complexity economics, which views the economy as a dynamic, evolving system rather than a static equilibrium-based model.[5] Complexity economics focuses on how economies continuously adapt, evolve, and self-organize in response to innovations, new technologies, and the shifting interactions among individuals, firms, and institutions. In this view, economic processes are not deterministic, but rather shaped by non-linear dynamics, feedback loops, and adaptive behaviors, which are more reflective of real-world economic activities.[6]

As complexity economics gained traction, the concept of economic complexity began to take shape, particularly through the work of Ricardo Hausmann from Harvard University and César Hidalgo from MIT. Building on the foundational ideas from the Santa Fe Institute, Hausmann and Hidalgo introduced the Product Space framework in the early 2000s.[52] This framework conceptualizes the interconnectedness of products in terms of the capabilities required to produce them, showing how economies evolve by moving into more complex industries that are closely related to their current production. This shift, known as "related diversification," occurs when a nation leverages its existing knowledge and resources to create products that require similar or higher levels of sophistication. The Product Space, therefore, maps the potential paths through which an economy can expand its industrial base and diversify its production, thereby increasing its economic complexity.

Hausmann and Hidalgo's empirical work revealed a critical insight: economies with

diverse and sophisticated export portfolios tend to experience higher rates of economic growth.[51] They argued that a country’s productive complexity—reflected in the range and sophistication of products it can produce—directly correlates with its economic potential. This concept shifted the focus from traditional resource-based theories of growth toward a more knowledge-driven understanding of development. The capacity to produce a wide variety of complex products is now seen as a hallmark of a nation’s ability to innovate, adapt, and remain competitive in the global economy.

In 2011, the introduction of the Economic Complexity Index (ECI) by Hausmann, Hidalgo, and their colleagues provided a quantitative measure of a country’s productive capabilities[46]. The ECI evaluates the diversity and sophistication of a country’s export basket and is used to predict future economic performance. This index has become an essential tool for policymakers and economists, offering a deeper understanding of the underlying structural factors that contribute to economic growth. The ECI highlights that economic complexity is not simply a matter of producing a large quantity of goods, but of producing goods that require a broad base of specialized knowledge and capabilities. Nations with higher ECI scores are generally better positioned to innovate, move up the value chain, and achieve sustained economic growth.

The development of the ECI and the Product Space has had profound implications across various academic disciplines, including economic geography, international development, and innovation studies[6]. These concepts have provided new ways of thinking about economic development, moving away from traditional models based on comparative advantage and natural resource endowments. By emphasizing the importance of innovation, diversification, and the accumulation of productive knowledge, economic complexity theory has helped reshape how we understand the dynamics of economic growth. It has also opened up new pathways for research into how countries can develop more diversified and resilient economies, especially in an increasingly interconnected and technology-driven global landscape.

In conclusion, the concept of economic complexity emerged from interdisciplinary research combining complexity science, network theory, and economics. Researchers at institutions like the Santa Fe Institute, along with the empirical analyses of Hausmann and Hidalgo, provided the intellectual framework for understanding the role of innovation and diversification in shaping the economic success of nations. This shift in perspective offers a richer, more dynamic view of how economies grow and evolve, emphasizing the importance of knowledge, technological innovation, and diversification in fostering long-term prosperity. Economic complexity continues to be a valuable tool for understanding the global economic landscape and guiding nations toward sustainable development.

2.2 Theoretical Foundations of Economic Complexity

Economic complexity represents a departure from traditional economic theories, which often focus on simplistic metrics such as GDP per capita or resource endowments. Rather than just measuring economic output, it emphasizes the sophistication and diversity of the productive capabilities within an economy[51]. This perspective arose in the late 20th century, driven by a growing recognition of the complex and dynamic nature of economies. Scholars at the Santa Fe Institute, including W. Brian Arthur and others, contributed to the shift in understanding, integrating concepts from complexity science

into economic analysis. This new paradigm suggests that economies, much like ecosystems or other complex systems, are characterized by constant change, adaptation, and evolution[5].

The theoretical foundations of economic complexity lie in the idea that the wealth of a nation is not just determined by the resources it has, but by the capabilities it has accumulated to transform these resources into a wide range of products. The success of an economy depends on its ability to produce not only a variety of products but also products that require a high degree of specialized knowledge and innovation[11]. In contrast to traditional economic models that often assume economies are in equilibrium and follow predictable paths, the economic complexity framework views economies as complex adaptive systems. These systems are in a constant state of flux, shaped by the interactions of various agents—firms, individuals, and institutions—that together generate emergent behaviors, or patterns of development that cannot be understood by simply studying individual components in isolation.

Central to the concept of economic complexity is the notion of "related diversification." This refers to the process by which economies expand into new sectors that build upon the capabilities and knowledge already embedded within existing industries[52]. For example, a country with a strong manufacturing base might diversify into producing more advanced machinery or electronics, leveraging the skills and infrastructure already in place. The Product Space framework, introduced by César Hidalgo and Ricardo Hausmann, helps illustrate this process. It maps products according to the capabilities needed for their production, showing how economies tend to evolve in a manner where new products are often closely related to those they already produce. This interconnectedness allows countries to develop more complex products by capitalizing on existing expertise and infrastructure, thereby increasing their economic complexity.

Economic complexity theory also challenges the traditional assumption in economics that economies naturally move toward equilibrium. In classical economics, it is often assumed that markets and economies will tend to stabilize over time, with supply meeting demand. However, in complex systems, equilibrium is not the norm[93]. Instead, economies are in a perpetual state of non-equilibrium, with constant disruptions, innovations, and shifts in global dynamics driving continuous change. This characteristic of economic complexity makes it an ideal framework for understanding the dynamics of economic growth and development, especially in an era of rapid technological advancement and global interconnectedness.

The methodological tools used to analyze economic complexity have evolved alongside the theoretical framework. One of the most widely recognized tools is the Economic Complexity Index (ECI), which quantifies a country's productive capabilities based on the diversity and sophistication of its export portfolio[106]. The ECI uses trade data to determine how complex the products a country exports are, and how easily those products could be produced by other nations. A country that exports a broad range of sophisticated products, such as high-tech machinery or pharmaceuticals, has a higher ECI, indicating a more complex economy.

Empirical research has shown that there is a strong correlation between economic complexity and long-term growth, suggesting that countries with higher complexity are better positioned for innovation, technological development, and economic stability[43].

The rise of economic complexity has broad implications for policy. One of the key

lessons from this framework is the importance of fostering diversification. Simply relying on natural resource exports, for example, does not lead to sustainable growth. Rather, countries must invest in building up capabilities across a variety of industries[17]. This involves not just supporting the industries that exist today, but also fostering the growth of new, more complex sectors that can drive future innovation and growth. To facilitate this transition, investments in education, technological research, infrastructure, and strong institutions are essential[46].

Economic complexity also highlights the importance of global trade and integration. A country's position in the global economy—especially in relation to trade networks—has a profound effect on its ability to grow economically[36]. The interconnectedness of economies means that countries that are deeply integrated into international trade networks are better positioned to acquire new technologies, knowledge, and production techniques. This is particularly important in an era where the pace of technological change is rapid, and the ability to innovate is often the key determinant of a country's economic trajectory[73].

In conclusion, economic complexity offers a richer, more dynamic understanding of how economies grow and develop. It underscores the importance of knowledge, diversification, and innovation in building a sustainable economic future. This theory is particularly relevant in the context of raw materials, as it provides a framework for understanding how resource-dependent economies can transition from simple extraction-based industries to more complex, knowledge-driven economies[26]. Through strategic investments in education, infrastructure, and technological innovation, countries can enhance their economic complexity, move beyond reliance on raw materials, and achieve long-term, sustainable growth.

2.3 Measuring Economic Complexity

The most widely used tool for measuring economic complexity is the Economic Complexity Index (ECI), which quantifies the sophistication of a country's productive capabilities based on the products it produces and exports. The ECI is derived from trade data, specifically examining the diversity of a country's exports and the ubiquity of those exports across other countries. Countries that produce a wide range of complex products, such as high-tech machinery or pharmaceuticals, are classified as having high economic complexity.

The ECI takes into account two main aspects: the diversity of a country's export basket (the range of different products) and the ubiquity of these products (the extent to which these products are produced by other countries). A higher ECI indicates that a country is not only producing a wide variety of products but that these products require advanced capabilities that are not easily replicated by other countries.

Conversely, countries with low ECI values tend to focus on fewer, less complex products, often related to primary commodities, which are less sophisticated and have lower value-added content.

Empirical studies have shown that countries with high economic complexity tend to experience higher rates of economic growth. The ECI has been proven to be a robust predictor of future economic performance, as countries with more complex economies are better positioned to innovate and adapt to changing global markets. This connec-

tion between economic complexity and growth underscores the importance of fostering industries that require specialized knowledge and capabilities[51].

2.4 The Product Space Framework

The concept of the Product Space serves as a pivotal framework for understanding the evolution of a nation's comparative advantage and its capacity for economic diversification. Introduced by Hidalgo and Hausmann (2009), the Product Space is a network that illustrates the relatedness between various products based on the capabilities required for their production. This framework posits that countries are more likely to develop industries that are closely related to their existing ones, facilitating a path toward more complex and diversified economic structures.

2.4.1 Understanding the Product Space Framework

The Product Space is constructed as a network where each node represents a product, and edges connect products that are frequently co-exported, indicating a high degree of relatedness in the capabilities required for their production. This structure reveals that products within the dense core of the network are typically more complex and require a broader set of capabilities, while products on the periphery are less complex and more isolated.

Hidalgo and Hausmann (2009) demonstrated that the pattern of relatedness among products significantly influences a country's ability to diversify its exports. Countries tend to expand into products that are adjacent to their current exports in the Product Space, leveraging existing capabilities to move toward more sophisticated and diverse industries.

2.4.2 Visualizing the Product Space

To illustrate the Product Space, we can utilize the interactive tools provided by the Observatory of Economic Complexity (OEC). The OEC offers visualizations that map out the network of products for various countries, highlighting their positions within the global trade landscape. The following visualizes and compares the Product Spaces of Italy, Germany, and the United States to explore the unique economic structures of these nations and how green technologies may further shape their economic futures.

Figures 2.3, 2.2, and 2.3 illustrate the Product Spaces of Italy, Germany, and the United States, respectively. These graphs, sourced from the Observatory of Economic Complexity (OEC), offer a visualization of how different sectors are interconnected within each country's export network. Each graph highlights the dominant industries and potential areas for diversification. The Product Space visualizations allow us to observe how each country could enhance its economic complexity by leveraging its existing industries or transitioning into new sectors.

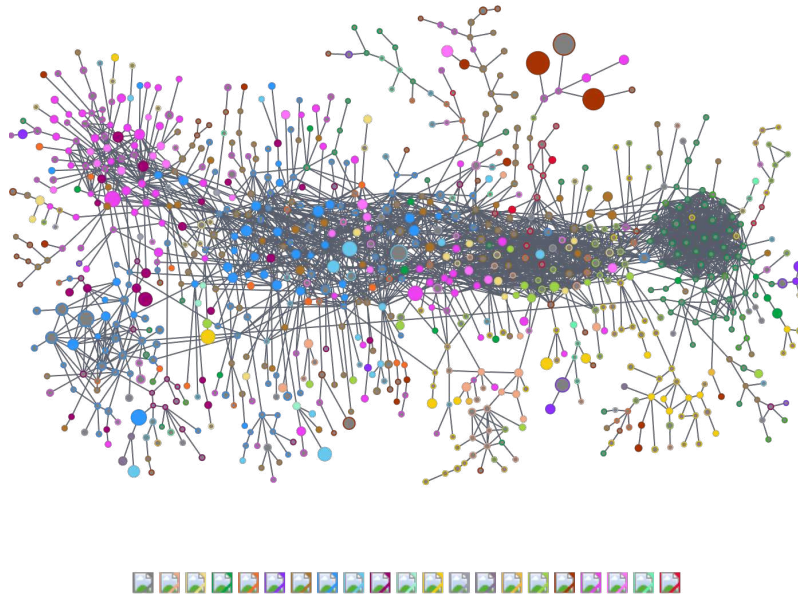


Figure 2.1: Product Space of the United States, showcasing its export relationships and the density of product clusters.

- The United States' Product Space (Figure 2.1) is much more diversified than those of Italy and Germany, reflecting its large and varied economy. The U.S. has a wide array of interconnected industries spanning technology, aerospace, pharmaceuticals, and energy. This diversity positions the U.S. advantageously for continued growth across multiple high-value sectors. The country's dominant role in technology and innovation, particularly in information technology and biotechnology, offers it a unique opportunity to lead in emerging sectors such as green technologies, including solar energy, electric vehicles, and smart grids. However, while the U.S. has a strong presence in many advanced sectors, it must focus on sustainable practices, particularly in energy and manufacturing, to ensure that these sectors are not only technologically advanced but also environmentally sustainable.

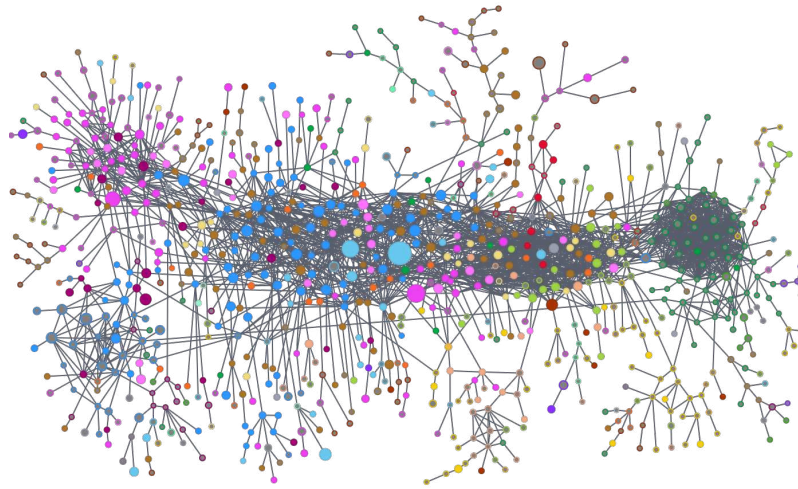


Figure 2.2: Product Space of Germany

- Germany's Product Space (Figure 2.2) is characterized by a strong focus on industrial sectors such as machinery, automotive, and chemicals, which have long been the cornerstone of the nation's economy. These industries are highly interconnected, indicating that Germany has a deep-rooted industrial base that is integrated within the global supply chain. The nation's proficiency in high-tech manufacturing and engineering provides a solid foundation for further expansion into cutting-edge sectors such as electric vehicles, renewable energy technologies, and Industry 4.0 innovations. Expanding into these sectors could further elevate Germany's economic complexity by incorporating more sustainable, high-tech solutions into its industrial ecosystem.

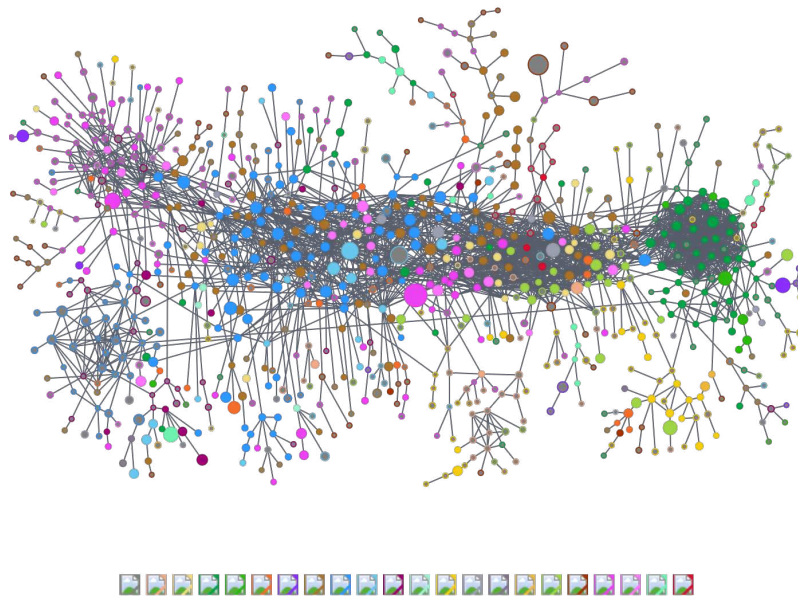


Figure 2.3: Product Space of Italy

When comparing these three countries, distinct patterns emerge that reflect their individual economic strengths and potential pathways for growth.

- Italy's Product Space (Figure 2.3) is concentrated in sectors such as luxury goods, fashion, automotive, and machinery. The high degree of interconnectedness in these sectors suggests that Italy's comparative advantage lies in high-value, design-oriented exports. Italy's economy is heavily driven by traditional industries with significant brand recognition, especially in fashion and automotive sectors. By diversifying further into adjacent high-tech industries, such as renewable energy or advanced manufacturing, Italy could expand its economic complexity and lessen dependence on traditional sectors.

The comparison between these three countries highlights their different strengths and strategies for future growth. While Italy may need to further diversify into emerging sectors to enhance its economic complexity, Germany can leverage its existing industrial prowess to lead the way in the development of green technologies. The United States, with its vast industrial base, is uniquely positioned to innovate across various high-tech sectors, though it must address the challenges of sustainable raw material sourcing and environmental impact as it continues its transition to a green economy.

As the global demand for critical raw materials like lithium, cobalt, and rare earth elements increases due to the growing reliance on green technologies, these countries will need to secure sustainable access to these resources. The concentration of raw material extraction in specific regions, such as China and the Democratic Republic of Congo, adds complexity to global supply chains and creates geopolitical risks. Countries rich in these materials have the opportunity to capitalize on these resources by becoming key players in the green technology supply chain, but they must also consider the environmental and social implications of raw material extraction.

Furthermore, the concept of resource efficiency will become increasingly important as the demand for raw materials grows. Nations that focus on improving the efficiency of material use, advancing recycling technologies, and developing sustainable mining practices will be better positioned to manage the growing demand for these critical resources. Innovation in material science and advanced recycling technologies will allow countries to reuse critical materials, such as those from used batteries and electronics, helping to reduce the need for primary extraction and fostering circular economies.

In conclusion, the Product Space visualizations for Italy, Germany, and the United States provide valuable insights into each country's economic structure and potential for diversification. As green technologies continue to evolve and the demand for critical raw materials increases, these nations can enhance their economic complexity by diversifying their industrial base, improving resource efficiency, and investing in sustainable technologies. By focusing on innovation, sustainability, and strategic diversification, these countries can secure a leading role in the global green economy while mitigating the risks associated with raw material dependence.

2.4.3 Implications for Economic Development

The structure of the Product Space has profound implications for economic development:

- **Diversification Opportunities:** Nations situated in the periphery of the Product Space face challenges in diversifying their economies due to the lack of related products. Moving toward the core requires significant investment in developing new capabilities.
- **Strategic Policy Planning:** Understanding the Product Space aids policymakers in identifying strategic areas for investment and development, aligning with products that are closely related to existing industries.
- **Predicting Economic Trajectories:** The Product Space framework allows for the prediction of a country's potential economic evolution by analyzing its current position and the density of connections within the network.[\[52\]](#)

The Product Space provides a valuable lens through which to view the complexities of economic development and diversification. By examining the relatedness of products and the capabilities required for their production, countries can better strategize their paths toward sustainable economic growth and increased complexity.

2.5 Drivers of Economic Complexity

Economic complexity is driven by a confluence of factors, which include related diversification, technological innovation, human capital, institutional quality, financial development, macroeconomic stability, and global integration. These elements interact dynamically, collectively enabling nations to increase their capacity to produce diverse and sophisticated products. Over time, economies develop more complex industries that rely on specialized skills, advanced technology, and robust institutional frameworks. The process of enhancing economic complexity is essential for fostering long-term economic growth and prosperity[\[45\]](#).

2.5.1 Related Diversification

At the core of economic complexity is the process of related diversification. This refers to the expansion of economies into new industries that are technologically and knowledge-wise similar to their existing sectors. This type of diversification leverages the existing industrial base and facilitates the transition from simpler to more complex products. The Product Space framework, developed by Hidalgo and Hausmann (2009), provides a useful tool to visualize this process, showing how nations can evolve by building on their current capabilities to explore new industries that require specialized knowledge and infrastructure. Economies that succeed in related diversification are better equipped to move up the global value chain, reducing their dependence on low-value-added industries such as raw materials extraction. This transition is often seen in nations that successfully integrate high-tech sectors like renewable energy, biotechnology, and advanced manufacturing[51].

2.5.2 Technological Innovation

Technological innovation is one of the most significant drivers of economic complexity. The ability of an economy to generate, adopt, and diffuse new technologies determines its capacity to diversify into more sophisticated sectors. Technological advancements enhance production processes, improve the quality of goods, and enable the creation of entirely new products. Countries that prioritize research and development (R&D) and foster environments that facilitate innovation are better positioned to transition into knowledge-intensive industries. For example, the ongoing advancements in green technologies, such as lithium-ion batteries and solar panels, have helped countries like China, South Korea, and the United States expand their industrial bases and increase their economic complexity.

Technological innovation also plays a central role in global competitiveness. Nations that can produce cutting-edge technologies, such as electric vehicles (EVs) or renewable energy systems, gain a competitive advantage in international markets. For instance, the development of new materials and energy-efficient technologies has enabled countries like Germany and Japan to move beyond traditional manufacturing into specialized industries with higher value-added products[34].

2.5.3 Human Capital

The development of human capital is another critical driver of economic complexity. The accumulation of knowledge, skills, and education within the workforce enables economies to produce more sophisticated goods and services. Higher levels of education and specialized training allow workers to contribute to the development and implementation of advanced technologies. Economies that invest in human capital can create a skilled workforce capable of supporting complex industries, such as software development, artificial intelligence, and high-tech manufacturing. This relationship between human capital and economic complexity is particularly evident in countries that focus on STEM (science, technology, engineering, and mathematics) education and technical vocational training[41].

2.5.4 Institutional Quality

Strong institutions are fundamental to fostering economic complexity. Efficient, transparent, and robust institutions provide the foundation for innovation, entrepreneurship, and investment. Institutions that ensure the protection of property rights, uphold the rule of law, and minimize corruption create a stable environment where businesses can flourish and invest in new technologies and industries. Countries with strong institutions are better able to attract foreign investment, implement complex policies, and encourage the growth of diversified industries.

Empirical studies have consistently demonstrated that nations with higher-quality institutions exhibit greater economic complexity. For example, countries like South Korea and Singapore, with well-functioning institutions, have been able to transition from resource-based economies to highly sophisticated, diversified industrial economies.[42]

2.5.5 Financial Development

Access to capital is another crucial driver of economic complexity. A well-developed financial sector ensures that businesses, especially small and medium-sized enterprises (SMEs), can secure the funding necessary for expansion, innovation, and diversification. Financial systems that facilitate the efficient allocation of resources contribute to economic complexity by supporting industries with high growth potential. This access to capital also enables the adoption of new technologies, infrastructure projects, and R&D initiatives that are essential for moving up the value chain. Countries with robust financial systems are better positioned to support industries that require significant investment, such as renewable energy, high-tech manufacturing, and biotechnology[101].

Furthermore, the development of venture capital and private equity markets can drive innovation by funding startups and emerging technologies.

2.5.6 Macroeconomic Stability

Macroeconomic stability is essential for promoting economic complexity. Stable inflation rates, sound fiscal policies, and predictable exchange rates create an environment conducive to long-term investments in complex industries. Economic stability reduces the uncertainty that firms face, encouraging them to invest in diversification and innovation. Countries that experience frequent economic instability or volatile inflation rates often find it difficult to attract investment in high-tech or knowledge-intensive industries. In contrast, nations with stable macroeconomic conditions are more likely to see sustained investments in innovation, industrial diversification, and economic development[2].

2.5.7 Global Economic Integration

Finally, global economic integration plays a significant role in driving economic complexity. By participating in global trade networks, economies gain access to foreign markets, technologies, and knowledge. Globalization facilitates the exchange of ideas, products, and services, enabling nations to integrate into global value chains and adopt new production techniques. This integration not only helps economies diversify their industrial bases

but also exposes them to international best practices, fostering innovation and technological diffusion. Countries that are well-integrated into the global economy benefit from increased access to capital, expertise, and new markets, which are critical for enhancing their economic complexity[47].

Economic complexity is the result of a dynamic interplay of various factors that together enable nations to diversify their industrial base, develop new technologies, and enhance their production capabilities. Key drivers include related diversification, technological innovation, human capital development, institutional quality, financial development, macroeconomic stability, and global integration. These factors, when effectively combined, lead to sustained economic growth, technological advancement, and increased economic resilience. As economies continue to evolve and build their capabilities, they move toward higher levels of economic complexity, which in turn supports sustainable development and long-term prosperity[50].

2.6 Economic Complexity and Economic Growth

Economic Complexity (EC) is a framework that links the structure of a country's economy to its growth prospects. Unlike traditional economic models that focus primarily on resource accumulation and technological innovation, the EC framework emphasizes the importance of a country's industrial capabilities and the interconnections between industries for driving sustained economic growth. The seminal work by Hidalgo and Hausmann (2009) introduced the concept of EC, which highlights that the complexity of a nation's economy—measured by the diversity and sophistication of its industries—can be a key determinant of long-term economic growth.

According to Hi[51], the economic performance of a country is not just a matter of its resources or capital accumulation, but rather its ability to diversify its economy and move into more advanced and interconnected sectors. Their study, "The Product Space Conditions the Development of Nations," argues that the structure of a country's exports and industrial sectors determines its future growth trajectory. Countries with a higher degree of economic complexity have the potential to innovate, adapt to global shifts, and accumulate the necessary capabilities to enter new, higher-value industries.

The relationship between EC and economic growth has been the subject of extensive research. Empirical studies have shown that more complex economies, characterized by a diversified industrial base, tend to experience higher rates of economic growth. This is because such economies are better equipped to absorb external shocks, innovate, and diversify into more sophisticated industries. As new industries emerge, they create high-value jobs and spur technological advancements, leading to overall economic expansion. This is in contrast to economies that remain dependent on a narrow range of sectors, which are often more vulnerable to fluctuations in global commodity prices and external demand.

The role of EC in economic growth is particularly evident in the context of the green economy. As the world shifts toward sustainability and environmental consciousness, countries with higher EC are better positioned to capitalize on the growth of renewable energy, sustainable manufacturing, and green technologies. The ability to diversify into these emerging sectors, such as solar power, electric vehicles, and energy storage technologies, is linked to the sophistication of a nation's existing industrial base and its capac-

ity to innovate. This transformation fosters new economic opportunities, which contribute to a more resilient and diversified economy.

For instance, the work of [74] further supports the idea that countries with more complex economies tend to experience greater economic growth. The authors argue that the knowledge accumulated from producing a diverse range of goods allows economies to absorb and implement technological innovations, ultimately contributing to higher productivity and economic expansion. Similarly, studies by [44] show that countries with higher levels of EC, as measured by the variety and sophistication of their exports, tend to grow faster and enjoy higher levels of income per capita.

Furthermore, the concept of resource efficiency is central to understanding the relationship between EC and growth. As the demand for raw materials—especially those required for green technologies—continues to rise, countries with complex economies are better positioned to manage these resources sustainably. They are more likely to develop technologies for efficient material use, recycling, and the adoption of alternative materials, which further enhances their competitiveness in the global market.

In conclusion, the relationship between Economic Complexity and economic growth is fundamental to understanding how economies transition from resource-dependent structures to more diversified and technologically advanced systems. The ability to innovate and diversify into high-value industries is a key driver of long-term growth, as evidenced by the work of [51]. Countries that successfully develop and expand their industrial capabilities will not only experience higher economic growth but will also be better positioned to navigate the challenges of a rapidly changing global economy.

2.7 Challenges of Economic Complexity

While the framework of economic complexity offers valuable insights into the pathways of economic development, it is essential to acknowledge the challenges that many countries face in achieving and sustaining high levels of economic complexity. These challenges are multifaceted and often vary depending on a country's level of development, resource endowments, institutional strength, and economic policies[46].

One of the most significant challenges for many developing economies is their over-reliance on raw material exports. Resource-rich countries often face the "resource curse," where the abundance of natural resources impedes diversification and hinders the development of more sophisticated industries. The reliance on raw material exports can lead to economic volatility, as fluctuations in global commodity prices directly impact national income and economic stability. Moreover, such dependence limits the incentives for innovation and investment in higher-value sectors, as revenues from raw material exports are often used to sustain existing industries rather than diversify into new, more complex areas[99].

The quality of institutions plays a crucial role in shaping a country's ability to build economic complexity. Weak institutions—such as inefficient legal systems, corruption, inadequate regulatory frameworks, and poor governance—are significant barriers to the development of complex economies.

These institutional weaknesses increase transaction costs, deter foreign direct investment, and limit the effectiveness of policies designed to foster diversification and innovation.

Technological innovation is a key driver of economic complexity, but many developing countries face significant barriers to accessing advanced technologies. The global innovation gap remains wide, with developed countries leading in technological advancement, while developing nations often struggle to catch up. This technological divide is exacerbated by inadequate RD investments, limited access to cutting-edge knowledge, and a lack of skilled labor capable of adopting and adapting advanced technologies[33].

Access to finance is a critical enabler of economic complexity, yet many developing economies face challenges in mobilizing capital for innovation and industrial diversification. Inadequate financial systems, lack of access to venture capital, and limited credit availability often restrict the ability of businesses to invest in new technologies, infrastructure, and value-added production processes.

Economic complexity provides a powerful framework for understanding how nations develop and diversify their economies. By focusing on the accumulation of knowledge, the diversification of industrial capabilities, and the fostering of innovation, economic complexity challenges traditional models of economic growth. However, achieving high levels of economic complexity is not without its challenges, particularly for countries that are heavily dependent on raw materials. Overcoming these challenges requires strategic investments in human capital, technology, infrastructure, and institutions, as well as policies that encourage innovation and industrial diversification.

Chapter

Raw Materials

3.1 Introduction

Raw materials are unprocessed or minimally processed substances extracted from natural resources, serving as fundamental inputs in manufacturing processes to create finished goods. These materials encompass a wide range of resources, including metals, minerals, agricultural products, and forest-based materials. They are essential for transforming natural resources into products that meet human needs and desires[69].

Throughout human history, the utilization of raw materials has been pivotal, marking significant technological and economic milestones. In the prehistoric era, early humans relied on naturally occurring materials like stone, wood, and bone to craft tools and shelter. The discovery and use of fire marked a pivotal advancement, leading to the development of ceramics and metallurgy[76].

The Agricultural Revolution introduced raw materials such as grains, fibers, and hides into human societies. These materials facilitated the development of agriculture-based economies and the rise of permanent settlements. The Industrial Revolution further amplified the importance of raw materials, as the demand for coal, iron, and other minerals fueled unprecedented technological and economic advancements[12].

In contemporary industrial contexts, raw materials are indispensable, influencing various facets of manufacturing and production. They serve as the foundation of manufacturing, enabling the creation of products ranging from everyday items to advanced technological devices. The quality, availability, and cost of raw materials directly influence production efficiency, product quality, and profitability. Effective management of raw materials ensures a smooth manufacturing process, minimizes costs, and supports the timely delivery of products to markets[95].

Understanding the multifaceted role of raw materials provides insight into their critical position within industrial processes and their broader economic and technological significance.

3.2 Classification of Raw Materials

Raw materials play a fundamental role in industrial processes, serving as essential inputs for the production of a wide range of products. Their classification is multifaceted,

reflecting the diverse origins, properties, and applications of the materials, and it is essential for industries to have a comprehensive understanding of these classifications to optimize sourcing, processing, and utilization strategies effectively.

Raw materials can broadly be divided into natural and synthetic categories, with each type of material serving different industries and purposes[22]. Natural raw materials, for instance, are substances that are extracted directly from the Earth and require minimal processing before being incorporated into manufacturing processes. These materials are typically classified based on their origin, and they include a range of products from different sectors. Mineral-based raw materials are perhaps the most well-known, including metals like iron, copper, and aluminum, which are essential for various industrial applications such as construction, electronics, and manufacturing. Non-metallic minerals like limestone, gypsum, and silica, extracted through mining, also play a pivotal role in industries ranging from construction to chemical manufacturing. Agricultural raw materials, on the other hand, come from crops and livestock. Examples include cotton, wheat, corn, and tobacco, all of which are crucial for industries such as textiles, food production, and tobacco manufacturing. Similarly, forest-based raw materials, such as timber and pulp, are derived from forests and are primarily used in producing paper, furniture, and other construction materials. These natural raw materials are indispensable to the manufacturing sector and global economies at large[109].

In addition to natural raw materials, synthetic raw materials have become increasingly important in modern manufacturing processes. These materials are produced through human-driven chemical processes designed to mimic or enhance the properties of natural materials. Among the most significant synthetic materials are polymers, which are large molecules formed by repeating structural units. Plastics such as polyethylene, polypropylene, and polystyrene are widely used in packaging, automotive manufacturing, and consumer goods industries due to their versatility and cost-effectiveness. Another category within synthetic raw materials is composites, which are engineered materials made from two or more constituent materials that have significantly different physical or chemical properties. These composites, such as fiberglass and carbon fiber, are particularly prevalent in industries like aerospace and automotive manufacturing due to their strength-to-weight ratios and durability. Elastomers, commonly known as rubbers, are another type of synthetic material that is essential in the production of tires, seals, and gaskets. Their flexibility and resilience make them invaluable in applications that require stretch and durability[8].

Raw materials are also classified according to the specific industrial applications they support. In industries focused on construction, raw materials such as cement, sand, gravel, and aggregates are essential for building structures, roads, and infrastructure. These materials are foundational to urban development and housing projects across the globe. In the textile industry, raw materials such as cotton, wool, silk, and various synthetic fibers are crucial for manufacturing fabrics and garments that cater to both fashion and everyday comfort. Likewise, agricultural products like fruits, vegetables, grains, and meats are vital in the food processing industry, where they undergo various forms of processing to create consumable food items, thereby contributing to food security and nutritional needs globally. The chemical industry also relies heavily on raw materials, especially chemical feedstocks like petrochemicals, which serve as precursors for producing a wide range of essential products such as fertilizers, pharmaceuticals, and detergents. These materi-

als are indispensable to many industrial supply chains, highlighting their central role in economic development and consumer markets[110].

From an accounting and production perspective, raw materials are often distinguished based on their direct involvement in the manufacturing process. Direct raw materials are those that are incorporated directly into the final product, contributing to its composition and quality. For example, timber used in furniture manufacturing or cotton in textile production is considered a direct material. Indirect raw materials, on the other hand, do not form part of the finished product but are essential for the production process. These materials, such as lubricants for machinery, cleaning agents, and safety equipment, support the manufacturing operation but do not directly contribute to the end product[53].

The origin of raw materials also plays a key role in their classification. Primary raw materials are virgin materials extracted directly from natural sources, such as newly mined ores or freshly harvested timber. These materials are used in their natural form or undergo minimal processing before being utilized in manufacturing. Secondary raw materials, however, are materials that have already been used and are subsequently recycled or repurposed for reuse in production. Examples include recycled paper, glass, and metals like aluminum. The recycling of these materials reduces the need for primary extraction, promoting environmental sustainability and reducing the environmental footprint of manufacturing processes.

In the context of global markets, some raw materials are considered critical due to their strategic importance and the risks associated with their supply. Critical raw materials, such as rare earth elements, lithium, and cobalt, are essential for high-tech applications in electronics, renewable energy technologies, and defense systems. These materials are crucial for technological advancement and economic development but face supply chain risks due to their limited geographic distribution and concentrated production in specific regions. For instance, rare earth elements are primarily mined in China, while lithium, a key component of batteries used in electric vehicles, is largely sourced from countries like Argentina, Bolivia, and Chile. This concentration of supply poses significant challenges for global industries reliant on these materials, making their sourcing, trade, and geopolitical implications highly sensitive[31].

In conclusion, the classification of raw materials is a multifaceted process that takes into account a variety of factors, including their origin, application, and processing requirements. Understanding these classifications is essential for industries to effectively source, process, and utilize raw materials, thereby ensuring efficiency, sustainability, and economic viability in their operations. As industries evolve and new technological demands arise, the role of raw materials will continue to be central to global manufacturing and economic development, highlighting the ongoing need for strategic management and sustainable practices in raw material sourcing and utilization.

3.3 Raw Materials and Economic Complexity

The increasing dependence on Critical Raw Materials (CRMs) such as lithium, cobalt, and rare earth elements is reshaping industries, especially those driving the green technology revolution, including electric vehicles (EVs), renewable energy infrastructure, and sustainable manufacturing. These raw materials are essential for manufacturing the technologies that underpin the global transition to a low-carbon economy. As such, the avail-

ability and access to CRMs are critical drivers of a nation's economic complexity. In particular, countries rich in these resources can leverage their natural endowments to advance their economic development and technological sophistication, thereby enhancing their position in the global economy.

3.3.1 Critical Raw Materials in Green Technologies

Critical raw materials are indispensable for the production of modern green technologies. For instance, lithium is a key component in batteries that power electric vehicles, while cobalt and nickel are integral to battery efficiency and energy storage solutions. Rare earth elements, such as neodymium and dysprosium, are essential for the manufacture of high-performance magnets used in wind turbines and electric motors. As green technologies expand, the demand for these raw materials is expected to surge, presenting both opportunities and challenges for countries that possess significant reserves.

For example, [79] emphasize that as electric vehicles become more mainstream, countries rich in these materials, particularly in the lithium sector, can capitalize on their resources by developing advanced industries such as EV manufacturing and energy storage systems. The increased demand for these materials enhances the potential for economic complexity by driving the development of high-tech industries that are crucial for sustainable development and reducing dependence on traditional resource-extraction industries.

3.3.2 Geopolitical and Sustainability Risks

Despite the clear opportunities, there are significant geopolitical and sustainability risks associated with the extraction and trade of CRMs. The concentration of CRMs in a few countries creates vulnerabilities in global supply chains. For instance, [28] discuss the geopolitical tension surrounding the mining of cobalt in the Democratic Republic of the Congo, a country that holds a substantial portion of the world's cobalt reserves. This geopolitical risk is compounded by concerns over the environmental impact of mining practices and the often poor labor conditions associated with raw material extraction.

Additionally, the environmental impact of CRM mining raises sustainability concerns. For example, large-scale mining operations have been linked to habitat destruction, soil degradation, and water pollution, which can have long-term effects on local ecosystems and communities. These issues must be addressed through better mining practices and the adoption of more sustainable sourcing strategies. Countries that rely heavily on raw material extraction may face public backlash and international scrutiny if these concerns are not properly managed.

3.3.3 Innovation in Sourcing and Recycling CRMs

One promising solution to mitigate the challenges posed by the increasing demand for CRMs is innovation in recycling and material science. Advances in advanced recycling technologies can help recover critical materials from end-of-life products, such as used batteries and electronic waste. As [79] note, this not only reduces the demand for newly extracted materials but also contributes to a more circular economy, where resources are reused and waste is minimized.

Moreover, research into alternative materials, such as sodium ion batteries and solid-state batteries, is gaining traction as a way to reduce reliance on scarce and environmentally damaging materials like cobalt and lithium. The development of these alternatives could significantly alleviate the pressure on raw material supply chains while providing more sustainable solutions for energy storage and manufacturing processes.

In conclusion, the relationship between raw materials and economic complexity is multifaceted and critical for the future of global economic development. As green technologies continue to drive economic growth, the demand for CRMs will only increase. Countries that can manage the sustainable extraction, recycling, and sourcing of these materials are positioned to enhance their economic complexity, diversify their industries, and establish themselves as leaders in the global green economy. However, addressing the geopolitical, environmental, and social challenges associated with CRMs will be key to ensuring that this growth is both sustainable and equitable. By investing in innovation, recycling technologies, and alternative materials, nations can secure a more stable and resilient economic future.

3.4 Global Supply Chains of Raw Materials

The global supply chains of raw materials form intricate networks that span across continents, linking various stakeholders, including producers, transportation providers, manufacturers, and retailers. These networks are critical for converting raw materials into finished products, impacting industries such as manufacturing, technology, and energy[60]. Understanding the dynamics of these supply chains is essential for businesses and policy-makers to mitigate risks, promote sustainability, and foster economic growth.

A supply chain, in its simplest form, is a system that oversees the journey of raw materials as they are transformed into finished goods. The process begins with the sourcing of raw materials, which involves identifying and procuring resources from global suppliers. Once acquired, these raw materials are transported to manufacturing facilities, often crossing international borders. At the manufacturing stage, raw materials undergo various processing techniques, turning them into finished or semi-finished products. These products are then distributed to retailers and, eventually, to consumers, completing the supply chain cycle. However, the journey does not end with the sale of products; post-sale services, such as customer support, returns, and feedback, also form a crucial part of the broader supply chain network. Effective management of these stages is key to ensuring that supply chains operate efficiently, reduce costs, and maximize customer satisfaction. Unfortunately, disruptions at any point—such as transportation delays, production halts, or geopolitical tensions—can have cascading effects throughout the supply chain, resulting in significant challenges for businesses, consumers, and governments.

Several factors pose significant challenges to the stability and efficiency of global raw material supply chains. Geopolitical risks are among the most influential, as political instability, trade disputes, and policy changes can disrupt the smooth flow of raw materials[100]. For example, the U.S. implementation of auto tariffs has had a ripple effect on countries such as Thailand, altering the dynamics of automotive supply chains and forcing businesses to adapt. In addition to geopolitical risks, environmental factors also play a critical role. Climate change and natural disasters can damage infrastructure,

reduce the availability of raw materials, and hinder production. Greenland's melting ice, for instance, has exposed new opportunities for accessing rare earth elements, but it has also introduced environmental and logistical challenges in extracting these materials[114]. Market volatility is another issue facing raw material supply chains. Fluctuations in both demand and supply can result in price instability and shortages. The shift in demand patterns following the end of China's commodities supercycle, for example, has influenced the global market for materials like steel and iron ore[107]. Moreover, the concentration of raw material production in a limited number of countries creates vulnerabilities in the supply chain. China's dominance in rare earth refining, for instance, has prompted other nations to reconsider their reliance on a single supplier and seek ways to diversify their sources of critical materials.

To address these challenges, businesses and governments are adopting various strategies to strengthen the resilience of raw material supply chains. One such strategy is the diversification of supply sources. By establishing relationships with multiple suppliers across different regions, companies can reduce their dependence on a single source and safeguard against supply disruptions. The European Union, for example, is accelerating efforts to produce critical minerals within its borders, aiming to reduce reliance on external suppliers[96]. Another approach is the investment in recycling and the promotion of circular economies. Recycling technologies, particularly those aimed at recovering rare earth elements from industrial magnets, can help supplement primary sources of raw materials and reduce the environmental impact of extraction. Furthermore, advancements in technology are playing a crucial role in enhancing supply chain resilience. The use of real-time tracking and data analytics allows for improved visibility and responsiveness, enabling businesses to better manage potential disruptions. Maintaining strategic reserves of critical raw materials is another key strategy, providing a buffer against short-term supply interruptions. Lastly, international partnerships, such as those established through initiatives like the Minerals Security Partnership, allow countries to collaborate in securing stable supplies of critical minerals while adhering to high environmental, social, and governance standards.

The role of policy and regulation cannot be overstated in shaping the dynamics of raw material supply chains. Trade policies, including tariffs, quotas, and trade agreements, directly influence the flow of raw materials across borders. Recent U.S. trade policies, such as the imposition of auto tariffs, have had significant impacts on global supply chains, affecting countries like Thailand[70]. Environmental regulations also play a critical role, as stricter laws can impact the extraction and processing of raw materials. In China, for instance, the government has identified certain minerals as critical for advancing high-tech industries, which has profound implications for both domestic and international supply chains. Furthermore, labor standards are increasingly under scrutiny, with global supply chains facing growing pressure to ensure ethical labor practices in the extraction and processing of raw materials. The use of forced labor in regions like Xinjiang, China, has raised ethical concerns, leading to calls for the implementation of stricter regulations and ethical sourcing practices across supply chains.

In conclusion, the global supply chains of raw materials are highly complex and influenced by a multitude of factors, ranging from geopolitical developments and environmental changes to market dynamics and policy decisions. To ensure the stability and resilience of these supply chains, a multifaceted approach is necessary, one that includes diversifica-

tion of sources, investment in recycling, technological advancements, strategic reserves, and robust policy frameworks. As the demand for critical raw materials increases, particularly with the transition to renewable energy and advanced technologies, it will be essential to maintain the stability and ethical integrity of these supply chains to promote long-term economic and social well-being.

3.5 Case Studies in Sustainable Raw Material Supply Chains

In this section, we explore several case studies that illustrate sustainable practices in raw material supply chains. These examples are vital in understanding how the global supply chain for critical raw materials is evolving to meet the increasing demand driven by the rise of green technologies[19]. By examining real-world cases, we gain insights into the challenges and innovations that are helping reshape the landscape of sustainable raw material sourcing and management.

3.5.1 Patagonia – Pioneering Sustainable Supply Chains in the Apparel Industry

Patagonia has long been a leader in promoting sustainability within the apparel industry. Known for its commitment to environmental stewardship, Patagonia has integrated sustainability into its supply chain practices. The company sources raw materials responsibly, prioritizing the use of recycled and organic fibers to reduce environmental impacts[91]. For example, Patagonia uses recycled polyester in its products, significantly reducing the need for virgin materials and minimizing the associated environmental costs of production.

The company's efforts go beyond just material sourcing. Patagonia is also committed to ensuring ethical labor practices within its supply chains. By working closely with suppliers and engaging in fair trade practices, Patagonia ensures that its raw material supply chains do not contribute to human rights violations. In addition, the company has made significant strides in promoting the circular economy, encouraging customers to repair their products rather than discard them, further reducing the environmental footprint.

Patagonia's approach demonstrates that sustainable raw material supply chains are not just a necessity but also an opportunity for companies to innovate, build brand loyalty, and gain a competitive edge in the marketplace. The company's success highlights the role of responsible sourcing and circularity in driving both environmental sustainability and business growth.

3.5.2 Tesla – Managing Raw Material Demand for Electric Vehicles

Tesla's role in the global transition to electric vehicles (EVs) has had a significant impact on the demand for raw materials such as lithium, cobalt, and nickel, all of which are essential for the production of lithium-ion batteries[103]. As a leader in the EV market, Tesla is uniquely positioned to drive change in how raw materials are sourced, processed, and utilized.

Tesla's strategy focuses on securing a sustainable supply of these critical materials by forming partnerships with mining companies and investing in innovations in battery

technology. For example, Tesla has announced efforts to develop its own supply chain for lithium, reducing its reliance on third-party suppliers. In addition, the company is investing in battery recycling technologies to recover valuable materials from used batteries, thus reducing the need for new raw material extraction and minimizing the environmental impact of mining operations.

Tesla's approach reflects the growing importance of securing sustainable, ethical sources for the materials needed to support green technologies. The company's ability to balance the demand for critical materials with sustainable practices will play a crucial role in the broader transition to electric mobility and the scaling of green technologies.

3.5.3 China – Dominance in Rare Earth Elements and Supply Chain Challenges

China has long been the dominant player in the global supply of rare earth elements (REEs), which are essential for the production of high-tech devices, renewable energy systems, and electric vehicles[?]. These materials, such as neodymium, dysprosium, and praseodymium, are critical for the manufacture of permanent magnets used in wind turbines, electric vehicle motors, and other green technologies.

While China's dominance in the supply of REEs has enabled the country to exert significant influence over global supply chains, it has also raised concerns about sustainability and geopolitical risk. The extraction of rare earth elements is often environmentally damaging, leading to soil and water contamination, habitat destruction, and pollution. Furthermore, China's near-monopoly in the production of these materials has led to concerns about supply chain vulnerabilities, particularly in the context of rising global demand for green technologies.

In response to these challenges, China is making efforts to improve the sustainability of its rare earth extraction processes. These efforts include the development of more efficient mining techniques and the implementation of stricter environmental regulations. Additionally, China is working on expanding its recycling programs for rare earth elements to reduce the need for primary extraction. The country's approach to managing rare earth supply chains offers valuable lessons in balancing environmental sustainability with economic and technological growth, highlighting the need for diversification and responsible resource management in global supply chains.

3.5.4 IKEA – Circular Economy and Sustainable Raw Material Sourcing

IKEA is another company that has made significant strides in creating sustainable raw material supply chains. As a global leader in the furniture and home goods industry, IKEA is heavily reliant on raw materials such as wood, metals, and textiles. The company has committed to sourcing these materials sustainably, with a focus on ensuring that its wood comes from responsibly managed forests and that its textiles are made from recycled or sustainable materials[58].

One of IKEA's key sustainability initiatives is its focus on the circular economy. The company has introduced a range of products that are designed with end-of-life considerations in mind, encouraging recycling and reusing materials. IKEA has also launched a

product take-back program, where customers can return old furniture for recycling, further promoting the principles of a circular economy[56].

IKEA's commitment to sustainable sourcing and circularity demonstrates the company's recognition of the need to reduce the environmental impact of its supply chains. By integrating sustainability into its raw material sourcing and product design, IKEA not only reduces its carbon footprint but also creates new business opportunities in the growing market for sustainable products[57].

These case studies illustrate the diverse approaches to sustainable raw material supply chains across industries, from apparel and electric vehicles to rare earth elements and home goods. Each case demonstrates the growing recognition of the importance of sustainability in raw material sourcing and the management of supply chains. By adopting responsible sourcing practices, investing in circular economy initiatives, and fostering innovation in material efficiency, these companies contribute to both the sustainability of the environment and the long-term economic viability of their industries[61].

As the global demand for green technologies continues to rise, these case studies serve as important examples of how businesses can integrate sustainability into their supply chains to drive economic growth, technological innovation, and environmental stewardship.

Chapter

The Relationship Between Raw Materials and Economic Complexity

4.1 Introduction

Economic complexity is a concept that attempts to explain the intricate and dynamic structures that underpin the production, consumption, and export activities within an economy. It is often measured by the diversity and sophistication of the products that a country produces and exports. The Economic Complexity Index (ECI), introduced by Hausmann and Hidalgo, quantifies the knowledge embedded in an economy's production and export sectors, emphasizing how the capabilities required to produce different goods relate to each other[51]. This index has become an important tool for understanding how nations can move toward more complex economic activities, which in turn promote sustainable development, innovation, and economic growth.

Raw materials play a pivotal role in the economic complexity framework, serving as the foundation for a wide variety of industries. These materials, which are derived from the Earth, range from metals like iron, copper, and rare earth elements to agricultural products, timber, and fossil fuels[46]. Historically, many nations' economies have been built upon the extraction and exportation of these natural resources. However, while raw materials have provided the necessary inputs for industrialization, their relationship with economic complexity is far more nuanced than simply being a catalyst for development. The dependence on raw materials has often led to a paradox: while these resources can drive economic growth, they can also impede a country's ability to diversify and increase its economic complexity over time[99].

The traditional view of raw materials as a means to wealth creation has been challenged by the concept of the "resource curse," which suggests that countries rich in natural resources often face slower economic development, greater inequality, and more political instability compared to their resource-poor counterparts. As raw material extraction typically involves limited diversification in production activities, nations that are heavily reliant on the export of raw materials may struggle to develop other sectors of their economies, ultimately hindering their ability to transition to more complex industries. In other words, while raw materials can enable the initial stages of industrialization, they may also limit long-term growth potential by stifling the development of knowledge-based, high-skill industries.

On the other hand, raw materials, when managed responsibly and strategically, have the potential to serve as a springboard for economic diversification. The concept of economic diversification suggests that economies can transition from basic extraction and processing of raw materials into more complex and higher-value industries. This transition is influenced by factors such as technological advancements, the development of specialized capabilities, and the knowledge embedded in a nation's industrial sectors. Countries that are able to move beyond the raw material extraction phase into more sophisticated manufacturing or service sectors are better positioned to increase their economic complexity.

An example of this progression is seen in countries that leverage their natural resources to diversify into sectors such as electronics, automotive, and renewable energy. The link between raw materials and economic complexity is evident in the case of China, where its access to rare earth metals has supported its expansion into high-tech manufacturing and clean energy technologies[54]. These materials, which are essential for the production of electronics and green technologies, have enabled China to transition into one of the world's most advanced economies. Similarly, China's vast copper reserves have allowed the country to develop a thriving mining industry, which has been a key driver of its economic complexity as it gradually diversifies into other sectors such as agriculture, manufacturing, and services.

In this chapter, we aim to explore the intricate relationship between raw materials and economic complexity, emphasizing how access to and management of raw materials can either promote or hinder economic growth and diversification. We will examine how raw materials are not just commodities but vital components that can shape the direction of an economy's industrialization and technological development. At the same time, we will address the challenges that arise from over-reliance on raw material extraction and the potential for economic diversification through the utilization of these materials.

By analyzing the role of raw materials in shaping the development of economies, this chapter will shed light on how sustainable practices in raw material management can drive long-term economic growth and technological innovation. Through examples and case studies, we will demonstrate how countries that effectively harness their raw material resources can transition to more complex and resilient economic structures, ultimately contributing to global sustainability and innovation.

In the following sections, we will discuss how raw materials influence technological advancement, innovation, and industrialization, and explore the strategies countries can employ to leverage their natural resource wealth to increase their economic complexity and competitiveness on the global stage.

4.2 Economic Complexity and Raw Material Dependence

Economic complexity refers to the capacity of an economy to diversify and produce a wide variety of sophisticated goods. A key factor influencing a country's economic complexity is its ability to innovate, diversify its industrial base, and create value-added products. However, the relationship between raw materials and economic complexity is far from straightforward. While raw materials are often seen as the foundation of industrialization, excessive dependence on them can limit an economy's potential for diversification and advancement into more complex industries[51].

A country's reliance on raw material exports typically leads to a narrow focus on extraction-based industries, where value-added processing is minimal. This can create a cycle where the economy is tied to the fluctuations of global commodity markets, making it vulnerable to volatility in prices and demand. Moreover, countries heavily reliant on raw materials often face the challenge of *Dutch disease*, a term used to describe the negative impact that the exploitation of natural resources can have on the development of other sectors of the economy[24]. As a country's resource sector expands, the local currency strengthens, making non-resource exports more expensive and discouraging investment in manufacturing and other complex industries. This dynamic underscores the difficulty of shifting away from a raw material-dependent economy toward a diversified, high-value production model.

In contrast, countries that have successfully leveraged their raw material wealth to expand into more complex sectors offer valuable lessons in economic development. The key to this success lies in the ability to move beyond basic extraction into higher-value stages of production. For instance, some countries have utilized their raw material industries as a springboard for developing advanced manufacturing capabilities, technology-intensive industries, and service sectors. This transformation involves significant investment in human capital, infrastructure, and innovation to move up the value chain.

4.2.1 Technological Development and Raw Materials

Technological development plays a critical role in reducing raw material dependence and advancing economic complexity. As industries become more technologically advanced, the demand for certain raw materials may shift, and the processes by which raw materials are utilized become more sophisticated. Raw materials are essential in supporting technological innovations, especially in high-tech industries like electronics, renewable energy, and biotechnology[35]. For instance, the demand for rare earth metals, critical for the development of advanced electronics, solar panels, and wind turbines, exemplifies how raw materials can facilitate the growth of complex, high-tech sectors.

Technological innovation in resource extraction and processing can also help economies reduce their dependency on raw material exports by adding value to these materials within the country. This transition not only enhances economic complexity but also supports a more sustainable approach to raw material use. Countries like Chile, which is a major copper exporter, have begun to integrate more processing and value-added activities, moving beyond simple extraction into refining and advanced product manufacturing[13]. The ability to innovate in raw material processing enables nations to capture more of the value chain and reduce vulnerability to global price fluctuations in raw materials.

4.2.2 Raw Material Diversification and Economic Growth

The diversification of raw material exports is another key factor in enhancing economic complexity. While many countries have long been dependent on the extraction of a single resource, there is growing recognition that economic resilience can be bolstered by diversifying raw material exports. South Africa, for example, is a major producer of platinum and gold but has also diversified its exports to include more value-added products such as processed metals and machinery. This strategy allows countries to maintain their position

in global markets while expanding into higher-value industries[59].

Diversification, however, is not limited to raw materials. It also involves developing human capital, fostering innovation, and investing in infrastructure to facilitate the transition to more complex production processes. Countries like Norway, which initially relied heavily on oil exports, have diversified their economy by investing in other sectors such as renewable energy, technology, and finance. The move toward diversification, while initially driven by resource extraction, now incorporates significant technological, social, and political changes. By expanding into knowledge-based industries and reducing reliance on raw material exports, Norway has successfully enhanced its economic complexity[18].

4.2.3 The Role of Policy in Mitigating Raw Material Dependence

Governments play a critical role in managing the relationship between raw materials and economic complexity. Effective policies can support the transition from raw material extraction to more complex industrial activities by fostering innovation, improving education and skills, and creating an environment conducive to investment in higher-value sectors. Governments can also encourage sustainable practices in the raw material industries to ensure that economic complexity does not come at the expense of environmental health or social equity[108].

Countries that have successfully transitioned away from raw material dependence have typically done so through strategic investments in infrastructure, education, and technology. Policies that support the development of high-tech industries, research and development (RD), and industrial diversification can significantly enhance economic complexity. For instance, Singapore has been successful in transitioning from a small port economy dependent on raw materials to a thriving hub for electronics, biotechnology, and financial services[21]. The government's focus on developing human capital and technology-driven industries has been central to this transformation.

Furthermore, the establishment of specialized economic zones and the promotion of public-private partnerships can also encourage the development of value-added industries. For example, establishing innovation hubs where raw materials are processed into finished goods can help create the necessary infrastructure for higher-complexity industries to thrive. Such zones can attract foreign direct investment, provide opportunities for local businesses, and create a more diversified industrial base.

4.2.4 The Path Forward: Moving from Raw Material Dependence to Economic Complexity

While raw materials continue to play an essential role in many economies, their potential to foster economic complexity depends on how they are managed and integrated into the broader economic structure. The challenge lies in balancing the short-term benefits of raw material extraction with the long-term need for economic diversification. The key to overcoming raw material dependence lies in fostering the development of industries that add value to these materials and investing in technological innovation, human capital, and infrastructure. Countries that successfully manage this transition are better positioned to enhance their economic complexity, ensuring that their growth is driven by innovation

and diversification rather than a reliance on the extraction of finite resources[97].

By focusing on diversification, technological innovation, and sustainable development, economies can mitigate the risks associated with raw material dependence and move toward a more sophisticated and resilient economic structure. This transition requires not only careful economic planning but also the ability to adapt to global trends, such as the rise of green technologies, digital transformation, and the growing demand for complex products.

4.3 Diversification Through Raw Materials

Economic diversification is a key element for long-term economic growth and resilience, especially for nations heavily reliant on raw material extraction. While raw materials serve as the foundation for many economies, they can also act as catalysts for the development of more complex and diversified industries. Raw materials, when managed strategically, have the potential to be the cornerstone for broadening an economy's industrial base, driving technological innovation, and fostering economic resilience. The process of diversification involves moving from a concentration on primary raw material production into industries that process these materials, add value, and innovate to create more sophisticated products and services.

4.3.1 Economic Diversification and Raw Materials as a Catalyst

For many resource-rich economies, the challenge lies in avoiding the trap of over-dependence on the extraction of raw materials, which can inhibit the development of other sectors. However, raw materials themselves can serve as critical building blocks for economic diversification[9]. The key is to use the revenue generated from raw material exports to finance investments in more complex industries. The path to economic diversification through raw materials involves expanding the scope of production beyond basic extraction and processing into higher-value activities such as manufacturing, technology, and services.

A striking example of this process is seen in Chile, a country that has built much of its economic strength around copper exports. Copper, as a critical raw material, has played a significant role in supporting the nation's industrialization efforts[80]. By investing the revenue generated from its copper exports into infrastructure, education, and technological advancements, Chile has been able to expand its industrial base and diversify its economic activities. While copper remains a cornerstone of the Chilean economy, the country has diversified into sectors such as food processing, chemicals, and even high-tech industries such as lithium-ion battery production, thanks to the demand for lithium and other minerals essential for renewable energy technologies.

Similarly, Norway, once primarily dependent on oil exports, has used its natural resource wealth to foster diversification. The Norwegian government has invested heavily in diversifying its economy, with a particular focus on technology, renewable energy, and financial services[16]. Today, Norway is a leading global player in the green energy sector, including wind and solar energy, demonstrating that raw material wealth, particularly from oil and gas, can provide the capital and infrastructure needed to transition into more

sustainable and innovative sectors. This transformation highlights the importance of investing in both technological and human capital to enable diversification away from raw material dependence.

4.3.2 Technological Innovation: A Driver of Diversification

Technological innovation is at the heart of diversification through raw materials. As new technologies emerge, they open the door for new applications of raw materials, which can lead to the development of entirely new industries[82]. For example, the growing demand for electric vehicles (EVs) and clean energy technologies has spurred the need for critical raw materials such as lithium, cobalt, and nickel. These materials, which were once primarily used in traditional industries, now play a critical role in the green technology sector, creating new avenues for economic growth. The mining and refining of these materials are often followed by value-added activities such as battery manufacturing, electric vehicle production, and the development of renewable energy systems.

Countries like Australia, which is rich in lithium, are beginning to invest in local processing facilities for these materials, rather than simply exporting them in raw form. This move towards value-added processing not only provides a higher return on the raw materials but also facilitates the growth of industries related to clean energy, technology, and advanced manufacturing. These industries, in turn, generate high-value employment opportunities, foster innovation, and contribute to the development of an economy's economic complexity.

4.3.3 Raw Materials as a Gateway to High-Value Industries

Diversification through raw materials is not limited to the primary sectors of mining or agriculture. Raw materials also serve as a key input for high-value industries, including pharmaceuticals, electronics, aerospace, and automotive manufacturing. The processing of raw materials into refined products often marks the first step in the value chain that leads to more complex industries. For example, China, a country rich in rare earth elements, has used its access to these materials to develop a global high-tech industry, including electronics, renewable energy technologies, and telecommunications[116].

The strategic use of raw materials in the development of high-tech industries has also been a cornerstone of South Korea's industrial success. The country has leveraged its raw material imports to build robust electronic, automotive, and shipbuilding industries. By investing in research and development (RD) and capitalizing on the knowledge embedded in the raw material industries, South Korea has transformed itself into one of the world's most advanced economies[78]. The synergy between raw materials and advanced manufacturing has propelled South Korea's global competitiveness, demonstrating the link between resource extraction and high-tech industrialization.

4.3.4 Sustainability and Circular Economy in Diversification

As the world shifts toward sustainability, the concept of the circular economy has emerged as a key strategy in the diversification process. The circular economy model emphasizes reducing waste, reusing materials, and recycling raw materials to minimize resource

extraction and environmental impact. Raw materials, when managed within a circular economy framework, can help foster the growth of green industries and sustainable practices. For instance, in Germany, policies that support recycling and waste reduction in the manufacturing sector have resulted in a thriving green economy, where raw materials are recycled and reprocessed to create new products. The incorporation of circular economy practices into the raw material sector can help diversify economic activities while promoting environmental sustainability[84].

A specific example of circular economy-driven diversification can be found in Sweden, where the country is using its natural raw material wealth to foster the growth of eco-friendly technologies, such as waste-to-energy systems. The Swedish government's investments in renewable energy, combined with a focus on sustainability in raw material extraction and processing, have positioned the country as a global leader in green technologies. This approach not only contributes to a diversified economy but also enhances Sweden's competitiveness in the emerging global green market[4].

4.3.5 Challenges in Diversification through Raw Materials

Despite the potential for diversification, challenges persist. One of the most pressing issues is ensuring that the wealth generated from raw material exports is reinvested into sectors that promote long-term economic growth. Without the proper investments in infrastructure, education, and technology, countries may continue to face the risk of becoming trapped in a cycle of raw material extraction with limited economic diversification. Additionally, the volatility of global commodity markets poses a significant challenge for countries heavily reliant on raw material exports. Prices for raw materials can fluctuate widely, leading to economic instability and undermining the prospects for sustained diversification.

Another key challenge is the environmental and social impacts of raw material extraction. While diversification offers opportunities for higher-value industries, it is crucial to ensure that the extraction and processing of raw materials do not come at the expense of environmental sustainability or social equity. Countries must adopt sustainable practices in the raw material industries, ensuring that diversification efforts are aligned with broader goals of sustainability and ethical business practices.

4.4 Raw Materials as Enablers of Technological Advancement

Raw materials, often seen as the building blocks of industries, have played a crucial role in enabling technological advancements across the globe. These materials, derived from natural resources, not only serve as inputs for basic manufacturing processes but also provide the essential foundation for high-tech industries and cutting-edge technologies. As industries continue to evolve and the global economy moves toward increasingly sophisticated and environmentally conscious solutions, raw materials have become central to the development and proliferation of new technologies that are revolutionizing sectors such as electronics, energy, transportation, and healthcare.

4.4.1 The Role of Raw Materials in Emerging Technologies

One of the most profound ways in which raw materials have enabled technological advancement is through their role in the development of emerging technologies. Key raw materials such as rare earth metals, lithium, cobalt, and graphite are integral to industries focused on innovation, especially in sectors like electronics, renewable energy, and electric vehicles (EVs). These materials are crucial for producing high-efficiency batteries, wind turbines, solar panels, and advanced consumer electronics.

For instance, lithium is a fundamental component of lithium-ion batteries, which are at the core of powering modern technologies, from smartphones to electric vehicles. The demand for lithium has surged as the world increasingly shifts toward green technologies and sustainable transportation options. Lithium, along with other materials like nickel and cobalt, enables the production of batteries that power electric vehicles, which play a pivotal role in the global transition to clean energy.

Similarly, rare earth elements, such as neodymium and dysprosium, are essential for producing powerful magnets used in wind turbines and electric motors, as well as in the hard drives of computers and high-tech medical equipment. These materials are indispensable for the development of renewable energy systems and advanced electronics, sectors that have become increasingly important in the face of climate change and technological progress.

The growing importance of these raw materials highlights the critical role they play in the advancement of technology. Their availability and the innovation surrounding their extraction and processing are central to the ongoing development of sectors that are key to both economic growth and the global shift toward sustainability.

4.4.2 Raw Materials in the Green Energy Transition

The global transition toward green energy is one of the most significant technological shifts of the 21st century, and raw materials are at the heart of this transformation. The shift away from fossil fuels toward renewable energy sources such as wind, solar, and hydropower has placed raw materials at the center of the technological infrastructure needed to support these energy systems. The production of solar panels, wind turbines, and energy storage solutions relies heavily on specific raw materials that are indispensable for generating and storing clean energy[65].

For example, silicon, the key material for photovoltaic solar panels, is essential in converting sunlight into electricity. The increasing demand for renewable energy technologies has made the extraction and processing of high-purity silicon critical. Similarly, materials such as copper and aluminum are crucial for the development of electrical grids and power transmission infrastructure, which are required to distribute clean energy from renewable sources efficiently. These raw materials, in turn, contribute to the advancement of technologies that are aimed at reducing the carbon footprint of global energy systems[67].

In addition to supporting the infrastructure of renewable energy, raw materials also play a role in developing technologies for energy storage. The transition to clean energy is contingent not only on generating renewable power but also on efficiently storing and distributing that power. Raw materials such as lithium, vanadium, and sodium are used in the production of advanced batteries, which are essential for storing energy generated

from renewable sources. As energy storage technologies continue to improve, raw materials will remain vital for enabling the grid modernization necessary for a more sustainable and efficient energy future[?].

4.4.3 Technological Innovations in Raw Material Extraction and Processing

The advancement of technology is not limited to the sectors that use raw materials; raw material extraction and processing itself have seen significant technological innovations. Advances in mining technology, materials processing, and recycling technologies have enabled more efficient extraction, refinement, and reuse of raw materials. These innovations not only reduce the environmental impact of raw material extraction but also enhance the economic viability of raw material industries, making them more sustainable and aligned with modern technological standards[63].

For example, automation in mining and materials processing has significantly increased the efficiency of extraction and reduced the human labor required for dangerous and labor-intensive tasks. Furthermore, advances in hydrometallurgy and bioleaching have opened up new methods for extracting metals and minerals from ores in a more environmentally friendly manner, minimizing the need for traditional energy-intensive smelting processes. This innovation has allowed countries to access raw materials that were previously difficult or uneconomical to extract, expanding the global supply of essential materials.

Recycling technologies have also advanced in recent years, enabling the recovery of valuable raw materials from discarded electronic products, batteries, and industrial waste. For instance, the development of more efficient methods to extract rare earth elements from electronic waste has significantly reduced the pressure on natural resources while promoting the circular economy. These technologies not only reduce the environmental footprint of raw material extraction but also contribute to a more sustainable and circular approach to raw material use[111].

4.4.4 Raw Materials as Catalysts for Industrialization and Technological Ecosystems

Beyond their role in specific technologies, raw materials also serve as catalysts for the creation of entire industrial ecosystems. The availability of critical raw materials allows countries to establish specialized industrial clusters around industries such as electronics manufacturing, automotive production, and aerospace engineering. These clusters foster technological advancements by encouraging collaboration, knowledge-sharing, and the development of specialized infrastructure.

For example, the development of Silicon Valley in the United States was made possible by access to materials essential for the semiconductor and electronics industries[102]. The presence of materials such as silicon, along with the innovation in processing technologies, enabled the creation of an entire ecosystem of tech companies, research institutions, and skilled labor that fueled the technological boom. Similarly, access to high-quality steel and aluminum has supported the growth of the automotive and aerospace

sectors, where these materials are key to producing lightweight, durable, and efficient vehicles and aircraft.

These industrial ecosystems not only promote technological advancement but also generate significant economic value through the creation of high-paying jobs, the development of new products, and the fostering of innovation. By creating these clusters around raw material industries, nations can build dynamic technological hubs that serve as centers of innovation and growth.

4.4.5 Challenges and Opportunities in Raw Materials and Technological Development

While raw materials have undoubtedly enabled significant technological advancement, challenges persist in ensuring their sustainable and equitable use. The extraction and processing of raw materials, particularly those used in high-tech industries, can have significant environmental and social impacts. These impacts, if left unmanaged, can hinder the progress of technological development and the broader sustainability goals that these technologies aim to support.

For instance, the extraction of materials like cobalt and lithium, which are vital for battery production, often involves complex ethical and environmental challenges[62]. Cobalt mining, for example, is notorious for human rights violations, particularly in the Democratic Republic of the Congo, where many of the world's cobalt reserves are located. Addressing these challenges through responsible sourcing, ethical labor practices, and more sustainable extraction techniques is essential to ensuring that raw materials continue to contribute positively to technological progress without causing harm to people or the planet.

Furthermore, as the demand for raw materials used in high-tech industries continues to rise, the global competition for these resources may lead to geopolitical tensions and supply chain disruptions. Ensuring that access to critical raw materials remains stable and equitable is vital for the long-term success of technological advancements.

4.5 Raw Materials and Innovation

Raw materials are integral to the process of technological innovation and economic development. Beyond their role as the foundation for traditional manufacturing, raw materials have become the bedrock upon which industries built on advanced technologies, new materials, and cutting-edge processes are being developed. Innovation in industries such as electronics, renewable energy, automotive manufacturing, and biotechnology hinges significantly on the availability and use of raw materials, which are redefined and repurposed to create new products, improve efficiencies, and drive advancements in multiple fields.

4.5.1 Raw Materials as a Source of Innovation

Raw materials, especially metals, minerals, and natural resources, often undergo extensive transformation through innovation, turning basic materials into sophisticated products that enhance the functionality and efficiency of industrial processes. The mining and extraction processes themselves have also become the site of ongoing innovation, with

advances in techniques like hydrometallurgy, biomining, and nanotechnology facilitating the efficient and sustainable extraction of valuable materials. This innovation not only increases resource recovery but also ensures that previously inaccessible materials can be utilized.

For example, graphene, a form of carbon derived from graphite, is one of the most exciting raw materials in modern science due to its exceptional strength, conductivity, and flexibility. The development of graphene-based technologies has opened new frontiers in electronics, energy storage, and even medical applications. From improving the performance of batteries and capacitors to enabling faster, smaller, and more efficient electronics, graphene is a prime example of how raw materials can drive groundbreaking innovation in both existing and emerging technologies.

Similarly, raw materials play a key role in the development of high-performance materials, which are critical in industries ranging from aerospace to medicine. Materials like titanium and carbon composites have revolutionized the aerospace sector, enabling the production of lighter and more fuel-efficient aircraft. In the medical field, biocompatible materials derived from raw substances, such as metals and polymers, have led to innovations in prosthetics, drug delivery systems, and implantable devices. The connection between raw materials and industrial innovation is clear: raw materials are the fundamental building blocks that facilitate the advancement of both new and existing technologies.

4.5.2 Innovation in Raw Material Processing and Recycling

The advancement of raw material processing techniques has not only enabled more efficient production of existing materials but has also created entirely new industries around the recycling and reuse of raw materials. In the context of a circular economy, innovation in recycling processes has become increasingly important for ensuring that raw materials are utilized to their fullest potential and not wasted. Techniques like closed-loop recycling, where materials are continuously recycled and reused in the production process, are changing the way industries view raw material consumption.

For example, electronics recycling has led to the recovery of valuable metals such as gold, silver, and copper, as well as rare earth elements like neodymium and dysprosium, which are essential for manufacturing high-tech devices such as smartphones, computers, and renewable energy equipment[92]. Companies are now investing in innovative ways to recover these materials from electronic waste (e-waste), reducing dependence on virgin raw materials and lessening the environmental impact of mining operations. Innovations in this area are contributing not only to resource efficiency but also to the development of more sustainable business practices across industries.

4.5.3 The Role of Raw Materials in Green Technologies and Sustainability

Innovation in raw material applications is also central to the development of green technologies, which are driving global sustainability efforts. As the world confronts the challenges of climate change and environmental degradation, raw materials are being repurposed in ways that reduce carbon footprints and facilitate the transition to renewable energy systems. The development of energy-efficient technologies, such as solar panels,

wind turbines, and energy storage solutions, heavily depends on the availability and use of specific raw materials that are indispensable for generating and storing clean energy.

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4.5.6 Challenges and Opportunities in Raw Materials and Technological Development

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Furthermore, as the demand for raw materials used in high-tech industries continues to rise, the global competition for these resources may lead to supply chain vulnerabilities and geopolitical tensions. Ensuring that access to critical raw materials remains stable and equitable is vital for the long-term success of technological advancements.

4.6 The Role of Sustainability in Raw Material-Driven Economic Complexity

The concept of sustainability has become central to discussions surrounding economic development, particularly in resource-rich economies. As global pressures to reduce environmental harm and promote ethical practices intensify, integrating sustainability into raw material-driven economic complexity is crucial for ensuring long-term, balanced growth. Raw materials are essential to technological innovation and industrialization, but their extraction, processing, and consumption often have significant environmental and social consequences. Therefore, adopting sustainable practices in raw material management is pivotal not only for mitigating adverse impacts but also for enhancing economic complexity and fostering more diversified, resilient economies.

Sustainability in the context of raw material-driven economic complexity goes beyond minimizing environmental degradation. It encompasses a broader set of considerations, including the social equity of labor practices, the long-term viability of resource extraction, and the adoption of circular economic models. A key challenge lies in ensuring that raw material extraction and use do not come at the expense of future generations' ability to meet their needs, thereby supporting a transition toward a more sustainable and complex economic model.

4.7 Sustainability and Raw Material Supply Chains

The sustainability of raw material supply chains is critical for the future of global economies, particularly in the context of economic complexity. As countries strive to diversify their industrial base and transition to more sustainable industries, the supply chains for raw materials that underpin these industries must evolve. The raw materials necessary for green technologies such as electric vehicles, renewable energy systems, and energy storage solutions often face challenges related to environmental degradation, social equity, and resource scarcity.

The concept of a sustainable supply chain goes beyond merely sourcing materials responsibly. It encompasses the entire lifecycle of raw materials, from extraction through to disposal and recycling. In the context of economic complexity, sustainable supply chains not only reduce environmental impacts but also enhance the resilience and efficiency of the economy. Economies that successfully integrate sustainability into their supply chains are better equipped to manage the challenges of raw material dependence, price volatility, and geopolitical risks.

The growing demand for critical raw materials such as lithium, cobalt, and rare earth elements, which are essential for the production of green technologies, places added pressure on these supply chains. Many of these materials are sourced from regions with limited infrastructure, often leading to challenges such as environmental degradation and human rights concerns. As nations ramp up their efforts to secure access to these materials, sustainable practices in mining, production, and recycling become increasingly vital.

To achieve sustainability, industries must prioritize resource efficiency, recycling, and the circular economy. By developing technologies that recycle and repurpose materials, it

is possible to reduce the demand for new raw materials and minimize the environmental impact of extraction processes. In the case of green technologies, recycling raw materials such as batteries and electronic waste can help meet the growing demand for critical materials while reducing environmental damage. Advances in recycling technologies, such as the efficient extraction of lithium and cobalt from used batteries, are critical to ensuring a sustainable supply of these essential materials.

In conclusion, the sustainability of raw material supply chains is a key factor in the ability of nations to achieve higher levels of economic complexity. As green technologies and sustainable industries continue to grow, the adoption of responsible practices in sourcing, manufacturing, and recycling will shape the future of global economies. Nations that succeed in developing sustainable supply chains will not only enhance their technological capabilities but also foster more resilient and diversified economies.

4.8 Challenges in Raw Material-Driven Economic Complexity

The relationship between raw materials and economic complexity is not without its challenges. While raw materials have historically supported industrial growth and technological innovation, over-reliance on their extraction can hinder the evolution of a diversified and complex economy. Raw materials, particularly in developing countries, can both enable and constrain economic development. The extraction and export of these materials often serve as the primary economic drivers, but this focus can present significant obstacles to achieving high levels of economic complexity. Understanding these challenges is crucial for crafting policies and strategies that foster both sustainability and innovation, allowing economies to maximize the benefits of their raw material resources while avoiding pitfalls that may limit future development.

4.8.1 Resource Dependence and Limited Economic Diversification

One of the most significant challenges faced by economies that are heavily reliant on raw materials is the risk of *resource dependence*, where the economy becomes overly focused on the extraction and export of primary commodities. This dependence often leads to limited diversification, as other sectors of the economy, such as manufacturing, services, and knowledge-based industries, receive less attention and investment[3]. The lack of diversification can leave an economy vulnerable to fluctuations in global commodity prices, economic downturns, and supply chain disruptions.

In countries that rely heavily on raw material exports, economic growth may become inherently volatile due to the unpredictable nature of commodity prices. For instance, fluctuations in the price of oil, copper, or agricultural products can dramatically affect the economy's stability, creating boom-bust cycles that undermine long-term development and progress. As a result, resource-rich nations may find themselves struggling to build resilient, diversified economies capable of weathering economic shocks.

This phenomenon is often referred to as the “*resource curse*,” where natural resource abundance fails to translate into sustained economic growth or increased economic complexity. Countries like Venezuela, which once thrived on oil exports, serve as stark ex-

amples of the dangers of relying too heavily on raw materials for economic growth. In these cases, over-dependence on a single resource can stifle innovation and economic diversification, reducing the nation's capacity to develop high-tech industries or expand into complex manufacturing sectors.

4.8.2 Environmental and Social Impacts of Raw Material Extraction

Another significant challenge tied to raw material-driven economic complexity is the *environmental and social impact* of raw material extraction. The processes of mining, logging, and agricultural production, among others, often come with substantial environmental costs, including deforestation, soil degradation, water contamination, and loss of biodiversity. Moreover, the extraction of raw materials can exacerbate social issues such as land displacement, poor working conditions, and human rights violations.

In countries where the extraction of raw materials is carried out with minimal regulation or oversight, environmental degradation can severely limit the ability to sustain future generations' livelihoods. The depletion of natural resources due to unsustainable extraction practices can create long-term consequences for the country's economy, particularly as raw material reserves become scarcer or harder to access. Similarly, poor labor conditions in industries like mining, where workers often face hazardous conditions, can lead to inequality and social unrest.

For example, cobalt mining in the Democratic Republic of the Congo (DRC) is a widely cited case of the social and environmental challenges tied to raw material extraction[62]. The DRC holds significant reserves of cobalt, a vital component for batteries in electric vehicles and smartphones. However, much of the mining is conducted under unsafe conditions, with laborers working in hazardous environments and facing human rights abuses. Additionally, the environmental damage caused by the extraction of cobalt threatens the long-term health of the region's ecosystems.

To mitigate these risks, it is essential that countries adopt responsible and sustainable practices for raw material extraction. This includes stronger regulations around labor rights, the reduction of environmental damage, and the promotion of technologies that minimize resource waste and pollution. Innovation in sustainable mining technologies and eco-friendly practices can significantly reduce the environmental footprint of raw material extraction, contributing to more balanced and equitable economic growth.

4.8.3 The Geopolitical Risks of Resource Concentration

The geopolitical dimension of raw material-driven economic complexity also presents challenges. Many critical raw materials, such as rare earth metals, lithium, and cobalt, are concentrated in specific regions of the world[54]. This concentration creates geopolitical risks, as countries or regions that control these materials can exert significant leverage over global supply chains and markets.

For instance, China's dominance in the rare earth element market has raised concerns over the stability of global supply chains, as these materials are essential for the production of high-tech electronics, renewable energy technologies, and military applications. The control over these materials provides China with considerable geopolitical influence, which can be used strategically in trade negotiations or global political relations. Simi-

larly, the rising demand for lithium for electric vehicles has led to geopolitical tensions in regions like South America, where major lithium reserves are found, particularly in countries like Chile and Argentina.

Resource concentration and geopolitical tension can disrupt supply chains and create instability in global markets. Economies dependent on raw material imports may find themselves vulnerable to price hikes, supply disruptions, or trade restrictions imposed by resource-rich countries. In light of these risks, many nations are increasingly looking to diversify their sources of raw materials and seek alternatives to reduce reliance on a single supplier. Countries like the European Union are exploring alternative sources for critical minerals, including efforts to promote domestic mining and increase recycling rates to ensure a more secure and diversified supply chain.

4.8.4 Technological Barriers to Raw Material Extraction and Processing

Even as technological advancements have enabled more efficient extraction of raw materials, significant barriers remain. In particular, the extraction of certain materials requires specialized technologies, and many of the techniques used in raw material processing can be energy-intensive, costly, and environmentally damaging[83]. This is particularly true for minerals such as rare earth elements and precious metals, which are often found in low concentrations and require complex processing methods to extract.

Technological advancements can help mitigate some of these challenges, but they also require substantial investments in research, infrastructure, and capital. Without access to cutting-edge extraction and processing technologies, countries may struggle to develop their resource sectors in a way that supports economic diversification and enhances economic complexity. For instance, developing countries with large mineral deposits often lack the technical expertise and financial capacity to invest in modern mining technologies, which limits their ability to process raw materials domestically and adds value to the economy.

Furthermore, innovations in recycling and material recovery technologies are still emerging, and many raw materials remain underutilized despite their potential for reuse. A greater focus on innovation in these fields could help alleviate resource constraints, reduce environmental damage, and support more sustainable raw material supply chains.

The role of raw materials in driving economic complexity is both profound and multifaceted. Raw materials have historically been the cornerstone of industrialization, facilitating the rise of global economies and contributing to the foundation of diverse economic sectors. However, their relationship with economic complexity is not a straightforward one. While raw materials provide the essential inputs for technological innovation and industrial production, their over-reliance can limit economic diversification and complexity, particularly in economies heavily dependent on primary commodity exports.

This chapter has explored the intricate relationship between raw materials and economic complexity, beginning with the fundamental role raw materials play in shaping industrial processes and advancing technological capabilities. Through the historical lens of raw material-driven industrialization, we have examined how the availability and use of raw materials such as copper, lithium, rare earth metals, and graphite have spurred

innovation across sectors including electronics, energy, automotive manufacturing, and biotechnology. These materials are indispensable for developing high-tech industries and enabling the transition to a low-carbon economy, marking their critical importance in fostering both technological and economic development.

However, as highlighted, the over-dependence on raw material extraction presents significant challenges. Economic reliance on a limited range of raw materials can lead to vulnerability to price volatility, hinder the development of complex, diversified economies, and create significant social and environmental challenges. The *resource curse*, where countries rich in raw materials fail to diversify economically and remain dependent on the extraction of primary commodities, is a central concern for nations seeking to increase economic complexity.

Addressing these challenges requires a shift toward sustainable and responsible management of raw materials. This chapter has emphasized the importance of integrating sustainability into raw material supply chains, focusing on reducing environmental impacts, improving labor practices, and promoting circular economic models. Sustainable raw material management, coupled with technological innovation in mining and material processing, has the potential to mitigate the negative effects of raw material extraction while enabling the development of new industries and enhancing economic diversification.

The concept of the circular economy has emerged as a key driver for reducing resource dependence and fostering more sustainable, complex economies. By promoting the recycling and reuse of raw materials, we can reduce the environmental footprint of industrial processes, lower the demand for virgin materials, and stimulate the creation of more sustainable, high-value industries. Furthermore, innovations in recycling technologies, such as the recovery of rare earth elements from electronic waste, provide new avenues for tapping into raw materials without depleting natural resources[37].

In conclusion, raw materials remain foundational to economic growth and technological advancement, but their role in economic complexity is highly dependent on how they are sourced, processed, and utilized. While raw materials are essential to fostering innovation, it is the responsible, sustainable, and efficient use of these materials that can drive the development of more diversified, resilient, and complex economies. The integration of sustainability principles into raw material management is not merely a regulatory requirement but an opportunity to enhance long-term economic growth, foster innovation, and ensure that the benefits of raw material wealth contribute to sustainable development for future generations. As we move forward, the challenge lies in balancing the immediate economic gains from raw material extraction with the need for long-term economic complexity and sustainability.

4.9 Export Complexity Profiles of Selected Countries

To complement the econometric investigation of the relationship between the Economic Complexity Index (ECI) and Critical Raw Material (CRM) imports, it is useful to examine the export structures and product sophistication of the countries under study. Using data from the Observatory of Economic Complexity (OEC, 2023), this section briefly presents the trade-based ECI rankings and the Product Complexity Index (PCI) scores of the main export items for each country. These insights help ground the econometric

findings in real-world trade patterns, further illustrating how increasing complexity aligns with reliance on technologically intensive and often resource-dependent exports.

South Korea ranked 4th out of 132 countries in 2023 with a trade-based ECI of 1.83. Its top exported products are integrated circuits, cars, and refined petroleum. Notably, integrated circuits—ranked among the top 10% most complex products globally—have a PCI of 1.21, reflecting their knowledge- and resource-intensive nature. In contrast, cars hold a PCI of 0.72, and refined petroleum—despite being a major trade item—registers a negative complexity score of -1.16 , indicating limited value-added complexity.

China, with a 2023 ECI of 1.14 (22nd out of 132), also displays a strong export orientation toward technologically advanced products. Its main exports include telephones (PCI = 1.38), computers (PCI = 1.14), and integrated circuits (PCI = 1.21). The consistently high PCI values underscore China's increasing foothold in the global market for complex electronics, a development consistent with its climbing ECI.

Poland, with an ECI of 1.02 (28th out of 132), exhibits an export basket centered around electric batteries (PCI = 1.48), motor vehicles (PCI = 0.97), and cars (PCI = 0.72). The presence of electric batteries—one of the most technologically sophisticated and CRM-intensive products—highlights Poland's integration into high-tech European value chains, particularly in the clean energy and automotive sectors.

The United States, despite its high ECI of 1.50 (10th out of 132), relies heavily on resource-based exports. Its leading products—crude petroleum (PCI = -2.33), refined petroleum (PCI = -1.16), and petroleum gas (PCI = -1.88)—exhibit low or negative PCI scores. This apparent paradox suggests that a high overall ECI can coexist with an export mix dominated by low-complexity, extractive products, reflecting the U.S. economy's dual strength in high-tech innovation and natural resource endowments.

These trade patterns reinforce the empirical thesis that increasing economic complexity—especially when directed toward high-tech manufacturing—correlates with a greater reliance on rare and technologically critical materials. Countries such as South Korea and China, whose export baskets are increasingly composed of high-PCI products like semiconductors and electronics, naturally exhibit greater dependency on CRMs. Conversely, nations whose export complexity remains concentrated in low-PCI commodities may experience less direct pressure on rare metal imports but face other forms of technological reliance.

Chapter

Green Technology and Raw Materials

5.1 Introduction to Green Technology

Green technology, or clean technology, represents an innovative approach to tackling the pressing environmental issues of our time[68]. As industrialization has advanced, the need for energy, raw materials, and land has increased dramatically, leading to environmental degradation, resource depletion, and the acceleration of climate change. Green technologies aim to mitigate these impacts by providing solutions that are both economically and environmentally sustainable. These technologies focus on creating new systems, products, and processes that reduce energy consumption, promote the use of renewable resources, and minimize waste and pollution.

The concept of green technology has evolved over the past few decades in response to growing global awareness of environmental issues[88]. It spans a wide range of applications across sectors such as energy, transportation, agriculture, and manufacturing. While it initially focused on renewable energy sources like wind and solar power, the scope of green technology has expanded to include energy-efficient building materials, sustainable agriculture practices, electric vehicles (EVs), and eco-friendly manufacturing techniques. These innovations are reshaping the way industries operate, contributing to a global shift towards sustainability.

The global drive for sustainability is being propelled by a combination of factors. The growing recognition of climate change's economic and social consequences, as well as increasing pressure from governments, corporations, and consumers, has spurred rapid advancements in green technologies. International agreements such as the Paris Agreement have set ambitious goals for reducing greenhouse gas emissions and limiting global warming, reinforcing the need for widespread adoption of clean technologies. Simultaneously, technological innovations and advancements in energy storage and smart grids are accelerating the transition to cleaner, more efficient energy systems.

Green technologies not only address environmental concerns but also offer substantial economic opportunities. The transition to green energy, energy storage, and sustainable manufacturing presents avenues for economic diversification and growth, especially in nations that are heavily dependent on resource extraction and fossil fuel industries. By investing in and developing green technologies, countries can reduce their reliance on finite resources, improve their technological base, and create new industries that contribute to long-term economic resilience.

Raw materials play a crucial role in enabling the widespread adoption of green technologies. The production of solar panels, wind turbines, electric vehicle batteries, and other sustainable solutions requires specific raw materials such as silicon, cobalt, lithium, and rare earth elements. The demand for these materials has surged alongside the growth of green technology sectors, driving changes in global supply chains and creating new geopolitical dynamics. The need for critical raw materials in green technologies underscores the importance of sustainable resource management and responsible mining practices.

As green technologies become more integral to economic systems, they also influence the complexity of global economies[88]. The adoption of renewable energy and green manufacturing techniques helps drive economic diversification, enabling countries to shift away from raw material-dependent industries toward more technologically advanced and sustainable economic models. This transition enhances economic complexity by fostering high-value-added sectors such as clean energy production, sustainable infrastructure, and green manufacturing.

In this chapter, we will explore the role of green technologies in driving economic complexity and sustainability. We will examine various types of green technologies, their impact on raw material demand, and the challenges associated with ensuring sustainable supply chains for these critical resources. By understanding the interconnections between green technologies, raw materials, and economic complexity, we can better grasp how innovation in clean technology can drive future economic development while ensuring environmental protection.

5.2 Types of Green Technology

Green technology represents a broad spectrum of innovations designed to address environmental challenges while fostering sustainable economic growth[87]. As global attention shifts toward mitigating the effects of climate change and reducing resource depletion, the development and implementation of green technologies have become critical to achieving long-term sustainability. Green technologies, which span a variety of sectors, contribute to reducing energy consumption, curbing greenhouse gas emissions, and minimizing environmental degradation. These technologies not only aim to meet the growing demand for resources but also to ensure that industrial processes and energy systems operate in harmony with the planet's ecological limits.

A primary category of green technology is renewable energy, which includes solar, wind, geothermal, and hydroelectric power[86]. These technologies harness natural resources that are replenished over time, making them a key part of the transition from fossil fuels to cleaner energy sources[85]. Solar energy, for instance, involves capturing sunlight and converting it into usable power through photovoltaic cells or solar thermal systems. As technology advances, the efficiency of solar panels continues to improve, reducing costs and making solar energy an increasingly viable option for both residential and commercial applications. Wind energy, too, has become an essential part of the global renewable energy mix. Wind turbines convert the kinetic energy of wind into electricity, and advances in turbine design have enhanced their efficiency and capacity. Offshore wind farms, in particular, offer great promise due to their ability to harness stronger and more consistent wind patterns over the oceans, further enhancing the potential for large-scale

renewable energy generation.

In addition to solar and wind, geothermal energy plays a crucial role in the green technology landscape. By tapping into the Earth's natural heat, geothermal plants can provide a reliable and continuous source of power. Geothermal systems are particularly advantageous because they can produce energy consistently, unlike solar or wind, which are intermittent by nature. The growing adoption of these technologies reflects the global commitment to reducing reliance on fossil fuels and embracing energy sources that have minimal environmental footprints.

Energy storage technologies are equally critical to the effectiveness of renewable energy. Because solar and wind power are not available continuously, energy storage systems are essential for balancing supply and demand. Advanced batteries, such as lithium-ion and solid-state batteries, allow for the efficient storage of electricity generated during peak periods, making it available when demand exceeds supply. These storage systems play a pivotal role in enabling a reliable and resilient energy grid. Additionally, hydrogen storage has emerged as a promising alternative for large-scale energy storage. Green hydrogen, produced using renewable energy to split water into hydrogen and oxygen, offers a clean and versatile energy carrier that can be stored and used for various applications, including in fuel cells and industrial processes.

Beyond energy generation and storage, green manufacturing technologies are reshaping industrial production by promoting sustainability and resource efficiency. Green manufacturing emphasizes the adoption of energy-efficient processes, the use of renewable resources, and the minimization of waste. Advances in additive manufacturing, also known as 3D printing, allow industries to produce goods with less material waste compared to traditional subtractive manufacturing techniques. This technology not only conserves raw materials but also enables the production of complex and customized parts with minimal energy consumption. Additionally, green manufacturing encourages the use of eco-friendly materials such as biodegradable plastics and recycled metals, further reducing the environmental impact of industrial production.

One of the most transformative green technologies in the transportation sector is the electric vehicle (EV). As the world seeks to reduce carbon emissions and fossil fuel consumption, EVs have become a key solution to achieving more sustainable mobility. Electric vehicles are powered by electricity stored in batteries, and their widespread adoption is facilitated by advancements in battery technology that have led to improved energy density, longer driving ranges, and faster charging times. The increasing shift toward electric mobility is supported by government policies, corporate investments, and consumer demand for more sustainable alternatives to conventional internal combustion engine vehicles.

However, the shift to electric vehicles brings about a significant increase in demand for certain raw materials. Lithium, cobalt, and rare earth elements, critical for the production of EV batteries and electric motors, are becoming increasingly sought after. This growing demand raises concerns about the environmental impact of extracting these materials, as well as the geopolitical risks associated with supply chain dependence on a limited number of countries. Consequently, the development of green technologies must go hand in hand with efforts to ensure the sustainability of the raw materials used in their production.

Green technologies are also making substantial inroads into agriculture. As global

populations increase, the demand for food continues to rise, placing pressure on natural resources. Sustainable agricultural practices, such as precision farming, vertical farming, and hydroponics, are addressing the need for more efficient and environmentally friendly food production. Precision farming uses advanced technologies like GPS, drones, and sensors to optimize the use of water, fertilizers, and pesticides, thereby increasing crop yields while reducing waste and environmental impacts. Vertical farming, which involves growing crops in stacked layers within controlled indoor environments, allows for more efficient use of space and resources, making it an ideal solution for urban agriculture. Hydroponics, an alternative to traditional soil-based farming, enables crops to grow in nutrient-rich water, further reducing the land and water use typically associated with conventional farming.

Despite the numerous advantages of green technologies, their widespread adoption is not without challenges. The production and deployment of these technologies require substantial investment in infrastructure, research, and development. The cost of renewable energy systems, for example, remains higher than that of fossil fuel-based power generation in many regions, although this is rapidly changing as technology improves and economies of scale come into play. Similarly, while green manufacturing technologies offer significant environmental benefits, they often require large upfront investments in new equipment and processes. Furthermore, the shift toward electric vehicles and renewable energy systems increases the demand for certain raw materials, which could strain global supply chains if not managed responsibly.

Ultimately, green technologies offer a pathway to more sustainable industrial practices and greater economic complexity. By integrating these technologies into industries and economies, countries can not only reduce their environmental footprints but also foster innovation and diversification. As the global economy shifts toward cleaner and more efficient technologies, the role of green technology in driving economic complexity will continue to grow, offering new opportunities for growth and development.

5.3 Green Technologies and Raw Materials Demand

The growing adoption of green technologies, driven by the need for sustainable development and the transition to a low-carbon economy, has brought about significant shifts in the demand for raw materials. Green technologies, including renewable energy systems, electric vehicles (EVs), energy storage, and sustainable manufacturing methods, all rely heavily on specific raw materials. These materials, many of which are classified as critical due to their scarcity, geographic concentration, and importance for technological advancements, are integral to the production and functionality of green technologies. As these technologies scale, the demand for these raw materials continues to grow, creating both opportunities and challenges for the global supply chain.

5.3.1 Critical Raw Materials for Green Technologies

Among the key raw materials in green technologies are lithium, cobalt, nickel, rare earth elements, and silicon[66]. Each of these materials plays a crucial role in enabling the functionality of different green technologies.

Lithium, for example, is vital for the production of lithium-ion batteries, which power electric vehicles, smartphones, and other electronic devices. As the demand for electric vehicles and energy storage systems rises, so too does the need for lithium. Over the past decade, the demand for lithium has skyrocketed, with projections indicating that this trend will continue as the global shift towards EVs and renewable energy accelerates.

Cobalt is another critical material used in the production of rechargeable batteries, particularly in lithium-ion and nickel-cobalt-manganese (NCM) batteries. The demand for cobalt is closely tied to the growth of the electric vehicle industry, as well as to the expanding use of batteries in stationary energy storage applications. However, the geopolitical concentration of cobalt mining in regions such as the Democratic Republic of Congo (DRC) raises concerns regarding the ethical implications of sourcing and the potential for supply chain disruptions.

Rare Earth Elements (REEs) such as neodymium, dysprosium, and praseodymium are integral to the manufacturing of high-performance magnets used in wind turbines and electric vehicle motors. These elements are indispensable for creating efficient, compact, and lightweight motors, which are crucial for maximizing the performance of renewable energy technologies and electric vehicles. The geopolitical risks associated with rare earth elements, with China controlling a significant portion of global supply, add another layer of complexity to the raw material supply chain.

Nickel is increasingly being used in the production of batteries for electric vehicles and energy storage systems. As the demand for high-energy-density batteries increases, nickel, along with other materials like manganese and cobalt, becomes essential for producing batteries with longer lifespans and higher performance.

Silicon, the fundamental material used in the production of solar panels, plays a critical role in the renewable energy sector. Solar power systems rely on high-purity silicon for photovoltaic cells, and the demand for silicon is expected to rise significantly as more countries and regions ramp up their investments in solar energy infrastructure.

5.3.2 The Impact of Green Technologies on Raw Material Supply Chains

The rapid rise in demand for raw materials associated with green technologies is putting considerable strain on global supply chains. The extraction, processing, and distribution of these materials involve complex systems and often have significant environmental, social, and economic implications.

Geopolitical Factors: The geographic concentration of certain critical raw materials creates significant risks for supply chains[20]. For example, much of the world's supply of rare earth elements is concentrated in China, which has used its control over this resource to exert political and economic leverage. Similarly, cobalt, which is predominantly mined in the DRC, has faced ethical concerns due to labor practices and environmental degradation. Countries dependent on these raw materials are increasingly seeking to diversify their supply chains, either by exploring new sources or investing in recycling technologies to reduce dependence on primary extraction.

Supply Chain Volatility: As green technologies scale, fluctuations in the supply and demand for raw materials can create significant market volatility. The increasing demand for materials like lithium, cobalt, and nickel has already led to price increases,

and the potential for supply shortages in the future could hamper the growth of green technology sectors. In addition, the environmental and social impacts of raw material extraction—ranging from deforestation to water contamination—further complicate the picture.

Recycling and Circular Economy: One of the most promising solutions to mitigating the strain on raw material supply chains is the development of efficient recycling and reuse systems[64]. In the context of green technologies, recycling materials such as lithium, cobalt, and rare earth elements from used batteries, electronics, and other waste streams can help meet growing demand without further depleting natural resources. Recycling technologies, however, are still evolving, and the scale at which they can be implemented to support the green technology industry is still being explored.

Environmental and Ethical Considerations: As the demand for critical raw materials grows, the environmental and ethical challenges of mining these materials become more pressing[?]. Mining operations for materials such as cobalt and lithium often take place in ecologically sensitive areas and can result in habitat destruction, pollution, and adverse impacts on local communities. The drive for more sustainable raw material sourcing is leading to greater scrutiny of mining practices and a push for responsible sourcing, as well as the development of technologies to reduce the environmental impact of material extraction.

5.4 The Future of Green Technology in Raw Materials and Economic Complexity

The future of green technology promises to redefine the dynamics of both raw material demand and the economic complexity of nations worldwide[105]. As the transition to a green economy accelerates, driven by the urgent need to mitigate climate change, green technologies will continue to reshape industries and economies by fostering innovation, increasing resource efficiency, and diversifying production capabilities[71]. This transformation, however, is not without challenges, particularly in terms of securing sustainable access to the raw materials essential for these technologies. Understanding the relationship between green technologies, raw material supply chains, and economic complexity is essential for navigating the opportunities and risks that lie ahead.

As green technologies evolve and expand, they will play an increasingly central role in driving economic complexity. Countries that are at the forefront of adopting and scaling these technologies are likely to experience enhanced economic diversification, with new industries emerging in renewable energy, sustainable manufacturing, energy storage, and electric vehicles. These industries, characterized by their technological sophistication and high value-added production, will contribute to the overall complexity of national economies by fostering innovation, developing advanced skills, and promoting high-tech sectors that are less reliant on traditional resource extraction.

One of the key factors that will shape the future of green technology is the growing demand for critical raw materials such as lithium, cobalt, nickel, and rare earth elements. These materials are indispensable for the production of batteries, renewable energy systems, and electric vehicles, all of which are central to the green technology revolution[15]. As the global transition to a green economy intensifies, so too will the demand for these

materials. This increased demand presents both opportunities and risks. On the one hand, countries rich in these materials will have the opportunity to capitalize on their natural resources by becoming key players in the green technology supply chain, thus enhancing their economic complexity. On the other hand, the concentrated supply of critical raw materials, combined with the environmental and geopolitical challenges associated with their extraction, poses risks to the stability and sustainability of global supply chains.

The future of green technologies in the context of raw materials will depend heavily on how nations manage their access to these resources. The concept of resource efficiency will become more critical as the demand for raw materials grows[113]. Countries that focus on improving the efficiency of material use, developing recycling technologies, and advancing sustainable mining practices will be better positioned to navigate the challenges of raw material scarcity and supply chain vulnerabilities. Innovations in material science and advanced recycling technologies will enable the reuse of critical materials from old products, particularly batteries and electronic waste. This will reduce the pressure on primary extraction while promoting the development of circular economies, where materials are continuously reused, recycled, and repurposed, thereby reducing waste and the need for new raw material inputs.

Moreover, the development of alternative materials that can replace scarce and environmentally damaging raw materials is likely to play a crucial role in shaping the future of green technology[77]. Research into new materials for batteries, for example, is already underway, with efforts focused on reducing the reliance on cobalt and lithium. Sodium-ion batteries and solid-state batteries offer promising alternatives that could reduce material dependencies and improve the overall sustainability of energy storage solutions. Similarly, the use of bio-based and biodegradable materials in manufacturing could help reduce the environmental footprint of green technologies and create new markets for sustainable goods.

The future of green technologies is also intricately linked to technological advancements in areas such as artificial intelligence (AI), machine learning, and the Internet of Things (IoT), all of which are expected to drive further efficiencies in green energy systems and raw material management[27]. For example, AI can be used to optimize energy production and consumption, predict material shortages, and improve the efficiency of recycling processes. Smart grids, powered by AI and IoT, will enable more efficient energy distribution and storage, while predictive analytics will help manufacturers optimize their use of raw materials. These technological innovations will not only support the transition to greener economies but also enhance economic complexity by driving technological leadership and fostering the development of new industries.

As the role of green technologies expands, so too will the global demand for skilled labor[81]. The green technology sector is expected to create millions of jobs worldwide in fields such as renewable energy, energy storage, sustainable manufacturing, and green construction. The need for skilled workers in these industries will drive investments in education, training, and research, further enhancing the sophistication and capabilities of economies. Nations that invest in the development of a highly skilled workforce will be better positioned to capitalize on the opportunities presented by green technologies, fostering innovation and creating a competitive edge in the global market.

Governments will play a crucial role in shaping the future of green technology and its relationship with raw materials and economic complexity. Policy frameworks that

promote sustainability, innovation, and the responsible management of raw materials will be essential for ensuring that the green transition is equitable, resilient, and economically beneficial. These policies may include incentives for green technology adoption, support for research and development, and regulations that encourage sustainable practices in manufacturing and resource extraction. Additionally, international cooperation will be necessary to address the global challenges associated with raw material supply chains, including issues of trade, geopolitical risks, and environmental impacts.

The future of green technology will undoubtedly require significant investment in infrastructure and innovation. As nations transition to cleaner energy systems and sustainable manufacturing processes, the demand for green infrastructure—such as smart grids, electric vehicle charging stations, and renewable energy installations—will surge. The construction of these systems will require not only raw materials but also skilled labor, financing, and technological expertise. In this context, green technology will drive investment in infrastructure that supports sustainable urban development, efficient transportation, and low-carbon energy systems.

In conclusion, the future of green technology in raw materials and economic complexity is one of transformation and opportunity[10]. As green technologies continue to evolve and scale, they will play a pivotal role in enhancing economic diversification, driving innovation, and fostering sustainability. However, this transition will also require careful management of raw material supply chains, investments in resource efficiency and recycling, and the development of alternative materials to reduce dependency on scarce resources. By focusing on these areas, nations can ensure that the future of green technology not only addresses environmental challenges but also contributes to long-term economic growth, technological advancement, and increased economic complexity.

5.5 Raw Materials and the Paradox of the Green Transition

While green technologies promise a more sustainable and low-carbon future, their material basis reveals an inherent paradox: the transition toward a cleaner economy is critically dependent on materials whose extraction and processing are environmentally intensive, socially problematic, and often geopolitically contentious.

As de Cunzio et al.[28] argue, environmental innovation tends to “trickle down” into sectors of higher technological complexity, generating new productive opportunities. However, this process also deepens the structural dependence on a narrow set of raw materials that are anything but environmentally benign. The push for electrification—particularly in electric vehicles (EVs), renewable energy systems, and digital infrastructure—has amplified the global demand for lithium, cobalt, rare earth elements, and nickel. These materials are essential for batteries, turbines, and solar cells, yet their extraction entails significant ecological degradation, water usage, and carbon emissions.

This paradox is exacerbated by the *geographical concentration* of raw materials in regions that face weak regulatory oversight and fragile ecosystems. Cobalt mining in the Democratic Republic of Congo and rare earth extraction in China are often cited as cases where the environmental cost of the green transition is externalized onto vulnerable communities and ecologies. In this context, the promise of a green future risks replicating

the very extractivist patterns that sustainability agendas seek to overcome.

Moreover, the growing demand for critical raw materials increases global supply chain volatility, placing pressure on both producer and consumer nations. Countries pursuing green industrial strategies now face strategic trade-offs between accelerating decarbonization and securing the sustainable supply of inputs. As highlighted by the European Commission[32], the need for autonomy in CRM sourcing has become a key geopolitical concern, prompting policies that aim to boost domestic mining, improve recycling rates, and invest in material substitution technologies.

A potential path forward lies in the *reconfiguration of material flows*, especially through:

- Advancing urban mining and high-efficiency recycling systems;
- Supporting closed-loop supply chains and circular economy principles;
- Fostering green material innovation, including bio-based and synthetic alternatives to CRMs.

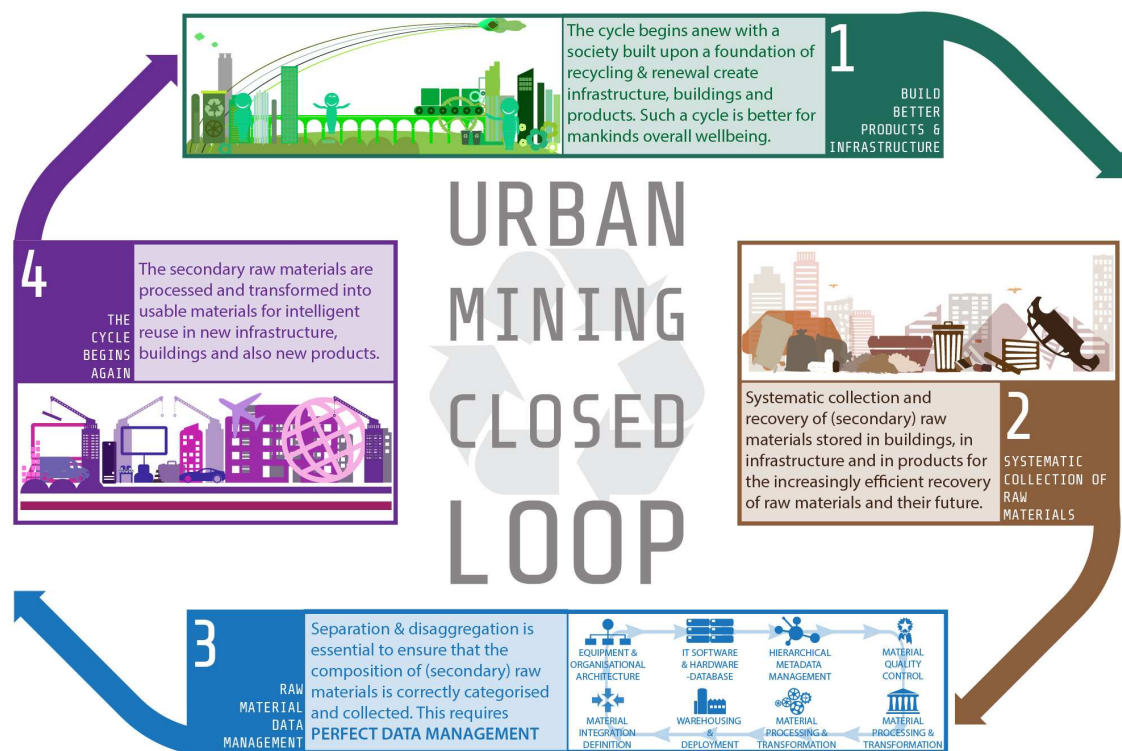


Figure 5.1: The Urban Mining Closed Loop, A visual model of circular resource recovery and reuse.

Figure 5.1 visually illustrates the concept of a closed-loop circular economy through urban mining. This model emphasizes systematic collection, intelligent sorting, and reintegration of secondary raw materials, reducing the dependency on primary extraction and aligning with the principles of sustainable resource management.

These transformations not only reduce dependency on primary extraction but also offer new avenues for increasing economic complexity in a truly sustainable way. However, as[28] warn, unless policy frameworks are designed to align environmental innovation with material sustainability, the green transition may become a “green illusion”—reducing emissions at one end while perpetuating unsustainable practices at the other.

In conclusion, the relationship between raw materials and green technologies is not just one of support and enabler—it is also one of *contradiction and constraint*. Addressing this paradox requires a multi-dimensional strategy: rethinking resource governance, innovating in material science, and ensuring that green growth does not come at the cost of ecological degradation and social inequity. The future of green technology, therefore, lies not only in its capacity to decarbonize production but also in its ability to *redefine how, where, and at what cost raw materials are obtained and used*.

5.6 Policy Recommendations for a Sustainable Raw Material Strategy in the Green Transition

The increasing dependence on raw materials for the deployment of green technologies presents both an opportunity and a systemic challenge for policymakers. To ensure that the green transition does not replicate the extractive and environmentally harmful models of past industrial transformations, a strategic and forward-looking approach is necessary. The following policy recommendations aim to reconcile the imperative of decarbonization with the realities of raw material constraints.

A crucial first step is to promote circular economy principles. Moving away from linear extraction-to-disposal models toward regenerative systems can reduce the environmental burden of raw material use. Governments must support initiatives that encourage the reuse, refurbishment, and recycling of critical raw materials—particularly those embedded in batteries, wind turbines, and electronic components. Investments in high-efficiency recycling systems, alongside the development of urban mining technologies, can significantly reduce dependence on primary extraction. Simultaneously, policies that mandate eco-design standards and product modularity can make products easier to disassemble and recycle, enabling smoother integration into closed-loop supply chains. Such policies not only reduce material waste but also increase resilience to supply shocks[32].

Second, it is essential to diversify global supply chains and increase transparency. The concentration of critical raw materials in a few geopolitical hotspots introduces significant risk. To mitigate this, states should foster new international partnerships, support domestic geological exploration, and enhance traceability systems through tools like blockchain and digital ledgers. This would help reduce overdependence on a single supplier, bolster resilience, and ensure more ethical sourcing practices.

Moreover, governments must strengthen environmental and social governance (ESG) standards in both domestic and international extraction processes. Ensuring robust environmental assessments, mine rehabilitation programs, and meaningful community engagement—particularly with Indigenous populations—will help address the social and ecological costs of mining. Establishing independent oversight, promoting certification schemes such as IRMA or Fairmined, and enforcing international labor and environmental standards will further ensure that raw material supply chains align with broader sustain-

ability goals.

In addition, strategic investments in green material substitution and innovation are urgently needed. Material science research can help develop alternatives to scarce or environmentally damaging raw materials—such as replacing lithium or cobalt in batteries with more abundant elements like sodium or magnesium. Public-private partnerships can accelerate the scaling of such technologies, while R&D subsidies and green innovation funds can catalyze the discovery of new materials and more efficient uses of existing ones[117].

Aligning industrial policy with raw material strategy is another vital element. This includes integrating critical raw material assessments into national innovation, energy, and manufacturing strategies. Governments should maintain strategic stockpiles, develop foresight tools for anticipating material bottlenecks, and ensure that national green technology roadmaps are consistent with long-term material availability and sustainability.

Lastly, the global nature of both climate change and resource extraction necessitates stronger international cooperation. The benefits of the green transition should be equitably shared, and its burdens should not be disproportionately imposed on resource-rich but vulnerable regions. Technology transfer mechanisms, shared sustainable mining standards, and inclusion of raw material governance in global climate negotiations—such as under the UNFCCC, G20, or SDG frameworks—are essential. A truly just green transition must ensure that the shift to renewable technologies does not replicate extractivist inequalities but instead fosters global solidarity, ethical stewardship, and long-term ecological balance[115].

To ensure that the green transition leads to genuine environmental and socio-economic sustainability, the role of raw materials must be fundamentally rethought. Without strategic interventions, the pursuit of decarbonization risks becoming entangled in new forms of environmental degradation, geopolitical tension, and social injustice. The path forward must reconcile green growth with material justice, ensuring that the transition does not merely shift the burden of environmental externalities onto the extractive margins of the global economy. Through holistic governance, scientific innovation, and equitable global collaboration, it is possible to construct a materially sound and ethically defensible foundation for the future of green technologies.

Chapter

Metodology

6.1 Data and Variables

This section presents the empirical component of the thesis, whose aim is to investigate the long-run relationship between economic complexity (ECI) and the imports of critical raw materials (CRM) across selected emerging economies. Building on the theoretical and institutional context developed in previous chapters, the empirical analysis applies panel cointegration techniques to assess whether increases in a country's economic complexity are systematically associated with higher demand for specific categories of raw materials, particularly those embedded in technologically advanced production. This exercise contributes to the broader understanding of the resource requirements underpinning economic diversification and industrial upgrading.

This study uses annual panel data covering the period from 1994 to 2017, originally collected for a broader set of 33 countries. However, our empirical analysis focuses on four emerging economies—South Korea, Mexico, Hungary, and Poland—which were selected based on the criterion that they exhibit a simultaneous and consistent increase in both the Economic Complexity Index (ECI) and imports of Critical Raw Materials (CRM) over time.

Although data for ECI and CRM imports were available for a larger group of countries, many entries—especially for earlier years—were missing, incomplete, or inconsistent across sources. Therefore, the 1994–2017 window was selected as it represents the longest continuous and complete period for which all relevant variables are available across the chosen countries. This ensures the robustness and comparability of the econometric analysis.

6.1.1 Dependent Variable: Economic Complexity Index (ECI)

The dependent variable in this analysis is the *Economic Complexity Index (ECI)*. ECI is a composite measure developed by the MIT Media Lab and the Harvard Growth Lab, designed to capture the amount of productive knowledge embedded in a country's export structure. It reflects both the diversity of a country's exports (how many different products it exports) and the ubiquity of those products (how many other countries are able to produce them).

ECI increases when a country exports a wide range of sophisticated, less ubiquitous

products—those typically associated with advanced capabilities and higher value-added production. It is widely used as a proxy for industrial development, technological capacity, and long-term economic potential.

In this study, ECI values are obtained from the *Atlas of Economic Complexity*. The data are provided on an annual basis and standardized to allow for cross-country comparison. Since the index includes both positive and negative values, we use the original (non-transformed) values for visualization, but apply natural logarithmic transformations where needed in regression analysis to stabilize variance and improve interpretability.

6.1.2 Independent Variables: CRM Imports per Unit of GDP

The main independent variables in this study are the imports of *Critical Raw Materials* (CRM), expressed as a ratio to GDP. This transformation controls for country size and enables meaningful comparison across economies and over time. CRM imports are selected based on their relevance to high-value manufacturing, industrial inputs, and strategic sectors tied to economic complexity.

To better capture sector-specific effects and material intensity, we analyze both the aggregate CRM import ratio and its disaggregated components, based on four product categories classified by the Harmonized System (HS) codes:

- HS25: Salt; sulphur; earths and stone; plastering materials, lime and cement
- HS26: Ores, slag and ash
- HS27: Mineral fuels, mineral oils and products of their distillation
- HS28: Inorganic chemicals

Each of these materials plays a different role in industrial production and economic upgrading. For example, HS27 relates to energy-intensive sectors, while HS28 is closely tied to high-tech manufacturing, electronics, and chemical processing.

The import values are expressed in current USD and normalized by annual GDP, sourced from *UN Comtrade* and the *World Bank*. All series are later transformed using natural logarithms to reduce skewness, stabilize variance, and allow for elasticity-based interpretation of regression coefficients.

The selection of HS25–28 as the focus for CRM imports is both economically and methodologically justified:

1. Relevance to Industrial Production:

These four HS chapters capture materials that are foundational to manufacturing, construction, energy, and advanced industrial processes—all of which are directly linked to a country's economic complexity.

2. Strategic Role in Economic Complexity:

- HS25 (e.g., lime, cement) is vital for construction and infrastructure, sectors that support industrial expansion.
- HS26 includes ores and slag, used in metallurgy and heavy industry, often marking the early stages of industrial upgrading.

- HS27 represents mineral fuels and oils—critical for powering complex production systems and enabling energy-intensive industries.
 - HS28 (inorganic chemicals) are used in high-tech, pharmaceutical, and electronic manufacturing, often associated with more sophisticated and less ubiquitous exports—thus closely tied to the rise in ECI.
3. Consistent Data Availability:
These four categories offer relatively complete and consistent annual import data across countries and over time, especially when compared to more granular or niche materials, which often suffer from reporting gaps.
4. Coverage of Broad Raw Material Spectrum:
Together, HS25–28 span a comprehensive range of input types—from basic construction materials to energy sources and technologically advanced inputs. This diversity supports a robust examination of how complexity and raw material dependence co-evolve.

6.1.3 Visual Inspection of Time Series

Before proceeding with formal statistical testing, we begin by visually examining the time series patterns of our main variables: the *Economic Complexity Index (ECI)* and the *imports of Critical Raw Materials (CRM)* per unit of GDP, both in aggregate and by specific subcategories (HS25–HS28).

This preliminary step is essential not only for exploring the long-term trends and volatility profiles of each variable but also for assessing whether they exhibit parallel evolution, which is a necessary condition for cointegration.

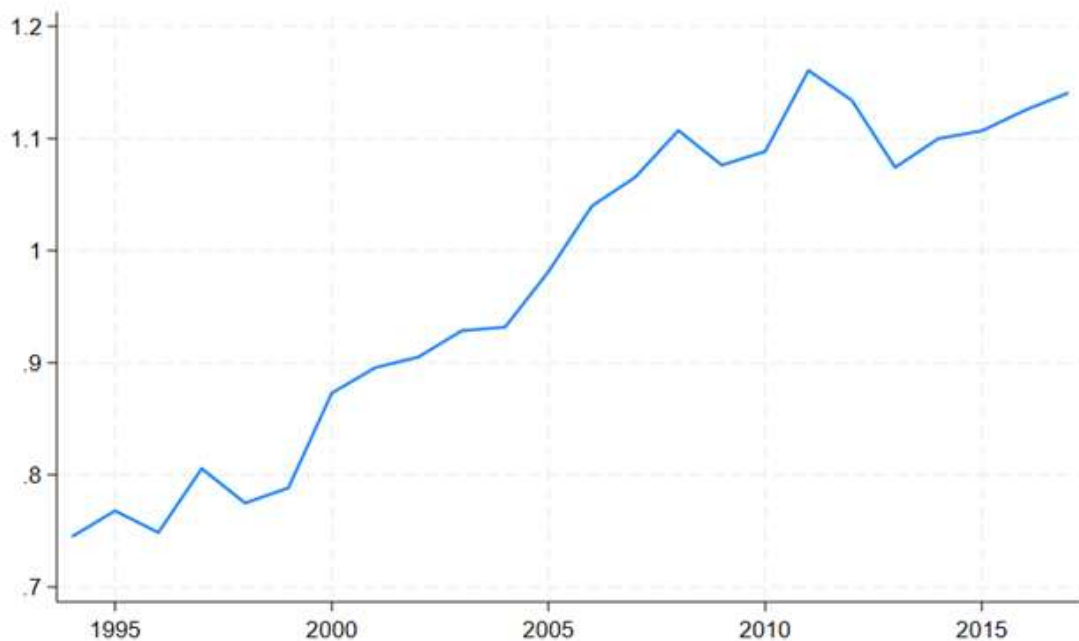


Figure 6.1: Economic Complexity Index (ECI), 1994–2016

The graph 6.1 illustrates the evolution of the *Economic Complexity Index (ECI)* over the period from 1994 to 2016 for one of the four emerging economies in our sample (South Korea, Mexico, Hungary, or Poland).

Key Observations:

- Overall upward trend: The ECI shows a steady and significant increase over the time period, moving from approximately 0.73 in 1994 to above 1.1 by 2016.
- Acceleration after 2000: The rate of increase becomes more pronounced after 1999, suggesting a period of structural transformation or intensified industrial diversification.
- Temporary volatility: There are minor fluctuations, notably around the years 2008–2010, likely corresponding to the global financial crisis. Despite this, the index quickly recovers and continues its upward path.
- Stabilization and maturity: Post-2012, the growth moderates, potentially indicating a saturation in complexity growth or a period of consolidation in export capabilities.

Interpretation: This trend suggests increasing sophistication in the export structure of the country, with a shift toward more complex, knowledge-intensive products. The rise in ECI reflects improvements in productive knowledge and capability embedded in the country's economy, consistent with the hypothesis that economic complexity grows alongside development and diversification.

This upward movement also provides supporting evidence for a non-stationary series, which will be formally tested using unit root tests (e.g., ADF). If raw material imports exhibit a similar upward trend, it would strengthen the basis for conducting cointegration analysis.

Figure 6.2 shows the time series for imports of *Critical Raw Materials (CRM)*—specifically HS codes 25 to 28—per unit of GDP for the same country depicted in Figure 6.2, spanning the years 1994 to 2017.

Key Observations:

- Volatility: Unlike the smoother trend observed in ECI, CRM imports exhibit substantial year-to-year variation, particularly after 2005.
- Upward Trend until 2011: From the late 1990s to 2011, CRM imports generally increased, peaking at over 80 units per GDP.
- Sharp Decline After 2011: Post-2011, a steep and sustained decline is observed until around 2015, after which a modest rebound occurs.
- Short-term Spikes: Abrupt increases and drops, notably in 2007–2009 and again in 2011, are likely influenced by global commodity cycles or domestic industrial shocks.

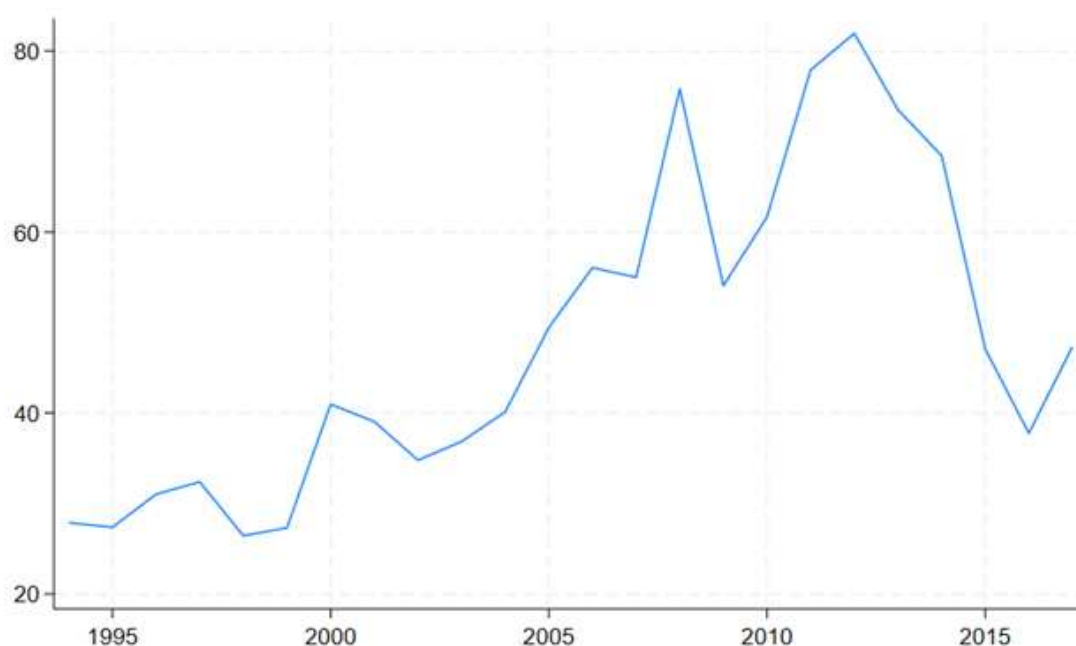


Figure 6.2: Imports of CRM (HS25–28) per Unit of GDP, 1994–2017

Methodological Implication: Despite the volatility, the CRM import series also suggests the presence of a stochastic trend, possibly indicating non-stationarity. This reinforces the need to apply formal unit root testing. If both ECI and CRM imports are found to be integrated of order one, $I(1)$, then we proceed with cointegration analysis to examine whether a long-run equilibrium relationship exists between the two.

Furthermore, the pattern justifies the use of *Dynamic Ordinary Least Squares (DOLS)* in the regression phase, as this technique adjusts for short-term fluctuations—such as price shocks and demand volatility—while estimating the long-run cointegration vector.

Figure 6.3 presents the evolution of HS25 imports, a disaggregated component of CRM, measured per unit of GDP from 1994 to 2017. This series shows a distinctly different dynamic compared to total CRM imports.

Key Observations:

- **Declining Trend (1994–2005):** The series shows a steady decline from approximately 1.25 in 1994 to 0.85 in 2005, likely reflecting an increase in domestic production capacity or substitution effects in construction materials.
- **Extreme Volatility Post-2008:** A sharp spike in 2009 (reaching nearly 1.3) is followed by a sudden drop to below 0.8, suggesting a shock possibly tied to post-crisis infrastructure investment or price fluctuations.
- **Post-crisis Stabilization:** From 2011 onward, values stabilize between 0.85 and 0.9, suggesting a new structural baseline in import behavior.

Methodological Implication: This figure emphasizes the importance of analyzing sub-categories of raw materials, as aggregate CRM trends may mask divergent behaviors

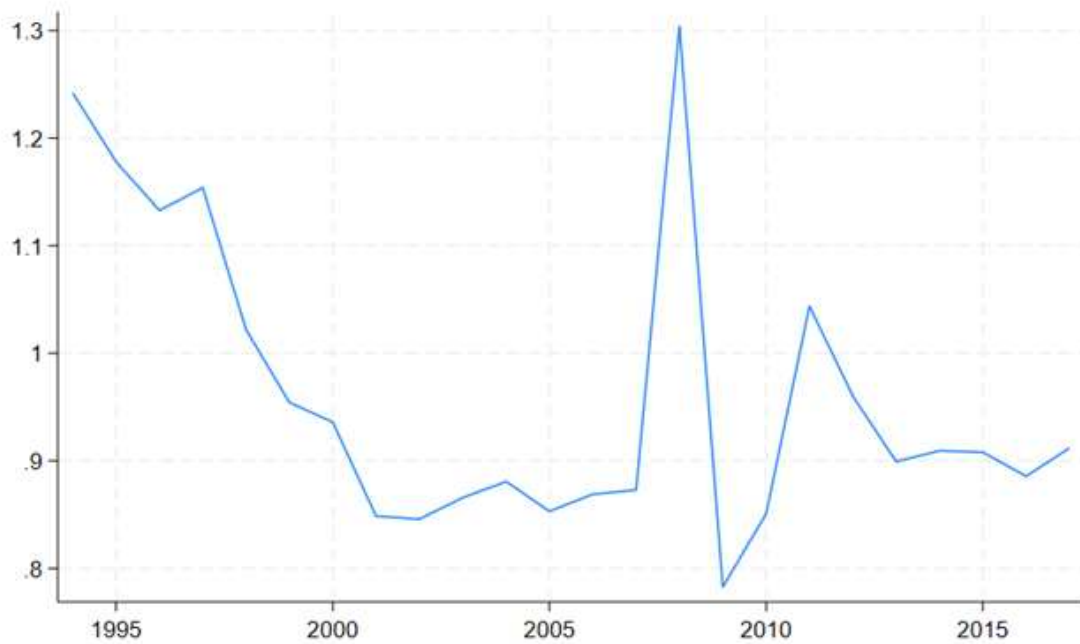


Figure 6.3: Imports of HS25 (Construction Materials)

within constituent goods. Despite the volatility, the underlying decline and post-shock stabilization suggest potential non-stationarity, warranting unit root tests for HS25 specifically.

Furthermore, the sharp break in 2009–2010 could imply a structural break, which should be accounted for in the cointegration framework (e.g., with dummy variables or the Gregory-Hansen test for cointegration with structural breaks). This ensures robustness in estimating long-run relationships between disaggregated imports and economic complexity.

Figure 6.4 illustrates the trend in imports of HS26 products—specifically ores, slag, and ash—as a share of GDP over the period 1994 to 2017. These materials are core inputs in heavy industry and metallurgy, making their import behavior particularly relevant for analyzing industrial complexity.

Key Observations:

- **Stable Low Plateau (1994–2003):** From 1994 to around 2003, the imports of HS26 remained relatively flat and low, hovering around 1.1–1.4 units per GDP.
- **Sharp Growth Phase (2003–2011):** Beginning in 2004, the import intensity increased rapidly, peaking at nearly 3.9 in 2011. This may reflect industrial expansion or increased reliance on imported ores due to depletion of domestic sources.
- **Volatile Decline (2012–2016):** After reaching a peak, the values dropped sharply—first in 2012, and again in 2015—before a mild recovery in 2017.
- **Cyclical Pattern:** The series suggests cyclical dynamics, possibly aligned with global commodity price cycles or trade policy shifts.

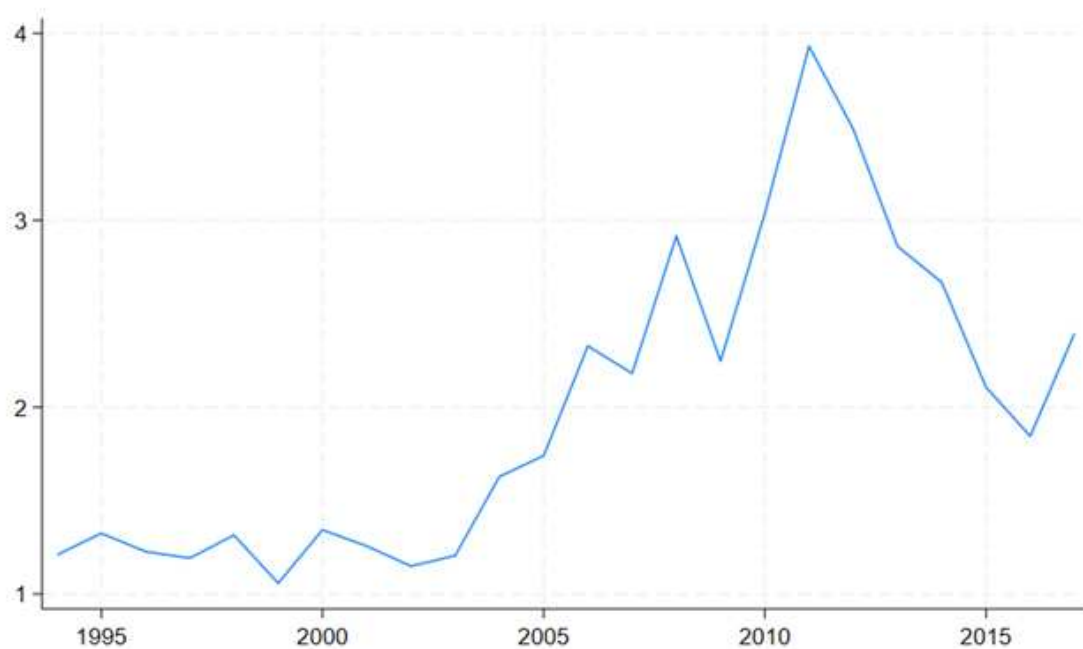


Figure 6.4: Imports of HS26 (Ores, Slag and Ash)

Methodological Implication: This subseries exhibits a clear non-linear trend with structural shifts, suggesting the likely presence of non-stationarity and potential structural breaks. These characteristics make a strong case for applying unit root testing with break points (e.g., Zivot-Andrews or Perron tests) and motivate the use of cointegration methods that accommodate regime changes (e.g., Gregory-Hansen test).

Additionally, the steep mid-2000s rise aligns chronologically with increases in economic complexity (see Figure ??), hinting at possible co-movement, which we assess formally through Johansen or Engle-Granger cointegration tests in the following section.

Figure 6.5 depicts the trend in HS27 imports—chiefly mineral fuels and oils—measured relative to GDP over the period 1994 to 2017.

Key Observations:

- Long-term upward trend (1994–2012): The series shows a consistent increase, rising from approximately 23 in 1994 to a peak of nearly 75 by 2012. This mirrors both growing industrial energy demand and possibly rising global fuel prices.
- Notable fluctuations:
 - A sharp spike in 2009, possibly driven by post-crisis inventory effects or commodity price volatility.
 - A major correction after 2012, dropping to around 35 by 2016, possibly due to a combination of falling global oil prices and domestic energy substitution policies.
- Partial recovery (2016–2017): The final uptick suggests a rebound, but the trend remains more volatile than in previous years.

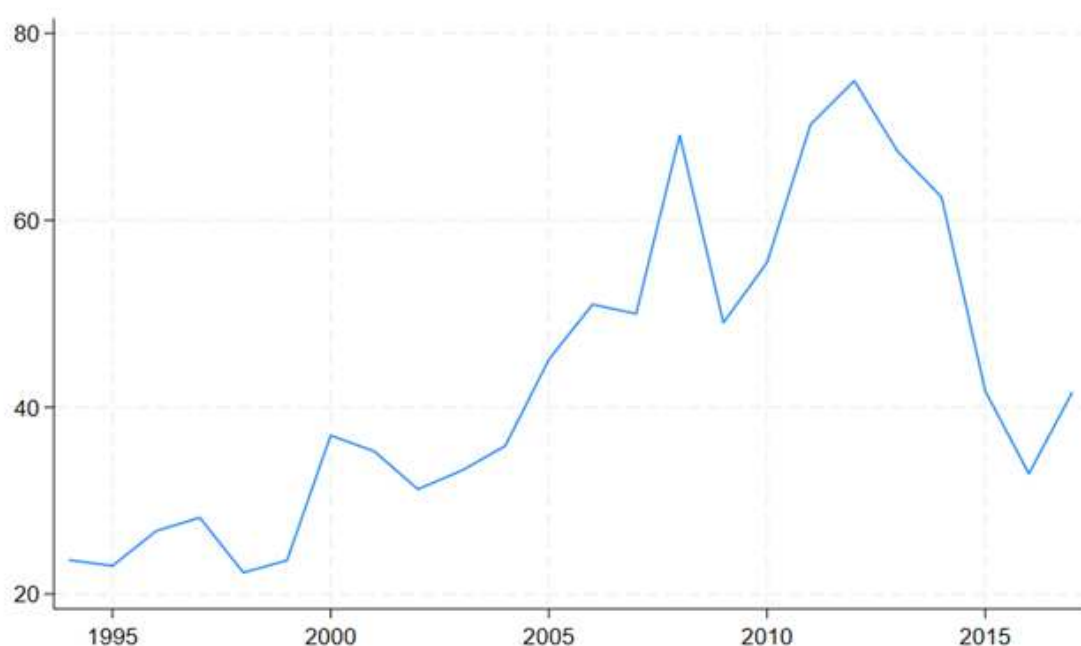


Figure 6.5: Imports of HS27 (Fuels and Oils)

Methodological Implication: This sub-series shows strong evidence of non-stationarity, consistent with commodity-related trade flows. The co-movement with global price shocks and the non-linear response to GDP growth underscore the need for both unit root tests and models that allow for structural breaks or nonlinear adjustments.

Given its centrality to industrial production and export capacity, HS27 is likely to be closely related to Economic Complexity (ECI) in emerging economies. Its dynamic pattern strengthens the rationale for using cointegration analysis, and in the estimation stage, Dynamic Ordinary Least Squares (DOLS) will capture short-run dynamics (lags/leads) and possible endogeneity between energy imports and economic diversification.

This series captures the trend of inorganic chemical imports, which includes products such as industrial gases, halogens, acids, alkalis, and chemical catalysts. These substances are crucial inputs in industries like electronics, pharmaceuticals, semiconductors, energy, fertilizers, and precision manufacturing—sectors that are often deeply connected to economic complexity.

Observed Trend:

1. 1994–2003: Mild fluctuations, overall stagnation

The ratio hovers between 1.6 and 1.9, showing no consistent upward momentum. This suggests that in this early stage, the country's industrial structure may have been either less chemical-intensive or more reliant on domestic supply.

2. 2004–2011: Rapid growth and volatility

This period marks a significant upward phase, with the import ratio rising from below 1.8 to over 2.5, peaking in 2011. The growth appears non-linear, with a sharp spike in 2008 followed by a drop in 2009, and another steep rise in 2010–2011.

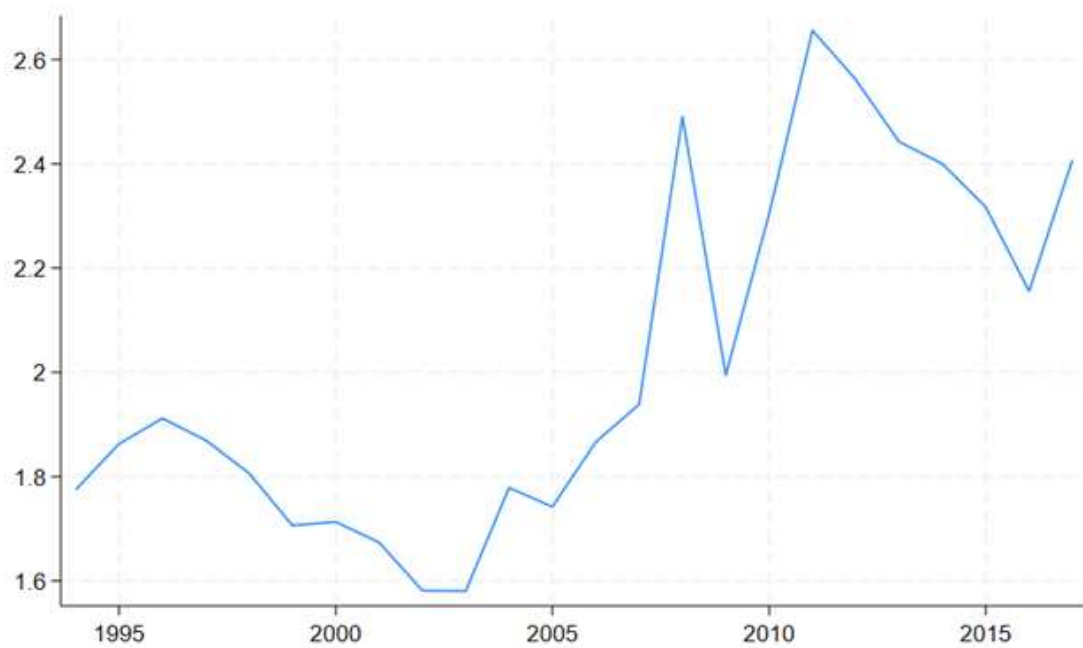


Figure 6.6: Imports of HS28 (Inorganic Chemicals)

Possible explanations:

- Entry into higher-tech industrial segments requiring more specialized chemicals.
 - Structural reforms or trade liberalization increasing reliance on foreign chemical inputs.
 - Global trends in electronics or clean energy sectors boosting demand.
3. 2012–2016: Correction and rebalancing
After reaching a peak, the import ratio gradually declines, reflecting:
- A slowdown in certain industries.
 - Price changes or substitution effects.
 - Efficiency improvements in industrial chemical usage.
4. 2017: Noticeable rebound
The series rebounds toward 2.4, possibly indicating a renewed phase of industrial activity, recovery from prior shocks, or increased investment in sectors like pharmaceuticals or semiconductors.

Interpretation and Relevance to ECI:

- HS28 imports appear to track phases of technological upgrading, making them a strong candidate for cointegration with ECI.
- The cyclical but upward-trending nature of the series supports the idea that rising economic complexity is associated with increased reliance on chemical inputs.

- Unlike HS25 or HS26, which show saturation or structural decline, HS28 continues to respond dynamically to economic developments.

Econometric Implication:

- The visible trend and cycles suggest the series is non-stationary and likely integrated of order one (I(1)).
- Its behavior aligns conceptually with ECI, making it the most likely CRM component to exhibit long-run cointegration.
- Given the volatility around 2008–2011, it may also benefit from modeling with short-run dynamics (e.g., DOLS) and even structural break adjustments.

Summary: Taken together, the figures show that:

- ECI and CRM imports (especially HS28) may be linked in the long run.
- All series exhibit signs of non-stationarity, supporting the need for unit root testing.
- Some CRM subcategories (e.g., HS26, HS27) display structural breaks or strong short-term volatility, calling for robust cointegration techniques.
- Visual inspection is consistent with a cointegrated system, but formal tests are needed to confirm direction, strength, and significance.

The next sections apply CIPS panel unit root tests to verify integration order, followed by Westerlund’s cointegration test and Dynamic OLS regressions to estimate long-run relationships.

6.2 Unit Root Testing

Before estimating any long-run relationship between variables using cointegration techniques, it is essential to determine the time series properties of those variables. Specifically, we need to check whether the variables are stationary or non-stationary.

A *stationary series* fluctuates around a constant mean and variance, while a *non-stationary series* contains a unit root, meaning its statistical properties change over time and shocks have permanent effects. If non-stationary variables are used in regression without cointegration, it can lead to spurious results.

In the context of this study, both the Economic Complexity Index (ECI) and CRM import variables are expected to exhibit non-stationary behavior, as shown by the visual inspection in Section 4.2. However, this must be formally verified using unit root tests.

We employ the Cross-sectionally Augmented Im, Pesaran, and Shin (CIPS) test developed by Pesaran (2007), for several important reasons:

1. Panel data structure: Our dataset includes multiple countries ($N = 4$) over multiple time periods ($T = 24$), forming a panel.

2. Cross-sectional dependence: Economic time series for countries are often correlated due to shared global shocks, trade links, or policy spillovers. Traditional panel unit root tests (e.g., Levin-Lin-Chu) assume independence, which can lead to misleading conclusions.
3. CIPS test advantage: CIPS addresses this issue by incorporating the cross-sectional averages of the series into the testing equation, capturing common stochastic trends.

Test Procedure

- Null hypothesis (H_0): All series are non-stationary (contain a unit root).
- Alternative hypothesis (H_1): At least some of the series are stationary.
- The test is performed for the following variables:
 - Economic Complexity Index (ECI)
 - Aggregate CRM imports (HS25–28) per GDP
 - Four disaggregated CRM categories: HS25, HS26, HS27, HS28

We conduct the test in two forms:

- Level form: Includes a constant and linear trend, suitable for trending variables like ECI.
- First-difference form: Includes a constant only, as trends are removed through differencing.

Results and Critical Values

The results are summarized in table below.

- At levels: None of the CIPS test statistics exceed the critical threshold (e.g., -2.76 at 10% significance). Therefore, we fail to reject the null of a unit root $\Rightarrow$ all series are non-stationary in levels.
- At first-difference: All test statistics are well below the 1% critical value (e.g., -2.51), and statistically significant. We reject the null, confirming that the differenced series are stationary.

Table 6.1: Panel unit root test (Pesaran 2007)

Panel A: ECI		CIPS
<i>Levels (c, t)</i>	ECI	-2.693
<i>First differences (c)</i>	Δ ECI	-4.093***
Panel B: Import CRM/GDP		CIPS
<i>Levels (c, t)</i>	$\ln$ CRM/GDP	-2.744
	$\ln$ HS25/GDP	-1.948
	$\ln$ HS26/GDP	-2.540
	$\ln$ HS27/GDP	-2.751
	$\ln$ HS28/GDP	-2.329
<i>First differences (c)</i>	$\Delta \ln$ CRM/GDP	-5.079***
	$\Delta \ln$ HS25/GDP	-5.208***
	$\Delta \ln$ HS26/GDP	-4.559***
	$\Delta \ln$ HS27/GDP	-5.173***
	$\Delta \ln$ HS28/GDP	-4.658***

Notes: All the tests with variables in levels include an intercept and a linear trend. All the tests with variables in first differences include only a constant. The 10%, 5%, and 1% critical values are -2.76, -2.94, and -3.3, with an intercept and a trend, and -2.12, -2.25, and -2.51 with only a constant.

*** denotes significance at the 1% level.

How the Westerlund Test Works

The Westerlund test is based on the following error correction model (ECM), estimated for each country i :

$$\Delta y_{it} = \alpha_i + \delta_i(y_{i,t-1} - \beta_i x_{i,t-1}) + \sum_k \gamma_{ik} \Delta y_{i,t-k} + \sum_k \theta_{ik} \Delta x_{i,t-k} + \varepsilon_{it} \quad (6.1)$$

Where:

- y_{it} is the dependent variable (e.g., CRM imports),
- x_{it} is the independent variable (e.g., ECI),
- δ_i is the error-correction coefficient, which is the key parameter of interest.

Interpretation:

- If $\delta_i < 0$, the system adjusts back toward a long-run equilibrium after a deviation—this indicates cointegration.
- The null hypothesis (H_0): no cointegration, i.e., $\delta_i = 0$ for all i .
- The alternative hypothesis (H_1): at least one country is cointegrated, i.e., $\delta_i < 0$ for at least one i .

Westerlund provides several test statistics. This study uses the Group-mean statistics (Gt and Ga), which are well-suited when cointegration is not assumed to be homogeneous across countries and when dynamics vary across panel units.

Application to Our Panel

We implement the Westerlund test in two stages:

1. Aggregate relationship:
 - ECI vs. total CRM imports per GDP
2. Disaggregated relationships:
 - ECI vs. HS25 imports
 - ECI vs. HS26 imports
 - ECI vs. HS27 imports
 - ECI vs. HS28 imports

Each test includes:

- Country-specific intercepts and deterministic trends to account for idiosyncratic paths.
- Automatic lag/lead selection based on the Akaike Information Criterion (AIC) to address serial correlation.
- Bootstrapped p-values to improve accuracy given the small panel size.

Interpretation:

- If the null hypothesis is rejected, it provides strong statistical evidence that at least one panel unit exhibits cointegration between ECI and the relevant CRM import variable.
- This supports the hypothesis that growing economic complexity is structurally linked to sustained demand for raw materials, especially technologically relevant inputs (e.g., HS28).
- If cointegration is not found in certain subcategories (e.g., HS25), this may reflect sectors that are decoupling from complexity (e.g., construction becoming less central in advanced economies).

The results of these tests are presented in the next section, followed by long-run elasticity estimates using the *Dynamic Ordinary Least Squares (DOLS)* technique.

6.2.1 Westerlund (2005) Cointegration Test: Theoretical Foundation

The cointegration analysis in this study is based on the methodology introduced by Westerlund (2005), who developed new and intuitive tests for detecting panel cointegration. Specifically, we implement the group-mean variance-ratio (VR) test as proposed in his seminal work:

Westerlund, J. (2005). New simple tests for panel cointegration. *Econometric Reviews*, 24(3), 297–316.

This test is designed to evaluate whether a long-run equilibrium relationship exists between two or more non-stationary panel variables—in our case, between the Economic Complexity Index (ECI) and imports of Critical Raw Materials (CRM). It is particularly suited for settings in which cointegration may be present in only a subset of the cross-sectional units (countries).

Panel-Specific Features In our implementation, the cointegrating regression model includes both panel-specific intercepts (fixed effects) and deterministic time trends. This allows for country-level heterogeneity in both level and trend behavior, which is essential given the diverse industrial and economic trajectories of the four countries in our dataset (South Korea, Mexico, Hungary, and Poland).

Null and Alternative Hypotheses The null hypothesis of the Westerlund VR test is that there is no cointegration among the panel units:

- H_0 : No cointegration for any panel unit ($\delta_i = 0 \forall i$).
- H_1 : Cointegration exists for at least one panel unit ($\delta_i < 0$ for some i).

Error Correction and Estimation Strategy The group-mean VR statistic is derived from a panel error-correction model (ECM) in which the autoregressive (AR) parameter in the Dickey-Fuller regressions is allowed to vary across panels. This formulation improves the flexibility and robustness of the test when panel units do not follow identical dynamic processes.

The test compares three different estimators of the long-run cointegrating relationship:

1. Ordinary Least Squares (OLS)
2. Fully Modified OLS (FMOLS)
3. Dynamic OLS (DOLS)

Under the assumption of cointegration, both FMOLS and DOLS yield consistent estimators, even in the presence of endogeneity and serial correlation. In contrast, OLS is generally biased and inconsistent when cointegration is present. The test thus measures the deviation of the OLS estimator from FMOLS and DOLS. If these differences are statistically large, it suggests the absence of cointegration; if they are small, the test supports the presence of a stable long-run equilibrium relationship.

Limitations and Interpretation It is important to note that this is a first-generation panel cointegration test, meaning it assumes cross-sectional independence across panel units. While the small number of countries ($N = 4$) in this study may reduce the severity of this limitation, it is nonetheless important to interpret results with caution. If substantial cross-sectional dependence is suspected (e.g., due to global shocks or synchronized macroeconomic trends), more advanced second-generation panel cointegration tests could be considered as a robustness check.

6.2.2 Residual-Based Panel Cointegration Framework

Cointegration refers to a long-run equilibrium relationship between two non-stationary variables, typically integrated of order one, $I(1)$. Westerlund (2005) examines the presence of cointegration in panel settings using the following cointegrating model:

$$y_{it} = \alpha_i + \beta_i x_{it} + u_{it} \quad (6.2)$$

This represents the long-run relationship between y_{it} and x_{it} for each cross-sectional unit (country) i .

Step 1: Estimate the Cointegrating Residuals To test for cointegration, residuals from the cointegrating relationship are computed as:

$$\hat{u}_{it} = y_{it} - \alpha_i - \beta_i x_{it} \quad (6.3)$$

Step 2: ADF Regression on Residuals Next, the residuals are tested for stationarity using an augmented Dickey-Fuller (ADF) type regression:

$$\Delta \hat{u}_{it} = \rho_i \hat{u}_{i,t-1} + \sum_j \gamma_{ij} \Delta \hat{u}_{i,t-j} + \varepsilon_{it} \quad (6.4)$$

Where:

- ρ_i is the autoregressive coefficient for unit i ,
- The null hypothesis $H_0 : \rho_i = 0$ (no cointegration),
- The alternative hypothesis $H_1 : \rho_i < 0$ (cointegration exists for at least one unit).

The Westerlund Group-Mean Variance-Ratio (VR) statistic aggregates evidence across units. It provides a formal test of the Engle-Granger two-step logic in panel data settings:

1. Estimate the long-run relationship between y and x ,
2. Test whether the residuals are stationary. If they are, y and x are cointegrated.

Assumptions of the Test:

- No cross-sectional dependence (i.e., a first-generation test),
- Large time dimension ($T \rightarrow \infty$) relative to the cross-section (N),
- DOLS is assumed to be a consistent estimator under cointegration.

Table: Panel Cointegration Test (Westerlund, 2005)

The Westerlund (2005) panel cointegration test evaluates whether a long-run equilibrium relationship exists between two non-stationary variables—here, the Economic Complexity Index (ECI) and various CRM import measures. The test is based on error-correction dynamics and produces Group-mean G_t statistics. More negative G_t values indicate stronger statistical evidence of cointegration.

Table 6.2: Panel Cointegration Test (Westerlund, 2005)

Panel A	at least one
ECI $\rightarrow$ lnCRM/GDP	-1.148
lnCRM/GDP $\rightarrow$ ECI	-0.934
ECI $\rightarrow$ lnHS25/GDP	1.545*
lnHS25/GDP $\rightarrow$ ECI	-1.431*
ECI $\rightarrow$ lnHS26/GDP	0.202
lnHS26/GDP $\rightarrow$ ECI	-1.207
ECI $\rightarrow$ lnHS27/GDP	-0.535
lnHS27/GDP $\rightarrow$ ECI	-0.957
ECI $\rightarrow$ lnHS28/GDP	1.714**
lnHS28/GDP $\rightarrow$ ECI	-0.776

Note: *, ** indicate significance at the 10% and 5% levels, respectively.

Interpretation of Cointegration Results The strongest evidence of cointegration is found in the direction from ECI to HS28 imports (inorganic chemicals and rare Earth metals), where the group-mean G_t statistic is statistically significant at the 5% level. This supports the hypothesis that rising economic complexity leads to increased imports of rare Earth materials, but not vice versa.

- For HS25 (salt, sulfur, earths, and stone), both directions show weak evidence of cointegration at the 10% level. This suggests a marginal and potentially bi-directional long-run relationship, although it is not statistically robust.
- For HS26 (ores, slag, and ash) and HS27 (mineral fuels, oils, etc.), no cointegration is detected in either direction. This indicates an absence of long-run equilibrium between these inputs and economic complexity over the observed period.

To estimate the magnitude of the long-run relationship, we apply the *Dynamic Ordinary Least Squares (DOLS)* method. This technique accounts for fixed effects across panel units and uses lead-lag differencing to control for endogeneity and serial correlation. DOLS allows us to compute elasticity coefficients, representing the percentage change in CRM imports associated with a one-unit change in ECI.

Table 6.3: DOLS Regressions

Dep. Var.	(1) HS28	(2) HS25	(3) ECI
ECI	0.461***	0.074	0.352
ln(HS25/GDP)	(0.041)	(0.130)	(1.194)
Demeaned data	Yes	Yes	Yes
FE	Yes	No	Yes
Adjusted R^2	0.89	0.92	0.36
N. obs.	93	93	93
Lags	1	1	1
Leads	1	1	1

Notes: Standard errors are reported in parentheses. FE = Fixed Effects.

*** Significant at 1% level; ** significant at 5% level.

Interpretation of DOLS Regression Results

- In Column (1), the coefficient on ECI is 0.461, which is positive, statistically significant at the 1% level, and economically meaningful. This implies that as countries become more economically complex, their demand for HS28 (inorganic chemicals and rare Earth metals) increases substantially.
 - A one-unit increase in ECI is associated with a 46.1% increase in HS28 imports per unit of GDP.
 - Alternatively, a one-standard deviation increase in ECI leads to an estimated 40% increase in HS28 imports.
- In Column (2), the coefficient on ECI for HS25 is not statistically significant. This suggests that economic complexity does not drive increased imports of basic mineral materials like salt, sulfur, or stone (HS25).
- In Column (3), reversing the causal direction—by using CRM imports to predict ECI—yields no statistically significant results. This reinforces the idea that causality runs from ECI to HS28, not the other way around.

Summary of Findings The combined results from the Westerlund cointegration test and DOLS regressions strongly support a Granger-type causality flowing from Economic Complexity (ECI) to HS28 imports. There is no evidence that higher imports of rare Earth materials directly contribute to greater economic complexity.

- These findings suggest that as economies become more diversified and technologically advanced, they increase their demand for inputs like rare Earths, which are critical for high-tech sectors such as electronics, batteries, semiconductors, and green technologies.
- Simply increasing imports of such materials, however, is not sufficient to generate complexity. Structural productive capabilities must precede demand for advanced raw materials.

- The lack of significant long-run relationships between ECI and HS25–HS27 highlights that not all raw materials are equally important for complex economic development. Only those tied to high-tech value chains (e.g., HS28) exhibit robust linkage.

Policy Implication From a policy standpoint, these results underscore the importance of securing long-term access to rare Earth elements. For emerging economies aiming to climb the economic complexity ladder, stable and affordable supply chains for strategic materials like HS28 are essential for sustaining technological advancement and industrial competitiveness.

Final Comment Overall, the results confirm that a higher ECI causes a higher import of HS28 (rare metals) per unit of GDP. Specifically, a one-standard deviation increase in ECI corresponds to an estimated 40% rise in rare Earth imports. The analysis rules out the possibility that greater imports of HS28 cause higher ECI. For HS25, the DOLS regressions confirm that the estimated coefficients are not statistically different from zero, implying no long-run relationship.

Chapter

Conclusion

7.1 Research Question and Purpose

This thesis has explored the long-term relationship between the Economic Complexity Index (ECI) and the imports of Critical Raw Materials (CRMs), aiming to uncover whether increasing economic sophistication drives rising dependence on specific categories of raw materials. The central research question guiding this analysis asked: *Does a rise in economic complexity, as captured by ECI, lead to a greater reliance on imports of CRMs, and if so, are these effects uniform across all raw material types or concentrated in technologically critical subcategories?*

The motivation for this inquiry stems from growing policy concerns about strategic autonomy and the security of raw material supply chains in an increasingly digital and interconnected global economy. As many nations pursue industrial upgrading and green technological transitions, understanding the resource demands of complex economic structures becomes imperative. This study, therefore, sought to make a dual contribution: empirically, by testing the cointegration and causal relationships between ECI and CRM imports using panel econometric methods, and theoretically, by connecting economic complexity theory to structural dependency on material inputs.

7.2 Summary of Key Findings

Through a series of robust empirical exercises, this thesis has identified a significant and directionally meaningful relationship between economic complexity and CRM imports. The Westerlund (2005) panel cointegration test provided compelling evidence of a long-run equilibrium relationship between ECI and the import of HS28 commodities, which consist of rare Earth elements. The test results were statistically significant in the direction from ECI to HS28 imports, but not in the reverse, suggesting that economic complexity is a driver—rather than a consequence—of rare metal demand.

This conclusion was further reinforced by the application of Dynamic Ordinary Least Squares (DOLS) estimation. The long-run elasticity estimates revealed that a one-unit increase in ECI corresponds to a 46.1% increase in HS28 imports per unit of GDP, while a one-standard deviation increase in ECI leads to an approximate 40% rise in rare Earth material imports. These findings confirm the hypothesis that rare Earth metals are central to the functioning of complex economies. In contrast, other CRM categories such as

HS25 (salt, sulfur, earths and stone), HS26 (ores, slag and ash), and HS27 (mineral fuels, oils) exhibited no significant cointegration with ECI, suggesting that their role in high-complexity production systems is comparatively marginal.

These results provide empirical backing to the broader theoretical assertion that economic development is increasingly tied to the consumption of technologically relevant raw materials. As countries evolve from agriculture and basic manufacturing toward advanced manufacturing and digital services, the structure of their material demand transforms in tandem. The evidence gathered here supports the notion that complexity not only involves an expansion of productive knowledge but also generates structural dependencies on finite and geopolitically sensitive inputs.

7.3 Theoretical and Practical Implications

Theoretically, this thesis contributes to an emerging literature that links development and economic complexity to material resource use. By grounding the analysis in the framework of the ECI and panel cointegration, the study confirms that the evolution of technological capabilities is not resource-neutral. Rather, as shown by Li et al. (attached in the supervisor's comments), technological advancement, particularly in digital domains, increases reliance on a narrow set of CRMs. This confirms the material basis of knowledge-intensive growth: economies that aim to move up the value chain must do so with greater input intensity in rare and specialized materials.

This material dependency has far-reaching implications. From a policy standpoint, it raises concerns about supply chain vulnerabilities and strategic autonomy. The European Union's recent initiatives, such as the Critical Raw Materials Act and ongoing discussions around economic sovereignty, highlight how advanced economies are beginning to internalize the material prerequisites of industrial upgrading. The findings in this thesis provide empirical weight to these concerns by demonstrating that rising complexity indeed correlates with increased import dependence on scarce CRMs.

Practically, the results underscore the urgency of diversifying CRM sources and investing in recycling and substitution technologies. If the trajectory toward economic complexity inherently increases demand for rare inputs, nations lacking domestic reserves will face heightened geopolitical and economic risks. Moreover, for developing countries aspiring to become complex economies, access to these materials will be a necessary—though potentially constraining—condition for industrial advancement.

7.4 Limitations of the Study

While this study presents a robust analysis grounded in contemporary econometric techniques, it is not without limitations. One notable constraint is the panel structure of the dataset, consisting of only four countries—Hungary, Mexico, Poland, and South Korea. Although these countries were selected for their relevance to the European trading system and their diverse positions in the global economy, the limited cross-sectional dimension reduces the generalizability of the findings.

Furthermore, the study relies on HS code classifications to delineate CRM categories, which, while precise in trade accounting, may obscure more granular variations in mate-

rial use across industries. For instance, some critical raw materials may appear in different subcategories or be embedded in complex manufactured products in ways that standard trade data cannot fully capture.

Another limitation relates to the cointegration methodology itself. Although the West-erlund test is well-suited for small panels with medium time series dimensions, the results are sensitive to assumptions about cross-sectional independence. Given increasing global integration, future studies could employ second-generation panel cointegration tests that allow for cross-sectional dependence to test the robustness of the findings.

7.5 Suggestions for Future Research

Future research could address several of these limitations and expand upon the current analysis. A natural extension would be to include a larger and more diverse panel of countries, including emerging economies with varying degrees of economic complexity. Such an expansion would allow for a more nuanced understanding of whether the observed relationship between ECI and CRM imports holds across different development trajectories.

Moreover, integrating patent data or innovation indices into the empirical framework could offer deeper insights into the mechanisms linking technological advancement to material dependence. For example, it would be valuable to examine whether specific innovation domains (e.g., green energy, digital infrastructure) are more tightly coupled to CRM demand.

Additionally, future research could explore the role of CRM policies in mediating the ECI–CRM relationship. How do domestic policies on resource security, recycling, or international trade agreements influence this dynamic? Incorporating policy variables or event studies could help disentangle the institutional factors that shape the strategic responses of countries to raw material dependencies.

Finally, further work could investigate the feedback loop between CRM dependence and economic complexity. While this study has emphasized the unidirectional causality from ECI to CRM imports, future work could explore potential long-term bidirectional effects, including whether CRM access constraints might eventually inhibit complexity growth.

In conclusion, this thesis has shown that the path to economic sophistication is deeply interwoven with material realities. As nations pursue ambitious development agendas and technological leadership, securing access to critical raw materials will remain a foundational—if often underappreciated—challenge.

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