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affiliée à l'Université de Montréal

**GeoPolRisk Assessment of Critical Minerals
in Canada's Battery Supply Chain**

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Mémoire présenté en vue de l'obtention du diplôme de *Maîtrise ès sciences appliquées*

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présenté par **Irune Maria Eva ECHEVARRIA GONZALEZ**

en vue de l'obtention du diplôme de *Maîtrise ès sciences appliquées*

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DEDICATION

This work is lovingly dedicated to my parents, who have been the beacon of inspiration and fortitude in my life. Your unwavering support and encouragement have been the pillars upon which I have built my dreams. I am forever grateful for your love, wisdom, and the sacrifices you have made for my growth. I would also like to extend my heartfelt appreciation to Sophie and the many people who have stood by me throughout this journey. Your kindness, encouragement, and belief in my capabilities have been instrumental in the completion of this endeavor. Without your understanding and profound empathy, I would not be here.

RÉSUMÉ

Alors que le Canada s'oriente vers les énergies renouvelables, il est confronté à d'éventuelles ruptures d'approvisionnement en minéraux essentiels pour les batteries au lithium-ion, en raison de leur distribution mondiale inégale et de la complexité de la géopolitique. Cette étude évalue ces risques géopolitiques à l'aide d'une méthode GeoPolRisk améliorée qui inclut des facteurs environnementaux, sociaux et de gouvernance (ESG). Cet outil offre une perspective globale sur les risques géopolitiques, en intégrant à la fois les paramètres traditionnels et les considérations ESG. La recherche introduit une nouvelle analyse des indices de saturation de la production et des exportations d'un pays et préconise de passer d'une perspective de concentration de la production à une perspective de concentration des exportateurs à l'aide de l'indice Herfindahl-Hirschman. Étant donné que les pays, y compris le Canada, dépendent de plus en plus de ces minéraux essentiels, les conclusions de cette étude éclairent les stratégies de gestion des risques géopolitiques et d'atténuation des perturbations potentielles de la chaîne d'approvisionnement en minéraux essentiels.

ABSTRACT

As Canada pivots towards renewable energy, it grapples with potential supply disruptions of critical minerals essential for lithium-ion batteries due to their uneven global distribution and complex geopolitics. This study assesses these geopolitical risks using an enhanced GeoPolRisk method that includes Environmental, Social, and Governance (ESG) factors. This tool offers a comprehensive perspective on geopolitical risks, incorporating both traditional parameters and ESG considerations. The research introduces a novel analysis of a nation's production and export saturation indices and advocates a shift from production to exporter concentration perspective using the Herfindahl-Hirschman Index. As nations, including Canada, increasingly rely on these critical minerals, the findings of this study inform strategies for managing geopolitical risks and mitigating potential disruptions in the critical mineral supply chain.

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LIST OF SYMBOLS AND ABBREVIATIONS

Al	Aluminium
API	Application Programming Interface
BGS	British Geological Survey
CO ₂	Carbon dioxide equivalent
Co	Cobalt
Cu	Copper
CMI	Critical Materials Institute
DDPP	Deep Decarbonization Pathways Project
ESP	Economic Scarcity Potential
EV	Electric vehicles
ECCC	Environment and Climate Change Canada
ERMA	European Raw Materials Alliance
EU	European Union
GPRS	Geopolitical risk supply
GeoPolRisk	Geopolitical supply risk
HS	Harmonized System cod
HHI	Herfindahl-Hirschman Index
ESSENZ	Integrated Method to Assess Resource Efficiency
ISO	International Organization for Standardization
LCA	Life cycle assessment
LCSSA	Life cycle sustainability assessment
Li-ion	Lithium-ion
LIBs	lithium-ion batteries
MT	Metric tonnes
AoP	Natural Resource Areas of Protectio
Ni	Nickel
ND-GAIN	Notre Dame Global Adaptation Initiative
OEM	Original Equipment Manufacturer
WGI-PV	Political Stability and Absence of Violence/ Terrorism
DDP	The Deep Decarbonization Pathways Project

UN Comtrade	United Nations United Nations International Trade Statistics Database
US	United States
USGS	US Geological Survey
WEF	World Economic Forum
WGI	World Governance Indicator
WMD	World mining data

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CHAPTER 1 INTRODUCTION

The transition to renewable energy represents one of the most urgent and transformative challenges of our time. Canada is in the path forward towards renewable energy. A commitment to sustainability is visible in the nation's investment in clean technologies, energy efficiency measures, and advanced storage technologies, accompanied by policies aimed at curtailing carbon emissions. Integral to this transformative vision is the lithium-ion battery—central to renewable energy storage and a backbone of clean technologies. In synchrony with this green transition, the country also faces the challenge of ensuring a secure, reliable supply of critical minerals, notably those integral to lithium-ion batteries. However, the production and supply of these critical minerals are not evenly distributed worldwide, leading to a complex geopolitical landscape fraught with potential supply disruptions, environmental concerns, and social implications.

This study focuses on evaluating the geopolitical risks for Canada in maintaining a stable supply chain of these critical minerals, using an enhanced GeoPolRisk method that incorporates Environmental, Social, and Governance (ESG) factors. Existing methodologies for evaluating the geopolitical risk around minerals supply have often focused on a set of specific, often restrictive, parameters. One such methodology is the GeoPolRisk method, initially formulated to estimate supply disruption risks by factoring in political stability, production levels, and the diversity of supply among producing countries. This research aims to contribute by augmenting the GeoPolRisk method to integrate ESG considerations, thereby encompassing a broader spectrum of vulnerabilities and opportunities. By doing so, the study aligns itself with a growing body of research that recognizes the critical need for a more GeoPolRisk holistic approach to supply chain assessment (Gemechu et al., 2015; Helbig et al., 2016; Cimprich et al., 2019; Santillan et al., 2022).

As the world, including Canada, increasingly depends on these minerals to fuel its energy transition, understanding and managing geopolitical risks emerge as a critical challenge for both sustainability and minerals security. The findings from this study will add to the academic dialogue, propose recommendations for improving a risk assessment method, and ultimately guide Canada and other nations on their path towards a sustainable future.

1.1. Problem statement

While existing methodologies like the GeoPolRisk method offer a foundational understanding of the geopolitical elements tied to mineral supply, they often fall short in accounting for broader disruptor risks. Such frameworks hardly integrate considerations such as environmental hazards and social unrest—factors that gained renewed significance during global crises like the COVID-19 pandemic and have far-reaching implications on global supply chains. Moreover, given the concentrated geographical distribution of critical mineral production—often in geopolitically unstable or environmentally vulnerable regions—the influence of social and environmental factors cannot be underestimated. These factors often translate into significant disruption probabilities, making them critical considerations for any nation seeking to ensure a stable supply of these critical minerals. Thus, there is a need to expand traditional geopolitical risk assessment to include ESG factors.

1.2. Research question and objectives

This study is guided by the central research question: "How can the existing geopolitical evaluation methods be expanded to offer a holistic and comprehensive understanding of environmental and social risks in the critical minerals supply chain for Canada?" To address this question, the research has two main objectives:

1. Incorporate Environmental, Social, and Governance (ESG) factors into the existing GeoPolRisk method, thereby enhancing its capacity to capture a multidimensional spectrum of risks related to the supply of critical minerals.
2. To introduce a new perspective focusing on exporter market concentration—measured by the Herfindahl-Hirschman Index (HHI)— to shed light on potential vulnerabilities in the intermediary stages of the supply chain, specifically in the context of Canada.

In concordance, the research will test the following hypotheses:

- The integration of ESG factors into the GeoPolRisk method will yield a more comprehensive and nuanced understanding of the probability of supply disruptions of the share of critical minerals imported to Canada from a partner country.

- Shifting the focus to exporter concentration, as captured by the HHI, will offer a more effective assessment of risk probability across multiple stages of the critical minerals supply chain.

1.3. Contributions

The current study endeavors to fill a gap in the existing body of research by expanding the GeoPolRisk method to encompass a broader array of rising social and environmental risk factors, specifically focusing on those critical for lithium-ion batteries. This research aims to offer academics, policymakers, and industry professionals an improved tool for evaluating geopolitical risks tied to critical mineral supply chains. The proposed framework will be tailor-made to address Canada's unique position in the global landscape, but its insights could be extended to assess other countries.

As climate change accelerates, geopolitical landscapes shift, and the social fabric of many mineral-producing regions becomes increasingly volatile, a nuanced understanding of these multiple risk vectors is crucial for both sustainability and international security of minerals exchange. Thus, the research aims to make a multi-faceted contribution: advancing academic understanding by refining risk assessment methodologies. By improving our understanding of these interconnected domains, this research aims to contribute actionable insights that will guide Canada, and potentially other nations, on their path toward a greener, more secure future.

As such, the research paper is structured into several key sections to provide a comprehensive overview of the subject matter. As the focus of this research is to improve the evaluation of the critical minerals' supply risk for Canada, the first section is a detailed explanation of the GeoPolRisk method and its evolution. Following, the Literature Review in chapter 3, assesses existing studies and information on the topic, providing a theoretical foundation for the subsequent discussion. This includes an examination of Canada's energy transition, the critical role of batteries and energy storage, and the geopolitical implications of critical mineral supply and demand. Following, the Methodology section outlines the research approach used in this study. This Additionally, it introduces a shift in focus from production to export concentration, offering a novel perspective on the risks in the critical minerals supply chain. The study then applies the

extended GeoPolRisk method to a specific case study of lithium-ion batteries in Canada within the Application section in chapter 5. This section presents the results of the analysis and their significance, providing practical insights into the theoretical concepts discussed earlier. In the Discussion section, the implications of the research results are explored. This includes a critical examination of data management, the shift in the Herfindahl-Hirschman Index perspective, correlation analysis, and environmental considerations. The discussion serves to connect the study's findings with broader contexts and implications. The Conclusion section summarizes the study's findings, its contribution to academic discourse, and recommendations for refining risk assessment methods. It emphasizes the importance of understanding and managing geopolitical risk, encapsulating the primary objectives of the research.

CHAPTER 2 LITERATURE REVIEW ON GEOPOLRISK EVALUATION

As the global economy becomes increasingly dependent on critical raw materials for various industries, managing supply risk becomes paramount. The GeoPolRisk method offers a robust approach to analyze and address the complexities of raw material supply chains, facilitating more informed and effective decision-making in an ever-changing global market landscape.

The GeoPolRisk method is a valuable tool for assessing and quantifying the supply risk associated with critical raw materials from a market perspective. With the increasing global demand for various raw materials, especially those used in emerging technologies like batteries and renewable energy systems, understanding and managing supply risk has become a crucial aspect of resource management and economic planning. Traditionally, market perspectives on raw material supply risk have primarily focused on factors such as market concentration, price volatility, and geopolitical stability. These perspectives recognize that the availability and accessibility of raw materials can be influenced by factors such as production concentration in specific regions or countries, political instability, trade barriers, and market fluctuations.

In this section, the review will be focused on the evolution, applications, strengths, and opportunities of the GeoPolRisk method. As an overview, the GeoPolRisk method builds upon a market perspective by providing a systematic framework for evaluating and quantifying supply risk at a global scale. It also considers the geopolitical factors that contribute to supply risk, allowing for a more holistic understanding of the dynamics and vulnerabilities of raw material supply chains. A central aim of this research is to contribute to the ongoing refinement and optimization of the GeoPolRisk method, targeting a more comprehensive and precise assessment of global supply risks.

2.1. Foundation

The GeoPolRisk method is an innovative approach to assessing criticality (Sonnemann et al., 2015). This method, which was introduced as a means of evaluating geopolitical risks associated with raw materials, has rapidly attracted the interest of researchers and professionals. This method was designed to assess the risk of resource supply disruptions caused by geopolitical instability,

according to a review of the existing literature (Santillan-Saldivar et al., 2022; Cimprich et al., 2019; Helbig et al., 2016; Sonnemann et al., 2015).

As an overview, the GeoPolRisk Method considers political stability, conflict rates, and trade policies of the countries that control the raw material supply (Santillan-Saldivar, 2020). The method integrates quantitative analysis framework that provide a comprehensive view of geopolitical factors associated with mineral resources. As shown in this section, literature demonstrates the method's applicability across various sectors and its potential to inform strategic resource procurement and management decisions.

Despite the growing popularity of the GeoPolRisk Method, a review of the relevant literature identifies several challenges and limitations, suggesting areas for future research and development. Among these are the need for continuous data updates to ensure the accuracy of risk assessments and the refinement of the method to account for shifting geopolitical landscapes, including environmental factors.

The discourse on criticality assessment methodologies as they relate to assessing the risk of supply disruption and the importance of resources has been extensive. Various methods deploy different weighting systems to ascertain criticality, an aspect highlighted by Sonnemann et al. (2015), who conducted a comparative analysis of these methods, with particular attention to the approach of Graedel et al. (2012).

Graedel et al. (2012) posited a method of criticality assessment that encapsulated supply risk, vulnerability to supply restriction at the corporate, national, and global levels, as well as environmental implications. These dimensions were assessed through indicators such as global supply concentration, political stability, and cost pass-through. They computed a single score for each dimension, derived from equally weighted indicators, to identify resource criticality. The inclusive approach of Graedel et al. (2012), covered a broad spectrum of criticality indicators. Nonetheless, the subjectivity and simplicity of their weighting system presented a weakness; users assigned weights to indicators without a standardized method. This subjectivity arguably undermined the objectivity and universality of the approach (Sonnemann, 2015).

Later, Sonnemann et al. (2015) also analyzed other criticality assessment methods proposed in the literature, such as those using net import reliance, recycling rate, and the Herfindahl-Hirschman index of primary material and ore producers. While helpful, at the moment these methods not fully encapsulated the complexity of the issue at hand (Gemechu, 2015).

All these methodologies underscored the necessity for a standardized, robust approach to criticality assessment in the context of life cycle sustainability assessment (LCSA). Incorporating criticality into LCSA would augment the assessment of the impact of resource use (Sonnemann, 2015). However, a need for further research was identified to develop a consistent methodology for LCSA criticality assessment and address associated challenges and limitations.

In Sonnemann et al. (2015), the authors also compared traditional life cycle assessment (LCA) with Graedel et al. (2012)'s resource criticality assessment method, illustrating how the latter addressed more effectively resource depletion and scarcity. Traditional LCA assessed resource impacts through long-term evaluations of resource supply and demand, concentrating on geological resource availability and depletion. However, it overlooked socioeconomic, regulatory, and geopolitical factors that influence resource accessibility, all of which the authors deemed critical to addressing resource scarcity (Sonnemann, 2015). In contrast, Graedel et al.'s approach incorporated geological, technological, economic, social, regulatory, and geopolitical indicators to assess resource criticality. It acknowledged that resource availability was affected by factors beyond geological abundance, including the proportion of a metal mined as a byproduct of other metals, contingent on technological and economic feasibility (Graedel, 2012).

In Sonnemann et al. (2015), the authors contended that LCA models for resource use should encompass social, regulatory, and geopolitical factors. They proposed a matrix of midpoint indicators for a more comprehensive evaluation of supply risk in resource protection. Furthermore, they suggested that Social LCA, which quantifies social impacts throughout the product life cycle, could shed light on the social aspects of resource criticality. Sonnemann et al. (2015) provided an integration of Graedel et al. (2012) criticality assessment into LCA context under LCSA framework.

According to the authors, traditional LCA also failed to address short-term resource impacts. They proposed incorporating Graedel et al.'s approach into LCA to assess short-term supply disruptions, enabling the LCA framework to integrate political and economic factors affecting resource availability. The authors' discourse underlined the limitations of traditional LCA in assessing resource criticality and the potential of Graedel et al.'s approach to provide a more holistic viewpoint. To address the socioeconomic, regulatory, and geopolitical aspects of resource availability and scarcity, they suggested integrating Graedel et al.'s approach into LCA (Sonnemann, 2015).

2.2. Structure of GeoPolRisk

The first introduction of the GeoPolRisk method was proposed by Gemechu et al. (2015). Their paper conducted an in-depth analysis of the geopolitical supply risk pertaining to raw materials within the framework of life cycle sustainability assessments (LCSAs). The researchers introduced an innovative method for evaluating the geopolitical supply risk, shifting the focus from global production distribution to import patterns. This extensive investigation included 14 resources predominantly imported by developed nations and growing economies.

The authors identified that rare earth elements, tungsten, antimony, and beryllium typically present high levels of geopolitical supply risk. This finding accentuated the importance of integrating geopolitical factors into LCSAs as it broadens the comprehension of resource accessibility in the face of political turmoil and concentrated markets (Gemechu, 2015).

The study also underscored the necessity of including a comprehensive supply chain analysis when evaluating geopolitical supply risk. To demonstrate this, the researchers utilized the example of cobalt, highlighting the complications associated with accounting for various supply chain tiers and the potential risks linked to industry concentration and confidentiality. This integration was seen as crucial to safeguarding the security and sustainability of raw material supplies. However, they acknowledged the challenge of data availability and called for further research to incorporate critical resources into life cycle assessment (LCA) databases and studies.

The calculation of the GeoPolRisk was based on several factors, as follows:

$$SR_{c,i} = \left[\left(\sum_{k=1}^n s_k^2 \right) * \left(\sum_{k=1}^n g_k * f_{i,k} \right) \right]$$

Where:

$SR_{c,i}$ expressed the supply risk of the evaluated country i concerning the commodity of interest c . s_k^2 reflected the share of country k in the global production (mining or refining) of the commodity c .

g_k is the political instability indicator of country k , which is derived from the World Governance Indicator (WGI) and,

$f_{i,k}$ is the import share of country k in the supply chain of country i of the commodity c .

The novelty of the model was reflected at different levels. First, the share of each country in the global production of a particular commodity is considered. Next, the political instability indicator of each country, derived from the World Bank's Worldwide Governance Indicators (WGI), weighted by the import share of that country in the supply chain of the evaluated country (Gemechu, 2015).

In the article, the GeoPolRisk was expressed as a midpoint characterization factor in the LCSA framework, ranging from 0 to 1. A GeoPolRisk factor of 0 indicated no supply risk, while a factor of 1 indicated a high risk of supply disruption. This methodology allowed for the assessment of the geopolitical supply risk of different resources in different countries. In addition, to account for uncertainty, a Monte Carlo simulation was performed considering the quality of the data used. This simulation helped identify potential variations in the results associated with data uncertainty. The results can be seen in the next chart.

The results of the study indicated that rare earth elements, tungsten, antimony, and beryllium generally posed a high geopolitical supply risk. This meant that these materials were susceptible to supply disruptions and volatility due to political instability and market concentration in certain regions. The study used a systematic analysis of risk, known as criticality assessment, which is based on the material flow approach (Gemechu et al, 2015).

Overall, this method expanded the scope of traditional life cycle assessments, which primarily focused on environmental impacts, to incorporating resource supply-risk assessment. By considering geopolitical and market concentration factors, the method provided valuable information for decision-making regarding resource strategy and long-term planning. This methodological innovation emphasised the necessity to address geopolitical supply risks and resource criticality within the sphere of LCA to foster more informed decision-making processes concerning sustainable resource strategies (Gemechu, 2016).

2.3. Considerations for the model and limitations

Although the first model considers only the fraction of imports from partner countries in its assessment, it is important to highlight two elements that are fundamental to the understanding of the GeoPolRisk method. The first has to do with the evaluation of market concentration and the second with the governance risk factors associated with the partner countries exporting the minerals, as explained below.

2.3.1. Herfindahl Hirschman Index – HHI

The Herfindahl-Hirschman Index (HHI) is a commonly accepted and used measure of market concentration, which compares country contribution to an industry or sector. It is calculated by squaring the market share of each competitor and summing the results. Then the market shares weighted averages determine the result. It can range from 0 to 1, from many countries, to a single monopolistic producer. The industry is closer to perfect competition when concentration is low, this means that many countries, contribute to the sector (Eurostat *Glossary*, 2021). As such, only one country that controls the production means 100% market share. In this case the HHI would equal 10,000 (100^2), indicating a monopoly. The HHI considers the relative size and distribution of the country in a market and approaches zero when a market consists of a large number of countries of relatively equal market size (Eurostat *Glossary*, 2021).

2.3.2. Geopolitical stability index (WGI)

The Worldwide Governance Indicators (WGI) project was created by Daniel Kaufmann, President Emeritus of the Natural Resource Governance Institute (NRGI) and Brookings Institution, and Aart Kraay, World Bank, Development Economics. It provides aggregate and detailed governance indicators for more than 200 countries and territories for the years 1996–2021 for six dimensions of governance: (I) Voice and Accountability; (II) Political Stability and Absence of Violence; (III) Government Effectiveness; (IV) Regulatory Quality; (V) Rule of Law; and (VI) Control of Corruption (Worldwide Governance Indicators | Data Catalog, 2022)

For this indicator, the World Bank understands Governance as the traditions and institutions that a nation uses to exercise its authority make up its governance. This includes the method by which governments are chosen, scrutinized, and replaced; the capability of the government to successfully develop and implement sound policies; and the respect of citizens and the state for the institutions that regulate their interactions with one another on a social and economic level (Worldwide Governance Indicators | Data Catalog, 2022)

These agglomerated indicators incorporate the opinions of numerous business, citizen, and expert survey respondents from industrialized and developing nations. They are based on more than 30 distinct data sources created by numerous survey institutes, think tanks, non-governmental organizations, global organizations, and private sector businesses. These data sources are rescaled and combined to create the six aggregate indicators using a statistical methodology known as an unobserved components model. A key feature of the methodology is that it generates margins of error for each governance estimate. These margins of error need to be taken into account when making comparisons across countries and over time (Worldwide Governance Indicators | Data Catalog, 2022)

Overall, from the foundational work of Helbig et al. (2016) to the comprehensive review by Cimprich et al. (2017b) the GeoPolRisk method has evolved to become an integral part of LCIA. Despite its limitations, its contribution to evaluating supply risks linked to political instability of trade partners and disruptions in specific import structures has positioned it as a significant tool for LCA studies. These works collectively stress the necessity of accounting for supply risk

alongside environmental impacts in LCA for informed decision-making in sustainable development.

As mentioned before, the GeoPolRisk method is one of the recommended methods for assessing the supply risk of mineral resources in life cycle impact assessment (LCIA). It focuses on the geopolitical stability of upstream raw material producing countries and incorporates the country concentration of production as a mediating factor in supply disruption probability arising from political instability of trade partner countries (Helbig, 2016).

In light of the above-mentioned studies, GeoPolRisk has emerged as an essential tool for LCA studies, allowing practitioners to take a more comprehensive approach in the evaluation of supply risks associated with mineral resource use. The method not only sheds light on geopolitical factors influencing the global distribution and accessibility of resources but also underscores the importance of considering the specific import structures of countries in risk assessment. The works of Helbig et al. (2016) and Cimprich et al. (2017b) have collectively contributed to expanding the scope of LCA by integrating a dimension of geopolitical risk.

Nonetheless, the studies also acknowledge the limitations of the GeoPolRisk method and highlight areas that require further development. While GeoPolRisk provides an in-depth examination of supply risks related to the political stability of trade partners, it does not currently consider the supply risk of secondary resources or anthropogenic stocks, nor does it provide a comprehensive evaluation of potential accessibility constraints. These areas, as pointed out by both Helbig et al. (2016) and Cimprich et al. (2017b), present opportunities for future research and refinement of the method. For instance, extending the method to include secondary resources and anthropogenic stocks could provide a more complete picture of the supply risk landscape, particularly in sectors where these resources play a significant role.

The evolution of the GeoPolRisk method highlighted the dynamic nature of LCA and the continuous need for its refinement considering changing resource landscapes and geopolitical dynamics. This journey underscores the significance of interdisciplinary collaboration between the fields of geopolitics, resource management, and life cycle assessment to create comprehensive

tools that facilitate informed and sustainable decision-making. As our global economy continues to evolve and our resource needs shift, tools such as GeoPolRisk will be paramount in guiding decisions around resource management and sustainability. Future research should continue to refine and build upon this tool to ensure its applicability and effectiveness in our ever-evolving world.

2.4. Comparison with other methods

In a pioneering work by Helbig et al. (2016), the authors presented a comprehensive review of 27 existing life cycle impact assessment (LCIA) methods for gauging the impacts of mineral resource use within life cycle assessment (LCA). Their study formulated critical questions surrounding the implications of mineral resource usage and evaluated the applicability of various LCIA methods. Notably, the GeoPolRisk method emerged as a recommended tool for assessing the supply risk of mineral resources. It was applauded for its focus on geopolitical stability and for acknowledging the concentration of raw material production as a key factor influencing supply disruption risk, primarily driven by political instability within trade partner countries (Helbig, 2016).

Helbig et al. (2016) expanded on Gemechu et al.'s (2015, 2016) GeoPolRisk method, considering the specific import structure of individual countries, thus facilitating a more detailed assessment of supply risk. In addition to identifying the limitations of GeoPolRisk, which was solely concerned with primary resources' supply risk, Helbig et al. (2016) proposed it as a robust tool for assessing country-specific supply risks, particularly when evaluating potential supply disruptions within unique import structures.

Further exploration of GeoPolRisk and other methods for evaluating raw material supply risk was conducted by Cimprich et al. (2017b). This research compared GeoPolRisk with two other methods, the Economic Scarcity Potential (ESP) and the Integrated Method to Assess Resource Efficiency (ESSENZ), on the basis of data sources, uncertainties, and methodological aspects. Each method presented a different lens to evaluate supply risk, considering variables like production concentration, political stability, and demand growth. This study underscored the significance of integrating supply risk within LCA to foster sustainable development, a perspective also shared by Helbig et al. (2016).

While acknowledging the uncertainties and simplified modeling inherent in the GeoPolRisk, ESP, and ESSENZ methods, Cimprich et al. (2017b) also highlighted potential avenues for future methodological advancement. This included the enhancement of supply risk factor coverage and integration of supply risk assessment into LCA software inspired from Cimprich et al. (2017b).

As shown in the following table, parameter uncertainty are key issues associated with all supply disruption probability and vulnerability factors in the GeoPolRisk, ESP, and ESSENZ methods and the inventory flows. First, all three methods require raw material production data and political stability of producing countries. The World Bank (2018) provides confidence intervals for its WGI indicator values, but USGS (2016) raw material production data does not. For the GeoPolRisk method, commodity trade data from the UNComtrade database (United Nations, 2018) lack uncertainty information. For example, trade data for rare earth metals like neodymium and gadolinium or HS261590 for "niobium, tantalum, vanadium ores and concentrates" can be difficult to obtain (Cimprich, 2019).

Another key element to supply risk assessment requires high-quality inventory data, which is difficult to obtain in LCA. Small inventory flows may be "cut-off" due to (presumably) low environmental impact categories and (long-term) resource accessibility impacts, but they may be crucial for supply risk assessment. Indium, antimony, and selenium are used in small amounts but are crucial to product functionality and may have limited substitution potential (Graedel et al., 2012). Thus, product-level supply risk assessment requires a complete inventory flow accounting, regardless of size. Some environmental LCA impact categories, like human toxicity and ecotoxicity, have small flows with large impacts.

From the LCA perspective, the product system boundary is another inventory factor in product-level supply risk assessment. "Background" inventory flows—e.g., manufacturing equipment, process chemicals, supplies, and energy flows—may be subject to supply risks that could affect the product system. However, the background system must distinguish between "consumable" inventory flows purchased continuously (e.g., fuels, lubricants, and process chemicals) and capital assets (e.g., machinery and infrastructure) amortized over time. Short-term supply risk is more

relevant to the former. Production losses and background inventory flows are not currently accounted for in GeoPolRisk, ESP, and ESSENZ due to data and methodological constraints (Cimprich, 2019).

2.5. Applications of the model

The first application of the GeoPolRisk method was a study in the context of Electric Vehicles (EV) (2016). The article highlighted the importance of the proposed GeoPolRisk index as a critical supplementary tool, extending the conventional environmental impact categorizations within life cycle sustainability assessment (LCSA). Copper, aluminium, steel, magnesium, and neodymium—metals essential to electric vehicle lifecycles—were studied (Gemechu, 2016).

The results showed that copper, aluminium, and steel had the greatest environmental impacts, contributing to human toxicity, freshwater ecotoxicity, and climate change. Geopolitical dynamics increased supply risk for magnesium and neodymium, according to GeoPolRisk. In addition, the GeoPolRisk considered trade partner precariousness and global supply concentration. Canada, India, and Norway displayed high-risk of neodymium imports because China controls global supply. By contrast, Neodymium imports from the politically stable US made Australia a lower supply risk (Gemechu, 2016).

This research showed that while the environmental impact assessment identified hotspots associated with extensive resource usage in the electric vehicle's lifecycle, the GeoPolRisk indicator emphasized trace elements vital to the LCSA. It added social and geopolitical factors to LCA, helping corporations and policymakers make better decisions (Gemechu, 2016). Moreover, the study also highlighted the shortcomings of the mineral reserve-based metals depletion indicator. Later, the GeoPolRisk considered geopolitical situations and trade patterns to address raw material accessibility issues. This approach allowed for a more holistic evaluation of resource criticality, especially important for modern technologies where critical resources are needed for key components. This amalgamation allowed for a more thorough assessment of direct impacts on Natural Resource Areas of Protection (AoP), laying the groundwork for sustainable product design and material management (Gemechu, 2016).

The first modifications to the GeoPolRisk were introduced by Cimprich et al (2017a). The method used in this study builds upon the previously developed geopolitical supply risk (GPSR) method by Gemechu et al, which aimed to quantify the risk of short-run supply disruptions in commodity trading between countries.

$$GeoPol_{AC} = HHI_A * \sum_i g_i \frac{f_{AiC}}{P_{AC} + F_{AC}}$$

The GeoPol is described as follows:

HHI_A - The Herfindahl-Hirschman Index (HHIA), for commodity *A*, is defined as the aggregate of each country's squared production shares.

g_i - The political stability or instability of each producing country *i* is gauged using the Worldwide Governance Indicator—Political Stability and Absence of Violence/ Terrorism (WGI-PV).

f_{AiC} - represents the quantity of commodity *A* that country *c* imports from country *i*

P_{AC} - corresponds to the domestic production of commodity *A* within country *c*.

F_{AC} - denotes the total imports of commodity *A* by country *c*,

In this study, the GPSR method was extended by incorporating the risk-mitigating effect of material substitutability. Material substitutability is a measure of how easily a particular material can be replaced by another material in a given application. The authors explain that the more readily substitutable a material is, the lower its vulnerability to supply disruption. To assess substitutability, the study incorporated semi-quantitative material substitutability indicator values, based on a study by Graedel et al. These indicator values represented the vulnerability dimension of criticality (Cimprich, 2017a).

The modified Geopolitical risk supply (GPRS) method considered the importance of each commodity input to the product system by applying a product-level importance factor. To demonstrate the application of the extended GPSR method, the study included an update of a previously published case study of a European-manufactured electric vehicle (EV) and a new case study of dental X-ray equipment. These case studies illustrated the significance of material substitutability in supply risk assessment. By incorporating measures of material substitutability,

the GPRS method added another dimension to supply risk assessment and provides valuable information for design and management decisions on a product-level (Cimprich, 2017a).

Later applications of the GeoPolRisk method were introduced in various studies to assess the supply risk of critical raw materials and understand their impacts on different aspects of sustainability. This introduction provides a brief overview of the application of the GeoPolRisk method in the most relevant articles.

In Santillan et al (2020), the GeoPolRisk method serves as the foundation for the development of the GeoPolEndpoint methodology. This approach aimed to evaluate the socio-economic damage caused by supply disruptions of mineral resources, with a focus on materials crucial for lithium-ion batteries. The study demonstrated the potential economic impact of specific raw materials and highlights the shifting of burden from environmental damages to economic costs (Santillan, 2020).

A second article (2021) explored the integration of the GeoPolRisk and GeoPolEndpoint methods into life cycle assessment to address the impact of resource accessibility. By quantifying the supply risk of critical raw materials from geopolitical and supply risk perspectives, the authors enhanced the understanding of the impacts of using these materials in the life cycle of lithium-ion batteries. The study emphasized the importance of considering raw material criticality and supply risk in LCA and provides insights into supply risk during product development (Santillan, 2021).

In a third article by Santillan et al (2021b), the GeoPolRisk method was extended to assess the risk-mitigating potential of domestic recycling for critical raw materials. By capturing the reduction in total imports and the redistribution of the import supply mix, this application explored how recycling could help manage materials criticality. The study emphasized the significance of domestic recycling and the reinsertion of recycled materials into the domestic economy to mitigate supply risk. The authors provided practical insights for industry and policy decision-makers to maximize the benefits of recycling critical raw materials (Santillan, 2021b). Overall, the application of the GeoPolRisk method in these articles demonstrated its versatility in evaluating supply risk, understanding socio-economic impacts, and informing decision-making processes related to resource management and sustainability assessment.

Later, a second modification to the GeoPolRisk method was introduced Santillan et al (2020). The article presented an extension to the GeoPolRisk methodology, called GeoPolEndpoint, for assessing the socio-economic damage of supply disruptions of mineral resources (Santillan, 2020). The method built upon the GeoPolRisk indicator, which measured the geopolitical supply risk of raw materials. The GeoPolEndpoint indicator incorporated price elasticity considerations and modeled the potential effects of supply disruptions on commodity markets (Santillan, 2020).

The study focused on aluminum, cobalt, nickel, and copper, which were important materials for lithium-ion batteries. The results showed that nickel and cobalt had the highest contribution to socio-economic damages due to their price and supply risk (Santillan, 2020). The analysis estimated that the use of these materials could lead to potential increased costs ranging from 0.30 to 1.86 USD/kWh, depending on the technology and year. The study highlighted the economic impact of using specific raw materials for technological development and identified the shifting of burden from environmental impacts to economic costs. The GeoPolEndpoint method provided a tool for decision-making processes by considering the accessibility and supply risk of raw materials in life cycle sustainability assessments. The authors acknowledged the limitations of the methodology, such as data availability and the need for more comprehensive data on supply disruptions and price elasticities. They suggested that future applications of the method could explore different perspectives and country groups for assessing the socio-economic impacts of mineral resource use (Santillan, 2020).

The same year, another publication focused in an integrated assessment of Li-ion batteries addressed the methodological gap in life cycle assessment for assessing the impacts of resource accessibility. The authors proposed the integration of the GeoPolRisk and GeoPolEndpoint methods as enhancements to current impact assessment methods in LCA. The GeoPolEndpoint method quantified the impacts of using critical raw materials from a supply risk perspective, while the GeoPolRisk method measured the perceived risk of using critical raw materials from a geopolitical perspective (Santillan, 2021).

The authors applied these methods to assess the impacts of four metals (Al, Co, Cu, and Ni) in the life cycle of lithium-ion batteries (LIB) from the EU perspective. They found that copper and nickel contributed significantly to environmental impacts, while cobalt had a high geopolitical supply risk indicator. The results highlighted the importance of considering specific raw materials with high supply risk as a complement to LCA. The authors concluded that impacts associated with the use of critical raw materials were not limited to environmental dimensions and suggested that the GeoPolRisk and GeoPolEndpoint methods could be integrated into LCA studies to provide new insights on supply risk during product development. They also emphasized the importance of evaluating raw material criticality in LCA, particularly for products that relied on critical raw materials throughout their life cycle. The article highlighted the potentials and limitations of the proposed methods and suggested future research directions to improve data availability and allow for broader application of the methods (Santillan, 2021).

In a third article, the authors extended the GeoPolRisk method to assess the risk-mitigating potential of domestic recycling for critical raw materials. As an extension to the previous model, the method captured the reduction in total imports and potential redistribution of the import supply mix. The authors applied the method to 13 raw materials used in information and communication technologies in the European Union. The results showed that recycling could mitigate supply risk, but the effectiveness depended on various factors. It was found that recycling should ideally take place domestically, recycled materials should be reinserted into the domestic economy, and the import supply mix should be considered (Santillan, 2021b).

The authors developed an automated calculation tool to facilitate the practical applicability of the method. This extension of the GeoPolRisk method advanced circular economy strategies for managing materials criticality. However, there were limitations in data availability and quality, as well as theoretical limitations in modeling multiple supply-chain stages and linking the method to the functional unit of a given product. Despite these limitations, the method intended to help industry and policy decision-makers maximize the potential benefits of recycling critical raw materials. Overall, the study supported the notion that recycling could mitigate raw material supply risk, but the reality was more complex (Santillan, 2021b).

In a most recent article (2022) Koyamparambath et al. discuss the application of the GeoPolRisk method to assess the supply risk evolution of raw materials for batteries and fossil fuels in selected OECD countries between 2000 and 2018. The study compares the supply risk of raw materials, such as rare earth elements, graphite, and magnesium, used in batteries to that of fossil fuels. The analysis revealed that raw materials for batteries have higher supply risk due to their concentrated production in a few countries. The article also explored the raw material security policies implemented by different countries, highlighting the emerging concern and the need for secure supply chains. While energy security policies have been successful in reducing the risk of fossil fuel supply, similar policies for raw materials are still under discussion. The study emphasized the importance of understanding the shift in supply risk from fossil fuels to raw materials for batteries and calls for policies to ensure raw material security in the face of increasing demand (Koyamparambath et al., 2022).

This last study focused on major metals used in batteries, including lithium, cobalt, nickel, and manganese, as well as broader categories of coal, natural gas, and petroleum for fossil fuels. The analysis covered the period from 2000 to 2018 to capture the evolution of battery technologies and the corresponding shift in supply risk. The authors acknowledge the limitations related to data uncertainties but consider the GeoPolRisk method a useful tool for comparing supply risk and informing resource policies (Koyamparambath et al., 2022).

Specifically, the analysis of supply risk from the perspective of Canada reveals that raw materials critical for battery production, such as cobalt, lithium, and graphite, carry higher supply risk compared to fossil fuels. Despite being a leading producer of zinc, nickel, and cadmium, Canada had not fully utilized its potential to meet the market demand for these materials. To mitigate supply risk, Canada has focused on stockpiling minerals and investing in minerals exploration. This approach aimed to ensure a stable and reliable source of critical raw materials for the country's battery industry, reducing dependence on foreign countries. The study emphasized the importance of securing a sustainable and reliable supply of raw materials for the battery industry's transition to cleaner energy solutions (Koyamparambath et al., 2022).

Overall, the study provided insights into the supply risk of raw materials for batteries compared to fossil fuels and highlights the implications for energy security. It underscored the need for strategic policies to ensure raw material security as the demand for batteries continues to grow and emphasized the importance of understanding the evolving supply risk landscape (Koyamparambath et al., 2022).

2.6. Further opportunities for research

The traditional landscape of risks affecting national stability is rapidly evolving due to the complex interplay between globalisation, environmental dynamics, and societal shifts. An emerging area of concern, where these trends converge, is the supply chains of critical minerals. These supply chains have been identified as potentially vulnerable to disruption due to novel risk factors such as environmental risks and social disturbances. A significant change in the stability of these supply chains may have far-reaching implications for national stability, pointing to the urgent need for effective risk assessment and management.

At present, however, existing risk management methodologies, such as the GeoPolRisk Method, may not adequately account for these new risk factors. While this model has served well in the past to capture geopolitical risk, it appears to fall short in considering environmental and social risks. This gap in the model is of concern as it suggests a potential blind spot in our understanding and management of risks to national stability.

For instance, the transition to a more sustainable, low-carbon energy system is a defining trend of the 21st century, with significant implications for geopolitics. IRENA identifies external shocks such as natural disasters as the number one factor for geopolitical risk. Subsequently, other factors of risk are resource nationalism, export restrictions, mineral cartels, political instability and social unrest and in number sixth -market manipulation. This shift is expected to change the distribution of power among states and impact the relative influence and status of nations. Critical minerals such as lithium, cobalt, nickel, and rare earth elements are essential for clean energy technologies and more often are impacted by external shocks difficult to manage (IRENA, 2023).

Likewise, the geopolitical landscape of these critical minerals is complex, and is subject to significant environmental and social factors, also known as "external shocks". These shocks can include environmental disasters, social unrest, labor disputes, political instability, and policy changes.

The geopolitics of the energy transition are intrinsically linked to the environmental and social dynamics surrounding the extraction of critical minerals. Understanding these dynamics is key to ensuring a smooth transition to a more sustainable energy system. Measures to mitigate these risks could include diversifying supply chains, improving mining practices, and investing in recycling and substitution technologies.

Firstly, environmental risks have increasingly been recognized as a significant factor influencing the stability of critical mineral supply chains. Climate change and other environmental phenomena have the potential to disrupt the availability of these minerals, either through direct impacts on mining and processing activities or through indirect effects on infrastructure and logistics. Moreover, environmental concerns can also lead to tighter regulatory measures, which may further affect the stability of these supply chains.

Social disturbances represent another critical, yet underrepresented factor in the GeopolRisk Method. Public opposition to mining projects, labour strikes, or social conflicts can create substantial disruptions in the supply of critical minerals. The increasing interconnectedness of societies due to globalisation can also amplify the effects of such disturbances, turning localised incidents into global supply chain disruptions.

However, the current tools used for risk evaluation, such as the Global Governance Index (WGI), also prove insufficient to capture these new, complex risk factors. The WGI, with its focus on political stability, institutional quality, and governance effectiveness, lacks sensitivity to environmental and social changes that increasingly cause tension within nations. Therefore, it fails to offer a comprehensive picture of the real risk scenario.

The evolving risk landscape requires new approaches that go beyond traditional political and economic considerations to capture environmental and social risks. The inclusion of these factors in risk assessment models can enhance our understanding of potential disruptions to the supply chains of critical minerals and, by extension, the threats to national stability. It is imperative to adapt and evolve our risk evaluation methods to effectively anticipate, mitigate, and manage the perturbations of national stability.

In assumption, there is a pressing need to reevaluate and expand current methodologies and indices used to assess risks to national stability. Addressing the gaps in the GeopolRisk Method and the Global Governance Index will allow for a more holistic and accurate assessment of risks, particularly in the context of critical mineral supply chains. Such an approach is necessary to effectively respond to the dynamic and increasingly complex risk landscape shaping our world.

CHAPTER 3 LITERATURE REVIEW

Historically, Canada has been a powerhouse in the global energy market. In recent years, it has been actively shifting from traditional fossil fuel reliance towards sustainable and renewable energy sources. This transition is driven by the country's commitments to international carbon neutrality and a growing awareness of climate change (Canada Energy Regulator, 2022). In congruence, the current Canadian energy strategies emphasize the investments in renewable technologies, energy efficiency measures and storage technologies. In addition, the nation is implementing policy initiatives and incentives including carbon pricing, sustainable energy regulations, and subsidies for renewable energy and electric vehicle adoption (Government of Canada, 2022).

The Canadian energy sector is increasingly defined by its focus on renewable energy sources, with hydroelectric power leading the charge. Significant infrastructure projects—including large-scale wind farms and solar installations—are in active development across the country, setting the stage for a more sustainable energy future (Canada Energy Regulator, Government of Canada, 2022). Concurrently, Canada is placing a strong emphasis on energy conservation and efficiency, thereby advancing toward a more sustainable energy model. A growing number of energy-efficiency initiatives, ranging from green building standards and carbon-neutral transportation programs to incentives for energy-efficient appliances, are gaining traction. However, it's important to note that these initiatives require an increased demand for minerals for their implementation (National Energy Board, IRENA, 2023).

Environment and Climate Change Canada (ECCC) publishes Canada's official analysis of emissions performance and performance against climate commitments. The ECCC's "Pathway to Canada's 2030 Target" estimated that the Pan-Canadian Framework would result in a 175 MT CO₂e emissions reduction by 2030. This represents a reduction of 23% from Canada's 2005 emissions level, or a shortfall of 44 MT. ECCC notes that its 175 MT estimate does not account for emission reductions resulting from other Pan-Canadian Framework commitments, such as investments in electrification public transit, green infrastructure, innovation, and sustainable technologies. The ECCC notes that these additional measures would place Canada on track to fulfill its commitments under the Paris Agreement (Government of Canada, 2022). However, there

is no discussion about the social, economic, and technological feasibility of achieving these targets. This could be a crucial point for policy considerations. Specially, as there is little or no mention in the literature whether recent events like the COVID-19 pandemic or natural disasters have affected these projections.

On the other side, at a general level, several Canadian studies have examined significant emission reductions through 2050 and beyond. The Deep Decarbonization Pathways Project (DDPP), the Trottier Energy Institute, and the Mid-Century Strategy of the ECCC are examples. The DDPP and Trottier reports demonstrate that significant emission reductions are technically feasible and will necessitate significant adjustments to the Canadian energy system and economy, including end use transition (Bataille et al., 2018). With this idea in mind, the energy transition will entail more than simply altering the energy source's mix. Future possibilities exist for altering how consumers utilize energy. These changes could involve technological advancements in energy-using electronics or alterations in how consumers utilize energy (Energy Technology Perspectives 2017 – Analysis, n.d.).

Future energy systems will be characterized by complex interdependencies among evolving technologies and energy sources. For example, the impact of autonomous vehicles on energy infrastructure could vary significantly depending on whether electric vehicles (EVs) continue to displace fossil fuel-powered cars. Likewise, the widespread adoption of EVs would present a different scenario if paired with a surge in solar photovoltaic (PV) installations. The integration of advanced digital technologies for optimizing electricity supply and demand will further influence how autonomous vehicles and EVs reshape energy systems (IEA, 2017). Finally, for Canada's green energy transition, The Pan-Canadian Framework encourages the modernization of Canada's electricity systems. The Framework includes funding for initiatives that improve electric systems' use of renewable energy, expand renewable capacity, and facilitate the integration of renewable energy storage (NRCan, 2018).

As electrification gains prominence, one key implication of this shift is an anticipated rise in demand for resources, including critical minerals essential for a sustainable energy transition. Despite being a producer of various metals, Canada faces supply risks for key elements like rare

earth elements (REE), magnesium, and lithium. Notably, Canada's limited lithium production heightens its supply risk. Additionally, although the country has its own reserves of REE, it primarily relies on imports from China, given the lower production costs there. To bolster its domestic capabilities, Canada has developed the Critical Minerals and Metals Plan (CMMP). This initiative aims not only to enhance competitiveness in the raw materials sector but also to prioritize responsible mineral development through strategic infrastructure investments and collaborative exploration strategies (Natural Resources Canada, 2020).

The Canadian Critical Minerals Strategy aspires to catalyze both Canada's and the world's green and digital economies by concentrating on the pivotal role of critical minerals and clean digital technologies. The strategy encompasses the entire value chain—from exploration and extraction to processing and recycling—with the goal of generating jobs and economic opportunities across Canada's mineral-rich regions. Given that critical minerals are fundamental to the worldwide energy transition, Canada aims to leverage this natural wealth to benefit all regions within the country (CMMP, 2020).

The Canadian Critical Minerals Strategy (CCMS) presents itself as a comprehensive plan for seizing a "once-in-a-generation opportunity," aimed at both sustainable job creation across Canada and establishing the nation as a leading supplier in clean energy and technology in a net-zero world (CCMS, 2020). While ambitious and laudable in its overarching objectives, the strategy is notably lacking in specificity. It doesn't offer concrete milestones or performance metrics, which casts doubt on how the government will hold itself accountable for achieving these ambitious goals. Moreover, the statement that the strategy will create jobs "in every region" raises questions about equitable distribution, as it leaves unclear how benefits will be disseminated, particularly in areas less rich in mineral resources (CCMS, 2020).

The CCMS also states its commitment to maintaining Canada's high environmental, social, and governance (ESG) standards, but omits details about how these principles will be tangibly integrated into mining and other practices. This is an evident oversight, especially given the ecological impact and sustainability concerns associated with mining for critical minerals. Further, the strategy sets forth the aim of creating a "more inclusive and highly skilled workforce," but falls

short of providing an actionable roadmap for reaching this objective. This is particularly concerning for communities that may not have ready access to the specialized training required for new and emerging industries (CCMS, 2020). As it stands, the CCMS is aspirational but requires greater clarity, detail, and an actionable framework to lend credibility to its promises.

Canada's List of Essential Minerals highlights 31 minerals and metals deemed crucial for the long-term economic well-being of Canada and its trade allies. Currently, the Canadian mining sector produces 21 out of these 31 critical minerals, offering opportunities for additional resource exploration and development. (CCMS, 2020). From these, the Canadian Critical Minerals Strategy focuses on six critical minerals, lithium, graphite, nickel, cobalt, copper, and rare earth elements. These minerals represent the greatest opportunity to fuel domestic manufacturing and will be the initial focus of federal investments. Other minerals present notable prospects such as vanadium, gallium, titanium, scandium, magnesium, tellurium, zinc, niobium, and germanium are considered promising for future exploration and development.

Aligning closely with the broader Canadian Minerals and Metals Plan (CMMP), developed in collaboration with provincial and territorial governments, the CCMS encompasses a range of applications for critical minerals, including their use in solar panels, electric vehicles, and a variety of household appliances. While the alignment between the CCMS and the CMMP is logical, this overlap may risk bureaucratic redundancies and unclear jurisdictional responsibilities. Effective implementation will largely depend on seamless coordination among federal, provincial, and territorial agencies, which is easier said than done.

With a dual focus on boosting the supply of responsibly sourced critical minerals and fostering domestic and global value chains, the CCMS aims to strengthen Canada's competitive standing in the global market. In doing so, Canada aims to cement its role as a reliable supplier of critical minerals, particularly for its historical allies, while also taking significant steps to combat climate change. However, the strategy's ambition to be a global leader in responsibly sourced critical minerals presents the complex challenge of balancing economic growth with environmental and social responsibilities, particularly in terms of cost, regulatory compliance, and supply chain certification.

The strategy also places significant emphasis on adding value across the entire mineral supply chain, from exploration and extraction to advanced manufacturing and recycling. This comprehensive approach is laudable but must align with key Canadian principles, such as environmental conservation, responsible labor practices, and Indigenous rights. Existing frameworks like the United Nations Declaration on the Rights of Indigenous Peoples Act (UNDA) are integrated into the strategy, yet the execution of these ideals into actionable policy remains uncertain.

The overarching objective of the CCMS is to empower businesses, workers, and communities across Canada, focusing on environmental sustainability and the rights of Indigenous peoples. While the strategy outlines these high-level objectives, details on how exactly it plans to mitigate the environmental impacts of increased mining activities are lacking. Given that mining can significantly impact communities and ecosystems, more concrete guidelines for environmental best practices would strengthen the strategy.

In conclusion, the Canadian Critical Minerals Strategy offers a robust framework for leveraging Canada's natural resources to meet the demands of a greener future. However, its success will hinge on addressing a range of complex issues, from diversification in mineral investment and intergovernmental coordination to balancing profit motives with ethical imperatives and environmental considerations.

3.1. Energy storage systems employing lithium-ion batteries.

As stated before, international agreements point that a key point to decarbonizing the world and combating climate change is electrification fueled by renewable energy, which includes the electrification of automobiles (e-mobility), structures, and cities (Chen, 2023). To ensure a transition to a green economy, it is necessary to increase the use of solar, wind, hydropower, and other low-carbon technologies, such as electric vehicles, storage capacity, microgrids, and smart grids (Bataille et al., 2018)

Because solar and wind power are still variable sources that produce varying quantities of energy, the contribution of batteries to renewable energy is especially significant. When there is no wind, the sun is obscured by clouds, or the sun has set, batteries can store energy and continue to function. Batteries allow the energy collected earlier to be stored and utilized more efficiently (Chen, 2023).

It is anticipated that the production of minerals such as lithium, cobalt, and graphite will skyrocket due to the rising demand for renewable energy technologies such as batteries, wind turbines, solar panels, and electric vehicles. Lithium-ion (Li-ion) batteries play a crucial role in current technological advancements and initiatives to electrify the economy. Lithium-ion batteries have become the preferred battery for most Original Equipment Manufacturer (OEM) electric vehicles due to their superior performance, efficiency, and safety compared to conventional batteries (Chen, 2023). In the past two decades, lithium-ion has become the most popular battery type for charging electric vehicles. World Economic Forum reports that the demand for lithium-ion batteries to power electric vehicles and energy storage has increased exponentially and is expected to fivefold in the coming years (WEF, 2020)

Batteries' rapid response, modular design, and flexible installation make possible both the decarbonization of the transportation industry and the integration of intermittent renewable energy technologies into the power grid. In lithium-ion batteries, the conductors consist of a cathode (positive electrode), an anode (negative electrode), and an electrolyte. These batteries are currently used in mobile phones, computers, and electric vehicles. They are significantly lighter, smaller, and more capable of holding a charge than previous rechargeable battery types. Batteries' function in energy storage systems (Mitali et al., 2022). Depending on the composition of these three components, batteries require various minerals. Many electric vehicles (EVs) still use lead-acid batteries, which contain lead and sulfuric acid. However, lithium-ion batteries (LIBs) are expected to swiftly dominate the market, so demand for lead-acid batteries will not increase significantly (Roberts, 2022).

As the majority of LIBs use graphite as the anode, graphite is the most demanded mineral for energy storage. Also, cathodes vary more than anodes. In addition to nickel, diverse mixtures of cobalt, lithium, and manganese are also common. (It is important to note that lithium is utilized in

all LIBs, not just the cathode) (*Roberts, 2022*). As an example, considering the current availability of LIB options, the cathodes of NMC111 batteries contain one part nickel, one part manganese, and one part cobalt, whereas the cathodes of NMC811 batteries contain significantly more nickel and significantly less cobalt. Tesla and other manufacturers are attempting to eliminate cobalt from their batteries in the future, but it is too early to tell how far they will get (*Roberts, 2022*).

None of the renewable energy technologies expected to flourish in the coming decades will put as much pressure on the supply of minerals as batteries. In an accelerated decarbonization scenario, they account for roughly half of the projected expansion in mineral demand over the next two decades (*Hund et al., 2020*.)

Batteries allow utilities and grid operators to maintain the reliability of the electrical system by compensating for the variable output of wind and solar power plants and averting the loss of excess energy. In addition to providing frequency response, reserve capacity, black-start capability (restoring an electric power system), and other grid functions, battery systems can upgrade mini-grids, facilitate "self-consumption" of rooftop solar power, and store electricity in electric vehicles (*Mitali et al., 2022*).

Moreover, the World Bank report on minerals for climate action (2020) explains that the pressure on batteries is due in large part to the anticipated increase in battery-powered electric vehicles, which will account for 90 percent of the growth in battery demand; the remaining 10 percent will come from growth in stationary storage, which is used to balance out wind and solar on the grid. It is important to highlight that if the world aims for the 2°C scenario, the demand for minerals from energy storage will double compared to the baseline scenario; if the world aims for 1.5°C, the demand will more than quadruple¹ (*Hund et al., 2020*).

¹ *Ibidem*

The Reference Technology Scenario (RTS) provides a baseline scenario that considers existing energy- and climate-related commitments by countries.

The 2°C Scenario (2DS) and the Beyond 2°C Scenario (B2DS) each sets out a rapid decarbonisation pathway in line with international policy goals. The 2DS has been the main climate scenario in the ETP series for many years, and it has been widely used by policy makers and business stakeholders to assess their climate strategies. For the first time, the B2DS looks at how far known clean energy technologies could go if pushed to their practical limits, in line with countries' more ambitious aspirations in the Paris Agreement (IEA, 2017).

Notably, these projections through 2050 are largely speculative, merely an extension of the average LIB expected into the future. LIB technology could evolve in a variety of ways, and other storage technologies may play a larger role in the coming decades. In the same report, The World Bank writes that the assumption that lithium-ion batteries will dominate the mobile and stationary markets over the next decade is conservative. Post-2030, the level of uncertainty is much higher, with a wide variety of options available in both markets (Hund et al., 2020).

Under these assumptions, David Roberts states that if manufacturers strive to reduce cobalt use, nickel demand would increase. Or, if solid-state batteries gain popularity, graphite demand could decrease. Another hypothesis is that if zinc-air batteries gain popularity, demand for lithium, graphite, nickel, and manganese could decrease (*Roberts, 2022*).

3.2. Future minerals demand and risks

The World Bank's projections show that, as a major component of batteries, graphite, lithium and cobalt are crucial to the energy transition, as depicted in the illustration below. Lithium and cobalt, for example, will experience close to 500 percent market growth, while indium and vanadium will experience close to 200 percent market growth. Even though the demand for certain essential minerals does not increase by a substantial amount in absolute terms, the markets for these minerals will grow by close to 500 percent. Those are possible stressor points (Hund et al., 2020). Also, Copper and zinc, which are extensively used outside of the energy sector, will experience substantial growth in absolute terms, but relatively modest growth in percentage terms. It is important to note, however, that the World Bank analysis does not include copper for transmission lines, which could be a significant development driver.

In an effort to consolidate this information, the World Bank developed a risk matrix for minerals under a 2-degree scenario. Notably, the matrix does not account for environmental hazards or potential supply constraints. It only captures the dynamics of demand.

The horizontal axis — "weighted coverage-concentration index" — assesses the mineral's cross-cutting nature. On the left are those utilized in fewer energy technologies, whose fates are closely

linked to those technologies; on the right are those utilized in numerous energy technologies, whose demand is likely to increase regardless of which technologies prevail.

The production-demand index vertical axis is a weighted measure incorporating relative and absolute demand growth. It approximates how much the mineral's demand is anticipated to increase. On top are the minerals whose demand will expand rapidly, while at the bottom are those whose growth will be modest.

This matrix's four quadrants provide a classification scheme for essential materials and their demand risks. Quadrant one comprises medium-impact minerals. They are utilized in a limited number of renewable energy technologies, and their growth will be modest overall. Among these are zinc, silver, titanium, and several rare earth elements.

Quadrant two comprises minerals with high impact. They are only utilized in a small number of technologies (primarily batteries), but demand is anticipated to increase significantly and rapidly. In terms of mining and refining, graphite, lithium, and cobalt are among the most detrimental to the environment.

Quadrant three contains the minerals with the greatest impact, which are essential to a variety of technologies and are anticipated to grow rapidly. Currently, this only applies to aluminium. It originates from bauxite mines, which are not ideal, but it is one of the most recyclable and recycled materials available. Approximately 75% of the aluminium ever produced by humans is still in use.

The fourth quadrant contains cross-cutting materials, which will not experience a rapid increase in demand like those in the second and third quadrants, but are essential to a wide range of technologies, making demand growth quite certain and predictable. Copper dominates the market, as it is used in virtually every clean-energy technology, but nickel will grow even faster. Additionally, lead, chromium, molybdenum, and manganese qualify.

The authors of this report (2020) defend that LIBs have made significant advancements in materials efficiency, which are likely to continue, that could influence the rate of demand growth

(World Bank, 2020). However, they finalise by saying that graphite, nickel, lithium, and cobalt are the most important minerals to monitor in terms of their geopolitical concentration and environmental toxicity, but it is impossible to predict their exact proportions. In agreement, the analysis for this study is conducted under the same minerals presented in the chart above. Further details are provided in the methodology section.

3.3. Geopolitical mineral security and criticality in the energy transition

As stated before, the transition to cleaner energy will impose extensive use of raw minerals such as nickel, cobalt, and lithium. And these materials will need to be mined and processed to produce items such as batteries for electric vehicles, wind turbines, and nuclear power facilities. Even though clean energy presently accounts for only a small portion of global mineral demand, this proportion is projected to increase rapidly. In addition, there is a challenge to incorporate the conversations regarding the social, environmental, and security risks of mining for the materials required to construct decarbonized economies.

Some minerals, including those essential to LIBs, are deemed "critical" by the EU, the U.S., and China, three main geopolitical actors in the trade of these minerals. However, their inventories of essential minerals differ. The U.S. list consists of 50 essential minerals, including well-known minerals such as copper and lesser-known resources such as vanadium and tantalum. The EU identifies thirty essential minerals, while China identifies thirty-seven (The Wilson Center, 2023).

As Cory Combs, Associate Director at Beijing-based Trivium China describes, there are disparities because the resources each actor identifies as "critical" are influenced by the nation's distinct objectives and industrial structures. He continues to argue that critical minerals cover governments' most strategic objectives. In a sense, they constitute an economic analysis of what's important for industry today and what is important for the industry requirement to build tomorrow (The Wilson Center, 2023).

The notoriety of energy transition on the global political agenda has led to the emergence of critical materials supply as a matter of geopolitical significance. Geopolitical considerations encompass the examination of emerging trade patterns in the future, as well as the potential for specific actors

to establish a dominant position in markets for critical minerals, exerting a certain control over prices and supply (Global Commission, IRENA, 2019). According to the most recent Energy Transition Outlook ensuring supply security is commonly achieved by implementing a strategy that emphasizes the diversification of supply sources (IRENA, 2022).

Nevertheless, the scarcity of minerals does not arise from a lack of minerals present in the Earth's crust. Rare earth deposits are distributed across various regions. However, the overall abundance of minerals within the Earth's crust holds significance in relation to the geopolitical dynamics surrounding minerals for renewable energy. The availability of minerals is also contingent upon the economic viability of extracting known mineral deposits using existing or anticipated technologies, as well as prevailing market conditions (Haglund, 1986). The supply of minerals is limited because under current market conditions only a small number of countries can mine minerals profitably (HCSS, 2011).

To IRENA, at present, graphite, cobalt, lithium, and neodymium emerge as the most sensitive minerals to geopolitical issues. Nevertheless, there are available solutions that can effectively mitigate dependencies. The estimation of forthcoming critical mineral requirements is characterized by a significant degree of uncertainty. Firstly, it is anticipated that there will be a significant increase in the demand for new products (IRENA, 2019). The rate at which this occurs in alignment with a 1.5°C trajectory, will be contingent upon the effective execution of policies that translate recently developed decarbonization goals for the middle of the century into tangible actions, previously discussed according to IEA's scenarios.

Numerous energy transition minerals are currently produced and processed in a small number of countries, making the system vulnerable to political instability, geopolitical risks, and potential export restrictions (Hatayama and Tahara, 2018; IEA, 2020). The figure below illustrates the concentration of few countries by critical mineral in 2019 and 2025.

The analysis of the current project pipeline by the IEA indicates that this scenario is unlikely to change in the immediate future. With the exception of copper, the majority of future output growth for lithium, nickel, and cobalt is anticipated to come from the main producers of today, indicating

a greater degree of concentration in the coming years. Under these conditions, physical disruptions or regulatory and geopolitical events in main producing nations can have a significant effect on the availability of minerals and, consequently, on their prices (Wood et al, 2021). Recent occurrences, such as Indonesia's export prohibition on nickel ore and China's export ban on rare earth elements, serve to emphasize these concerns. Recently, the military revolt in Myanmar has raised concerns about supply disruptions of heavy REEs, resulting in a price increase. In addition to accidents and labour disputes, natural disasters have become one of the most common causes of mineral supply disruption (Hatayama and Tahara, 2018).

While advocates of the green transition argue for an increase in supply, the mining industry remains cautious due to its previous encounters with supply challenges (IRENA, 2019). The financial outlook (2019) from IRENA expected that investors anticipated a significant windfall. In their report, the Agency describes that the stock prices of copper and lithium mining companies have experienced an upward trend, while there was a notable surge in the exploration of new mining projects. This is highly necessary due to the protracted timeline and inherent uncertainties associated with the development of new mines (IRENA, 2019).

For instance, The Resolution copper mine located in the state of Arizona in the United States serves as an illustrative example, wherein a substantial investment of USD 2 billion was made over the course of the last three decades, yet no copper has been extracted thus far (Klemetti, 2019). Another example is the proposed lithium-borate mine in Serbia by the Rio Tinto Group that was encountering scrutiny and demands for additional environmental assurances. Ted Klemetti (2019) argues that the proper management of new mining activities is imperative, and it is crucial to address both local and national concerns. The author provides another example when in 2020, Rio Tinto's iron mining operations resulted in the destruction of a significant prehistoric site in Australia, garnering widespread attention and adversely impacting the reputation of the prominent mining corporation for an extended period. Mining projects are also anticipated by local populations to generate local employment opportunities and foster economic development. The exploration and extraction of metals from the seabed is a topic of significant interest and scrutiny within the current context, as highlighted by Bloomberg (2021) ("Copper Boom Pushes Miners to Tap Trillions of Dollars From Waste," 2021).

An additional layer of complexity in assessing supply risk comes from the geographical distribution of resources. Governments and corporations are increasingly scrutinizing supply chains due to heightened awareness of vulnerabilities, such as environmental concerns, social factors, and rising geopolitical tensions. Managing these intricate supply dynamics necessitates adept governance to balance the allure of low-cost foreign supplies against the risk of geopolitical fallout (Purdy, 2022). Although geopolitics is predominantly a concern for governmental bodies, end-users like automobile manufacturers are not passive players; they actively employ contractual agreements to ensure a stable supply of essential materials.

Moreover, specialized national agencies, including the U.S. Geological Survey (USGS), Germany's Deutsche Rohstoffagentur, and the European Union's Joint Research Council, are tasked with continually evaluating the availability and risks associated with critical materials. These organizations play a pivotal role in informing governmental policies that aim to secure essential resources, thereby serving as a critical link in the chain of supply risk management (Purdy, 2022).

Geopolitics primarily falls within the view of governmental entities, yet consumers of critical minerals also exhibit awareness and possess the ability to undertake measures. For instance, automobile companies employ contractual agreements to secure a consistent supply of materials (Purdy, 2022). Governments play a crucial role in ensuring the procurement of essential materials. Currently, there exist multiple national agencies, such as the US Geological Survey (USGS), Deutsche Rohstoffagentur, and Joint Research Council, which are responsible for evaluating the availability of critical materials (Purdy, 2022).

However, there is a notable absence of an international organization fulfilling this role. The potential consideration of establishing such an entity has been contemplated. The Critical Materials Institute (CMI) is an Innovation Hub under the purview of the United States Department of Energy. It aims to expedite the advancement of scientific and technological breakthroughs (Ames Laboratory, 2021). The primary objective of CMI is to establish robust and secure supply chains for rare earth metals and other materials that are indispensable for the effective functioning of

clean energy technologies (Ames Laboratory, 2021). The Energy Resources Governance Initiative was established by the United States Department of State with the aim of promoting effective governance in the mining sector and ensuring the resilience of energy mineral supply chains (IRENA and USDoS, 2020). The Initiative additionally facilitates the advancement of robust and protected energy resource mineral supply chains. The discussion at hand, specifically references rare earth metals.

The European Commission's Communication on Critical Raw Materials (2020) disclosed the initiation of an industrial alliance with the objective of ensuring a sustainable provision of raw materials within Europe (European Commission, 2020). The alliance aims to enhance the European Union's resilience in the rare earth element and permanent magnet value chains by convening key stakeholders from strategic value chains and industrial ecosystems. This prioritization of needs is based on the European Commission's recent report (2021) and information from the European Raw Materials Alliance (ERMA). In 2021, Gauß et al. (2021) published a document outlining a strategy pertaining to rare earth elements. Additionally, it is worth noting that the Joint Research Centre of the European Commission has implemented a robust initiative aimed at monitoring critical raw materials, as highlighted by Bobba et al. (2020). Japan has implemented a proactive policy aimed at securing a steady supply of essential resources, including rare earth metals (Hui, 2021). In summary, it can be observed that governments possess an understanding of the issue pertaining to critical materials; however, a notable deficiency in coordination is evident. As such, each country needs to assess their own geopolitical risk according to their own criticality of minerals, and consequently their development strategy for the energy transition.

An additional international level of complexity is the Chinese dominant participant in the global supply chains for critical minerals and renewable energy products. China is home to over 90 percent of the world's wafer manufacturing capacity, and Chinese companies own two-thirds of the global polysilicon manufacturing capacity and 72 percent of the global module manufacturing capacity, regardless of the location of their factories. China has the majority of processing capacity for critical lithium-ion battery components (such as cathodes, anodes, separators, and electrolytes) and almost 80 percent of global battery cell manufacturing capacity (CSIS, 2021) (Ladislaw et al.,

2021). China has a significant presence in the wind turbine value chain, despite being less dominant; it is home to approximately half of the world's manufacturing plants for nacelles, blades, wind towers, turbine generators, and gearboxes (CSIS, 2021). Also, this nation is home to approximately one-third of the world's rare-earth reserves, which has contributed to the country's emergence as a key player in the clean energy technology value chain. However, this emergence also represents the culmination of China's long-term industrial policy, its ability to implement it, and the benefits derived from a regulatory latency in the extractive industry. And strategically, where China lacked access to resources, it has invested in overseas mining ventures (IAGS, 2010).

Moreover, Chinese companies invest in cobalt mines and participate in cobalt smelting initiatives in the Democratic Republic of Congo. One strategy to ensure stable access to cobalt resources, as nearly 60 percent of cobalt ore is mined in DRC and China is now responsible for 72% of the world's cobalt refining capability. In addition, although China is only the fifth country that produce lithium, it accounts for approximately 60 percent of the world's lithium refining capacity (Ladislav et al., 2021).

Nakano (2021), show the Chinese dominance in the clean energy mineral supply chains, including top suppliers. Throughout the value chain, the Chinese dominance is evident in the extraction as well as downstream activities for assembly of LIBS. Certainly, while China's commanding role in the critical minerals sector is undeniable, it doesn't exist in isolation. The global competition for these essential resources is heating up, involving other major players like the European Union, the United States, and various Asian countries such as Japan and South Korea. These entities are not merely passive consumers but are actively implementing strategies to challenge or at least mitigate China's dominance.

The European Union, for instance, has initiated the European Raw Materials Alliance aimed at strengthening its domestic production and processing capacities. Coupled with its ambitious Green Deal, the EU is trying to create a more self-reliant and sustainable supply chain that is also ethically sourced (European Parliament, 2023). The United States has been increasing its strategic stockpiles and seeking partnerships with allied countries to reduce its dependency on Chinese

supplies. The U.S. also aims to boost domestic production through regulatory reforms and investments in resource exploration and advanced processing technologies.

Asian countries like Japan and South Korea, leading the charge in high-tech manufacturing and being significantly dependent on imported minerals, are investing in overseas mining projects and entering long-term agreements to diversify their sources. Their efforts often include high levels of investment in research and development to discover alternative materials that could reduce this dependency (European Parliament, 2023)..

This global competition brings its own set of challenges and opportunities. On one hand, it spurs innovation in extraction technologies, recycling, and material alternatives, thereby potentially lowering costs, and environmental impact. On the other hand, the scramble for resources could exacerbate geopolitical tensions, leading to a resource-driven arms race of sorts, which in turn could hamper global efforts to transition toward sustainable energy systems.

Therefore, understanding Canada's role in the critical minerals market should be contextualized within this broader landscape of global competition and strategic maneuvering. The quest for these critical resources is not just a sprint for individual nations but a relay race involving multiple global players. Collaborative, internationally coordinated efforts are likely to be more effective than unilateral moves in ensuring a secure, sustainable supply chain that can support the global energy transition.

CHAPTER 4 METHODOLOGY

This section explains the approach taken to develop the extension to the GeoPolRisk indicator proposed by Koyamparambath et al, 2022. This chapter presents the research methods and description of the system that was implemented to obtain the geopolitical risk for Canada when assessing the dependency on the minerals needed for the production of lithium-ion batteries, the changes proposed to make the indicator more robust and the description of the computational techniques (data manipulation) to obtain the results.

The primary research question driving this investigation is: "How can the geopolitical evaluation techniques currently in use be expanded to provide a holistic and all-encompassing understanding of environmental and social risks in the critical minerals supply chain for Canada?" The study has two main goals to answer this question:

1. Enhance the GeoPolRisk method's ability to capture a multidimensional spectrum of risks related to the supply of critical minerals by incorporating Environmental, Social, and Governance (ESG) factors.
2. To present a fresh viewpoint that focuses on exporter market concentration, as determined by the Herfindahl-Hirschman Index (HHI), in order to highlight potential challenges in the supply chain's middle stages, particularly with regard to Canada.

Accordingly, the research will examine the following hypothesis:

- The integration of ESG factors into the GeoPolRisk method will yield a more comprehensive and nuanced understanding of the probability of supply disruptions of the share of critical minerals imported to Canada from a partner country.
- Shifting the focus to exporter concentration, as captured by the HHI, will offer a more effective assessment of risk probability across multiple stages of the critical minerals supply chain.

The first section of this chapter introduces the research approach and development to replicate the original results of the Geopolrisk. A first modification is presented in which the HHI index changes, from assessing the concentration of producing countries to exporting countries; thus, capturing intermediate flux of minerals. Then, the second extension is introduced which is the

inclusion of environmental social and governance variables. Finally, both extensions are evaluated together. The respective data sources and variables included are described in each section.

The geopolitical risk measured in this paper is from the perspective of Canada as the importer country. The range of time is from 2000 to 2020, with the purpose of showing the evolution of the geopolitical risk for the selected metals. These minerals are based on their criticality to produce a type-model lithium-ion battery which include cadmium, cobalt, copper, graphite, iron, lead, lithium, magnesium, manganese, nickel, rare earths, silver, and zinc.

4.1. Application of the GeoPolRisk

4.1.1. Step one: Baseline scenario

The initial phase of the analysis consisted in replicating the results from Koyamparambath et al (2022) to have a baseline of comparison for the next phases, extending the political in(stability) risk with environmental, social and governance factors and modifying the HHI index approach.

The first step of the tool development was to compute the original equation, previously described in this paper. For such task, the code was developed in python. This approach allowed for the automation of the process in calculating the risk for different minerals, selection of the importing country, commercial partners, and year².

The GeoPolRisk followed the original equation described as:

$$GPRS_{BASE} = HHI_{PROD} * \sum_i \frac{g_i * f_{AiC}}{P_{AC} + F_{AC}} \dots \dots \dots \text{equation (1)}$$

Where:

HHI_{PROD} = Herfindahl-Hirschman Index for resource A , calculated as the sum of the squared production shares of all producing countries. A higher index value indicates a higher concentration, suggesting that fewer countries dominate the market. In the context of resource A 's supply chain,

² The code is accessible in <https://github.com/iruneiro33/irune-api-consumption/tree/main>

this measure can provide valuable insights into the vulnerability and potential risk of disruption in the supply chain due to market saturation.

g_i = geopolitical (in)stability of country i , as measured by the Worldwide Governance Indicator - Political Stability and Absence of Violence and Terrorism (WGI-PV). The scale ranges from 0 to 1 after a normalization process, where 1 represents high instability or a high likelihood of violence and terrorism, and 0 represents high stability or a low likelihood of such events. This measure offers insights into the geopolitical risks associated with sourcing or trading in resource A from this country.

f_{Aic} = imports of good A from nation i to nation c . This variable represents the volume of imports of good A that is transported from country i to country c . Understanding the quantity of resource A that country c imports from country i can help to discern the reliance of country c on country i for the supply of resource A , and the potential dependency risks associated with any disruptions in country i .

F_{Ac} = total imports of good A into country c ; This measure represents the total volume of imports of good A into country c from all sources. It helps to evaluate the dependency of country c on foreign sources for the supply of resource A . It can also be useful for determining the level of country c 's exposure to global market fluctuations and supply chain risks for resource A .

p_{Ac} = domestic production of good A in country c . This refers to the total volume of good A produced within the boundaries of country c . Understanding the scale of domestic production of resource A can provide insights into the self-sufficiency of country c in terms of resource A supply. The difference between the total demand for resource A and the quantity produced domestically (P_{AC}) can also provide a measure of the reliance of country c on foreign sources for this resource. This measure can also capture amount of recycled material within a country.

4.1.2. Step two: GPRS - 1 - modification of the HHI from production (HHI_{PROD}) to export concentration (HHI_{EXP})

Once the original equation of the GeopolRisk was calculated, another modification is introduced to the GeopolRisk. Now, the change is applied to the approach of the Herfindahl-Hirschman Index. Instead of estimating the sum of the squared production shares of all producing countries for a specified mineral, the approach is in the measurement of the saturation of the exporting countries.

The difference in approaches lies in the fact that one focuses on the share of producing countries and the other in the contribution of countries that trade them as second or third exporters. This is an alternative provided to visualize intermediate flux of minerals which is not originally captured in the GeoPolRisk. Yet, for certain minerals, such as cobalt and niobium, the producing countries saturation score and the export countries score differs due to the configuration of their supply chains. More on this discussion in the subsequent sections of the paper.

As such the new equation results as:

$$GPRS_I = HHI_{EXP} * \sum_i \frac{g_i * f_{AiC}}{PAC + FAC} \dots\dots\dots \text{equation (2)}$$

where:

HHI_{EXP} = Herfindahl-Hirschman Index for resource A , calculated as the sum of the squared export shares of all exporting countries.

All the rest is calculated the same as equation (1)

The HHI modification is applied to show the changes in each risk estimation to obtain two potential settings. This modification calculates the HHI of exporting countries only measuring the political (in)stability of partner countries that export the specified mineral to Canada per year.

The Herfindahl-Hirschman index (HHI) has been used before by Canada and other nations such as the United States (assess market competition) and the Netherland (export and import

diversification) (Statistics Netherlands, 2023). In Canada, it has widely been employed to measure import and export diversification, by region and sector. This index has been chosen due to its ease of use and adaptability to various forms of imports and exports variation (such as product or geography). By squaring shares before adding them up, the Herfindahl-Hirschman index also gives larger share products (or markets) more weight. This is a crucial aspect to consider when measuring concentration because the quantity of commodities (or markets) and the distribution of their shares will both have an impact on the degree of concentration (Statistics Canada, 2017).

The selected index yields specific bounds with a range from a lower bound close to zero, $1/N$ (representing perfect diversification), to a maximum of 1 (representing perfect concentration of exports into a single product, to a single country of origin or destination). Higher values reveal a high degree of concentration of exported products or markets of destination/origin or, alternatively, a less diversified portfolio. Lower values of HHI indicate a diversified set of exporting countries (Statistics Canada, 2017).

In order to distinguish between concentrated and diversified exports, the United Nations Conference on Trade and Development (UNCTAD) uses a normalized Herfindahl-Hirschman index to measure export diversification. In addition, the Federal Trade Commission and the U.S. Department of Justice (August 2010), developed the Horizontal Merger Guidelines developed to distinguish between diversified, moderately concentrated, and highly concentrated exports or markets to improve the interpretation of the Herfindahl-Hirschman index. The three categories and thresholds used in the study are listed as follows:

- Exports or markets that are diversified (not centralized): $HHI < 0.15$
- Concentrically moderate Markets or exports: $0.15 \leq HHI < 0.25$
- Exports or markets that are intensely concentrated: $HHI \geq 0.25$

It's important to note that the Herfindahl-Hirschman index has an aggregation bias, meaning that the less disaggregated the input categories are, the less concentrated the resulting index will be. It also gives more weight to larger export categories (U.S. Department of Justice Antitrust Division, 2015).

4.1.3. Step 3: GPRS - 2 - Introduction of the ESG factors

One purpose of the research is to determine if the Geopolrisk method could be strengthened incorporating additional variables that capture environmental, social and governance factors as weighted risks associated to the share of trade imports to a country i of selected minerals.

As such, the extension of the model to include environmental, social, and economic variables, rather than solely considering political instability, constitutes a significant advancement in the ability to evaluate and manage risks. The inclusion of these additional variables responds to the increasingly interconnected and multifaceted nature of global risk factors, addressing the limitations of a purely politically-focused approach. Environmental variables bring to the forefront the tangible impacts of climate change and environmental degradation on the stability of supply chains, allowing for better prediction and mitigation of associated risks, even for political decisions. Social factors incorporate the nuances of societal changes, public sentiment, and social unrest, which can unpredictably disrupt supply chains and lead to socio-economic instability of a country. Lastly, the addition of economic variables offers a more comprehensive analysis of the financial resilience and economic interdependencies of nations. This extended model proposes a more holistic understanding of the broad spectrum of risks to national stability and the global supply chain, enhancing the capacity to anticipate and manage potential disruptions. By recognising the interplay and intersectionality of these factors, we can create more robust, resilient, and sustainable systems.

The extension incorporated environmental, social, and economic variables instead of only contemplating the political (in)stability (g_i) proposed by Gemechu et. al (2015) in the original Geopolrisk method. The modification only substituted the political (in)stability (g_i) from the previous formula, and introduces a new composed weighting factor calculated as:

$$GPRS_2 = HHI_{PROD} * \sum_i \frac{ESGi * f_{AiC}}{PAC + FAC} \dots \dots \dots \text{equation (3)}$$

Where:

ESG_i = geometric mean ($\sqrt[n]{x_1 * x_2 * \dots * x_n}$) of social, environmental and governance indicators of country i , as measured by the Notre Dame Global Adaptation initiative component indicators on a scale from 0 to 1, respectively.

All the rest is measured as usual as in equation (1)

The geometric mean is particularly useful when examining an average rate of change across multiple periods, especially in scenarios where values are multiplied to yield a product rather than summed up to a total. This method is frequently used in diverse fields including finance and population studies, as well as for calculating growth rates. Such sectors often deal with compound returns or changes over time, making the geometric mean a fitting tool for measuring trends accurately (Mathematical Network, University of Toronto, 2000). Rodriguez-Morales (2020) clarifies the significance of utilizing the mean metric, pointing out its capacity to normalize averaged ranges and thereby prevent any one range from overpowering the weighting. This ensures an equal effect on the geometric mean from any given percentage change in the properties under consideration.

4.1.4. Step 4: GPRS - 3 Combined assessment with the HHI_{EXP} and ESG_i modifications

The final calculation is GPRS – 3 scenario which refers to the computation of extension of the ESG_i weighting factor and the HHI for exporting countries. The idea of having the combine approach is to assess the combined effect from the two extension to the original GeoPolRisk method.

$$GPRS_3 = HHI_{EXP} * \sum_i \frac{ESG_i * f_{AiC}}{PAC + FAC} \dots \dots \dots \text{equation (4)}$$

Where:

HHI_{EXP} = Herfindahl-Hirschman Index for resource A , calculated as the sum of the squared export shares of all exporting countries.

ESG_i = geometric mean of social, environmental and governance (ESG) indicators of country i ,

4.2. Data sources and manipulation

The World Governance Indicator for Political Stability and Absence of Violence (WGI-PV), provided by the World Bank, serves as a key metric for assessing political stability or instability in countries. For the purposes of our calculations, the WGI-PV scores have been normalized, with a score of 0 indicating a highly stable country and a score of 1 representing a country that is greatly unstable. To better align this indicator with the level of geopolitical risk, we've inverted the original WGI-PV values. In this modified scale, a score of 0 corresponds to countries with high levels of stability, thereby indicating low geopolitical risk, while a score of 1 signifies countries that are highly unstable, indicating a higher level of geopolitical risk. The same logic applies to the rest of indices used in the construction of the ESG factors.

The international trade data for minerals was selected per year per country. This data was obtained through the United Nations United Nations International Trade Statistics Database (UN Comtrade) Application Programming Interface (API). An API is a “mechanisms that enable two software components to communicate with each other using a set of definitions and protocols”(Amazon, 2023.). Later, the *called* data was stored in a temporal database for future manipulations. The data identifiers for the countries are reported as per the ISO3 country code protocol and the minerals are identified under their Harmonized System codes in the 4-digit category (HS4).

The assesses minerals with their respective HS codes were chosen by their importance in the manufacturing of the lithium-ion batteries and with the effect to be comparable with previous studies (Koyamparambath et al 2022). Although the approach is on the measurement of mineral ores, there is an important fact to highlight as the selection of each mineral can vary across databases and sometimes, they are aggregated of mineral variation forms into one category, i.e. aluminum and bauxite are contained in the same group of analysis or rare earth elements such as

neodymium or tungsten into one category. For this study the minerals included in the analysis were:

Table 4.1 List of minerals used in the study

Mineral	HS-Code
Aluminium/Bauxite	2006
Cadmium Ore	8107
Cobalt Ore	8105
Copper Ore	2603
Iron Ore	2601
Lead Ore	2607
Lithium Ore	2836
Magnesium Ore	8104
Manganese Ore	2602
Natural Graphite	2504
Nickel Ore	2604
Silver Ore	2616
Rare Earth Elements (REE) (Metal compounds)	2846
Zinc Ore	2608

The data of domestic mining production was mainly obtained from the world mining data (WMD) website for the years from 2000 to 2020, from the government of Austria. In the case of lithium, the dataset was complemented with additional data from the US Geological Survey (USGS) and for the case of lithium, the British Geological survey (BGS). Likewise, this data also served to feed the estimate of the Herfindahl-Hirschman Index (HHI). The HHI was estimated by mineral as the sum of the squared share of each country contribution per year.

A key remark is the discrepancy of the reported records between databases (UN-Comtrade, USGS, BGS and WMD). One challenge when building the GeoPolRisk is the harmonized codes for minerals across trade and domestic production data. Usually, the domestic productions data reports on aggregated mineral categories or reporting codes that do not necessarily match the harmonized

code used in international trade reporting. In addition, each agency (USGS, BGS and WMD) estimate domestic production and reserves of the mineral's aggregates in different classifications. This forces to decide on how to categorize different families of minerals in one or several categories and can affect the results among different studies that estimate the GeoPolRisk.

4.3. Construction of the ESG – Environmental, social and governance factors

4.3.1. Notre Dame Global Adaptation Initiative as hub of data

The Notre Dame Global Adaptation Initiative (ND-GAIN) is a programme aimed at enhancing knowledge and addressing global challenges associated with climate change adaptation. One of its essential components is the ND-GAIN Country Index, which measures a country's vulnerability to climate change and its readiness to adapt. The ND-GAIN Country Index is intended to assist governments, enterprises, and organisations in prioritising investments, developing strategies, and allocating resources for enhanced climate change adaptation. As such they compile several data sources from different indicators (ND-GAIN, 2023). This is an advantage, as they filter relevant data from diverse official and peer-reviewed sources all in one site available in the raw (original) statistical record or normalized according to the ND-GAIN methodology.

As of today, as this is a recent tool it has been applied to a few publications. Most notably the in the article by Benzie et al. (2019), the authors highlight the transboundary implications of climate change, specifically within the context of the European Union (EU). They underscore the essential need for an understanding of the cross-border impacts of climate change for the development of effective policy responses applying the ND-GAIN methodology. However, there are other practical implementations to enhance understanding and responsiveness to climate-related threats. It is not a tool limited to a particular geography or region but is designed for universal application, aiding entities such as businesses, policymakers, and the public sector to better comprehend and react to climate-induced risks (Benzie et al., 2019).

The Notre Dame Global Adaptation Index (ND-GAIN) covers 46 indicators, including infrastructure, risk management, food capacity, water dependence, and ecosystem services, among others. Particularly, the ND-GAIN methodology scores a country's capacity to withstand disruptions while maintaining social stability and a healthy environment. The ND-GAIN index is

a combination of two scores: vulnerability and preparedness. The vulnerability score evaluates a country's exposure, sensitivity, and adaptability to the adverse effects of climate change, considering factors such as health, ecosystem services, agriculture, and infrastructure. In contrast, the readiness score measures a country's capacity to leverage investments and convert them into adaptation actions. It considers factors such as social readiness (including the WGI political stability), economic readiness (business climate, etc.), and governance readiness (ND-GAIN, 2023).

Yet, the data obtained from the ND-GAIN are the datasets in raw form. The ND-GAIN Country Index employs a comprehensive set of indicators to evaluate its own index, or that can be used for other purposes. For a detailed specification of each indicator, please refer to Annex I. These indicators are organised into six sectors of vulnerability and three components of preparedness (food, water and health sectors were left out of the scope), from which the following are relevant for this research.

In the Methodology section of this thesis, it is important to outline the simplifications made to facilitate data usage in the calculation of the Environmental, Social, and Governance (ESG) factor. Although the available data offers a high level of granularity, we restricted our focus to a single value per sector, per country, per year for inclusion in the calculation of the geometric mean. This constraint implies that any positive or negative correlations among the variables in relation to GeoPolRisk are not individually considered; instead, we utilize an aggregated value for each sector. To quantify the probability of risk, these aggregated sectoral values were normalized on a scale of 0 to 1. In this scaling, a value of 0 represents low risk while a value of 1 indicates high risk.

Table 4.2 ND-GAIN selected vulnerability and readiness indicators

Sector	Exposure Component	Sensitivity Component	Adaptive Capacity Component
Ecosystem services	Projected change of biome distribution	Dependency on natural capital	Protected biomes
	Projected change of marine biodiversity	Ecological footprint	Engagement in International environmental conventions
Human Habitat	Projected change of warm period	Urban concentration	Quality of trade and transport-related infrastructure
	Projected change of flood hazard	Age dependency ratio	Paved roads
Infrastructure	Projected change of hydropower generation capacity	Dependency on imported energy	Electricity access
	Projection of Sea Level Rise impacts	Population living under 5m above sea level	Disaster preparedness
Component	Indicators		
Economic Readiness	Doing business		
Governance Readiness	Political stability and non-violence (g_i) Control of corruption Rule of Law Regulatory quality		
Social Readiness	Social inequality ICT Infrastructure Education Innovation		

Furthermore, specific sub-indicators—namely Economic Readiness, Governance Readiness, and Social Readiness—were inversed in their original scoring system. In the modified scale, a score of 0 signifies optimal readiness and thereby a lower vulnerability, whereas a score of 1 denotes increased vulnerability due to a lack of economic, governance, or social preparedness. This inversion aims to standardize the representation of risk levels across all factors considered in this study.

While the data simplifications were made for ease of calculation and interpretation, it is crucial to note that statistical significance tests were conducted to ensure the validity and robustness of the chosen methodology. These tests were performed to assess whether the aggregated values per sector adequately represent the risk levels within each country on a yearly basis. Furthermore, the significance tests also aimed to validate the inversion method applied to Economic Readiness, Governance Readiness, and Social Readiness sub-indicators, confirming that the inversed values are reliable proxies for assessing vulnerabilities in these dimensions.

The results of the significance tests were carefully analyzed to ascertain whether the data simplifications or transformations introduced any potential bias or distortion in the representation of GeoPolRisk or the ESG factors. This step ensures that the methodology employed in this thesis is both statistically sound and methodologically rigorous, lending credibility to the study's findings.

For each indicator mentioned in the table above, the raw databases per year were downloaded and merged into one dataset. Each of these indicators, capturing environmental, social and governance factors, for each (available) country per year, were used as input for the geometric mean to calculate the ESG factor. Worth mention that the ND-GAIN website offers datasets already manipulated as well as the raw data directly from the original source. As in the first phase, the estimation of the GeoPolRisk for Canada as the importing partner was developed and automated in python.

4.4. Descriptive statistics

The study employs a multi-scenario approach—comprising Baseline, GPRS-1, GPRS-2, and GPRS-3—to assess Canada's GeoPolRisk over a 21-year period. These scenarios offer a nuanced framework for interpreting underlying risk trends and variations. Importantly, the statistical metrics summarized below serve as an aggregate representation of the GeoPolRisk results across different minerals evaluated in the study. For a detailed breakdown of descriptive statistics for each specific mineral, readers are encouraged to consult Annex II, which features individual descriptive charts for each mineral category.

The mean GeoPolRisk value progressively increases from the Baseline to the GPRS-3 scenario, which suggests escalating levels of perceived risk across these scenarios. Specifically, the mean value rises from the Baseline scenario to GPRS-3. This increment is particularly important as it represents an escalation in the average geopolrisk, implying a heightening of the general risk environment in the different scenarios.

Further nuances are revealed through the standard deviation, which also generally elevates from the Baseline to GPRS-3. This metric indicates that there is a higher variability in geopolrisk in the latter scenarios, suggesting that the data points are increasingly dispersed around the mean. This spread becomes even more apparent when considering the 'Range,' which also broadens from the Baseline to GPRS-3 scenarios, indicating that more extreme risk levels are possible in the latter situation.

Skewness and kurtosis provide insights into the shape and tail behavior of the distribution. In terms of skewness, while the Baseline and GPRS-1 scenarios lean slightly towards a right-skewed distribution, the GPRS-3 scenario almost achieves symmetry, indicated by a skewness value close to zero. This transformation in skewness is indicative of a more balanced distribution of risk levels in the GPRS-3 scenario. All scenarios exhibit negative kurtosis values, indicating a platykurtic distribution, meaning fewer outliers or extreme values compared to a normal distribution.

In summary, the descriptive statistics reveal critical insights into the evolving nature of geopolrisk across the four scenarios. The observed escalation in mean values and the accompanying increase in data variability highlight an increasingly complex and risky geopolitical landscape. These statistics are crucial for understanding the nuances of each scenario and form a foundational base for subsequent inferential statistical analyses.

4.5. Clustering technique

After assessing the statistical significance of the model and the descriptive statistics, a subsequent technique was applied to the results from the different scenarios. In order to assess which element from the extension proposed was relevant for the analysis, a k-mean cluster was used to categorize minerals into groups.

In the scope of this thesis, K-means clustering was employed for categorizing critical minerals based on the risks and market concentration factors. Specifically, these four attributes serve as the centroids for clustering: Governance Indicator (g_i), Environmental, Social, and Governance factor (ESG), Herfindahl-Hirschman Index for Exports (HHI_{exp}), and Herfindahl-Hirschman Index for Production (HHI_{prod}).

The K-means cluster was coded in python. Initially, the K centroids were selected, where each dimension represents one of the selected attributes: g_i , ESG, HHI_{exp} , and HHI_{prod} . Then, each mineral was allocated to the closest centroid, calculated by minimizing the sum of squared distances in the four-dimensional attribute space. After the cluster assignments, the centroid for each cluster was recalibrated. This involves calculating the mean value of each attribute for all minerals assigned to that specific cluster. Finally, these steps are reiterated until the centroids stabilize, signifying the algorithm's convergence to an optimal set of clusters.

CHAPTER 5 CASE STUDY: CANADA'S LITHIUM-ION BATTERIES

This section describes the results obtained in terms of the development of the tool and presents the case study of the Canadian supply risk evolution of the critical minerals found in the lithium-ion battery from the year 2000 to 2020. The calculation tool was automated allowing to perform the calculation of the supply risk calculations and downloaded the results for further analysis.

5.1. Results

This GeoPolrisk evaluation was done for the years 2000-2020 and the results obtained are shown in this chapter. Results show that the extension of the ESG factor are not significant. Yet, the bigger pattern change is found in the comparison of the HHI approach. To understand this, the first section shows the results for each GPRS scenario for all the minerals assessed.

Further in the analysis, the results are presented in two groups, the first are minerals that presented a higher risk mainly explained by the weight on the risk factor associated to the share of imports (the WGI or the ESG factors) and the other which was mainly driven by the HHI. This is an efficient way to understand in different layers the source of risk, derived from the geopolitical configuration of the production and trade of the minerals.

The first group where the ESG factor contribute more to the explanation of the risk include cadmium, cobalt, lead, rare earth elements and magnesium. The defining trait of this group is its reliance on extraction from one or two predominant country producers. The second group, which resulted in a higher risk for mainly driven by the modification of the HHI (export) are copper, graphite, iron, lithium, nickel silver and zinc. The results are assessed from the Canadian perspective as the importer partner.

Finally, for this section, for each category of minerals further analysis is presented in individual cases as there is no general explanation that applies to all minerals, but there is a general trend shared. The results show a pattern in the approach to assess the risk for the two groups of minerals, yet the production and trade tendencies differ from each other. The case studies are Cobalt and lithium.

It is possible to state that for countries that presented a higher risk associated to the WGI or ESG factors, such as REE, the domestic production of all is highly concentrated in one or two countries. On the other category, where the source of variation is the HHI_{exp} , the production mix is somewhat more diverse. Yet, it still can be found that for some minerals there are few producing countries, such as lithium. In the one hand, this means that where the concentration of production is higher (in this model captured by HHI_{prod}), the political stability associated to the country of major production is more relevant for the geopolrisk assessment. On the other hand, in the cases of the minerals where the country's production mix is more diverse, an analysis of the export saturation index is more relevant to understand the risk for the importing country.

Yet, the second conclusion should be analyzed case by case as this study only measures upstream supply. One limitation, that will be further explored in a subsequent section of this paper, is that the GeoPolRisk only measures upstream supply. The HHI modification approach signs that second or intermediate trade partners play an important role in the mitigation of geopolitical risk, even when the production is highly concentrated in few countries, the case of lithium.

5.1.1. GPRS baseline

Congruent with the results from Koyamparambath (2022), the following chart shows the results from the original research and the baseline GPRS of the Evolution of Canadian GeoPolRisk for selected minerals' imports from 2000-2020 shown as results from equation (1).

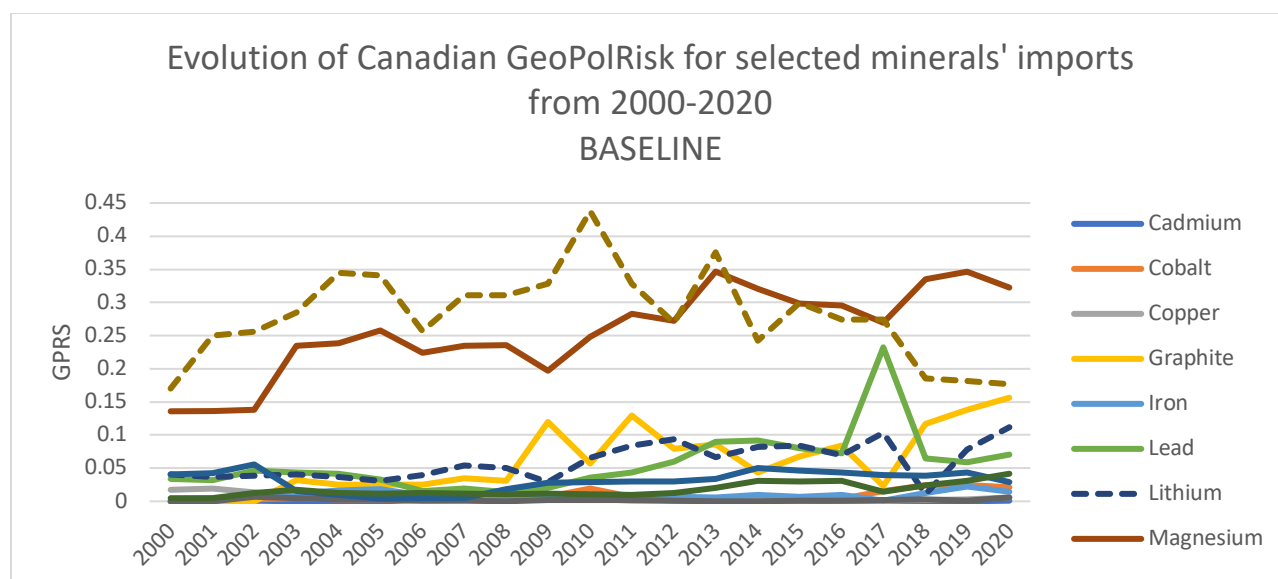


Figure 5.1 Results of the Baseline scenario

The table shows the results of the calculation of the geopolitical risk. The table includes data on the production of cadmium, cobalt, copper, graphite, iron, lead, lithium, magnesium, nickel, rare earth elements, silver, and zinc, excluding bauxite from the original study. This was due to access to data constraints.

The minerals at most risk for Canada from a geopolitical perspective are magnesium and rare earth elements followed by lithium and graphite. This is constant with the results from Koyamparambath et al (2022). However, even if the trends are similar, there is a difference in patterns between the original study and the results in this research. This is due the different sources of the datasets for each mineral and the aggregation in categories³. Is worth reminding that the main source for the production data in this study was the World Mining Data, while in Koyamparambath et al, the main source was the British Geological Survey.

³ For example, in the case of lithium, mineral ore deposits are often richer in lithium content than are salar brines, however, they are costly to access since they must be mined from hard rock formations. Due to the added energy consumption, chemicals, and materials involved in extracting lithium from mineral ore, the process can run twice the cost of brine recovery, a factor that has contributed to its smaller market share. In the World Mining data, only lithium-contend and spodumeneis sources are considered. In their projections, they exclude the extraction from lepidolite, petalite, amblygonite, and eucryptite minerals. It is estimated that while accounting for a relatively small share of the world's lithium production, all the five mineral ore deposits yield nearly 20 tons of lithium annually (spodumeneis, lepidolite, petalite, amblygonite, and eucryptite) (SAMCO,2023; World Mining Data, 2022).

Following, some observations can be made regarding the geopolitical risk associated with these materials:

First, cobalt, copper, rare earth elements, and lithium show a significant increase in geopolitical risk over the years. As mentioned in the previous sections, these materials are crucial to produce electric vehicles, renewable energy technologies, and electronic devices which can explain this trend. The increasing demand for these materials has led to concerns about their availability and the geographical concentration of their production. Countries with significant reserves and production capabilities, such as the Democratic Republic of Congo for cobalt, China for rare earth elements, and Chile for copper and lithium, have gained geopolitical leverage in these sectors. While lithium is a key element of concern to Canada, cobalt and copper risks are mitigated by the capacity of domestic production and diversification in the supply chain respectively.

Second, graphite, nickel, and zinc also show a steady production increase over the years. These materials are essential for various industries, including steel production, batteries, and electronics. The geopolitical risk associated with these materials can be influenced by the concentration of production in specific countries and concerns about supply chain vulnerabilities.

Finally, for Canada, some materials, such as cadmium and lead, show relatively stable geopolitical risk levels over the years, despite the risk increase of the lead in 2017. Even if these materials have various industrial applications, including ammunition, batteries, and electronics, they are not a main concern from this perspective. It is also important to mention that the reduction of their use can be associated with concerns about their environmental and health impacts, as well as regulations and restrictions on their use.

Also, iron, and silver geopolrisk levels remain relatively low and stable throughout the years. While these materials also have geopolitical implications, their widespread use and production in multiple countries reduce the intensity of risk.

5.1.2. GPRS – 1 : Observation of the effect HHI_{prod} vs HHI_{exp}

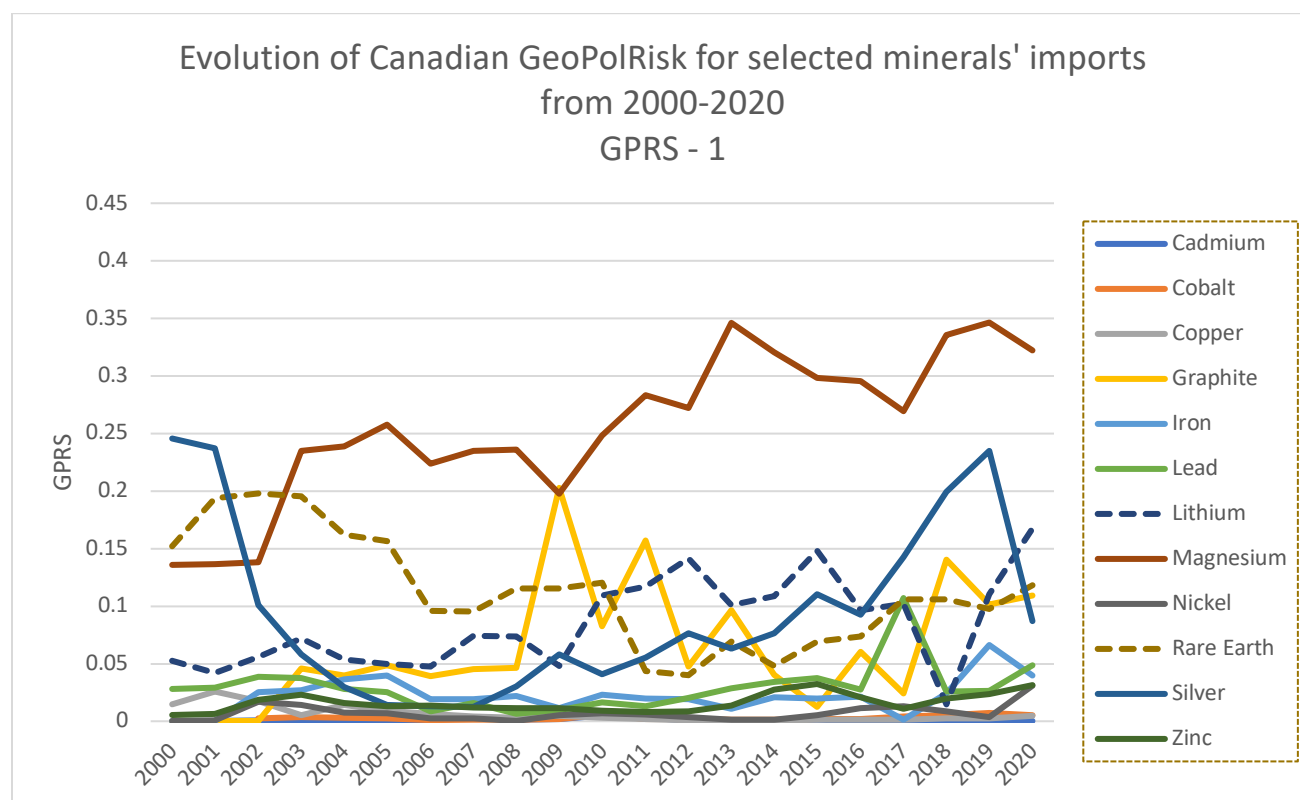


Figure 5.2 Evolution of Canadian GeoPolRisk for selected minerals' imports from 2000-2020, results of the GPRS-1

GPRS-1 scenario introduces the first substitution in the model that switch from the HHI_{PROD} to HHI_{EXP} . It refers to the calculation of the geopolitical risk keeping all the other variables the same, and only changing the evaluation of the Herfindahl-Hirschman Index for exports.

The results in the chart 19 show two major shifts. On one hand, there is a reduction effect of the Geopolrisk and on the other there is increase of it. In this first case, the main shift is seen in the rare earth elements, with a significant reduction of the risk. This behaviour is also observed in cobalt, cadmium, lead, magnesium, and zinc. In contrast, iron, nickel, silver, and lithium present the contrary behavior, an increase. Most notably from these last minerals is lithium, which it can also be seen how in the last years it keeps the increasing trend.

These initial results start to show some patterns in the clustering of the minerals. By introducing the modification of HHI_{PROD} to HHI_{EXP} , there is a general observation on how some minerals shift their trend. Typically, the increase of the geopolrisk is attributed to minerals with more complex supply chains. The comparison between GPRS-baseline and GPRS-1 provide an opportunity to compare how the evaluation of HHI_{EXP} captures the accessibility to minerals trade. This can connote that Canada is only taking advantage of a portion of the whole supply, or that the upstream in the chain is highly dominated by few players. Further in the discussion section.

Correspondingly in the opposite shift, the diminution of risk is observed in the minerals where domestic production is found in very few countries, hoarding more than half of extraction, or in other words, a high concentration upstream along the supply chain. Typically, as mentioned in the literature review, this is due the geographic distribution of the minerals and extraction capacity.

Additionally, there are minerals with mixed results; this is the case of copper, graphite. IN GPRS-1, there is a higher risk in the early years (2001-2004) compared to GPRS-Baseline, but then generally shows a lower concentration in later years.

The GPRS-2 utilizes the HHI_{PROD} index and incorporates the ESG factors (Environmental, Social, Governance) as a critical weighting factor. This approach of integrating the ESG factor acknowledges for a more holistic representation of risk trying to capture disruptive geopolitical factors that could obstacle the continues supply of minerals, compared to the previous model which employed a weighting factor (gi) exclusively focused on political stability.

5.1.3. GPRS – 2: Incorporation of ESG factors

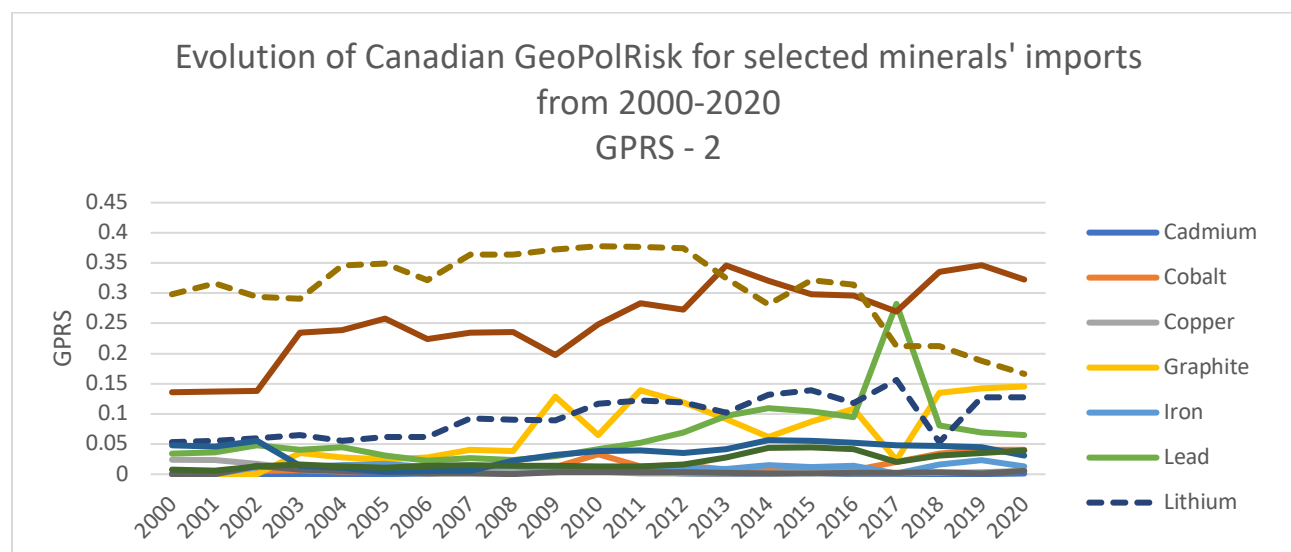


Figure 5.3 Evolution of Canadian GeoPolRisk for selected minerals' imports from 2000-2020, results of the GPRS-2.

When we delve into the differences between the GPRS-2 model and the original baseline model, similar trends and patterns emerge across various metals. The GPRS-2 model generally illustrates more pronounced fluctuations across most minerals, suggesting a slight increase in the level of volatility, yet not significant. Particular elements, like cadmium, cobalt, graphite, and lead display considerable differences between the two scenarios. This is consistent with the results observed in GPRS-1, meaning that countries with high concentration of production perform similarly across GPRS scenarios. Cadmium displays a rising trend from 2000 to 2020, though its trajectory under the GPRS-2 model is steeper than the baseline, reaching a maximum in 2010. Cobalt, while following a similar overall trend to the baseline, manifests a more pronounced peak around 2010 under the GPRS-2 model. Graphite undergoes a substantial surge, culminating around 2020 in the GPRS-2 model. As for rare earth, they follow a trend that closely mirrors the baseline, albeit with higher values in the GPRS-2 scenario.

The trend observed in Lithium is of note as it is the sole metal that portrays an increase followed by a decrease in both models. Meanwhile, the rise of Magnesium and the decline of copper remain consistent trends across both scenarios. Iron's trend under the GPRS-2 model echoes the baseline

scenario, peaking in 2001 and subsequently declining until 2019. Lead reaches its highest in 2017, with the GPRS-2 model indicating a significantly higher peak than the baseline scenario. Finally, nickel, under the GPRS-2 model, initially dips and then ascends, following a similar trend to the baseline scenario, but with an elevated value scale.

Upon examining the results of the GPRS-2 model that integrates the ESG weighting factor, it becomes apparent that the incorporation of this new metric does not significantly enhance our understanding or evaluation of geopolitical risks associated with various metals. The original g_i factor, focused on political stability, appears to have effectively captured much of the variation observed across the trends. Consequently, while the ESG factor provided a broader perspective, incorporating environmental, social, and governance considerations, it did not substantially contribute new, unique information or insights to the model. This suggests that political stability remains a dominant and significant influencer in determining geopolitical risk in the context of mineral production and availability. More on the possible reasons for this explanation in the discussion sections.

5.1.4. GPRS – 3 Evaluation of the geopolitical risk, HHI_{exp} and ESG

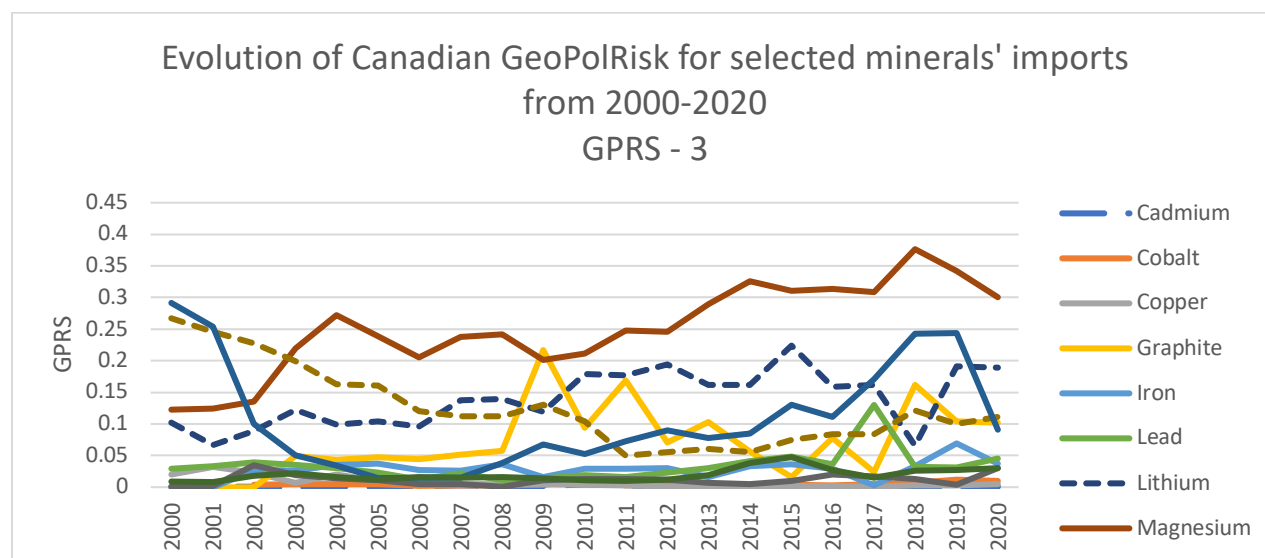


Figure 5.4 Evolution of Canadian GeoPolRisk for selected minerals' imports from 2000-2020, results of the GPRS-3.

The GPRS-3 model evolves from the previous models by incorporating the two proposed modifications in this study. Instead of relying on the Herfindahl-Hirschman Index (HHI) for domestic production, it utilizes the HHI for exports. Moreover, it replaces the political stability component (gi) with the broader ESG factor, thereby capturing environmental, social, and governance aspects.

When comparing GPRS-3 to the GPRS-1 model, a striking similarity is observed in their trend patterns, further underscoring the idea that the essence of geopolitical risk captured by these models remains consistent. Interestingly, the baseline and GPRS-2 models also demonstrate a similar trend pattern, rejecting the hypothesis that the inclusion of ESG significantly alter the risk assessment, despite its broader purview.

As such, from the observation of the 4 scenarios, the primary conclusion drawn from these analyses is the multi-dimensional nature of geopolitical risk, consistent with previous studies (Koyamparambath, 2022). The first dimension is market concentration. As evidenced by the HHI's switch from domestic production to exports, the focus has shifted to ensuring diversity in import sources for Canada. This means that even if a single country monopolizes production, the risk can be mitigated if importing countries have access to diverse sources. Consequently, countries that produce significant quantities of a mineral may not always be the most reliable or sole source due to trading patterns, value chains or hoarding practices.

The second dimension involves the probability of disruption in the producing country, which could directly impact the extraction and supply chain of the mineral. This dimension is largely determined by the country's political stability, which often implies a commitment to sustainable practices, hence the strong correlations with the ESG factor.

To better understand the statistical underpinnings of the different scenarios, a comprehensive statistical significance analysis and correlation evaluation follows. This provides an in-depth view of the model's nuances and a more detailed understanding of its functionality and implications.

5.2. Analysis

For the effect of analysis, the results are presented based on two minerals, lithium, and cobalt. Even if the method evaluated the evolution of risk for each mineral, the results from these two minerals were constant across most of them, hence the two minerals represent a case analysis. For reference of the significance assessment for the other minerals, refer to Annex II.

5.2.1. Lithium

As seen in the figure below, the model that suggests more risk is GPRS-3, this is the measurement of the Geopolrisk using the HHI for exports countries and the ESG_i weighting factor. Even is the trend is changing, the Following scenario is GPRS-2 and in more recent years, GPRS-2. The statistical analysis shows a highl correlation, and the results are not significative Yet, the scenarios that carried more weight are the ones using the HHI_{exp} modifications, demonstrating that the risk is mainly associated with the importance of the diversity of the trading partners. Less important are the scenarios with the HHI production, either for the measurement with the g_i or the composed ESG factors.

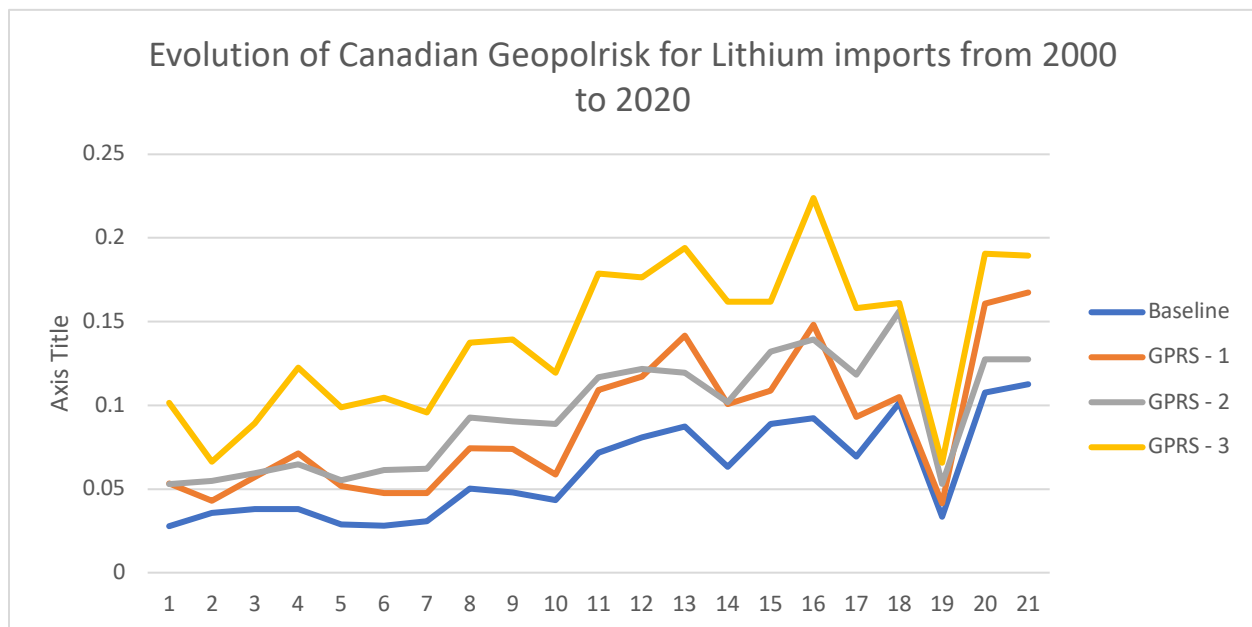


Figure 5.5 Evolution of Canadian Geopolrisk for lithium imports from 2000 to 2020

In the case of lithium, taking the baseline results, the shift of the HHI and the extension to the ESG factor, we observe a high correlation between the different scenarios. Figure 22 show the correlation matrix of the measured GPRS scenarios of lithium respectively. This is not surprising, as the extension of the methodology contains the political (in)stability factor (WGI-PV) in the governance (G factor from ESG) composed component. This is the case of lithium, copper, graphite, iron, nickel, silver, and zinc.

Table 5.1 Model correlation matrix for lithium

Baseline		GPRS - 1	GPRS - 2	GPRS - 3
Baseline	1			
GPRS - 1	0.94753274	1		
GPRS - 2	0.94199655	0.85702147	1	
GPRS - 3	0.87784405	0.93602793	0.9011431	1

There is a high correlation for all the models analyzed. The high relationship between GPRS-1 and GPRS-3 shows that even with the aggregation of environmental, social, and other governance factors (ESG), the political (in)stability WGI-PV explains as much as the ESG factors for the final risk assessment. It also indicates strong positive linear relationships between the all the GPRS scenarios. The high correlation between these variables suggests a consistent pattern of association. This exercise was included to assess if any was better at capturing the variability in the data, and to see if the GPRS-2 and GPRS-3 models were capturing different aspects of the data. In essence, this analysis helps to determine the reliability and stability of the models, and whether the changes in model inputs or parameters lead to significant changes in model outcomes. In this case, the baseline model, the replicability of the previous studies, captures most of the relevant data to provide a strong analysis when assessing the Geopolrisk, in this case Canada.

Continuing with the analysis, a further review of the factors that constitute the ESG indicator was conducted. As such, as the table below shows, the correlation between environmental, social and governance ESG factors were not as high as the total correlation. This is positive as it indicates that there is minimal or no linear relationship between these variables. This means that changes in one indicator is not likely to predict or cause systematic changes in the other. Consequently, each indicator might be capturing unique, distinct aspects of the phenomenon being studied, thus adding

independent value to the analysis. As such, for the assessment of correlation of ESG factors, each mineral should be analyzed separately as they are based on their trading partners and main producing countries for that mineral.

Having said that, in the case of lithium, the highest correlation with the political stability factor is Governance and Habitat indicators. As expected, the high correlation of the Governance factor, from the ESG extension, is highly correlated with the WGI-PV(g_i), as this indicator is included in the Governance estimation.

Also, a second indicator that has high correlation with the original measurement (weighting only with g_i) are those explaining habitat. The habitat sub indicators, as indicated before, is also composed by some quality of trade and transport-related infrastructure variables such as paved roads and estimation of flood hazards.

The indicators that show less correlations are social aspect, infrastructure and economic readiness, Ecosystems also present a relative low correlation. This might be understood from the nature of the indicators used in each category. They are measurements of the preparation of each nation to facilitate international trade like the economic readiness, physical characteristics that help face the challenges imposed by current climatological disasters like infrastructure, or that, in a way mitigate the possible effects of climate change on communities, like the factors captured in social.

Table 5.2 Correlation matrix for risk elements ESG and WGI-PV(g_i) for lithium

	<i>Economic (ESG)</i>	<i>Governance (ESG)</i>	<i>Social (ESG)</i>	<i>Ecosystem (ESG)</i>	<i>Habitat (ESG)</i>	<i>Infrastructure (ESG)</i>	<i>Political Stability (g_i)</i>
Economic (ESG)	1						
Governance (ESG)	-0.4921699	1					
Social (ESG)	0.41418125	-0.0104491	1				
Ecosystem (ESG)	0.43231402	0.04686555	0.66439486	1			
Habitat (ESG)	-0.4048842	0.61909964	0.04948596	0.41247208	1		
Infrastructure (ESG)	0.52881306	-0.2475119	0.20165475	0.27543577	-0.114717	1	
Political Stability (g_i)	-0.0019706	0.67850966	-0.0810654	0.23232689	0.55928384	0.185372719	1

5.2.2. Cobalt

As seen in the figure below, the model that suggests more risk is GPRS-2, this is the measurement of the Geopolrisk using the HHI for production countries and the ESG_i weighting factor. Followed by the baseline assessment which is the original formula used to calculate the GeoPolRisk. These two results, consistent in the trend, even though they are highly correlated, and the results are not significant, demonstrate that the risk is mainly associated with the importance of the trading partners. Less important are the scenarios with the HHI export modification, either for the measurement with the gi or the composed ESG factors.

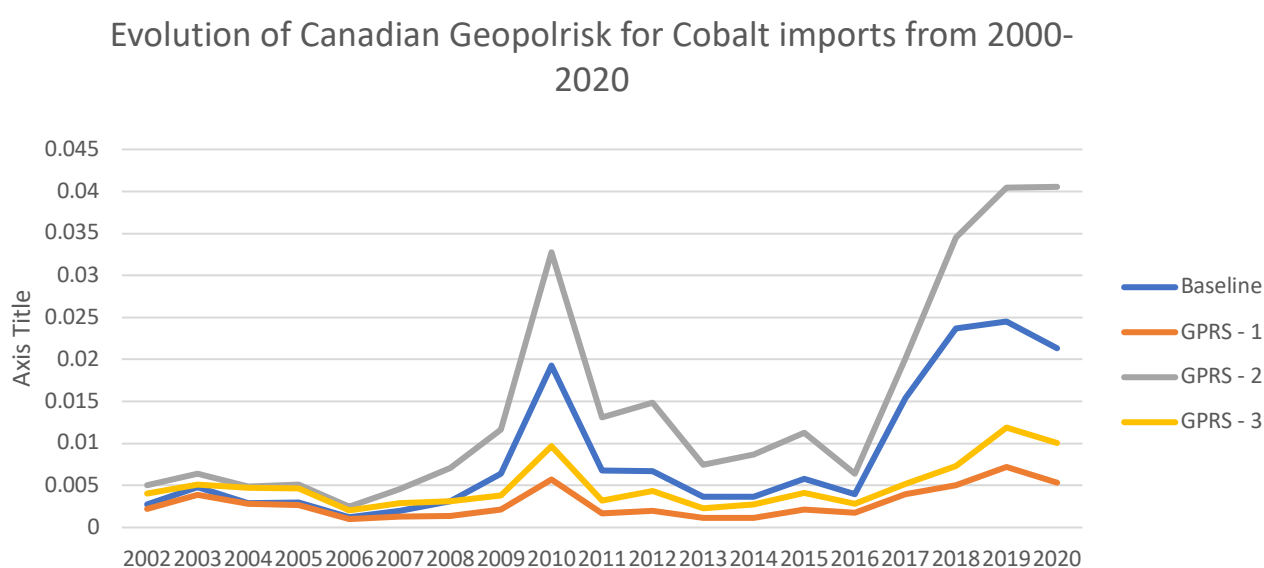


Figure 5.6 Evolution of Canadian Geopolrisk for cobalt from 2000-2020

To see that more clearly, the next chart shows how the factors with more weight in the equation are the ESG and HHI_{prod} . In such cases, the risk assessment for this type of minerals relies much on the factors that might affect local production. As there are few countries to assess the risk from, as the production is highly concentrated in just a few nations, the impacts of any of the environmental, social or governance factors takes more importance. This might be evident at a first look, however the approach to mitigate this type of risk implies to eventually deal with the risks that directly affect production rather than along the supply chain. More on the discussion.

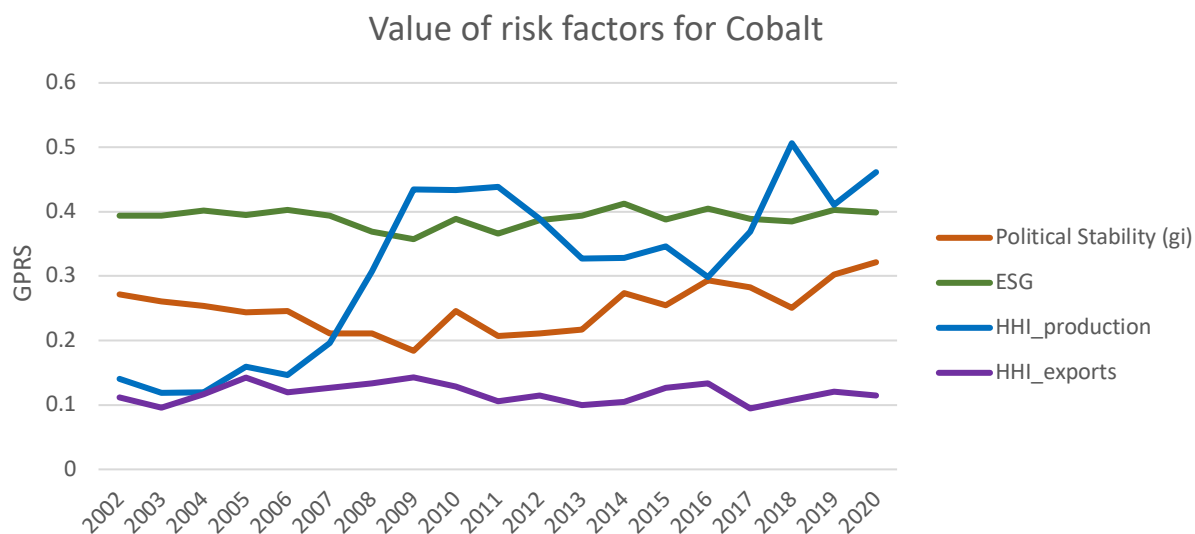


Figure 5.7 Value of risk factors for Cobalt

Nonetheless, an important remark for cobalt in the context of lithium-ion batteries is that, unlike other metals, cobalt is rarely found in its pure form. A small quantity is produced specifically from one of several metallic-lustered ores, such as cobaltite (CoAsS). However, the vast majority comes from ore usually produced as a by-product of copper and nickel mining. More recently, an increasing percentage also comes from recycling products that contain cobalt (The cobalt Institute, 2019).

As seen from the correlation matrix, there is high correspondence between the different scenarios. Correlations between scenarios they range from 0.87 to 0.97, all of which indicate strong positive relationships. This suggests that these three models align closely in their assessments and shifts in one scenario are likely to reflect similar shifts in the others. In summary, this matrix illustrates that all models are strongly positively related to one another for Cobalt, with the closest correlation observed between the Baseline model and GPRS - 2.

Table 5.3 Correlation matrix for Cobalt

Baseline		GPRS - 1	GPRS - 2	GPRS - 3
Baseline	1			
GPRS - 1	0.9048446	1		
GPRS - 2	0.98184124	0.8767699	1	
GPRS - 3	0.8970767	0.96968665	0.91326885	1

Next, it becomes crucial to examine the individual indicators that constitute the ESG aggregation to grasp their correlation. Given that ESG serves as the primary risk driver for these types of minerals, it is essential to understand how each category captures the various facets of environmental, social, and governance risk factors. One characteristic that prominently emerges is the high correlation among the Governance indicators, particularly those associated with institutional regulations and capacities. For instance, cobalt presents a strong correlation between governance, social, and economic factors, mirroring similar trends observed with cadmium, lead, rare earth elements (REE), and magnesium. The results can be seen in the figure below.

Table 5.4 Correlation matrix for risk elements ESG and WGI-PV(gi) for Cobalt

	<i>Economic (ESG)</i>	<i>Governance (ESG)</i>	<i>Social (ESG)</i>	<i>Ecosystems (ESG)</i>	<i>Habitat (ESG)</i>	<i>Infrastructure (ESG)</i>	<i>Political Stability (gi)</i>
Economic (ESG)	1						
Governance (ESG)	0.60678648	1					
Social (ESG)	0.70343872	0.78711357	1				
Ecosystems (ESG)	0.3103538	0.69987865	0.54505448	1			
Habitat (ESG)	0.50340697	0.50341847	0.56533286	0.55735095	1		
Infrastructure	0.12768858	0.04448071	0.19527062	-0.1376586	-0.0650527	1	
Political Stability (gi)	0.49940527	0.88459528	0.62869881	0.56712748	0.31318455	-0.066674	1

After the revision of the two case minerals, we can arrive to two general conclusions. First, one could argue that countries with higher measurement risk levels related to gi or ESG factors, like Rare Earth Elements (REE) or cobalt, have their domestic production predominantly concentrated in one or two nations. Conversely, in scenarios where the HHI_{exp} provides the source of variation for the measurement of the GeoPolrisk, the production composition tends to be more varied. However, it's worth noting that certain minerals, such as lithium, are produced by only a few countries.

In congruence with the post-analysis of the clustering, it emerged that HHI_{prod} and HHI_{exp} were the most pivotal centroids in determining the clustering outcome. This implies a pronounced importance of these two indices in assessing the criticality and market dynamics of minerals. The significance of a high HHI_{prod} value indicate that minerals produced by a monopolistic or oligopolistic set of entities are likely to be more sensitive to market distortions and therefore may fall within a particular risk-prone cluster. Conversely, a high HHI_{exp} value could denote that the exports of a mineral are concentrated among a few nations, rendering the mineral particularly vulnerable to geopolitical instabilities.

On one side, this indicates that when production concentration is high (captured in this model by HHI_{prod}), the political stability or ESG factors associated with the principal producing country becomes a crucial factor in assessing geopolitical risk. On the flip side, for minerals with a more diversified production mix, it becomes more important to analyze the export saturation index to comprehend the risk for the importing country.

However, the second conclusion warrants a case-by-case examination as this study only measures upstream supply. A key limitation, which will be discussed in more detail in a later section, is that the GeoPolRisk solely accounts for upstream supply. The modification to the HHI approach suggests that second or intermediate trading partners significantly contribute to geopolitical risk mitigation. This holds true even when production is intensely concentrated in a few countries, as is the case with lithium for Canada.

Then, we can draw a table of two clusters: the first where the measurement of the GeoPolRisk is driven by the ESG factor associated with the risk of disruption in the extracting nations. In this side, the ESG factor is the driver for assessing the risk, however, the HHI_{prod} is fundamental to understand the saturation risk. The other cluster are the countries where the saturation index of the exporting partners counts more.

We can subsequently create a bifurcation of two clusters: The first cluster is characterized by the GeoPolRisk measurement being primarily influenced by the ESG factor, which is associated with

the risk of disruption in the extracting nations. Here, while the ESG factor serves as the primary driver in risk assessment, the HHI_{prod} becomes pivotal in understanding the saturation risk. The second cluster, on the other hand, comprises countries where the saturation index of the exporting partners carries more weight in the risk evaluation. The following table summarizes which minerals follow each cluster.

Table 5.6 Groups of minerals by factors

Factor	HHI_{prod}	HHI_{exp}
ESG gi	Cadmium Cobalt Lead Magnesium Rare elements	Iron Lithium Nickel Silver Zinc

The two factors (HHI_{prod} and HHI_{exp}) are the main drivers to cluster two different groups of minerals. HHI_{prod} is linked with an ESG (Environmental, Social, Governance) grouping of minerals which includes Cadmium, Cobalt, Lead, Magnesium, and REE. This implies that for these minerals, the geopolitical risk measurement is mainly driven by the concentration of their production and associated ESG factors in the producing countries.

The second group associated with HHI_{exp} includes Iron, Lithium, Nickel, and Silver. This suggests that for these minerals, geopolitical risk evaluation is largely influenced by the concentration of their exports rather than production. The concentration of exports can affect the availability of these minerals in the global market, especially if a few countries dominate the exports.

As a note, copper and graphite have mixed results of the GeoPolRisk, interchanging the preponderance of HHI_{prod} and HHI_{exp} throughout their evolution. This might represent a venue for further analysis to explore which are the drivers that contributed to the shifts. However, as the current risk they represent for Canada is controllable, no further analysis will be conducted for these minerals. More information on the evolution of each, refer to Annex.

5.2.3. Cluster of minerals where the ESG factors contribute more to the risk.

This group of metals are cadmium, cobalt, lead, magnesium, and rare earth elements. All of these have a common characteristic of being largely produced by one or two countries. In 2020 in the case of cobalt, Congo is the major producer almost with almost 70% of global extraction. Interestingly, for lead, cadmium and rare earth elements, China accounts for almost half of the global production for the first two and almost monopolizes the market with more than 70% of global production of rare earth elements. Not to mention, that at the refinery stage, China controls most of the markets for all the previous minerals (The Observatory of Economic Complexity, OEC, 2023)

The minerals that display a high concentration of production, as manifested in the results, have a measurement risk that leans more heavily on the factors affecting domestic production. These factors encompass political stability (or lack thereof) as well as the environmental, social, and governance aspects related to the importing country's share from such producer nations, predominantly Congo and China for cobalt and REE. Reinforcing these findings is the fact that the weighted results for HHI_{prod} consistently exceed those of HHI_{exp} . A distinguishing trait of this group is the higher score of HHI_{prod} over the export measurement across all instances, as seen in figure 27, using Cobalt as an example.

It should be emphasized that while the general trend holds, the specifics change with each mineral, influenced by the unique production structure and the associated risk factors. Taking Cobalt as an instance, although Congo is the major producer, Canada's risk of import dependency is low due to its reliance on domestic production. Yet, in 2019, Canada's contribution to global production was slightly over 3% (OEC, 2022). This analysis brings to light that risk assessment is more tied to the factors impacting domestic production within the importing nations.

5.2.4. Mineral cluster with predominant export saturation

The second group encompasses iron, lithium, nickel, silver, and zinc. This cluster is primarily steered by the Herfindahl-Hirschman Index (HHI_{exp}), regardless the ESG or g_i factors. This implies that the degree of market concentration plays a more pivotal role in shaping the geopolitical risk

for these minerals than the average environmental, social, governance (ESG) or governance indicators of the producing countries.

In other words, the risk associated with these minerals hinges more significantly on the diversity, or lack thereof, of exporting nations. A higher HHI value, indicating a more concentrated export market, poses a greater risk as it amplifies the potential impact of any disruptions in supply from dominant exporting countries.

Nonetheless, it is crucial to underscore that this perspective does not necessarily suggest a diversified production landscape. Taking lithium as an example, while the production of this mineral is considerably concentrated in a few countries - Chile, Australia, Peru, and Bolivia - its supply chain to Canada is much more diverse. Canada procures lithium from several countries, including the United States, Slovenia, and directly from a major producer like Chile. As such, the geopolitical risk associated with lithium, stemming from the ESG or governance indicators of the producing countries, is attenuated by Canada's reliance on multiple, intermediate exporters. This, in turn, decreases the potential impact of disruptions in any single source country on Canada's lithium supply. Further discussion on the implications will be provided in the following section.

CHAPTER 6 DISCUSSION

This section discusses the results from the modification to the GeoPolRisk method and its potential significance for Canada's risk assessment on the critical mineral imports. The results obtained in the previous section are discussed to understand what they mean and how they contribute to academic practice. From the previous results we can derive three main conclusions to further discuss in this section.

The first deals with the aggrupation of mineral (data management). While most of the data collected were searched for their ore production capacity (not including reserves), a decision is made into which categories to add into each mineral or, alternatively, determine which Harmonized Code (HS) is to be used to measure the trade exchange and try to have the same data for production.

Second, as Koyamparambath et al. (2020) stated, the newest GeoPolRisk method measures supply disruption risk (as a function of probability and vulnerability). It is in this context that the inclusion of environmental, social and governance factors encompasses value to the analysis. More than pondered or averaged weighted variables, the inclusion of (specially) environmental and social factors that might affect the production of the minerals necessary to produce lithium-ion batteries contribute to the understanding of supply disruption risk. More so, now that climate data is becoming available, and we are starting to see the increase in frequency and higher magnitude of environmental catastrophes. Though, as in the case of the selection of primary data to control for mineral's production and trade, the selection of the indicators is key to assess the real risks.

This selection of indicators leads to the third conclusion, also well perceived in the case of cobalt and the group of minerals in which the results showed a high importance in the assessment of ESG factors. For this study, the selected the environmental, social, and economic factors presented high correlation with the previous indicator – political (in)stability from the World Governance Indicators. This can be explained as an institutional condition or capacity in countries with a higher score in their political stability. More politically stable nations, often rely on democratic or participatory mechanisms that allows for regulatory frameworks or adaptive instruments to respond to climate change effects or disturbances in the social sphere.

6.1. Data management

The first challenge of the study is the data mining and the categorization decisions involved. Although international trade is classified according to the Harmonize Code (HS), sometimes the data on domestic production does not follow the same classification. HS covers 98% of international trade identifying products exported or imported across borders. This code has 6–10 digits depending on how much countries want to segregate. It is precisely in the segregation of the components, that the matching between domestic production data and international trade is not completely equivalent. Some differences in results with previous studies may derive from this annotation.

In addition, there is a second level of discrepancy in the aggregation of data in the domestic production databases. For effects of traceability, for this research the sources considered for obtaining the domestic production data were the US Geological Survey and, trying to complement, the data from the British Geological survey. Evidently, the different methodological approach for data collection reflected a different in the reported numbers. This just shows how the classification of minerals is important for a specific desired outcome. For settling reasons, as explained in the methodological approach section, the main data source used was the world mining data. Ultimately, while this is not a problem that has big implications for Canada in the risk assessment analysis, it is a factor to consider when establishing the traceability baseline as some quantities may be adjusted.

6.2. Herfindahl-Hirschman Index perspective shift

Koyamparambath et al original contribution to the field of Geopolitical Risk involves two key elements in its calculation. First is the use of the Herfindahl-Hirschman Index (HHI) for production, which helps capture upstream market concentration. The second is the inclusion of risk - represented through political stability - associated with the proportion of imports to the country under evaluation, which considers domestic production.

In this paper, the framework has been expanded to consider additional risk factors that could potentially impact the share of imports. This extension shifts the focus from merely looking at the concentration of producers to assessing the concentration of exporters - a shift represented by the

inclusion of HHI for exports. This new perspective enables a more comprehensive understanding of geopolitical risk, accounting not just for production instability, but also for potential disruptions in the export market.

In essence, the HHI_{exp} measures the concentration of trade across the exporter partners. The intention behind this approach is to capture part of the intermediate trade risks. Whereas the original GeoPolRisk captured the risk at the upstream of the chain, either for market concentration or risk at production, the extension of the HHI exports allows for an additional assessment of intermediate trade that is not captured before and how this affects the risk perception. Again, this approach is not efficient in doing so, however it captures an occurrence in which the upstream producer country might not determine as much the risk, as the concentration in the supply chain. This is relevant in cases where trade exchanges are conducted mainly bilaterally. Or, in a lesser degree captured by this approach, when extracting countries do not export the totality of their production and instead is refined in-situ. This is the specific case of China.

For the case study of Canada in the evaluation of the mineral provision necessary for the lithium-ion batteries, this distinction is pertinent. Especially considering the results of this research, that shows that export concentration affects the risk analysis of several minerals including copper, graphite, iron, lithium, nickel silver and zinc. Distinctly, each case is, especially in the configuration of their export network, but a generalization is applied. For example, the case of lithium ores were the results showed that for Canada, this mineral risk is skewedly driven by the probability perturbation derived by the concentration in the exports. Lithium is a mineral with a high production HHI concentration. Yet, as seen in the diagram below, the exporter partners are limited, with the United States as the main trade partner being one of the small producers of lithium in the world and interestingly, Slovenia, without being a producer of lithium ores.

This study indirectly hints at an avenue ripe for future research: the concentration of trade flows in the global lithium market. Notably, most of the world's lithium flows to China. For example, over 90% of Australian lithium exports are destined for China. Interestingly, China's principal sources of imported lithium carbonates in 2019 were Chile, followed by Argentina, the Republic

of Korea, and Japan, (WITS, 2022). This suggests a multi-layered landscape of trade flow concentration that warrants a more nuanced examination.

Building on this, another focal point for future investigation is the importance of export concentration in addition to production concentration. For instance, Australia, despite being the largest producer of lithium globally, engage in little trade of lithium with Canada. However, due to Australia's significant role in both lithium production and exports, its impact can still be gauged indirectly through the Herfindahl-Hirschman Index for Exports (HHI_{exp}). This perspective allows for a more comprehensive evaluation of GeoPolRisk, even in the absence of direct or modest lithium trade between Canada and Australia. Therefore, an analysis that incorporates both exports and production metrics could offer a more complete picture of geopolitical risk in the critical minerals sector.

6.3. Correlation analysis

A second insight emerged from the analysis of the results. As mentioned in a previous section, the incorporation of environmental, social and governance indicators in addition to the measurement of political (in)stability from the World Governance Index (WGI-PV) was not significant. We found a high correlation between these categories, especially among the social and governance components.

Generally, countries with a high score in the WGI-PV index tend to base their normative and regulatory mechanisms exerted on institutions by the state or society. These organizational frameworks often promote the creation or adhesion to international protocols or National Development Plans encompassing the protection of the environment, and social and economic wellbeing.

To this regard, Adebayo et al (2022) recognize that Institutions can have a direct or indirect impact on the quality of the environment via regulations and policies. Even if numerous proxies for measuring institutional quality have been proposed in the literature political stability, and rule of law are the most prominent indications of a successful and well-functioning governance framework (Adebayo et al., 2022) . In addition, Wang et al (2022) justify that a functional

institutional structure is required for the development and application of sustainable initiatives. The authors continue explaining that, a strong administration with an anti-corruption attitude can establish an effective strategy that will be implemented across the country through strict rule of law (Wang et al., 2022)

To this research, the selection of the environmental, social and governance indicators relied strongly in available data. As the database source was the Notre Dame Global Adaptation Index ND-GAIN, it tracked most of the sub-indicators from institutional sources measuring the capacity of each nation-state to face the effects of climate disaster, changes in social indicators and economic resilience. All of these, incorporating the perspective of institutional capacity and/or adhesion to any environmental, human rights or economic agreement. The conclusion is that with the political stability indicator, we capture the effects on the institutional capacity of countries to respond to the risks imposed by the changing climate or social dissents. However, there conversation left is whether the political stability indicator captures the physical risks imposed by climate change. An advanced methodological refinement to consider for future research involves further disaggregating the sector-specific variables into individual indices. This would permit a more granular level of analysis, enabling to capture nuanced variations within each sector. Additionally, the process could facilitate the construction of new, more impactful variables specifically tailored to enhance the comprehensiveness and precision of the overall risk analysis. By retaining only those variables that substantively contribute to the understanding of socioenvironmental and geopolitical or market-related risks, this refined approach could significantly bolster the analytical insights for future studies.

Notwithstanding, another result from the correlation matrix showed that not all the categories used in the composition of the ESG indicator had high correlation issue. In fact, this is a new avenue to explore in future research. Infrastructure is the one category that was not correlated with any of the other factors. This points to an avenue where infrastructure could be explored to assess its pertinence in capturing the environmental impacts of climate change in alignment with the GeoPolRisk method. This is not a novel result as most of the environmental risk is conducted through the assessment of physical capacities or infrastructure. In fact, some environmental risk assessment methodologies document the risks associated with exposure to environmental threats

at a site and provides the justification for taking action to remediate or remove the threat (if possible) (IPCC, Chapter 7, 2023). The topic could be further explored along with the analysis of the new decarbonization plans of the mines in site. This leads us to the final insight.

6.4. Environmental considerations

As mentioned in the above sections, the categories utilized to constitute the ESG indicators measure level of readiness of a country to face the impacts of climate change and environmental threats. This approach does not truly capture risks consequential of the increase in climatic catastrophes, such as hurricanes, tornados, floodings, drought, and heavy rain among others.

If we retake the definition provided by Turner et al (2003) of vulnerability - the degree to which a system component is likely to experience harm due to exposure to a hazard, either a perturbation or a stress/stressor; they emphasise that this perspective on vulnerability is biocentric rather than anthropocentric because it understands environmental systems as being influenced by natural and anthropogenic drivers rather than as sources of hazards that affect human systems (Birkmann and Wisner, 2006)

Under this approach, for future research the selection of categories and indicator should aim at satisfying the risk sources that affect the (mining) system, rather than just the human system intersected. This seems and palpable conclusion, yet the difficulty relies in the availability of data and the approach to categorize the source of hazard that results in a risk.

The previous statement is relevant specially when gauging the causes that might affect local production in the mines, as that is the prime point of extraction and the beginning of the virgin critical minerals' supply chain. An example is the report from Mckinsey that concludes that severe weather conditions, coupled with rising sea levels, have the potential to harm processing or transport facilities situated close to shorelines. Also, escalating temperatures in already hot regions - notably Australia, China, and parts of North and West Africa - can lead to reduced workforce productivity and increased expenses for cooling. It also poses significant risks to the health of workers, and in certain cases, their lives could be at stake (Mckinsey, 2020).

In principle these risks were included in the configuration of the ESG indicator, but the results show that further exploration is needed to fine tune the indicators that truly capture the vulnerabilities and not just environmental or social exposure.

6.5. Affection for the mine production and export

The aim of the study is to show what are the risks that pose a threat to the supply of critical minerals used in the production of lithium-ion batteries. One proposed way to strengthen the current methods, GeoPolRisk, was to incorporate environmental, social and governance factors that could affect the production of minerals in the exporting partner countries.

At this point it is already evident that the inclusion of these factors was not significant, however they did show that composite risk factors are important in certain cases of minerals where production is concentrated in a few countries. From this perspective, the importance of considering the adequate environmental and social risk factors pose urgent attention. The probability of perturbation in the production countries signifies a major cascade effect in the chain of those minerals as there are less diversified in the supply. This is intensified when considering smelting and refining capacities. Therefore, the question remains open, up to what extent does geographical vulnerability affect production and what are its implications for the later export?

Once again, taking an environmental example, mining companies must prepare for climate hazards that vulnerate their operations. Currently, 30 to 50 percent of copper, gold, iron ore, and zinc production is concentrated in water-stressed regions. It is anticipated that climate change will increase the frequency of droughts and floods, altering the water supply and disrupting operations. Certain water-intensive mining processes can be compromised even in regions with low water stress. In the summer of 2018, a German potash miner was forced to close two locations due to severe water shortages, resulting in daily losses of nearly \$2 million per location. Noteworthy, Germany is not a country prone to drought (McKinsey, 2020).

As such, the assessment of environmental and social risk factors remains relevant as those are the stressors that might disrupt the operations in situ.

CHAPTER 7 CONCLUSION AND RECOMMENDATIONS

In conclusion, this study provides insightful observations into the geopolitical risks Canada faces in the supply chain of critical minerals, especially those utilized in lithium-ion batteries. By extending the GeoPolRisk method, the research attempts to incorporate a broader spectrum of factors, specifically environmental, social, and governance (ESG) aspects, that could potentially influence the production or export operations in trade partner countries.

Though the results established a significant correlation between ESG factors and the existing political instability measure from the World Governance Index, this study sheds light on the complex interplay of these factors and the inherent limitations in the current methods of geopolitical risk assessment. Moreover, the distinction between assessing a country's production saturation index and the impact of exportation saturation offers a novel perspective on the risks in the supply chain of critical minerals.

The findings from this research contribute valuable information to the academic discourse, and it is clear that further investigation is required to refine risk assessment methods, especially considering the increasing urgency posed by climate change and socio-economic upheavals. As the world continues to rely on critical minerals for technologies like lithium-ion batteries, understanding and managing geopolitical risk remains a crucial task for sustainability and security. This study underscores several key insights about the risk assessment of critical mineral imports for Canada, particularly those used in lithium-ion batteries.

The first conclusion revolves around data management and categorization. The process of data collection and classification was complex due to discrepancies between domestic production and international trade data. These differences underline the necessity for meticulous data categorization for achieving specific outcomes. Additionally, the study proposes a shift in perspective from production to exporter concentration in GeoPolRisk calculation. This shift, using the Herfindahl-Hirschman Index (HHI), helps encapsulate intermediate trade risks that could impact the probability of risk, particularly in countries like Canada.

The second conclusion drawn from this research is the high correlation between selected environmental, social, and governance (ESG) factors and political stability. This correlation suggests that countries with stable political environments are more likely to have the capacity to respond to risks posed by climate change and social unrest. However, this does not necessarily indicate that these countries are immune to the physical risks imposed by climate change. One surprising finding was that infrastructure showed no correlation with other factors, presenting an avenue for future exploration, particularly regarding its role in managing the environmental impacts of climate change. Or a second alternative is to deepen the level of assessment of the data at an index level for future composition of new ESG indicators.

Finally, the research highlighted the importance of understanding the social and environmental risks and their impact on mining operations and exports. While the current approach to assessing ESG factors largely focuses on a country's preparedness to face climate change and environmental threats, it does not adequately cover the risks arising from climatic catastrophes and social disturbance. Future research, therefore, should aim to identify and choose indicators that highlight the risks that directly impact the mining system. Although the integration of ESG factors into risk assessment did not have a significant impact on the results, they proved to be important in certain cases where production is concentrated in a few countries. This suggests a need for a more holistic risk assessment approach that goes beyond political stability and includes a wide range of environmental and social factors.

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APPENDIX A INDICATORS

Description of indicators used in the ESG factor

The following charts provide a brief description of the different indicators used in the composition of the ESG factors. The datasets, as well as further information of each indicator can be found in the website of the Notre Dame – Global Adaptation Index.

Table A.1 Projected change of biome distribution

Ecosystem services	Projected change of biome distribution
Description:	An indication of how climate change will impact the change of terrestrial biome biodiversity within a country by the end of the century. Data were taken from the global version of a dynamic vegetation model (MC1) (Gonzalez et al., 2010).
Rationale:	The indicator captures the threat of changes in biome function. It is based on the projected impact of climate change on the area occupied by different biomes within a country.
Calculation	The projected change is the fraction of land area within a country that is projected to become a different potential biome type under future climate (2070-2100, combining three Special Report of Emission Scenarios (SRES) and three GCMs relative to baseline years 1990.
Data Source	Gonzalez, et al. (2010). Global patterns in the vulnerability of ecosystems to vegetation shifts due to climate change.
Time Series	Single projection

Table A.2 Projected change of marine biodiversity

Ecosystem services	Projected change of marine biodiversity
Description:	An indication of how climate change will impact the change of marine biodiversity in a country's exclusive economic zones by mid-century. It is a measure based on projected changes in the distribution of 1066 exploited species of marine fish and invertebrates under climate envelope scenarios based on A1B scenarios (Cheung et al., 2009).
Rationale:	The indicator is a complement to the terrestrial biome diversity indicator, in order to capture the threat of changes in providing fishery or non-fishery marine resources.
Calculation	The projected change of marine biodiversity is the projected species turnover (invasion + local extinction) in 2050 relative to the 2001-2005 baseline. The Exclusive Economic Zones Boundaries map (World EEZ V8) released in 2014 from marineregions.org was used to aggregate the pixel-level (half-degree grid) species turnover data up to the country-level. All countries not adjacent to the ocean are assumed to have zero vulnerability in terms of marine biodiversity.
Data Source	Cheung, et al. (2009). Projecting global marine biodiversity impacts under climate change scenarios.
Time Series	Single projection
Notes	As a complementary indicator to the terrestrial biomes' biodiversity, marine biodiversity should ideally be considered in combination with freshwater biodiversity, especially for landlocked countries that count more on freshwater resources. So far, no model has been developed to produce such data that has global coverage.

Table A.3 Natural capital dependency

Ecosystem services	Natural capital dependency
Description:	Based on the World Bank's Natural Capital Accounting project. This indicator of the strength of the dependency of social systems on ecosystem goods and services is based on the deployment of natural capital in national accounting, including national income and savings in the form of all assets and capital goods that are inputs to economic well-being (The World Bank, 2011). The natural capital related to ecosystem services includes: crop, pasture, forest (timber), forest (non-timber) and protected areas. Sub-surface capital such as oil, gas and mineral reserves are not Included.
Rationale:	The indicator captures a country's reliance on ecosystem services, which are themselves exposed to disruption by climate change.
Calculation	The indicator is the ratio of natural capital over the total wealth of one country.
Data Source	The Changing Wealth of Nations: Measuring Sustainable Development in the New Millennium. World Bank (retired dataset)
Time Series	Three estimates: 1995, 2000, 2005

Table A.4 Ecological footprint

Ecosystem services	Ecological Footprint
Description:	The ecological footprint estimates the number of hectares of land and water, both within and outside the country, that are needed to meet the average demand on ecosystems services by the population's lifestyle. This is compared with the estimated capacity of a country's ecosystems to regenerate and maintain ecosystem services for either internal use or export. This indicator uses the surplus or deficit of capacity to cover the demand within each country.
Rationale:	A country with a surplus (more supply than demand) has the capacity to produce more from within its boundaries and thus is likely to have more options to adapt to a changing climate.
Calculation	-
Data Source	National Footprint and Biocapacity Accounts
Time Series	Periodic updates within data period from 1995 to Present

Table A.5 Protected biomes

Ecosystem services	Protected biomes
Description:	Taken directly from the Yale Environmental Performance Index (EPI), the indicator "assesses the protection of biomes weighted by the proportion of a country's territory the biome occupies." EPI defines the indicator as follows: "It measures the degree to which a country achieves the target of protecting 17% of each terrestrial biome within its borders, weighted by the domestic contribution of each terrestrial biome...all biome protection percentages were capped at 17% so that higher protection in one biome cannot be used to offset lower protection in another."
Rationale:	Countries with good protection of their core ecosystem types are likely to have the capacity to implement a wider range of actions to continue to protect and manage ecosystem services under a changing climate.
Calculation	The projected change is the fraction of land area within a country that is projected to become a different potential biome type under future climate (2070-2100, combining three Special Report of Emission Scenarios (SRES) and three GCMs relative to baseline years 1990.
Data Source	Terrestrial Protected Areas (National Biome Weights), Environmental Performance Index (retired dataset)
Time Series	Periodic updates within data period from 2007 to 2016

Table A.6 Engagement in international environment conventions

Ecosystem services	Engagement in international environmental conventions
Description:	An indicator based on the country's participation in international forums, which is an indicator of its capacity to engage in multilateral negotiations and to reach agreement on appropriate actions internally.
Rationale:	Although not a direct measure of capacity, the failure to take part in such forums is usually associated with either lack of technical capacity to deal with the issues and/or lack of political ability to reach decisions over appropriate engagement.
Calculation	The indicator is the ratio of a single country's current status of convention engagement to the maximum engagement among all countries. The current status is a comprehensive measure considering dates of signing in conventions, ratification of convention participation and denunciation of treaty agreement.
Data Source	Environmental Treaties and Resource Indicators (retired dataset)
Time Series	Annual from 1995 to 2011.
Notes	It has since gone stagnant and will be replaced in the future. The outcome for this indicator is strongly dependent on the process of selecting the agreements to be included. ND-GAIN includes "environmental treaties" in their broadest sense while avoiding any to do with military/warfare, gross marine pollution, safety at sea, and other shipping controls. ND-GAIN also excludes treaties directly setting up International organizations such as the World Bank etc. ND-GAIN also excludes agreements with less than 20 signatories. Some agreements have a limited regional scope (e.g. dealing with Atlantic tuna). ND-GAIN could have excluded them, but this would have limited the list (16 out of 54 have clear regional scope of application), and many were signed by countries beyond the region (e.g those with fishing fleets in the Atlantic). Many (17 out of 54) also deal with the agreements on oceans and this may disadvantage land-locked countries. However, land-locked countries are sometimes signatories to such conventions (e.g. those relating to whaling). It could similarly be argued that some agreements are not relevant to many countries on other grounds (e.g. those to do with desertification). Thus ND-GAIN retains a wide set of agreements rather than culling, thereby reducing the list to only 10 to 20.

Table A.7 Projected change of warm periods

Human habitat	Projected change of warm periods
Description:	An indication of the probability of extreme heat under climate change by midcentury. This indicator uses the Warm Spell Duration Index (WSDI), which defines periods of excessive warmth using a percentile-based threshold calculated for a calendar 5-day window in the base period 1961-1990. WSDI counts the number of days in a year when daily maximum of 29 near surface temperature exceeds the 90th percentile threshold for 6 consecutive days or longer (Alexander, et al., 2006; Sillmann, et al., 2013b).
Rationale:	Human living conditions are threatened by the increased intensity and/or frequency of extreme weather, including storms, flooding, landslides and heat waves, that climate change is bringing or will bring (Satterthwaite, 2008).
Calculation	The projected change is the absolute change of WSDI from the baseline year (1960-1990) to the future projection (2040-2070), using RCP4.5 emission scenario.
Data Source	• WSDI baseline projection (1960-1990) • WSDI future projection (2040-2070) • Sillmann, et al. (2013a). Climate extremes indices in the CMIP5 multimodel ensemble: Part 1. Model evaluation in the present climate. • Sillmann, et al. (2013b). Climate extremes indices in the CMIP5 multimodel ensemble: Part 2. Future climate projections
Time Series	Single projection
Notes	Another relevant index to measure the duration of warm spell is the Heat Wave Duration Index (HWDI), which counts the number of days when the daily maximum of near surface temperature exceeds more than 5 degree C above the mean daily maximum temperature in a calendar 5-day window in the base period 1961-1990. (Frich, et al., 2002; Sillmann, et al., 2013b). However, the 5 degree C threshold that HWDI uses is too high to detect the low variation of daily temperature, for example, in tropical areas. Therefore, an index calculated using a percentile-based threshold is more appropriate to capture various degrees of temperature variation.

Table A.8 Projected change of flood hazard

Human habitat	Projected change of flood hazard
Description:	Flood hazard is measured by the predicted, monthly maximum precipitation in 5 consecutive days (rx5day). Rx5day is defined as monthly maximum consecutive 5-day precipitation. It is a measure of precipitation extreme under climate change, a risk factor for flood hazard (Kundzewicz & Schellnhuber, 2004). The monthly rx5day data are extracted from ensemble mean of extreme indices generated by 19 GCMs (Sillmann et al., 2013a; Sillmann et al., 2013b).
Rationale:	The projected change is the percent change in the flood hazard from the baseline projection (1960-1990) to the future projection (2040-2070), using RCP 4.5 emission scenario. The annual figure is derived from averaging the monthly data.
Calculation	• rx5day baseline projection (1960-1990) • rx5day future projection (2040-2070) • Sillmann, et al. (2013a). Climate extremes indices in the CMIP5 multimodel ensemble: Part 1. Model evaluation in the present climate. • Sillmann, et al. (2013b). Climate extremes indices in the CMIP5 multimodel ensemble: Part 2. Future climate projections
Data source	• rx5day baseline projection (1960-1990) • rx5day future projection (2040-2070) • Sillmann, et al. (2013a). Climate extremes indices in the CMIP5 multimodel ensemble: Part 1. Model evaluation in the present climate. • Sillmann, et al. (2013b). Climate extremes indices in the CMIP5 multimodel ensemble: Part 2. Future climate projections
Time series	Single projection
Notes	

Table A.9 Urban concentration

Human habitat	Urban concentration
Description:	Urban concentration measures both concentration of a country's population within cities (i.e. the degree of urbanization in general) and concentration of the urban population within a small number of large population (cities of 750,000 inhabitants or more) centers via the Herfindahl Index (Henderson, 2000; Van Eck & Koomen, 2008).
Rationale:	Countries in which urban populations are concentrated in a single or a small number of urban areas are considered more sensitive to climate change (Lankao, 2008). According to this indicator, a country with a highly concentrated urban sector and a highly urbanized population is the most sensitive
Calculation	Urban concentration is the product of Herfindahl measure of concentration of the urban population weighted by the percent of a country's population that is urbanized. The Herfindahl measure takes the sum of the squared percent of the population residing in each large city over the total population in these large cities. The total urbanized population is the proportion of urban population to the total country population. Countries that do not have cities with more than 750,000 inhabitants are considered to have zero vulnerability due to high urban concentration.
Data Source	Urban population (% of total), UN Population Division, World Urbanization Prospects
Time Series	Annual from 1995 to Present
Notes	

Table A.10 Age dependency ratio

Human habitat	Age dependency ratio
Description:	An indication of the size of the vulnerable population in terms of ages. This indicator considers the population under 14 or above 65 as the vulnerable group.
Rationale:	Vulnerable age groups—under 14 or above 65—are susceptible to climate change impacts through direct and indirect channels. The direct effects of extreme weather may 31 disproportionately affect the old and the young (Wolf et al., 2010), and they may be indirectly affected by climate change impacts operating through social political structures or the economy.
Calculation	
Data Source	Population ages 65 and above (% of total), WDI; Population ages 0-14 (% of total), WDI
Time Series	Annual from 1995 to Present
Notes	

Table A.11 Quality of trade and transport infrastructure

Human habitat	Quality of trade and transport infrastructure
Description:	Logistics professionals' perception of country's quality of trade and transport related infrastructure (e.g. ports, railroads, roads, information technology), on a rating ranging from 1 (very low) to 5 (very high). Scores are averaged across all respondents.
Rationale:	Transportation infrastructure has been shown to be important for migration and development (Malik & Temple, 2009; Jayachandran, 2006). Migration away from challenging climates is important for improving human health over time (Deschenes & Moretti, 2009). The quality of trade and transport infrastructure shows the capacity to effectively supply and manage essential infrastructure by the public and private sectors. It is assumed here that same capacity is indicative of a capacity to sustain that infrastructure in the face of future changes, including climate change.
Calculation	
Data Source	Quality of trade and transport-related infrastructure, WDI
Time Series	First reported in 2007, then biennial from 2010 to 2018 for several countries. Others have no reported data available.
Notes	

Table A.12 Paved roads

Human habitat	Paved roads
Description:	Roads surfaced with crushed stone (macadam) and hydrocarbon binder or bituminized agents, with concrete, or with cobblestones, as a percentage of all the country's roads, measured in length. It reflects a country's capacity to acquire and deploy transportation improvements, especially in rural areas.
Rationale:	This is a measure of the sturdiness of the road system and all of the social and economic activity dependent upon it. This is also a measure to complement the first capacity indicator (which is mainly as a proxy to measure transport infrastructure between major cities). Paved roads capture a country's capacity to deploy transportation improvements, especially in rural areas.
Calculation	
Data Source	International Roads Federation
Time Series	1995 to 2011 but not annually for most of the countries. The frequency of data reported ranges from only once since 1995 to annual.
Notes	

Table A.13 Projected change of hydropower generation capacity

Infrastructure	Projected change of hydropower generation capacity
Description:	An indication of the potential risk of hydropower generation capacity weighted by the importance of hydropower to one country, i.e. the proportion of the electricity production from hydroelectric sources. The data of the projected change are available at the subcontinental level, drawn from (Hamududu & Killingtveit, 2012).
Rationale:	Due to the hydrological impact of climate change in the mid- to long- term (see the two exposure indicators in the water sector), climate change also is projected to directly impact hydropower generation capacity (Schaeffer et al., 2012).
Calculation	The projected change is the percent change in the hydropower generation capacity from the historical baseline (2005) to the future projection (2050), using the A1B emission scenario.
Data Source	Hamududu & Killingtveit (2012). Assessing Climate Change Impacts on Global Hydropower. Dependency on hydropower
Time Series	Annual from 1995 to 2015.
Notes	

Table A.14 Projected change of sea level rise impacts

Infrastructure	Projected change of sea level rise impacts
Description:	An indication of how coastal infrastructure will be impacted by the combined effect of sea level rise and potential storm surge by the end of the century. The indicator considers the proportion of land areas, adjacent to the ocean, that are lower than the projected sea level rise and the average height of storm surge.
Rationale:	Sea level rise due to climate change is a threat to coastal infrastructure, requiring resilient infrastructure that protects coastal areas (Lemmen& Warren, 2004; Tol, et al., 2008; Hallegatte, 2009). ND-GAIN assumes that the potential risk or damage to coastal infrastructure from sea level rise depends on the extent of coastal areas exposed to both sea level rise and potential storm surge.
Calculation	The global average of sea level rise by the end of the century under RCP 4.5 scenario is projected to be 0.32-0.63 m (IPCC, 2013). There is no consistent average height of storm surge because the factors vary tremendously. 1.5m or 2-3 m is considered to be the moderate zone (Smith et al., 2010). Taking 0.63 m of the projected change of sea level rise and 3 m of moderate height of storm surge, ND-GAIN estimates the impact to be the proportion of ocean-adjacent land areas lower than 4 m above sea level. The equal-area map projection is used to calculate land area. ND-GAIN assumes that land-locked countries do not have coastal risks.
Data Source	1 arc-minute global relief model of Earth's surface, integrating land topography and ocean bathymetry
Time Series	Single measure
Notes	

Table A.15 Dependency on imported energy

Infrastructure	Dependency on imported energy
Description:	A measure of the percentage of total energy use that is imported and thus not fully within a country's control. According to the IEA, energy use refers to the use of primary energy before transformation to other end-use fuels, equal to indigenous production plus imports and stock changes, minus exports and fuels supplied to ships and aircraft engaged in international transport.
Rationale:	The imported energy could increase in price or be cut off in crises. A higher proportion of imported energy implies higher sensitivity to price volatility and supply crises. Countries heavily dependent on imported energy are considered energy vulnerable (Gnansounou, 2008).
Calculation	-
Data Source	World Energy Balances, IEA
Time Series	Updates annually from 1995 to Present. Some countries have no reported data.
Notes	

Table A.16 Population living under 5m above sea level

Infrastructure	Population living under 5m above sea level
Description:	The proportion of the population living in the area where elevation is 5 m or less. It is a simple measure of the population sensitive to coastal risks.
Rationale:	An estimate of the population sensitive to the risks arising from seal-level rise, storm surge and similar effects, which are exacerbated by climate change.
Calculation	-
Data Source	Population living in areas where elevation is below 5 meters (% of total population), WDI
Time Series	Updated in 2000, 2010, and 2015
Notes	(1) Generally, this indicator should be continuously changing considering that many countries are experiencing population migration to coastal cities (e.g. Adebuseye, 2006; Chan, 2013). (2) A more consistent measure should be the coastal population living in areas where elevation is 4m or less, to line up with the exposure indicator (the second exposure indicator above). The population data available from the World Development Indicators database, however, are for 5 m.
Infrastructure	Population living under 5m above sea level
Description:	The proportion of the population living in the area where elevation is 5 m or less. It is a simple measure of the population sensitive to coastal risks.
Rationale:	An estimate of the population sensitive to the risks arising from seal-level rise, storm surge and similar effects, which are exacerbated by climate change.
Calculation	-
Data Source	Population living in areas where elevation is below 5 meters (% of total population), WDI
Time Series	Updated in 2000, 2010, and 2015
Notes	(1) Generally, this indicator should be continuously changing considering that many countries are experiencing population migration to coastal cities (e.g. Adebuseye, 2006; Chan, 2013). (2) A more consistent measure should be the coastal population living in areas where elevation is 4m or less, to line up with the exposure indicator (the second exposure indicator above). The population data available from the World Development Indicators database, however, are for 5 m.

Table A.17 Electricity access

Infrastructure	Electricity access
Description:	The proportion of the population with access to grid-power.
Rationale:	Access to electricity enables the poor to get the most basic services and economic opportunities to improve their standard of living. Considering the potential climate risks, access to electricity provides the basics that facilitate health care, disaster relief, food storage, and social services like education and ICT infrastructures. Therefore, electricity access is indicative of the capacity to delivery energy to a country's citizen and businesses, including technology and infrastructure, personnel, and the ability to respond to disruptions in supply.
Calculation	-
Data Source	Access to electricity (% of population), WDI
Time Series	Updated annually from 1995 to Present
Notes	

Table A.18 Ease of doing business index

Economic readiness	Ease of doing business index
Description:	The indicator took the World Bank Doing Business (DB) indicators as an indication of how countries are capable of attracting adaptation investment. The index assesses the investment climate in 10 topics using 40 indicators. The 10 topics are: starting a business, dealing with construction permits, getting electricity, registering property, getting credit, 35 protecting investors, paying taxes, trading across borders, enforcing contracts, and resolving insolvency.
Rationale:	The World Bank Doing Business (DB) indicators, which have been used by many studies to evaluate countries' investment climate by measuring procedures, time and cost of performing business activities through business life cycles (e.g. Commander & Svejnar, 2011; Hallward-Driemeier & Pritchett, 2011; Morris & Aziz, 2011; Collier & Duponchel, 2013). As the economic readiness in ND-GAIN seeks to capture the business conditions that attract adaptation investment, a description of the general investment climate is a good proxy for the economic component of readiness.
Calculation	There are 40 indicators in total provided by the DB database, available since 2003. But the overall DB scores have only been reported since 2012 by the World Bank. ND-GAIN recreated scores of the DB index for 2003-2020 using raw data and following the DB methodology. Countries are ranked by percentile on each topic, and the overall DB scores are obtained by averaging the percentile rankings of all 10 topics.
Data Source	Doing Business Index (retired as of 2022)
Time Series	Annually from 2003 to 2020
Notes	(1) Some of the DB sub-indices have incurred criticism, e.g., labor regulations; however, the overall DB is a widely accepted and applied indicator of countries' investment climate. (2) Some of the DB indicators are highly correlated with other readiness indicators, for instance, the rule of law indicator. The relevance of the index has also been challenged by some countries.

Table A.19 Political stability and non-violence

Governance readiness	Political stability and non-violence
Description:	An indicator directly from the World Governance Indicators (WGI), “capturing perceptions of the likelihood of political instability and/or politically motivated violence, including terrorism.”
Rationale:	There is a well-established relationship between foreign financial inflow (including investment and aid) and political stability and violence (e.g. Bennett & Green, 1972; Busse & Hefeker, 2007; McGillivray, 2011), suggesting that a stable political environment is more attractive to general investment from outside a country, including the adaptation investment.
Calculation	
Data Source	WGI Political stability and Absence of Violence/Terrorism: Estimate
Time Series	1996, 1998, 2000; Annual updates from 2002-Present for most countries
Notes	(1) Some of the DB sub-indices have incurred criticism, e.g., labor regulations; however, the overall DB is a widely accepted and applied indicator of countries’ investment climate. (2) Some of the DB indicators are highly correlated with other readiness indicators, for instance, the rule of law indicator. The relevance of the index has also been challenged by some countries.

Table A.20 Control of corruption

Governance readiness	Control of corruption
Description:	An indicator directly from the World Governance Indicators (WGI), “capturing perceptions from firms and households survey respondents and public, private, and NGO sector experts worldwide of public power exercised for private gain, including both petty and grand forms of corruption, as well as ‘capture’ of the state by elites and private interests.”
Rationale:	Corruption is known to have a negative impact on foreign investment (e.g. Beata& Wei, 2000; Habib & Zurawicki, 2002), and measuring the control of corruption implies government integrity and accountability (Sampson, 2004). It is also one of the important indicators in Country Policy and Institutional Assessment that attempts to assess how executives can be held accountable for fund uses (The World Bank Group, 2010). Control of corruption is therefore used as an indicator of governance readiness.
Calculation	
Data Source	WGI Control of Corruption: Estimate
Time Series	1996, 1998, 2000; Annual updates from 2002-Present for most countries
Notes	

Table A.21 Regulatory quality

Governance readiness	Regulatory quality
Description:	An indicator directly from the World Governance Indicators (WGI), “capturing perceptions of the ability of the government to formulate and implement sound policies and regulations that permit and promote private sector development.”
Rationale:	The quality of regulation measures the performance of country institutions, an important factor in deploying adaptation actions and adaptation-related policies (e.g. Globerman & Shapiro, 2003; Daude & Stein, 2007; Gani, 2007).
Calculation	
Data Source	WGI Regulatory Quality: Estimate
Time Series	1996, 1998, 2000; Annual updates from 2002-Present for most countries
Notes	

Table A.22 Rule of law

Governance readiness	Rule of Law
Description:	An indicator directly from the World Governance Indicators (WGI), “capturing perceptions from firms and households survey respondents and public, private, and NGO sector experts worldwide of confidence in and abide by the rules of society, and in particular the quality of contract enforcement, property rights, the police, and the courts, as well as the likelihood of crime and violence.”
Rationale:	Like political stability and control of corruption, rule of law is a quality of society that encourages foreign investment in general (e.g. Alesina & Dollar, 2000; Burnside & Dollar, 2004), hence the adaptation investments.
Calculation	
Data Source	WGI Rule of Law: Estimate
Time Series	1996, 1998, 2000; Annual updates from 2002-Present for most countries
Notes	

Table A.23 Social inequality

Social readiness	Social Inequality
Description:	The country's poorest quintile's share in national income or consumption.
Rationale:	The poorest populations are likely to be the most vulnerable to climate impacts (Tol, et al., 2004). Social inequality causes skewed distribution incomes and of vulnerability, and the exaggerated impacts on the poorest may further skew income distribution. Thus, social inequality exacerbates a country's capacity to adapt to climate change.
Calculation	
Data Source	Poorest quintile's share in national income or consumption, percentage, MDG Indicators
Time Series	1995 to 2012. Most of the countries do not have annual updates (retired).
Notes	

Table A.24 Information communication technology infrastructure

Social readiness	Information Communication Technology (ICT) infrastructure
Description:	A composite indicator from 4 sub-indicators that consider both the access to and the use of ICT infrastructure: mobile phone subscription per 100 persons, fixed phone subscription per 100 persons, fixed broad-band subscription per 100 persons, and percent of individuals using the internet. Data for all four are available from the annual ICT Development Index (IDI) database. The mobile phone subscription measures the subscription to public mobile services including the post-paid and prepaid subscriptions (World Development Indicators, 2014). The fixed phone subscription is assumed to measure of the active number of analog fixed telephone lines, ISDN channels, fixed wireless (WLL), public payphones and VoIP subscription (International Telecommunication Union, 2010). The fixed broad-band subscription refers to the number of broadband subscribers with a digital subscriber line, cable modem, or other high-speed technology (World Development Indicators, 2014). The individual internet use measures the proportion of internet users with access to the worldwide network (World Development Indicators, 2014).
Rationale:	ICT infrastructure can facilitate many features of adaptation. For example, it enables knowledge integration and learning and key ingredients of adaptive capacity (Pant and Heeks 2011); it provides technical support for early warning systems; and it can strengthen local organizations that implement adaptation (Singh and Singh 2012).
Calculation	The overall ICT infrastructure indicator takes the average over the scores of the four sub-indicators.
Data Source	• Mobile phone subscription per 100 persons • WDI Fixed phone subscription per 100 persons • ITU 38 Fixed broad-band internet subscription per 100 persons • WDI Internet user per 100 persons, WDI
Time Series	Not all sub-indicators have coverage from 1995 to Present. The range of data availability is from 4-5 updates since 1995 to annual report. But the overall score is the average of the available sub-indicators. Therefore, the scores in the end are on the annual basis.
Notes	

Table A.25 Education

Social readiness	Education
Description:	A measure of enrollment in tertiary education to represent the education level of a country. It is approximated by the ratio of the enrollment in tertiary education (regardless of age) to the population of the age group that officially corresponds to tertiary education attendance.
Rationale:	Education is considered as an important strategy to build up adaptive capacity and identify adaptation solutions appropriate to local context (Maddison, 2006; Smit & Pilifosova, 2001; Mercer, 2010). In particular, enrolment in secondary or tertiary education is a significant contributor, more than primary education, to adaptive capacity (Tol & Yohe, 2007).
Calculation	
Data Source	School Enrollment, tertiary (% gross), WDI
Time Series	1995-Present. The frequency of data reporting ranges from no report to annual update.
Notes	

Table A.26 Innovation

Social readiness	Innovation
Description:	A measure of the number of patent applications, filed through the Patent Cooperation Treaty procedure or with a national patent office, by residents per capita.
Rationale:	Innovation is the engine of growth (Solow 1994). It also is a fundamental force behind capacity building and climate change adaptation because research and technology are necessary to define adaptation solutions (Smit & Skinner, 2002; Adger, et al., 2008).
Calculation	A simple calculation of the per capita measure of the residents' patent applications.
Data Source	Patent applications, residents, WDI; Population, WDI
Time Series	Patent: 1995-Present. The frequency of data reporting ranges from no report to annual update. Population: 1995-Present.
Notes	The numbers of national patent registrations are not necessarily comparable across countries as the costs and incentives to register patents vary. There are alternative indicators of innovation, e.g. number of scientists, R&D expenditures, number of literature citations, etc. There is no comprehensive measure of innovation.

APPENDIX B RESULTS AND STATISTICAL TABLES OF GPRS FOR ALL MINERALS

Annex II. The following are the statistical and graphic results of each step in the assessment of the GeoPolRisk for each mineral. Each mineral is presented in a block, and the scales are not the same. As some of the results are very small in scale, this is with the purpose to be able to visualize the difference in the results between the different GPRS scenarios, and risk factors.

CADMIUM

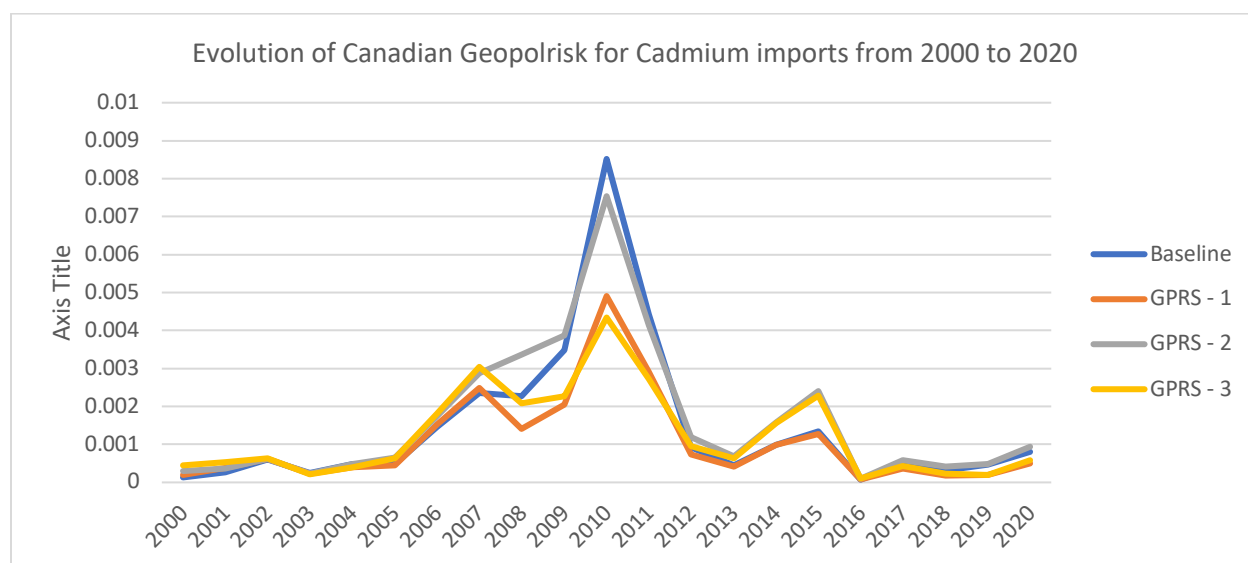


Figure B.1 Evolution of Canadian geopolrisk for cadmium imports from 2000 to 2020

Table B.1 Descriptive statistics for cadmium

<i>Baseline</i>		<i>GPRS - 1</i>		<i>GPRS - 2</i>		<i>GPRS - 3</i>	
Mean	0.001453 59	Mean	0.001059 36	Mean	0.001644 77	Mean	0.001242 69
Standard Error	0.000432 86	Standard Error	0.000259 95	Standard Error	0.000401 72	Standard Error	0.000253 24
Median	0.000595 3	Median	0.000497 83	Median	0.000688 33	Median	0.000631 53
Mode	#N/A	Mode	#N/A	Mode	#N/A	Mode	#N/A
Standard Deviation	0.001983 63	Standard Deviation	0.001191 23	Standard Deviation	0.001840 9	Standard Deviation	0.001160 47
Sample Variance	3.9348E-06	Sample Variance	1.419E-06	Sample Variance	3.3889E-06	Sample Variance	1.3467E-06
Kurtosis	7.860654 38	Kurtosis	4.564025 01	Kurtosis	4.172241 58	Kurtosis	0.872901 19
Skewness	2.639403 6	Skewness	2.031758 87	Skewness	1.928459 74	Skewness	1.204349 67
Range	0.008451 37	Range	0.004832 88	Range	0.007444 36	Range	0.004238 92
Minimum	6.7557E-05	Minimum	7.522E-05	Minimum	9.3214E-05	Minimum	0.000103 79
Maximum	0.008518 93	Maximum	0.004908 1	Maximum	0.007537 58	Maximum	0.004342 7
Sum	0.030525 4	Sum	0.022246 55	Sum	0.034540 15	Sum	0.026096 5
Count	21	Count	21	Count	21	Count	21

Table B.2 Correlation matrix for cadmium

	<i>Baseline</i>	<i>GPRS - 1</i>	<i>GPRS - 2</i>	<i>GPRS - 3</i>
Baseline	1			
GPRS - 1	0.97256266	1		
GPRS - 2	0.97733993	0.971572	1	
GPRS - 3	0.89639159	0.9613902	0.95148178	1

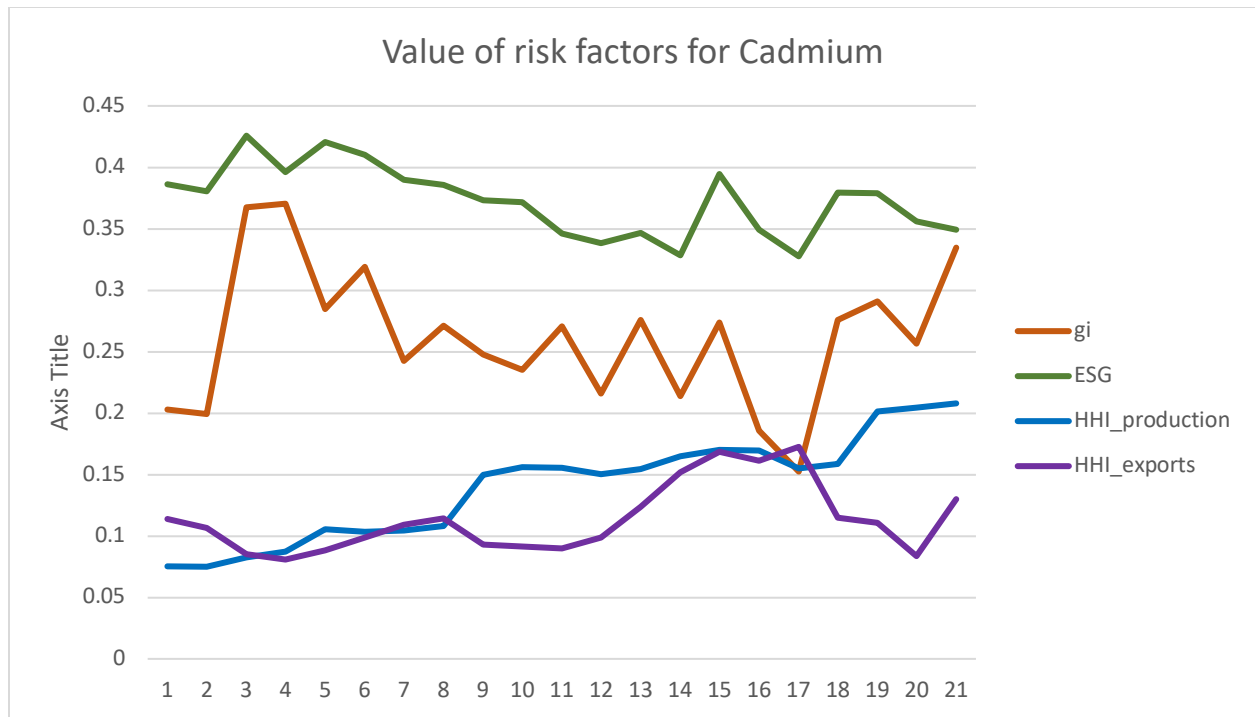


Figure B.2 Value of risk factors for cadmium

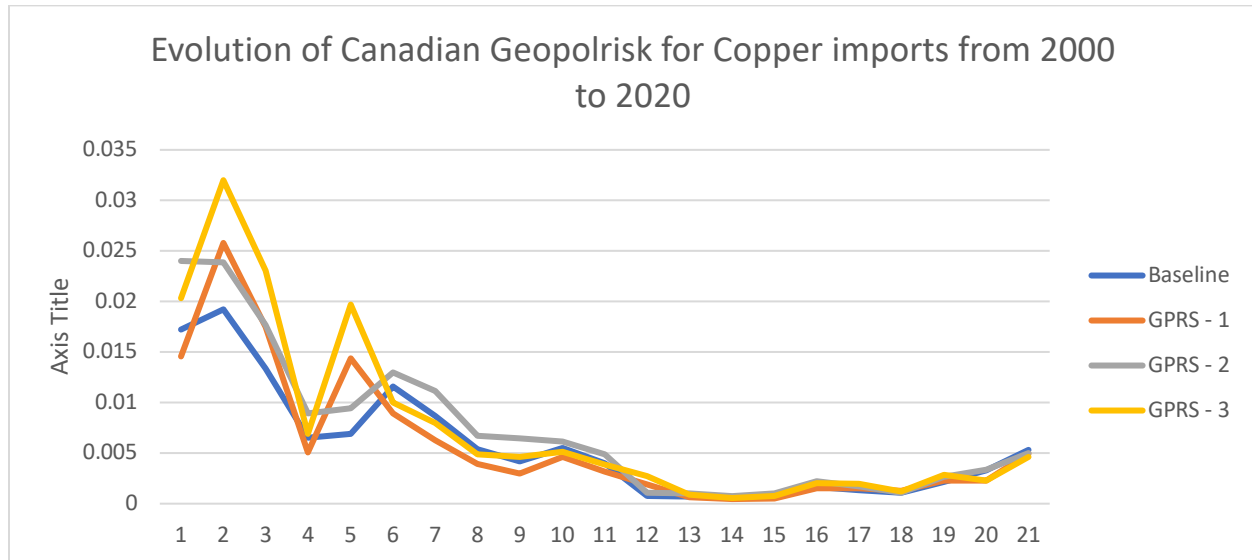
COPPER

Figure B.3 Evolution of Canadian geopolrisk for copper imports from 2000 to 2020

Table B.3 Descriptive statistics for copper

Mean	0.005716 33	Mean	0.005918 82	Mean	0.007236 17	Mean	0.007541 31
Standard Error	0.001196 47	Standard Error	0.001462 22	Standard Error	0.001559 47	Standard Error	0.001897 48
Median	0.004158 16	Median	0.003165 03	Median	0.005007 93	Median	0.004620 21
Mode	#N/A	Mode	#N/A	Mode	#N/A	Mode	#N/A
Standard Deviation	0.005482 93	Standard Deviation	0.006700 73	Standard Deviation	0.007146 39	Standard Deviation	0.008695 37
Sample Variance	3.0063E-05	Sample Variance	4.49E-05	Sample Variance	5.1071E-05	Sample Variance	7.5609E-05
Kurtosis	0.920679 99	Kurtosis	2.824042 23	Kurtosis	1.110508 75	Kurtosis	2.115329 27
Skewness	1.282375 93	Skewness	1.780739 52	Skewness	1.361409 56	Skewness	1.698440 89
Range	0.018619 51	Range	0.025339 07	Range	0.023265 17	Range	0.031438 4
Minimum	0.000603 05	Minimum	0.000453 97	Minimum	0.000744 98	Minimum	0.000560 82
Maximum	0.019222 56	Maximum	0.025793 04	Maximum	0.024010 15	Maximum	0.031999 22
Sum	0.120042 97	Sum	0.124295 15	Sum	0.151959 55	Sum	0.158367 57
Count	21	Count	21	Count	21	Count	21

Table B.4 Correlation matrix for copper

	<i>Baseline</i>	<i>GPRS - 1</i>	<i>GPRS - 2</i>	<i>GPRS - 3</i>
Baseline	1			
GPRS - 1	0.92137229	1		
GPRS - 2	0.99245327	0.91588221	1	
GPRS - 3	0.91376876	0.99569457	0.91934406	1

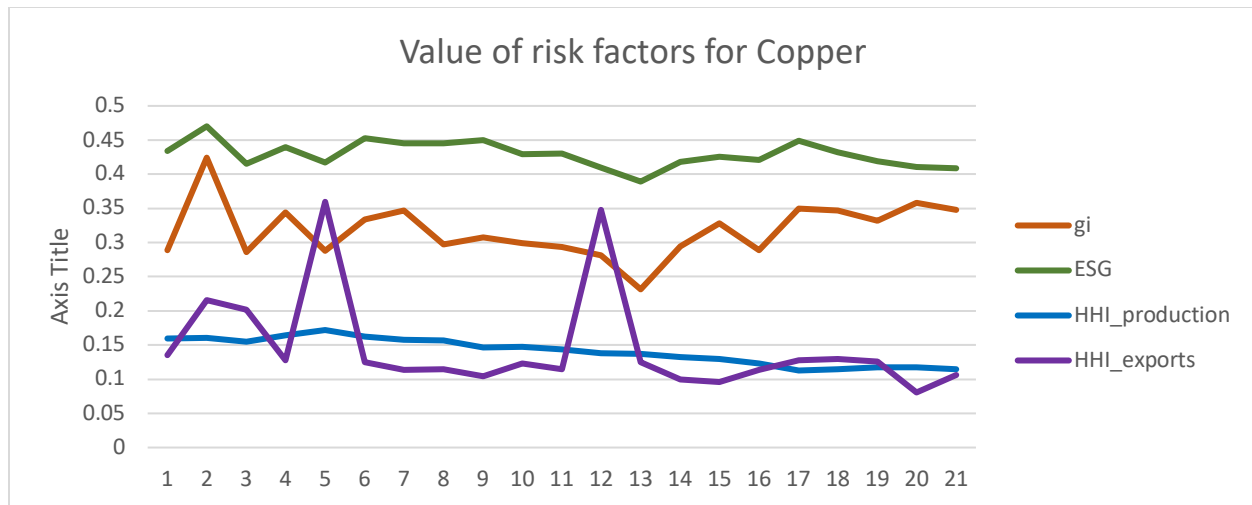


Figure B.4 Value of risk factors for copper

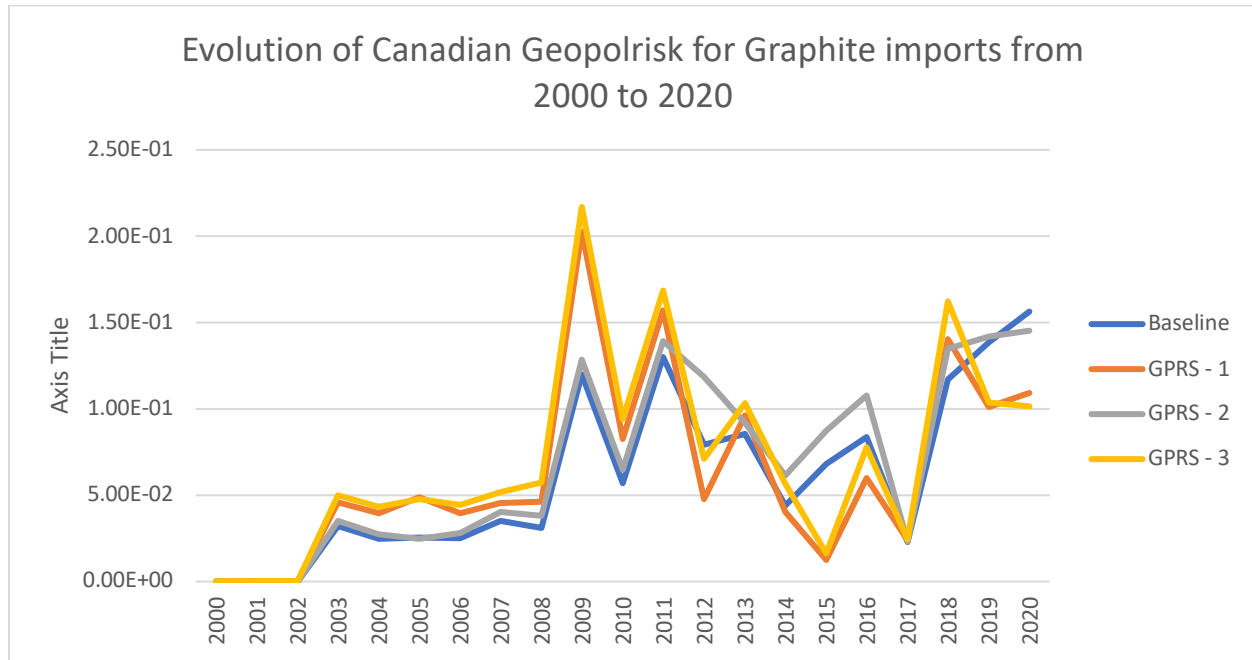
GRAPHITE

Figure B.5 Evolution of Canadian geopolrisk for graphite imports from 2000 to 2020

Table B.5 Descriptive statistics for graphite

Baseline		GPRS - 1		GPRS - 2		GPRS - 3	
Mean	0.060746 23	Mean	0.063798 04	Mean	0.068522 97	Mean	0.070980 15
Standard Error	0.010591 35	Standard Error	0.011781 65	Standard Error	0.011288 7	Standard Error	0.012554 81
Median	0.043936 42	Median	0.046285 2	Median	0.061497 95	Median	0.056551 21
Mode	#N/A	Mode	#N/A	Mode	#N/A	Mode	#N/A
Standard Deviation	0.048535 65	Standard Deviation	0.053990 29	Standard Deviation	0.051731 31	Standard Deviation	0.057533 35
Sample Variance	0.002355 71	Sample Variance	0.002914 95	Sample Variance	0.002676 13	Sample Variance	0.003310 09
Kurtosis	- 0.886961 8	Kurtosis	- 0.864581 76	Kurtosis	- 1.504801 64	Kurtosis	- 0.855902 15
Skewness	0.560329 28	Skewness	1.084519 66	Skewness	0.220824 92	Skewness	1.014870 02
Range	0.156331 26	Range	0.202713 25	Range	0.145251 38	Range	0.216888 7
Minimum	1.5983E-05	Minimum	3.8584E-05	Minimum	3.1906E-05	Minimum	7.7021E-05
Maximum	0.156347 24	Maximum	0.202751 83	Maximum	0.145283 29	Maximum	0.216965 72
Sum	1.275670 81	Sum	1.339758 79	Sum	1.438982 33	Sum	1.490583 18
Count	21	Count	21	Count	21	Count	21

Table B.6 Correlation matrix for graphite

	Baseline	GPRS - 1	GPRS - 2	GPRS - 3
Baseline	1			
GPRS - 1	0.82981744	1		
GPRS - 2	0.97856175	0.7944646	1	
GPRS - 3	0.81713297	0.99143931	0.80713051	1

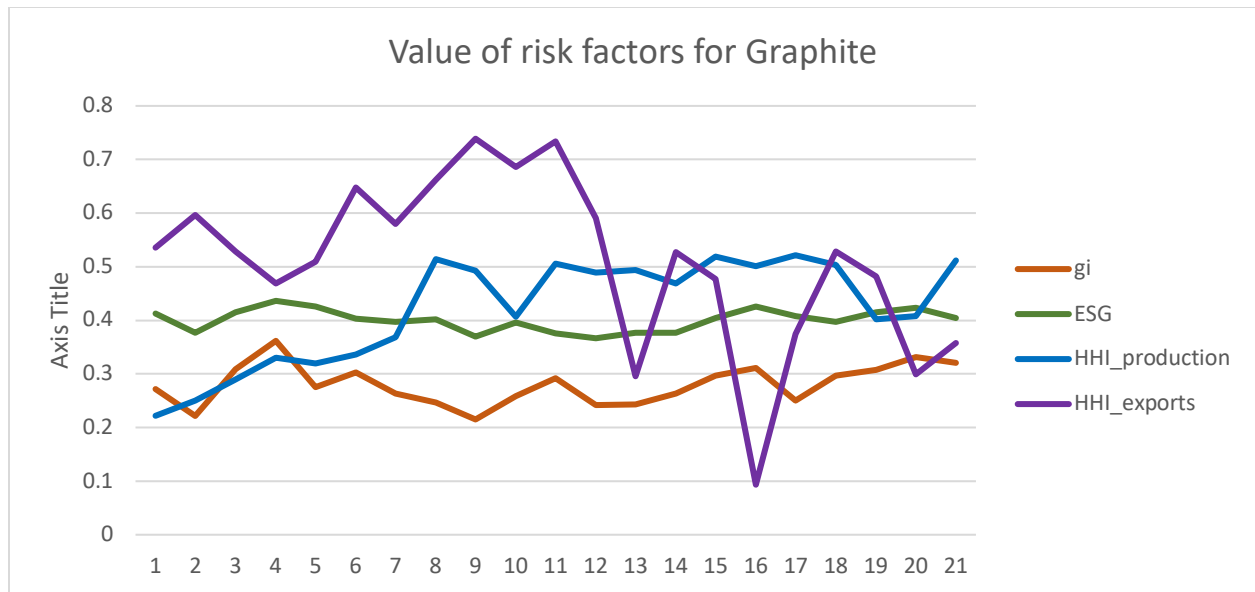


Figure B.6 Value of risk factors for graphite

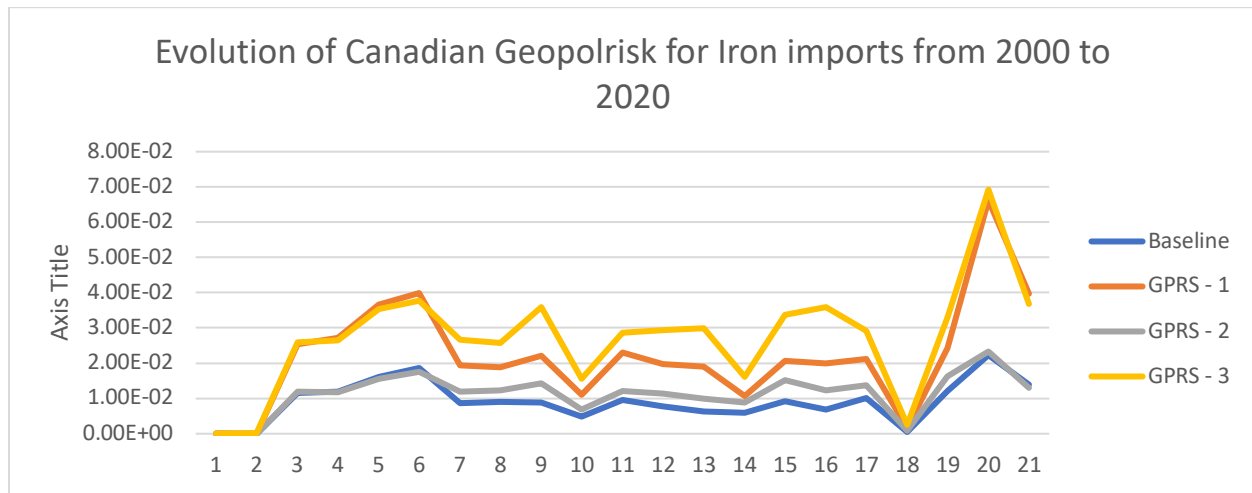
IRON

Figure B.7 Evolution of Canadian geopolrisk for iron imports from 2000 to 2020

Table B.7 Descriptive statistics for iron

Baseline		GPRS - 1		GPRS - 2		GPRS - 3	
Mean	0.00924738	Mean	0.02220308	Mean	0.01138332	Mean	0.02731705
Standard Error	0.00123796	Standard Error	0.00327454	Standard Error	0.00124923	Standard Error	0.00331807
Median	0.00909985	Median	0.02060902	Median	0.01204344	Median	0.02909953
Mode	#N/A	Mode	#N/A	Mode	#N/A	Mode	#N/A
Standard Deviation	0.00567304	Standard Deviation	0.01500583	Standard Deviation	0.00572471	Standard Deviation	0.01520532
Sample Variance	3.2183E-05	Sample Variance	0.00022517	Sample Variance	3.2772E-05	Sample Variance	0.0002312
Kurtosis	0.43339365	Kurtosis	2.7270245	Kurtosis	0.85430404	Kurtosis	2.35368261
Skewness	0.33546709	Skewness	1.07280282	Skewness	-0.593674	Skewness	0.29938227
Range	0.02229201	Range	0.06619625	Range	0.02329885	Range	0.06918456
Minimum	6.0844E-06	Minimum	1.9412E-05	Minimum	1.3146E-05	Minimum	4.1942E-05
Maximum	0.0222981	Maximum	0.06621567	Maximum	0.023312	Maximum	0.0692265
Sum	0.1941949	Sum	0.46626478	Sum	0.23904965	Sum	0.573658
Count	21	Count	21	Count	21	Count	21

Table B.8 Correlation matrix for iron

	Baseline	GPRS - 1	GPRS - 2	GPRS - 3
Baseline	1			
GPRS - 1	0.9656828	1		
GPRS - 2	0.92192155	0.88870749	1	
GPRS - 3	0.8866626	0.9317772	0.95299653	1

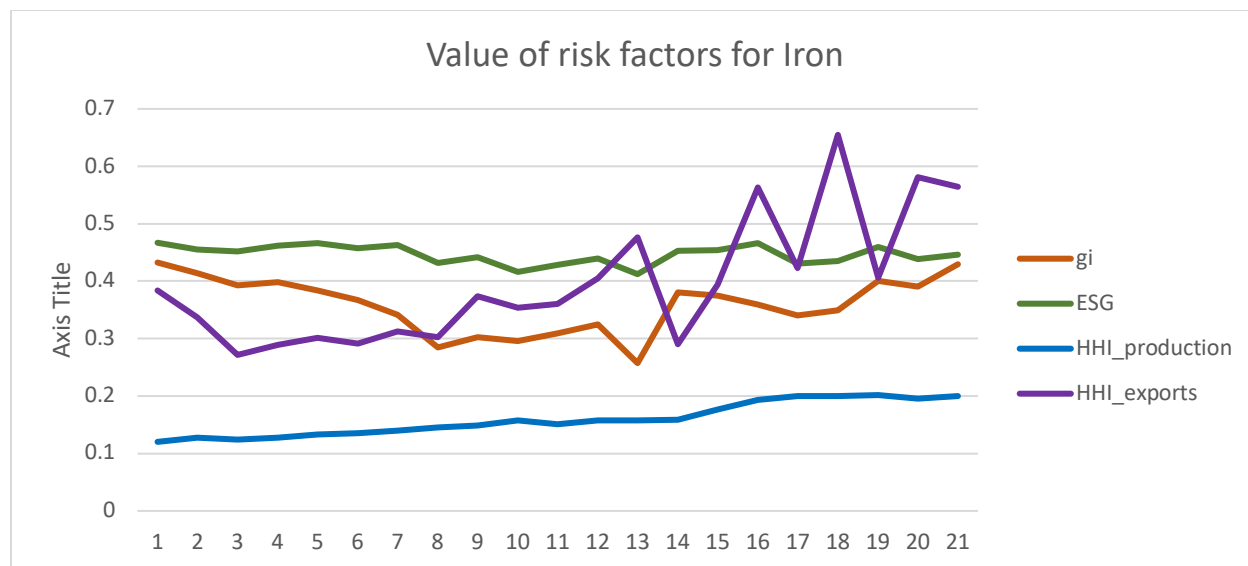


Figure B.8 Value of risk factors for iron

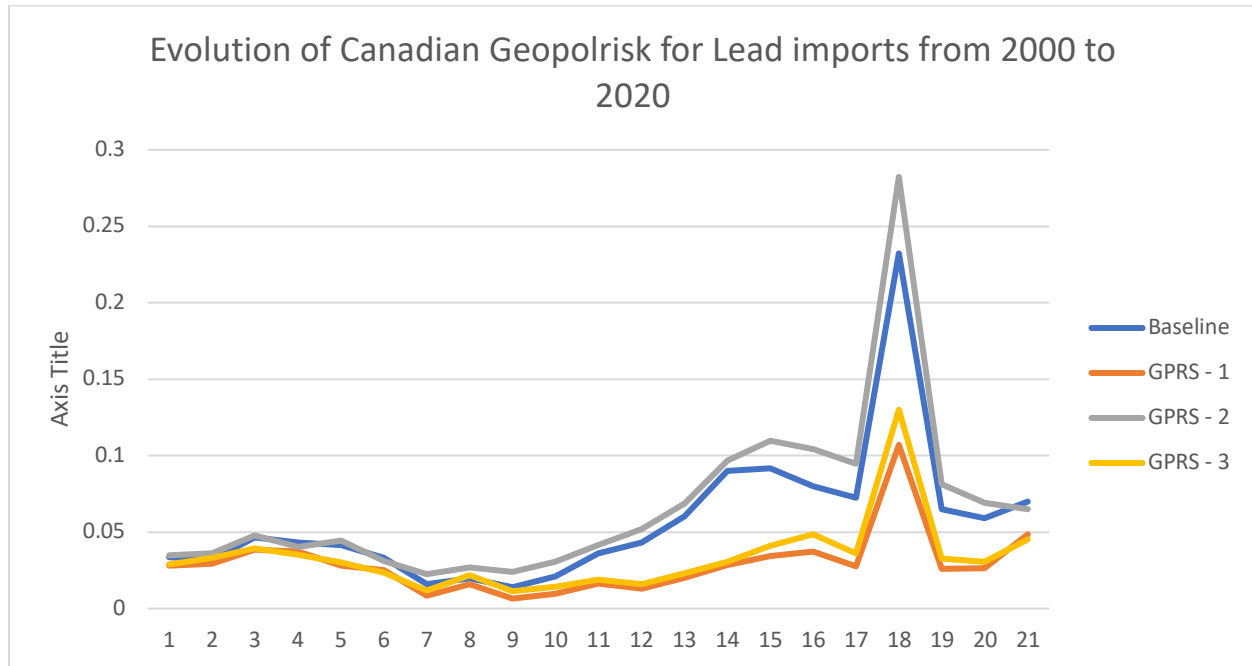
LEAD

Figure B.9 Evolution of Canadian geopolrisk for lead imports from 2000 to 2020

Table B.9 Descriptive statistics for lead

Baseline		GPRS - 1		GPRS - 2		GPRS - 3	
Mean	0.05709638	Mean	0.02915989	Mean	0.06676205	Mean	0.03342213
Standard Error	0.01014263	Standard Error	0.0045576	Standard Error	0.01233913	Standard Error	0.00535603
Median	0.04310251	Median	0.02766217	Median	0.04766182	Median	0.03062454
Mode	#N/A	Mode	#N/A	Mode	#N/A	Mode	#N/A
Standard Deviation	0.04647936	Standard Deviation	0.02088553	Standard Deviation	0.05654499	Standard Deviation	0.02454441
Sample Variance	0.00216033	Sample Variance	0.00043621	Sample Variance	0.00319734	Sample Variance	0.00060243
Kurtosis	1.34354376	Kurtosis	0.85962081	Kurtosis	1.90502148	Kurtosis	2.88255463
Skewness	2.84048371	Skewness	2.69660068	Skewness	2.98164996	Skewness	3.24427832
Range	0.2184675	Range	0.10053302	Range	0.25990757	Range	0.11877137
Minimum	0.01385562	Minimum	0.00650099	Minimum	0.02239757	Minimum	0.01128995
Maximum	0.23232312	Maximum	0.10703401	Maximum	0.28230514	Maximum	0.13006132
Sum	1.19902407	Sum	0.61235765	Sum	1.40200305	Sum	0.70186466
Count	21	Count	21	Count	21	Count	21

Table B.10 Correlation matrix for lead

	Baseline	GPRS - 1	GPRS - 2	GPRS - 3
Baseline	1			
GPRS - 1	0.90700991	1		
GPRS - 2	0.99181994	0.87383247	1	
GPRS - 3	0.94002446	0.98315348	0.92886088	1

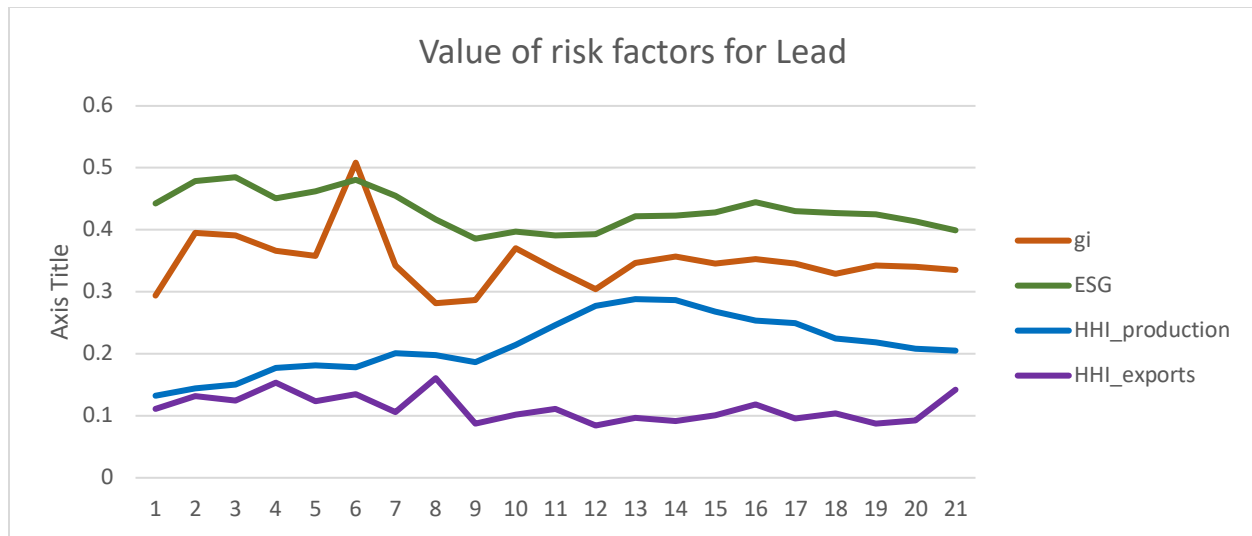


Figure B.10 Value of risk factors for lead

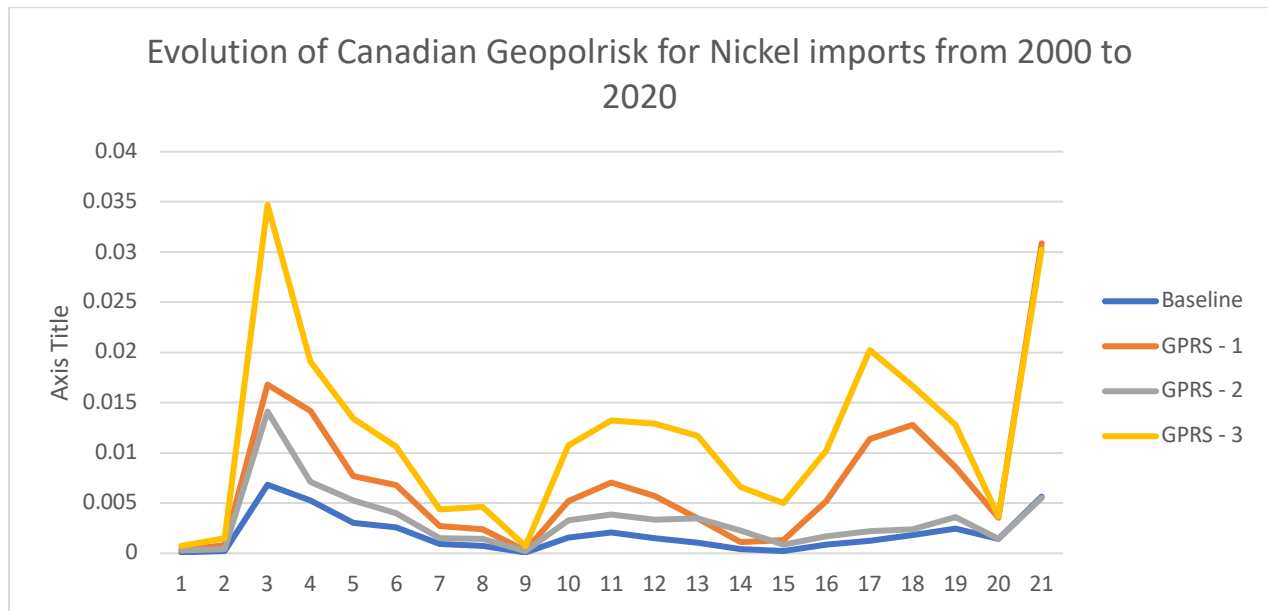
NICKEL

Figure B.11 Evolution of Canadian geopolrisk for nickel imports from 2000 to 2020

Table B.11 Descriptive statistics for nickel

Baseline		GPRS - 1		GPRS - 2		GPRS - 3	
Mean	0.001911 77	Mean	0.007062 76	Mean	0.003262 7	Mean	0.011608 88
Standard Error	0.000411 65	Standard Error	0.001572 4	Standard Error	0.000672 55	Standard Error	0.001964 79
Median	0.001409 32	Median	0.005226 29	Median	0.002418 42	Median	0.010741 65
Mode	#N/A	Mode	#N/A	Mode	#N/A	Mode	#N/A
Standard Deviation	0.001886 4	Standard Deviation	0.007205 64	Standard Deviation	0.003082 02	Standard Deviation	0.009003 82
Sample Variance	3.5585E-06	Sample Variance	5.1921E-05	Sample Variance	9.4988E-06	Sample Variance	8.1069E-05
Kurtosis	1.618642 97	Kurtosis	5.094304 29	Kurtosis	7.318380 43	Kurtosis	1.260465 75
Skewness	1.501390 73	Skewness	1.994434 01	Skewness	2.346877 8	Skewness	1.116172 36
Range	0.006744 51	Range	0.030600 06	Range	0.013899 22	Range	0.033987 15
Minimum	8.4212E-05	Minimum	0.000271 1	Minimum	0.000221 09	Minimum	0.000711 73
Maximum	0.006828 72	Maximum	0.030871 15	Maximum	0.014120 3	Maximum	0.034698 89
Sum	0.040147 13	Sum	0.148317 98	Sum	0.068516 69	Sum	0.243786 51
Count	21	Count	21	Count	21	Count	21

Table B.12 Correlation matrix for nickel

	Baseline	GPRS - 1	GPRS - 2	GPRS - 3
Baseline	1			
GPRS - 1	0.84682382	1		
GPRS - 2	0.91185462	0.63495299	1	
GPRS - 3	0.88277014	0.89595681	0.84673058	1

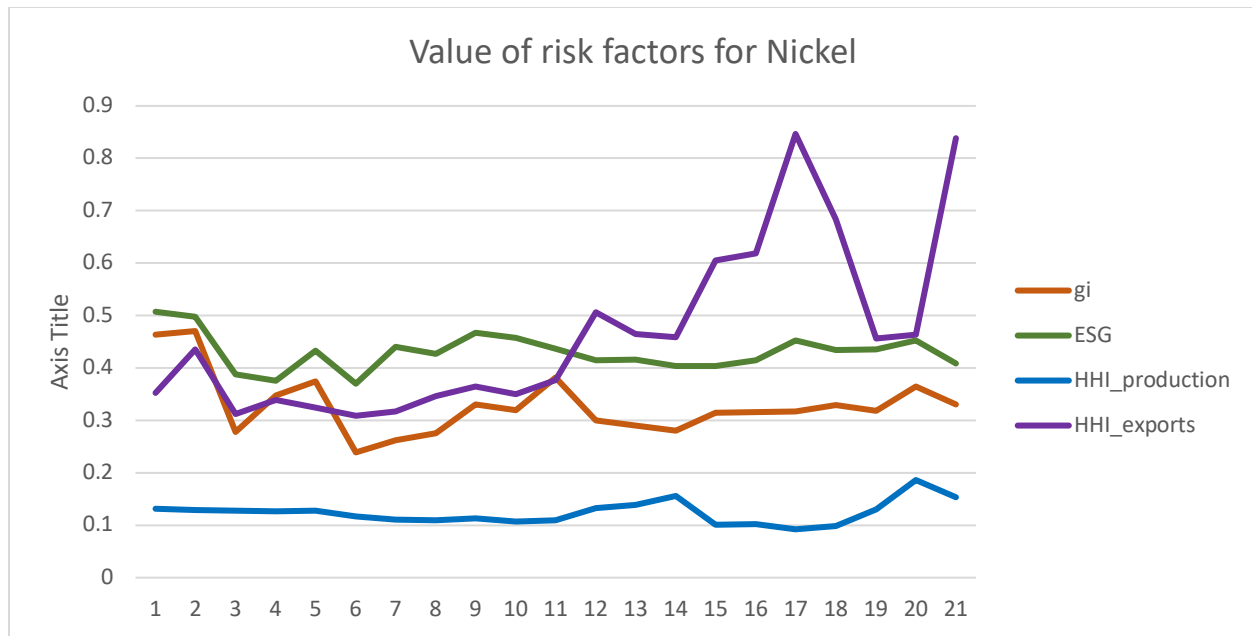


Figure B.12 Value of risk factors for nickel

RARE EARTH ELEMENTS (REE)

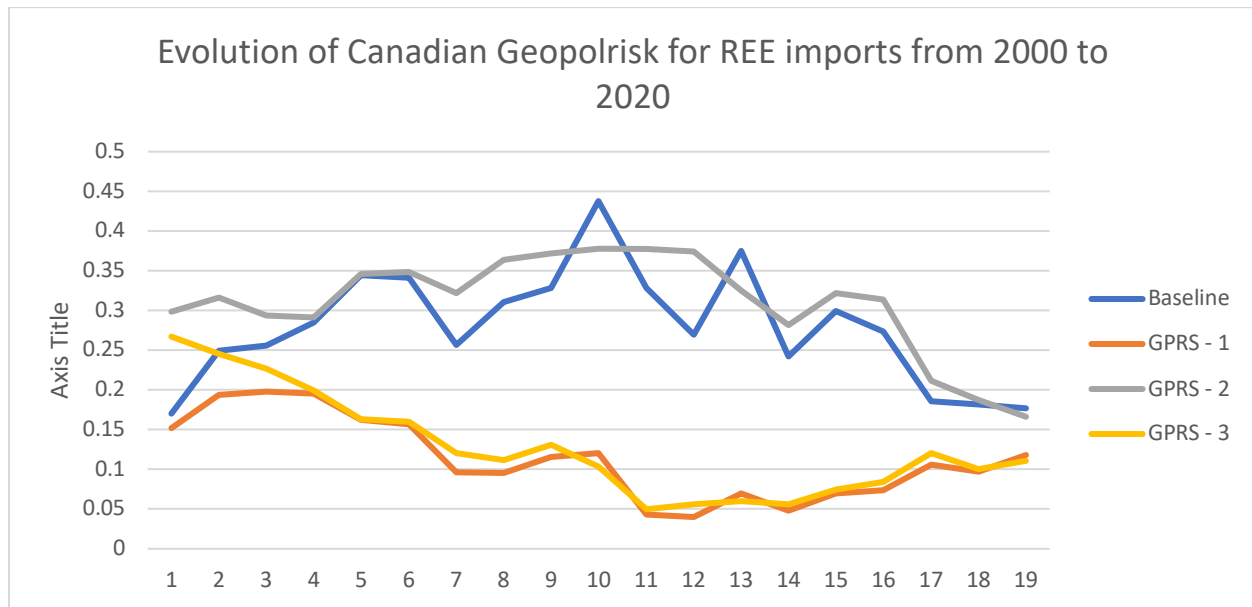


Figure B.13 Evolution of Canadian geopolrisk for REE imports from 2000 to 2020

Table B.13 Descriptive statistics for rare earth

Baseline		GPRS - 1		GPRS - 2		GPRS - 3	
Mean	0.279569 39	Mean	0.113157 37	Mean	0.309927 69	Mean	0.128488 52
Standard Error	0.016456 09	Standard Error	0.011731 27	Standard Error	0.014332 68	Standard Error	0.015132 34
Median	0.273874 68	Median	0.105850 58	Median	0.321625 96	Median	0.111828 71
Mode	#N/A	Mode	#N/A	Mode	#N/A	Mode	#N/A
Standard Deviation	0.071730 43	Standard Deviation	0.051135 43	Standard Deviation	0.062474 71	Standard Deviation	0.065960 35
Sample Variance	0.005145 25	Sample Variance	0.002614 83	Sample Variance	0.003903 09	Sample Variance	0.004350 77
Kurtosis	- 0.113452 1	Kurtosis	- 0.951755 5	Kurtosis	- 0.657043 99	Kurtosis	- 0.253508 8
Skewness	0.227135 13	Skewness	0.321834 06	Skewness	1.116477 7	Skewness	0.820837 02
Range	0.267559 93	Range	0.157895 56	Range	0.211521 69	Range	0.217338 88
Minimum	0.170198 21	Minimum	0.040002 66	Minimum	0.166267 41	Minimum	0.049788 98
Maximum	0.437758 13	Maximum	0.197898 23	Maximum	0.377789 1	Maximum	0.267127 86
Sum	5.311818 4	Sum	2.149990 05	Sum	5.888626 13	Sum	2.441281 87
Count	19	Count	19	Count	19	Count	19

Table B.14 Correlation matrix for rare earth

	Baseline	GPRS - 1	GPRS - 2	GPRS - 3
Baseline	1			
GPRS - 1	-0.0709191	1		
GPRS - 2	0.77434302	-0.1195986	1	
GPRS - 3	-0.2705778	0.91290273	-0.0921912	1

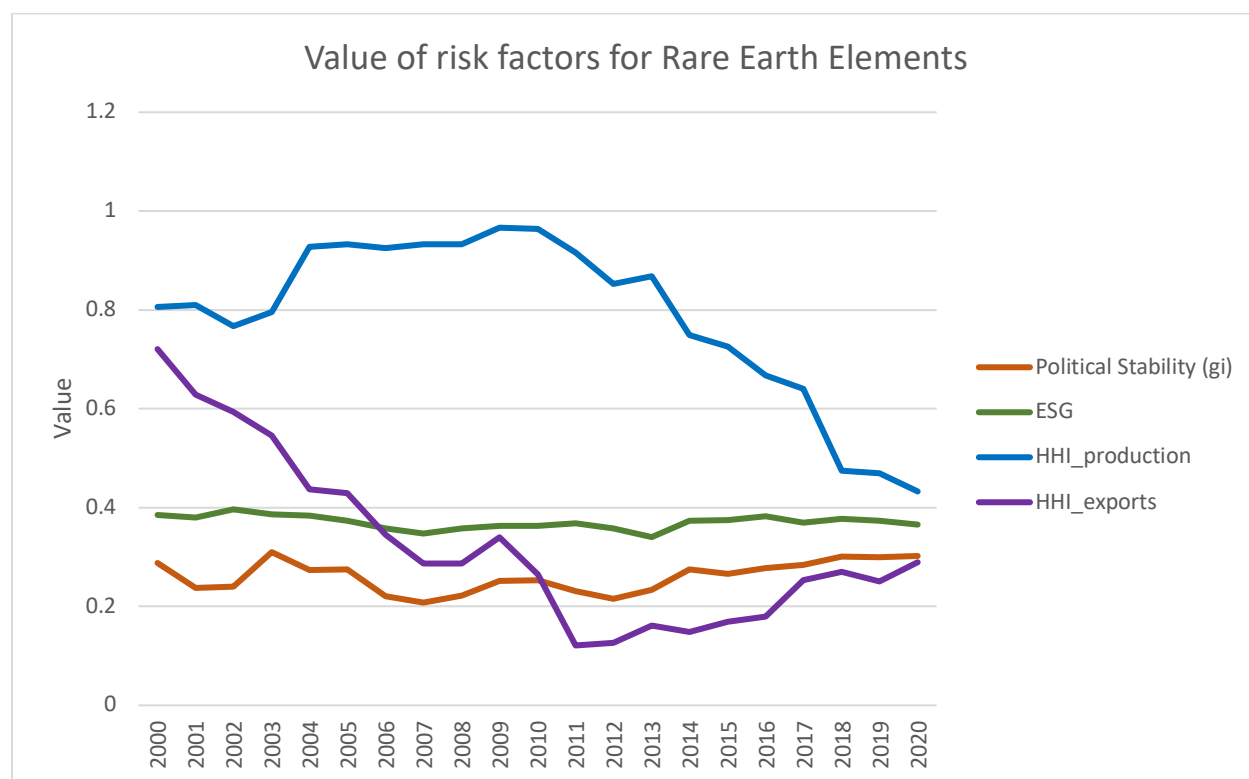


Figure B.14 Value of risk factors for REE

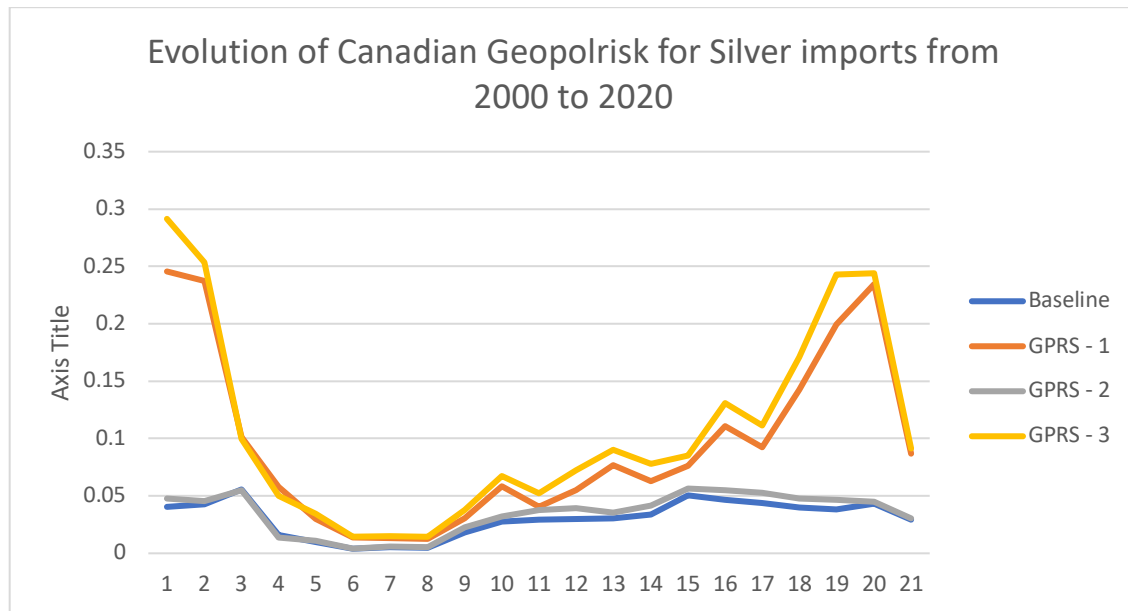
SILVER

Figure B.15 Evolution of Canadian geopolrisk for silver imports from 2000 to 2020

Table B.15 Descriptive statistics for silver

Baseline		GPRS - 1		GPRS - 2		GPRS - 3	
Mean	0.029770 81	Mean	0.087150 1	Mean	0.034521 79	Mean	0.100598 23
Standard Error	0.003702 13	Standard Error	0.016466 94	Standard Error	0.004217 97	Standard Error	0.019055 89
Median	0.030187 74	Median	0.062873 27	Median	0.039252 92	Median	0.077794 05
Mode	#N/A	Mode	#N/A	Mode	#N/A	Mode	#N/A
Standard Deviation	0.016137 21	Standard Deviation	0.071777 74	Standard Deviation	0.018385 69	Standard Deviation	0.083062 69
Sample Variance	0.000260 41	Sample Variance	0.005152 04	Sample Variance	0.000338 03	Sample Variance	0.006899 41
Kurtosis	- 1.020610 4	Kurtosis	- 0.594080 83	Kurtosis	- 1.163776 7	Kurtosis	- 0.538163 45
Skewness	- 0.320264 1	Skewness	- 1.204391 66	Skewness	- 0.580196 9	Skewness	- 1.193510 53
Range	0.051684	Range	0.233151 31	Range	0.052355 44	Range	0.277083 54
Minimum	0.003979 02	Minimum	0.012455 45	Minimum	0.004095 84	Minimum	0.014356 91
Maximum	0.055663 01	Maximum	0.245606 76	Maximum	0.056451 29	Maximum	0.291440 45
Sum	0.565645 32	Sum	1.655851 92	Sum	0.655913 95	Sum	1.911366 38
Count	19	Count	19	Count	19	Count	19

Table B.16 Correlation matrix for silver

	Baseline	GPRS - 1	GPRS - 2	GPRS - 3
Baseline	1			
GPRS - 1	0.65719813	1		
GPRS - 2	0.98251976	0.63078335	1	
GPRS - 3	0.6564077	0.99288046	0.64971289	1

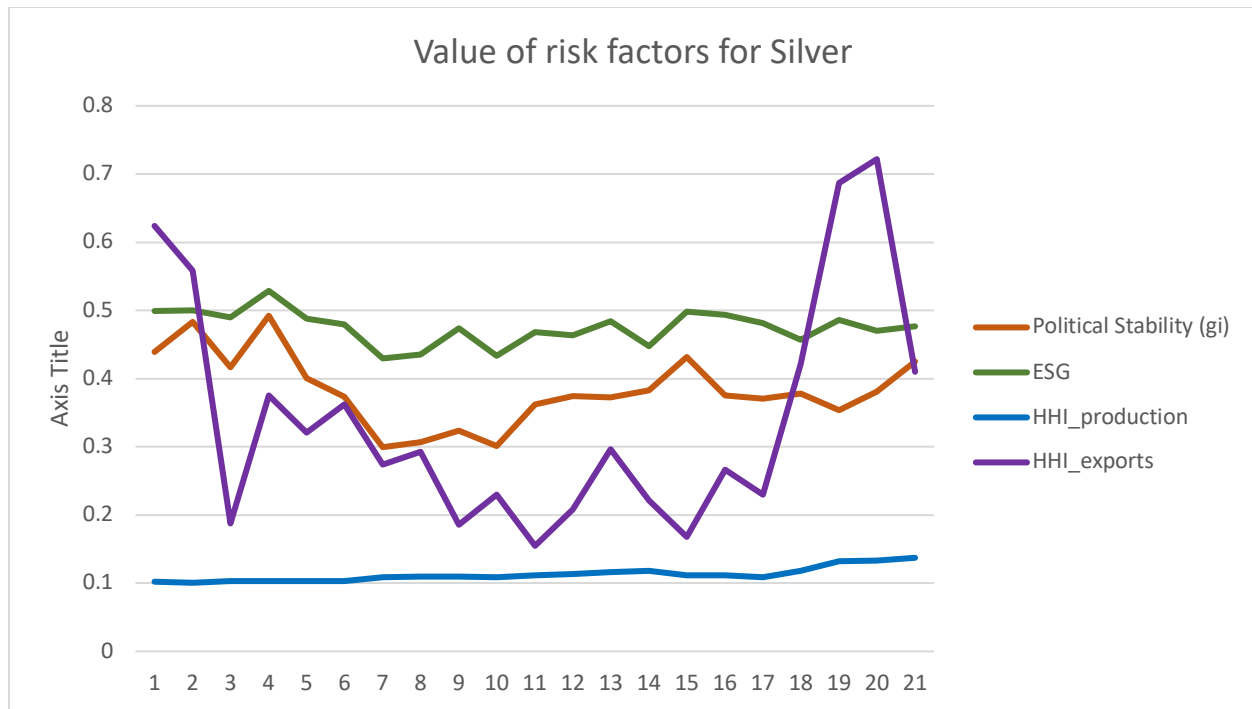


Figure B.16 Value of risk factors for silver

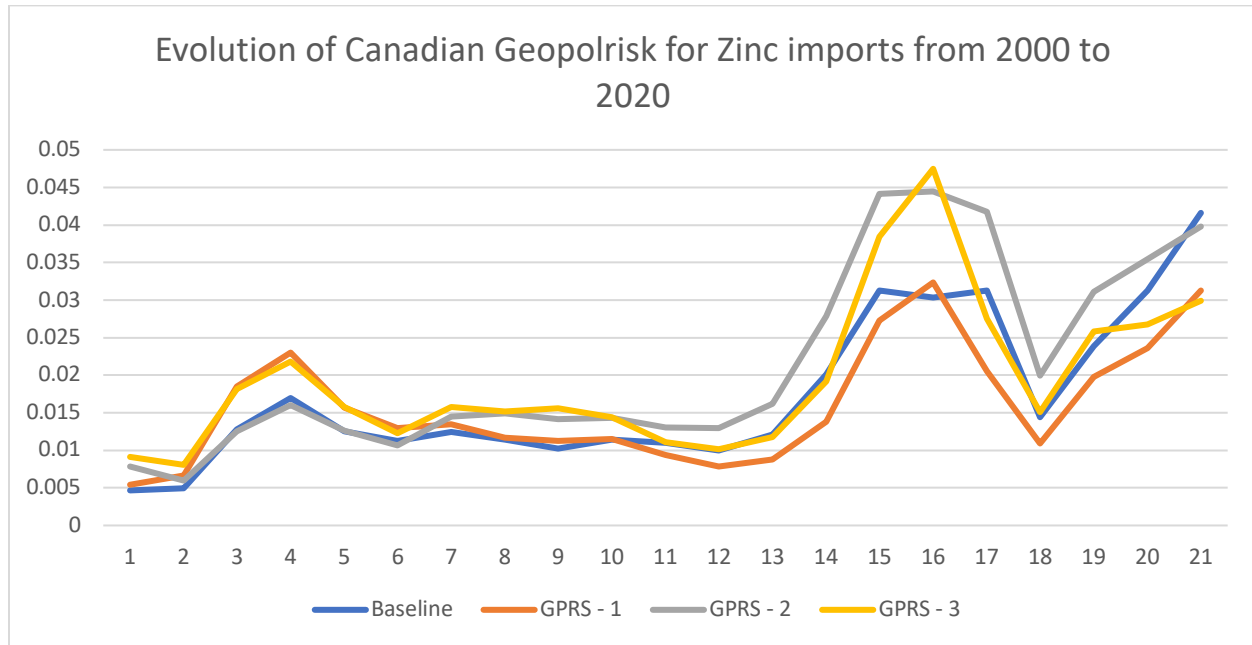
ZINC

Figure B.17 Evolution of Canadian geopolrisk for Zinc imports from 2000 to 2020

Table B.17 Descriptive analysis for zinc

Baseline		GPRS - 1		GPRS - 2		GPRS - 3	
Mean	0.017420 46	Mean	0.015993 06	Mean	0.021439 76	Mean	0.019492 61
Standard Error	0.002214 46	Standard Error	0.001723 43	Standard Error	0.002768 4	Standard Error	0.002197 97
Median	0.012549 95	Median	0.013483 96	Median	0.014906 61	Median	0.015743 17
Mode	#N/A	Mode	#N/A	Mode	#N/A	Mode	#N/A
Standard Deviation	0.010147 94	Standard Deviation	0.007897 75	Standard Deviation	0.012686 39	Standard Deviation	0.010072 38
Sample Variance	0.000102 98	Sample Variance	6.2375E-05	Sample Variance	0.000160 94	Sample Variance	0.000101 45
Kurtosis	- 0.024552 6	Kurtosis	- 0.376655 7	Kurtosis	- 0.856946 6	Kurtosis	1.819863 17
Skewness	0.967597 73	Skewness	0.749301 78	Skewness	0.829205 94	Skewness	1.390476 91
Range	0.036946 42	Range	0.026933 03	Range	0.038489 36	Range	0.039412 4
Minimum	0.004664 57	Minimum	0.005419 88	Minimum	0.005975 6	Minimum	0.008066 27
Maximum	0.041611	Maximum	0.032352 92	Maximum	0.044464 96	Maximum	0.047478 67
Sum	0.365829 65	Sum	0.335854 35	Sum	0.450234 93	Sum	0.409344 9
Count	21	Count	21	Count	21	Count	21

Table B.18 Correlation matrix for Zinc

	Baseline	GPRS - 1	GPRS - 2	GPRS - 3
Baseline	1			
GPRS - 1	0.89669173	1		
GPRS - 2	0.95037105	0.83826564	1	
GPRS - 3	0.85577555	0.92938154	0.91241276	1

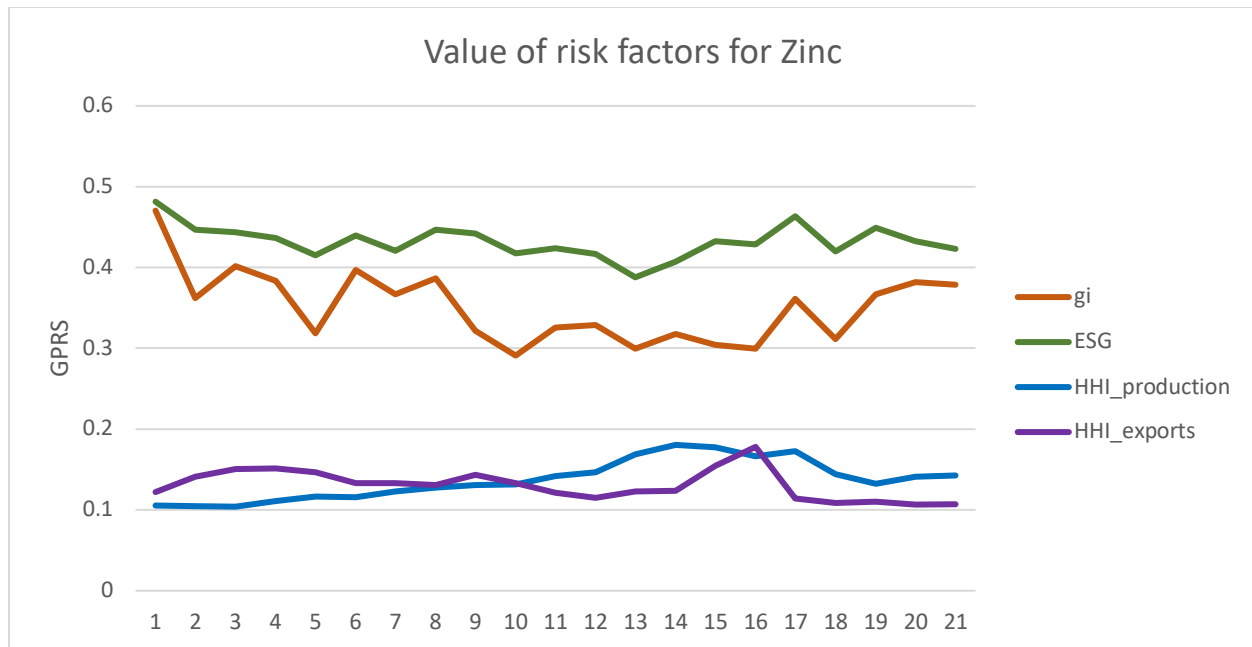


Figure B.18 Value risk factors for zinc