Integrated assessment of selected materials for criticality and environmental sustainability : application to the healthcare sector and methodological enhancements

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Integrated Assessment of Selected Materials for Criticality and Environmental Sustainability – Application to the Healthcare Sector and Methodological Enhancements

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EXECUTIVE SUMMARY

Titre : Évaluation Intégrée de Matériaux Sélectionnés pour leur Criticité et Durabilité Environnementale – Application dans le Secteur de la Santé et Améliorations Méthodologiques

Résumé : Les activités nécessaires pour fournir des services de santé posent plusieurs défis en termes de durabilité. Le secteur de la santé repose sur divers produits, services et installations, notamment des produits jetables, équipements complexes et moyens de transport. Ce domaine a été peu exploré sous l'angle de la durabilité et le niveau de sensibilisation à ce sujet est faible. Les méthodologies basées sur le cycle de vie ont le potentiel de caractériser la durabilité liée au secteur de la santé et à bien d'autres; toutefois, ces méthodes sont principalement - sinon exclusivement - liées à une voie *inside-out* pour évaluer les impacts. D'un point de vue *outside-in*, la criticité des ressources a le potentiel de répondre aux préoccupations relatives à la disponibilité des ressources pour le secteur de la santé, en particulier après son intégration dans le cadre de l'évaluation de la durabilité du cycle de vie (LCSA).

Une tâche en suspens autour de cette voie méthodologique proposée est d'explorer l'applicabilité et l'état de préparation des approches de risque d'approvisionnement, en particulier la méthode de risque géopolitique d'approvisionnement (GeoPolRisk), proposée pour évaluer les impacts liés aux ressources. Cette recherche fournit et intègre des techniques d'évaluation de la durabilité environnementale dans une perspective de cycle de vie, en particulier sur l'amélioration des indicateurs de criticité en tant que voie d'impact *outside-in* associée au domaine de protection "Ressources naturelles" dans l'analyse du cycle de vie (ACV); en outre, leur applicabilité est validée par de multiples études de cas, dont l'une fait partie du secteur de la santé.

La thèse est divisée en 9 chapitres et suit deux branches: "Durabilité des soins de santé" et "Criticité des ressources dans l'ACV". Le premier chapitre fournit une introduction au manuscrit et présente la question de recherche et les objectifs de la thèse ; il est suivi par l'état de l'art dans le chapitre 2. Le chapitre 3 présente le développement d'un nouveau cadre pour relever les défis de la durabilité dans le secteur de la santé par le biais de la pensée cycle de vie. Les chapitres 4 et 5 proposent et testent des développements méthodologiques pour évaluer le risque d'approvisionnement géopolitique. Ces aspects sont nécessaires pour mieux aborder les impacts liés aux ressources en ACV. Le chapitre 6 présente une évaluation intégrée de la criticité des ressources avec les catégories d'impact environnemental traditionnellement utilisées en ACV. Dans le chapitre 7, la méthode GeoPolRisk est utilisée pour mieux comprendre la pertinence de l'évaluation des impacts *outside-in* associés à un élément utilisé dans le secteur de la santé. Le chapitre 8 intègre les développements méthodologiques présentées précédemment pour étudier les impacts *inside-out* et *outside-in* dans le cadre d'une étude de cas associée à l'imagerie médicale. Enfin, les perspectives de développement sur le terrain sont examinées dans le dernier chapitre du manuscrit.

Dans la branche " Durabilité des soins de santé", ce travail contribue à l'élaboration d'un cadre intégré pour soutenir la recherche dans ce domaine et à la première application à une étude de cas dans le secteur de la santé d'une analyse intégrée du cycle de vie intégrant des indicateurs environnementaux et la méthode GeoPolRisk. Dans la branche "Criticité des ressources dans l'ACV", la thèse développe de nouvelles approches et propose des améliorations méthodologiques pour faire progresser l'évaluation de l'utilisation des ressources dans l'ACV.

Mots clés: Analyse du Cycle de Vie, Criticité de Matière Primaire, Secteur de la Santé, Durabilité Environnementale

Title: Integrated Assessment of Selected Materials for Criticality and Environmental Sustainability – Application to the Healthcare Sector and Methodological Enhancements

Abstract: The activities required to provide healthcare services bring challenges to environmental sustainability. The sector relies on diverse products, services and facilities, including disposable products, complex equipment and transportation. This domain has not been well explored from a sustainability lens and the level of awareness around healthcare sustainability is low. Life-cycle based methods have the potential to characterize systems related to the healthcare sector and many others; however, these methods are mostly – if not exclusively – related to an inside-out pathway to assess impacts. From an outside-in perspective, there is potential for raw material criticality to assess resource availability in the healthcare sector, especially after the proposal to integrate it into the Life Cycle Sustainability Assessment (LCSA) framework.

A pending task around this proposed methodological pathway is to explore the applicability and readiness of supply risk methods, specifically the geopolitical supply risk (GeoPolRisk) method has been proposed to assess resource related impacts. This research provides and integrates methods to assess environmental sustainability from a life cycle perspective with focus on enhancing criticality indicators as an outside-in impact pathway associated with the Area of Protection “Natural Resources” in Life Cycle Assessment (LCA); moreover, their applicability is validated with multiple case studies, being one of those a part of the healthcare sector.

The thesis is divided in 9 chapters along two branches: “Healthcare Sustainability” and “Raw Material Criticality in Life Cycle Assessment”. The first chapter provides an introduction to the manuscript and presents the research question and objectives of the thesis; it is followed by the state of the art in chapter 2. Chapter 3 presents the development of a novel framework to help address sustainability challenges in the healthcare sector through life cycle thinking. Chapter 4 and Chapter 5 propose and test methodological enhancements to the geopolitical supply risk method required to better address resource related impacts in life cycle assessment. Chapter 6 presents an integrated assessment taking into account the enhanced method and its relation to more traditionally used environmental impact categories in LCA. In chapter 7, the GeoPolRisk method is used to better understand the relevance of assessing outside-in impacts associated to an element used in the healthcare sector. Chapter 8 integrates the methodological enhancements previously presented to study inside-out and outside-in impacts for a case study associated with medical imaging. Finally, accomplishments and future opportunities for development on the field are discussed as part of the last chapter of the manuscript.

Along the branch of “Healthcare Sustainability” this work contributes to the development of an integrated framework to support research in this domain and the first application to a case study in the healthcare sector of an integrated life cycle assessment incorporating environmental indicators and the GeoPolRisk method. Along the branch of “Raw Material Criticality in LCA”, the PhD develops new approaches and proposes methodological enhancements to advance the assessment of resource use in LCA.

Keywords: Life Cycle Assessment, Raw Materials Criticality, Healthcare Sector, Environmental Sustainability

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Institutional support was key for the development of this project. Thank you to the Initiative of Excellence (IdEx) from the University of Bordeaux, which provided the funding for the PhD and encouraged me to work with diverse research groups inside and outside of France. Thanks to the IDS FunMatInno project for providing excellent training in their doctoral schools and financing the various research stays I completed. I am also grateful to the International Roundtable on Materials Criticality (IRTC) for allowing me to take part in multiple international meetings that were key to the exchange of ideas with experts in the fields related to my PhD.

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DEDICATION

A la abuelita Grise, siempre fuerte y luchadora.

A mis padres y hermana, soporte e impulso.

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ACRONYMS AND ABBREVIATIONS

AoP	Area(s) of Protection
ADP	Abiotic Depletion Potential
BGS	British Geological Survey
BRGM	Bureau de Recherches Géologiques et Minières
EC	European Commission
EcLCA	Economic Life Cycle Assessment
EoL-RIR	End of Life – Recycling Input Rate
ESP	Economic Scarcity Potential
ESSENZ	Integrated method to assess resource efficiency
EU	European Union
EV	Electric vehicle
GDP	Gross Domestic Product
GeoPolEndpoint	Geopolitical Supply Risk Endpoint Method
GeoPolRisk	Geopolitical Supply Risk Method
ICT	Information and Communication Technologies
ICU	Intensive Care Unit
ISO	International Organization for Standardization
JRC	Joint Research Centre – European Commission
LCA	Life cycle assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCIni	UNEP Life Cycle Initiative
LCSA	Life Cycle Sustainability Assessment
LIB	Lithium-ion batteries
MRI	Magnetic Resonance Imaging
NHS	United Kingdom National Health Service
NSTC	US National Science and Technology Council
OECD	Organisation for Economic Co-operation and Development.
OR	Operating Room
REE	Rare Earth Elements
SDG	Sustainable Development Goals
S-LCA	Social life cycle assessment
UN	United Nations
UNEP	United Nations for Environment Programme
US/USA	United States of America
USGS	United States Geological Survey
WB	World Bank
WCED	World Commission on Environment and Development
WGI	Worldwide Governance Indicators
WGI-PV	Political stability and absence of violence dimension of the WGI
WHO	World Health Organization

PREFACE

PhD director: Pr. Guido Sonnemann (Université de Bordeaux),

Co-director: Pr. Steven B. Young (University of Waterloo)

PhD thesis: from 01/11/2017 to 31/01/2021

The PhD project is the result of a long-term collaboration between the *CyVi group*, based in the *Institute des Sciences Moleculaires (ISM)* at the *Université de Bordeaux*, and the *Waterloo Industrial Ecology Group*, based in the *School of Environment, Enterprise and Development (SEED)* at the *University of Waterloo*. Following previous work on Life Cycle Assessment and Criticality Assessment, the two research groups displayed a strong interest on the application of these methodologies to the healthcare sector. As one outcome of the discussions, a PhD proposal was presented; the *Initiative of Excellence* from the *Université de Bordeaux* supported the thesis for a 3-year period and the IDS-FunMat-INNO provided a grant to finance research stays and facilitate the attendance to doctoral schools.

The design of the thesis project, its structure, and the most substantial work presented on this manuscript was carried out at the *Université de Bordeaux*; additionally, the following research stays were completed to support the progress of the project:

- *University of Waterloo*, Waterloo, Canada. October, 2018 – March, 2019. First visit to the *School of Environment, Enterprise and Development*. The outcomes of this research stay are presented in **Chapters 2, 3** and **4**.
- *University of Augsburg*, Augsburg, Germany. April – May 2019. Visit supported by the *ResourceLab* at the *University of Augsburg*. The outcomes of this research stay are presented in **Chapter 5**.
- *Bureau de Recherches Géologiques et Minières* (BRGM), Orléans, France. October – December 2019. Scheduled visit to the French Geological Survey for a case study application. The outcomes of this research stay are presented in **Chapter 6**.
- *University of Waterloo*, Waterloo, Canada. March – July, 2020. Second visit to the *School of Environment, Enterprise and Development*. The outcomes of this research stay are presented in **Chapters 7** and **8**.

In order to improve the readability and appealing to external audiences; efforts were made to maintain the core of this manuscript at about 100 pages. Extended information and results are available for supporting work that is published or is in preparation. These items are referenced at the beginning of each chapter, as indicated, with a statement contribution:

- G. Sonnemann; J. Santillán-Saldivar; S. Valdivia (to be submitted to Resources, Conservation and Recycling). Positioning the areas of protection Natural Resources and Human Health used in Life Cycle Impact Assessment within Life Cycle Sustainability Assessment. (Associated with **Chapter 1**).
- J. Santillán-Saldivar; A. Koyamparambath; S. Muller; J. Villeneuve; S.B. Young; G. Sonnemann (2021) The Geopolitical Supply Risk Method. Book Chapter in: Mineral Resources in Life Cycle Assessment: New research developments and feedback from private and public stakeholders. ECO SD Annual Workshop 2020 Paris, Presses des MINES. ISBN 978-2-35671-646-0 (Associated with **Chapter 2**).

- A. Cimprich; J. Santillán-Saldivar; C. L. Thiel; G. Sonnemann; S. B. Young (2019). Potential for industrial ecology to support healthcare sustainability: Scoping review of a fragmented literature and conceptual framework for future research. Journal of Industrial Ecology 23, 6, 1344-1352. https://doi.org/10.1111/jiec.12921. (Associated with **Chapters 2** and **3**).
- J. Santillán-Saldivar; A. Cimprich; N. Shaikh; B. Laratte; S. B. Young; G. Sonnemann (2021). How recycling mitigates supply risks of critical raw materials: Extension of the geopolitical supply risk methodology applied to information and communication technologies in the European Union. Resources. Conservation and Recycling 164, 1, 105-108. https://doi.org/10.1016/j.resconrec.2020.105108. (Associated with **Chapter 4**).
- J. Santillán-Saldivar; T. Gaugler; C. Helbig; A. Rathgeber; G. Sonnemann; A. Thorenz; A. Tuma (2020). Design of an endpoint indicator for mineral resource supply risks in life cycle sustainability assessment: The case of Li-ion batteries. Journal of Industrial Ecology. https://doi.org/10.1111/jiec.13094. (Associated with **Chapter 5**).
- J. Santillán-Saldivar; E. Gemechu; S. Muller; J. Villeneuve; S. B. Young; G. Sonnemann (to be submitted to the International Journal of Life Cycle Assessment). Integrated assessment of environmental and supply risk considerations for selected materials in the life cycle of Li-ion batteries. (Associated with **Chapter 6**).
- A. Siddhantakar; J. Santillán-Saldivar; T. Kippes; G. Sonnemann; S.B. Young (to be submitted to Resources, Conservation and Recycling). The geopolitical supply risk of helium: A multinational perspective. (Associated with **Chapter 7**).
- J. Santillán-Saldivar; A. Siddhantakar; T. Kippes; G. Sonnemann; S.B. Young (to be submitted to the Journal of Cleaner Production). Integrated life cycle assessment of MRI scans including supply risk considerations of helium use. (Associated with **Chapter 8**).

The work included in the thesis was presented in the following international conferences:

- Poster presentation at the LCIC 2018 in Berlin, Germany: A novel framework for life cycle thinking to support sustainable healthcare. August, 2018.
- Oral Presentation at the conference TMS 2019 in San Antonio, USA: Assessing the potential for recycling to mitigate raw materials supply risk. March, 2019.
- Oral Presentation at the conference SETAC 2019 in Helsinki, Finland: Extending the Geopolitical Supply Risk method: Potential for recycling as a risk mitigation strategy. May, 2019.
- Poster presentation at the ISIE 2019 in Beijing, China: A novel framework for life cycle thinking to support sustainable healthcare. July, 2019.
- Oral Presentation at the conference CILCA 2019 in Cartago, Costa Rica: Developing the Geopolitical Supply Risk Method: From a new method in research to a suggested tool to assess risk mitigation. July, 2019.
- Poster Presentation at the conference SETAC 2020 in Dublin, Ireland (virtual): Application of the GeoPolRisk method at Midpoint and Endpoint level: The case of Li-ion batteries for the EU. May, 2020.
- Oral Presentation at the conference ISIE Americas 2020 in Lima, Peru (virtual): The GeoPolEndpoint indicator: Measuring the economic impact of the use of critical raw materials. Application to Li-ion batteries. August, 2020.

- Oral Presentation at the conference ATA2020-EcoSD in Paris, France (virtual): Developing the Geopolitical Supply Risk Method: From a new method in research to a suggested tool to assess risk mitigation. October, 2020.
- Oral Presentation at the conference EcoBalance 2020 in Yokohama, Japan (virtual): Positioning the Areas of Protection Natural Resources and Human Health used in Life Cycle Impact Assessment within Life Cycle Sustainability Assessment. March 2021.
- Oral Presentation at the conference EcoBalance 2020 in Yokohama, Japan (virtual): Understanding the geopolitical supply risk of helium (He): A multinational perspective. March 2021.

Chapter 1: Introduction

The topics discussed in this chapter partially inspired the development of a perspective paper in preparation for publication:

G. Sonnemann; J. Santillán-Saldivar; S. Valdivia (to be submitted to Resources, Conservation and Recycling) Positioning the areas of protection Natural Resources and Human Health used in Life Cycle Impact Assessment within Life Cycle Sustainability Assessment.

Contribution Statement:

G. Sonnemann:	Conceptualization, Writing – Review and Editing
J. Santillán-Saldivar:	Conceptualization, Writing – Original Draft, Visualization
S. Valdivia:	Conceptualization, Writing – Review and Editing

1.1. The challenge of healthcare sustainability

There is a phrase made popular by Quino in Latin-American culture through his most famous character, Mafalda: “As usual: the urgent doesn’t leave time for the important”. This phrase can be applied to many aspects of our life and is highly featured in the Time Management Matrix, commonly used in business development and project management to classify tasks according to their urgency and profit potential (Covey, 2004). Being healthcare one of the most important and urgent services required for the population, it is one of the topics at the top of the list for many societies.

Healthcare is a fast-growing sector around the globe; in 2017 it was estimated that public spending represents 60% of the global spending on health (WHO, 2019). In line with the sustainable development goals, overall trends suggest an ongoing transition towards universal health coverage, although a great breach is evident between the expenditure on health per capita for low-income countries (~USD 40) and high-income countries (~USD 2940) (UN DESA, 2019). Health spending is growing faster than the gross domestic product (GDP), with an estimated growth of 3.9% from 2000 to 2017 versus a 3% GDP growth on the same period. As seen in Figure 1.1, this gap becomes wider in low-income and high-income countries, being an indicator of the increasing investment in healthcare infrastructure and services (WHO, 2019).

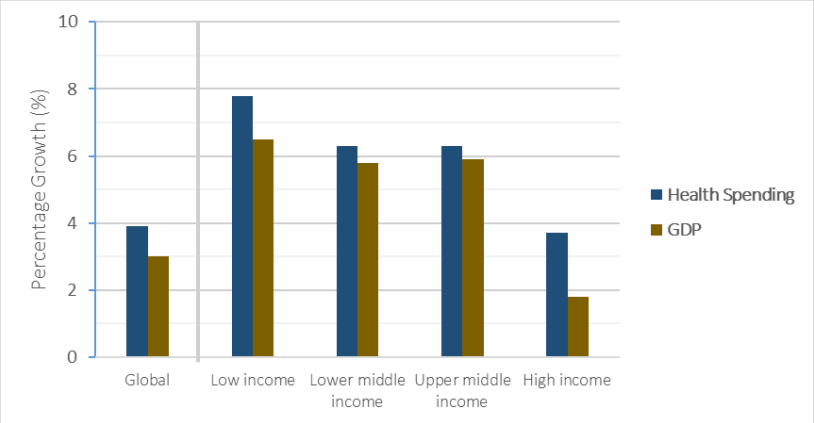


Figure 1.1 – Health spending and GDP growth by country income group from 2000 to 2017
(Adapted from WHO, 2019)

Studies have presented the combined direct and indirect carbon footprint of the healthcare sector in multiple developed countries. Greenhouse gas emissions from this sector have been estimated at 4.6% of the national total in Canada (Eckelman et al., 2018), 5% in the United Kingdom (NHS Sustainable Development Unit, 2016); 7% in Australia (Malik, et al., 2018) and 10% in the United States (Eckelman and Sherman, 2016). Climate change is the result of the constant release of greenhouse gases mainly attributable to human activity in the past century. As stated in a report by 35 globally recognized health institutions including, among others, the United Nations, the World Health Organization and the World Bank, climate change has become a health emergency (Watts et al., 2019).

Based on the concerns raised after studying the contribution of the healthcare sector to environmental impacts at a global scale; multiple definitions of sustainability in healthcare have been discussed. From

a management point of view, sustainable healthcare is defined by the resilience of the healthcare system: the ability to delivery healthcare services despite of external limitations (Schroeder, 2013). On the other hand, a broader definition of healthcare sustainability considers the continuous delivery of healthcare to the population guarantying a minimal consumption of natural resources and minimal impact on the environment and society, now or in the future (NHS, 2014; Schroeder, 2013).

The most recent global sanitary crisis, the COVID-19 pandemic, brought to surface different challenges that need to be addressed before achieving healthcare sustainability at global scale (IRP, 2020). The most important questions were related to the access to healthcare services and the availability of supplies to attend the needs of the patients; along with concerns on the financial situation of the sector after the global crisis (WHO, 2020). Among other efforts, research initiatives have been deployed around the world to understand the behaviour of the SARS-CoV-2 virus and to develop a vaccine (GAVI, 2020); production and trade of respirators, masks, medications and other medical items required to diagnose and treat the disease have increased (European Commission, 2020c); and, new facilities have been or are being constructed and reconditioned to serve as temporary treatment centers (BBC News, 2020). These and other new efforts add up to the regular activities that are part of the healthcare sector.

The urgency of the global sanitary crisis is understandably diverting attention from other important sustainability aspects of the healthcare sector. Representing a non-negligible percentage of the total carbon footprint of multiple developed countries, the healthcare sector is causing direct and indirect damages to the environment. The global yield potential for the most consumed crops in the globe has been decreasing since 1960; as a result, the younger generations have a high risk to suffer from the permanent effects of malnutrition (Smith et al, 2014). The temperature increase in the past few decades has led to a higher transmission of infectious diseases; dengue and cholera are some of the infections that propagate at higher rates in new areas affected by climate change (Hoegh-Guldberg et al., 2018). With the reported increase of extreme weather events such as wildfires and droughts, more people are suffering from respiratory illness associated to exposure to low air quality (Black et al., 2017) which is only exacerbated by an increase of air pollutants caused by industrial activities in highly populated areas.

In the complex world we live in, the healthcare sector is not only generating a significant footprint, but also suffering from its consequences: more common and new conditions that need to be treated, a higher number of patients and, as made evident during the COVID-19 pandemic, the potential supply disruptions of resources required to guarantee uninterrupted activities (Miller et al., 2020). Unfortunately, the sector has done little to address this major challenge and further work is required to identify opportunities for improvement towards healthcare sustainability (Sherman et al., 2020).

1.2. Life Cycle Assessment to assess healthcare sustainability

Along the past few decades, advancements in the healthcare sector and the improvement of living conditions for the population have led to an increased life expectancy with a continuous population

growth around the globe (Chang et al., 2017). Being healthcare one of the most important and urgent services required for the population, governments around the world are required to invest more to guarantee maximum coverage to a constantly growing and aging population (Mendelson and Schwartz, 1993). Intuitively, overall environmental impacts associated with the healthcare sector could be reduced by increasing the efficiency of the resource use to provide healthcare services.

First reports of efforts to reduce environmental impacts of production processes were identified during the 70's. Specific environmental aspects were assessed by companies to compare and decide between multiple options for a similar product; therefore, laying the baseline for the first life cycle assessments (US EPA, 2006). The environmental life cycle assessment (LCA) methodology is considered a relevant and recommended decision-making tool to analyze and compare environmental impacts associated to the design, manufacturing, transport, use and disposing of goods and services (ISO, 2006). As exemplified in Figure 1.2, a typical product life cycle will consider all its life cycle stages for analysis.

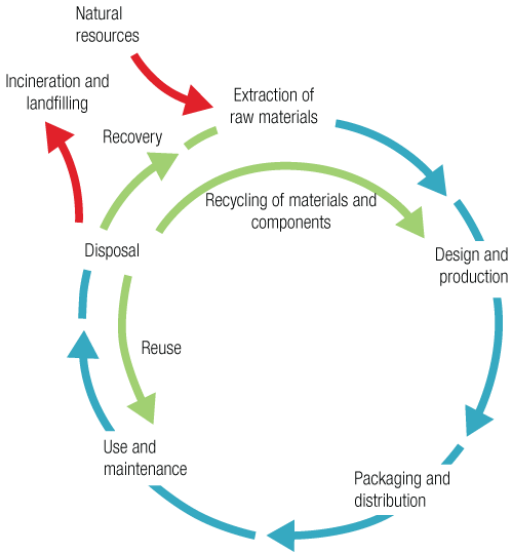


Figure 1.2 – Graphic representation of a product life cycle
(UNEP Life Cycle Initiative, 2018)

By compiling information on the inputs and outputs of product systems throughout their life cycle, the LCA methodology provides insights from a multicriteria perspective, allowing to quantify environmental impacts in different categories (Guinée et al., 2011). LCA provides an overlook of the full life cycle of product systems and allows to identify opportunities for improvement in production processes based on environmental considerations (Moltesen and Bjorn, 2017).

After the publication of the Brundtland report in 1987; the concept of sustainable development was formally introduced and defined as ensuring the fulfillment of needs of the present without preventing future generations to meet their own needs (WCED, 1987). The discussion around this novel term added new layers to be addressed when reducing impacts of human activity. Two main dimensions were added to the already existing and analyzed environmental dimension: social and economic sustainability (Passet, 1996). With the introduction of the now called "three pillars of sustainability", several new approaches to assess sustainable development were proposed and used by public and

private organizations; these would later be compiled and used to study and measure the progress towards the sustainable development goals proposed by the UN (UN DESA, 2014).

From a life cycle thinking perspective, enhancements were needed to address the contribution of product life cycles to sustainability in the three introduced dimensions. As a result, new methods were introduced and promoted as complements to environmental LCA as part of a Life Cycle Sustainability Assessment (LCSA) Framework (Figure 1.3) (UNEP, 2011).

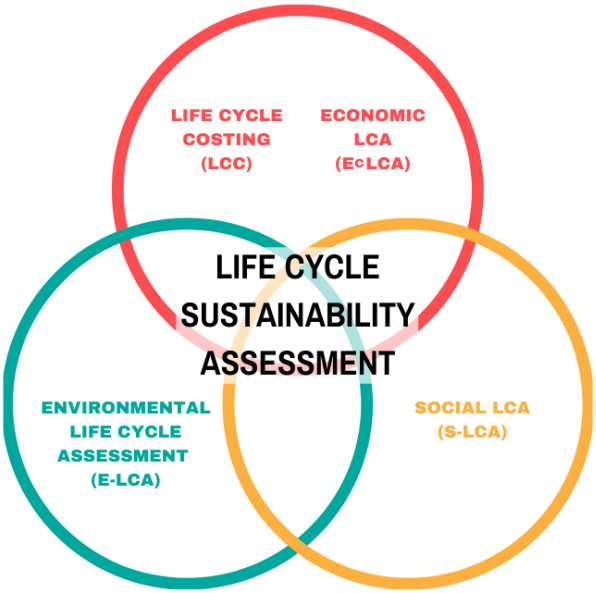


Figure 1.3 – Integration of life cycle methods in LCSA

From a social perspective, Social Life Cycle Assessment (S-LCA) is proposed to assess the social and sociological aspects of product systems, accounting for potential positive and negative impacts in society; with a mix of quantitative and qualitative data, S-LCA explores topics such as human rights, working conditions, health and safety, among others (UNEP, 2009, 2020). From an economic perspective, a methodology based on management and costing was developed to include economic considerations in LCA. Life Cycle Costing (LCC) has the aim to assess total costs of products, services or activities over its lifetime as a complement to environmental LCA (Swarr et al. 2011; UNEP, 2007). Economic Life Cycle Assessment (EcLCA) was later proposed to better represent the economic dimension in LCSA, with the aim to account for an economic impact pathway, not only focusing in the cost-driven approach provided by LCC (Neugebauer et al., 2016).

Life-cycle-based methodologies have been used as decision-making tools for multiple sectors; most notorious applications compare two or more products, technologies or variants of them in order to choose the one with less impacts. A common example is evident in studies that compare the environmental impacts of electric vehicles against those of combustion-engine vehicles; providing insights on the energy transition from fossil fuels to renewable energies and the associated consequences, such as the increasing demand for energy storage technologies such as batteries (Borah et al., 2020; Hawkins et al., 2013).

The healthcare sector, as any other in our society, has the potential to benefit from the application of life-cycle based methodologies. As will be presented in future chapters, efforts are being made towards the sustainability of healthcare systems. However, from a life cycle perspective, the sustainability assessment efforts are focused on understanding the impacts of healthcare-related activities inherent to the sector on the society and environment; also known as “inside-out” impacts (Porter and Kramer, 2006). Certain sustainability concerns relevant to the healthcare sector are not covered under this approach, such as supply constraints (Miller et al., 2020), policy, regulations, extreme weather events, among others that are considered “outside-in” impacts; this relation describes how companies and organizations – in this case, the healthcare sector – are impacted by external socio-economic and environmental conditions (Porter and Kramer, 2006).

1.3. Raw Material Criticality: Assessing impacts from the outside-in

In the context of environmental LCA, impacts are assessed in relation to three main areas of protection (AoP) (Figure 1.3b). The AoP Human health refers to the impacts of product systems in the quality of life for humans; the AoP Ecosystem Health is related to how the ecosystems are affected by human activities in a product life cycle and the AoP Natural Resources seeks to analyze how biotic and abiotic resources are consumed to serve product systems in LCA (Finnveden et al., 2009; Guinée et al., 2011). It can be said that more progress has been made in relation to the AoPs Ecosystem Health and Human Health than in Natural Resources; an adequate level of consensus has been achieved regarding impact categories such as ecotoxicity (Rosenbaum et al., 2008), water use (Boulay et al., 2011, 2018) or global warming potential (IPCC, 2014). However, there is not a practical consistent alignment among the diverse LCIA methods to address the impacts of resource use; this is due not only from a difference between the current methods, but from a conceptual divergence on what sustainable resource extraction is and why natural resources should be protected (Sonnemann et al., 2015).

The AoP natural resources considers elements extracted for human use (Udo de Haes and Lindeijer, 2002); and considers both biotic and abiotic resources. The main goal of most methods is to quantify the depletion due to their use to support the development of human activities and their value in the economy in the present and future. Commonly used methods are focused on reduced resource availability due to geological depletion (Guinée and Heijungs 1995; van Oers et al., 2002; van Oers and Guinée, 2016) or additional efforts required to guarantee continuation of human activities in the future (Itsubo and Inaba, 2012; Ponsioen et al., 2014; Vieira et al., 2016), both of which do not cover questions regarding accessibility to resources due to socio-economic factors (Sonnemann et al., 2015).

Accessibility considerations are studied in criticality assessments as part of the efforts to evaluate technical and economic dependency on a certain material for a defined stakeholder in a certain timeframe (Schrijvers et al., 2020). The topic of raw material criticality has served the industry and governments alike, notably to define policies associated with production, trade and risk mitigation strategies at regional and national level (Graedel, 2012; Graedel and Reck, 2015). Significant examples

of the use of criticality indicators are the “criticality lists”, published on a regular basis by multiple countries or regions (European Commission, 2017, 2020a; NSTC, 2018; BGS, 2015) to identify critical raw materials for the development of key industries such as energy generation and storage; robotics; information and communication technologies (ICT), mobility, aerospace, among others (European Commission, 2020b).

The question of accessibility to resources appears when analyzing impacts from the outside-in perspective. Based on this clear methodological gap in LCA; the concept of raw material criticality was introduced as a new perspective in LCSA to evaluate environmental, social and economic aspects that affect product systems. As proposed by Sonnemann et al. (2015), the LCSA framework has the potential to develop a more meaningful assessment of the impacts of resource use in the AoP Natural Resources.

A new question arises when following this methodological pathway: are the “outside-in” considerations associated with the AoP Natural Resources exclusively achievable through LCSA by exploring its economic dimension? Or, is the scope of E-LCA broad enough to include these aspects? (Figure 1.3, Figure 1.4) (Berger et al. 2020; Sonderegger et al. 2020). For the time being, these topics have been associated to the AoP Natural Resources in LCA (Cimprich et al., 2019) as the links to the overall LCSA framework are not fully defined. Moreover, a similar situation is seen when addressing impacts associated with the AoP Human health; an overlap between E-LCA and S-LCA is visible (Figure 1.4) since health is considered both a social issue and an area of protection in E-LCA (Figure 1.4). This is also evident when acknowledging considerations of access to healthcare and potential impacts of the healthcare sector.

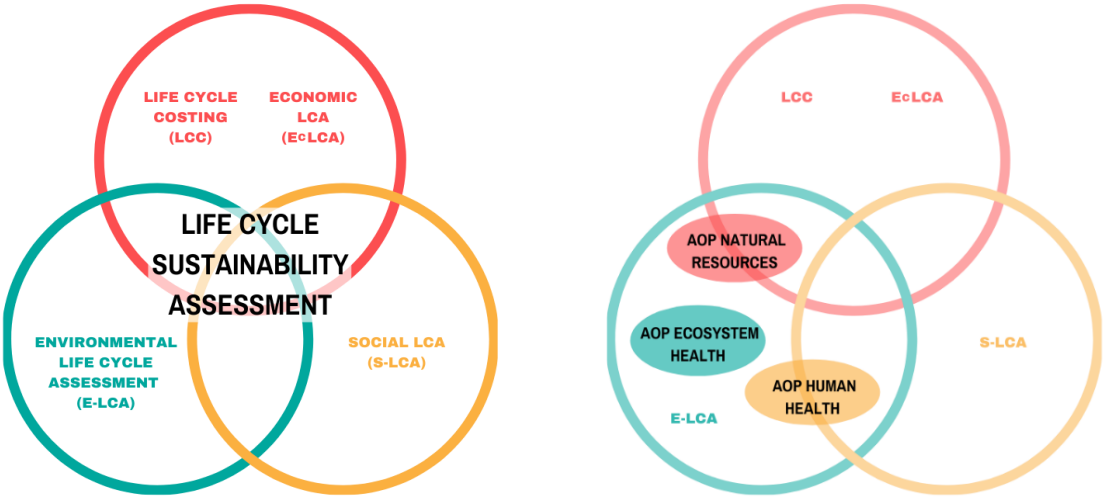


Figure 1.4 – The Areas of Protection of LCA as overlap of methodologies in LCSA

Among the previously mentioned methodologies, notable approaches to the assessment of raw material criticality are proposed by Graedel et al. (2012) and the European Commission (2017). The methodology presented by Graedel et al. (2012) considers three key dimensions to assess raw material criticality: supply risk, vulnerability to supply disruption and environmental implications. These are presented as

three indicators weighted into a final value to assess overall raw material criticality. As with many methodologies depending on multiple indicators, weighting procedures are a major limitation, sometimes being considered subjective and oversimplified. Therefore, these three dimensions were included as independent values in LCSA, similarly to the definition of a midpoint indicator in traditional LCA; the graphic representation of the integration of raw material criticality in LCSA can be seen in Figure 1.5. Further exploration of this proposal revealed several common points between the work on criticality developed by Graedel (2012), the European Commission (2017) and the methodological pathways in LCA; among these, it is possible to highlight the work done by the UN Environment for guidelines related to social LCA (UNEP, 2009, 2020); efforts to assess water use in LCA (Boulay et al., 2011, 2018); methods to assess environmental impact well covered by LCA such as IMPACTWorld+ (Bulle et al., 2019), ReCiPe (Goedkoop et al., 2013; Huijbregts et al., 2016) or ILCD (European Commission, 2012).

Overall, given the literature discussed above, the way impacts were defined in the AoP Natural Resources was not considered particularly meaningful. Sonnemann et al. (2015) proposed the integration of raw materials criticality into the LCSA framework and identified one main methodological gap required to better assess raw material criticality from an LCA perspective: to identify and measure the availability of raw materials related to geopolitical considerations as part of an economic dimension in LCSA (highlighted in Figure 1.5).

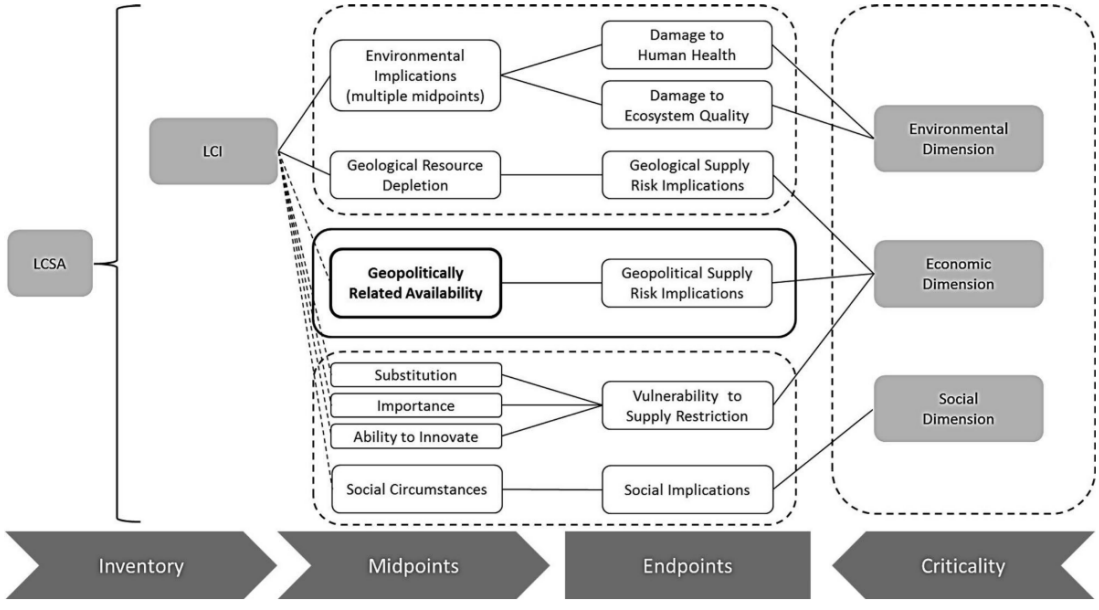


Figure 1.5 – Integration of criticality components within the LCSA framework
(Adapted from Gemechu et al., 2015)

The result of the exploration of this research opportunity is the development of the Geopolitical Supply Risk Method (GeoPolRisk). Gemechu et al. (2015) originally developed the GeoPolRisk method as a measure for the supply risk from the perspective of a country, region or company. It was designed following the proposed integration of raw material criticality into the LCSA framework and takes into account global production concentration and trade flows between multiple trade partners. In a recent

publication by the UNEP Life Cycle Initiative, life cycle impact indicators for addressing abiotic resources were comprehensively reviewed to develop recommended practices; the result of this effort was the volume 2 of the Global Guidance on Environmental Life Cycle Impact Assessment Methods (Frischknecht et al., 2019). The GeoPolRisk method was discussed and reviewed as part of the proposed methods for product-level supply risk assessment and a series of recommendations were given to advance its maturity and applicability. These aspects will be further explored in Chapter 2:.

1.4. Problem setting and research question

The activities required to provide healthcare services to a rapidly growing and aging population bring several challenges in terms of sustainability. The healthcare sector relies on diverse products and services such as facilities, disposable products, complex machines, transportation, among others that have been only superficially explored from a sustainability lens. Efforts exist to understand and act upon sustainability aspects associated with the healthcare sector, however the level of awareness around this topic is considered low (Sherman et al., 2020). Further endeavors are required to identify knowledge gaps and to arrive to a common baseline to assess healthcare sustainability.

Life-cycle based methodologies have the potential to address sustainability concerns related to the healthcare sector; however, these methods are mostly – if not exclusively – related to an inside-out pathway to assess impacts. From an outside-in perspective, there is potential for raw material criticality to address the concerns of resource availability to the healthcare sector, especially after the proposal to integrate it into the LCSA framework. As illustrated in Figure 1.6, a pending task around this proposed methodological pathway is to explore the applicability and readiness of the GeoPolRisk method, proposed to assess resource related impacts.

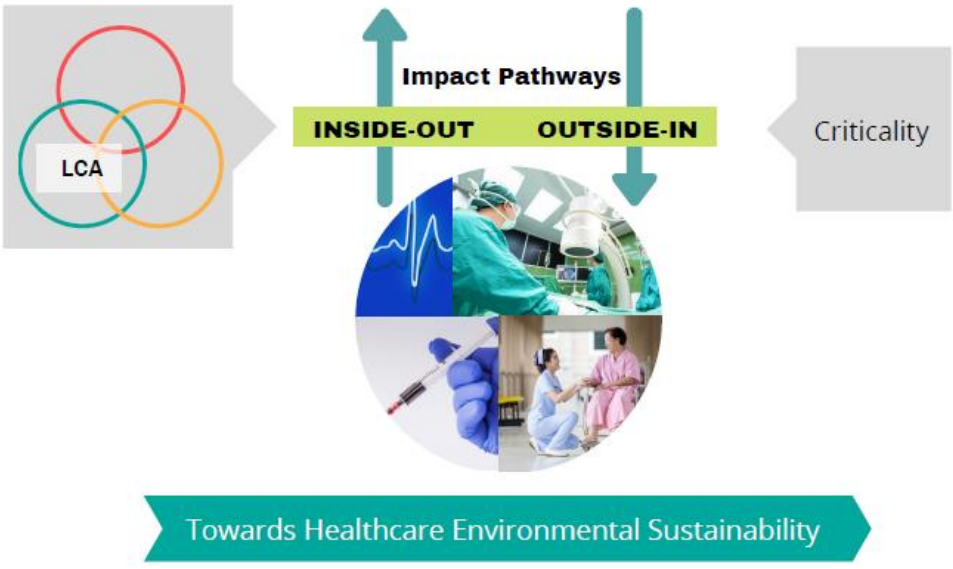


Figure 1.6 – Proposed integration of methodologies to assess resource related impacts in the healthcare sector

Based on the mentioned concerns; the research question for this thesis is defined as follows:

How to assess environmental sustainability aspects in the healthcare sector using life cycle assessment and advancing its methodological readiness to evaluate raw material criticality in an integrated way?

1.5. Hypotheses, objectives and thesis outline

The following hypotheses are formulated to answer the proposed research question:

- Hypothesis 1: LCA is an appropriate methodology to measure environmental sustainability impacts, extending the traditional scope to include an outside-in perspective.
- Hypothesis 2: Raw material criticality has the potential to address outside-in impacts associated with the AoP Natural Resources.
- Hypothesis 3: Products and services related to the healthcare sector can be analyzed in an integrated manner to account for impacts from the inside-out and outside-in pathways in LCA.

These hypotheses determine the starting point of this thesis project and set the direction of the research for this PhD dissertation. Therefore, the main objective of this thesis is: **to provide and integrate methods to assess healthcare environmental sustainability from a life cycle perspective with focus on enhancing criticality indicators as an outside-in impact pathway associated with the AoP Natural Resources**.

The following specific objectives (S.O.) are defined to support the main objective of the thesis:

a. To provide a detailed state of the art of the LCA applications in the healthcare sector while identifying the main methodological challenges for assessing healthcare systems from a life cycle perspective.

b. To provide a detailed state of the art of the methodologies to address outside-in impacts resulting from the integration of raw material criticality and LCA while identifying the main methodological challenges for its readiness.

c. To develop a framework to address healthcare sustainability from a life cycle perspective and provide its potential applications.

d. To enhance the existing geopolitical supply risk method to include recycling considerations as a mitigation strategy.

e. To advance the scope of the geopolitical supply risk method from a midpoint level indicator to an endpoint level indicator associated to the area of protection Natural Resources.

f. To demonstrate the added value of the geopolitical supply risk method at midpoint and endpoint level as a complement to environmental LCA with a case study.

g. To demonstrate the added value of the application of a method based on an outside-in impact pathway with a case study relevant to the healthcare sector.

h. To demonstrate the relevance of the application of an integrated assessment based on LCA considering outside-in and inside out impact pathways for the healthcare sector.

This thesis covers the completion of the main objective and associated specific objectives (S.O.); it is divided in 9 chapters. These chapters are classified in two branches, as illustrated in Figure 1.7, and contain the following information:

This introduction is the **Chapter 1** of the thesis and it is followed by **Chapter 2**: State of the art. That chapter is divided into two main sections: a state of the art that compiles the most relevant LCA applications to the healthcare sector and serves to identify knowledge gaps towards the application of life-cycle based methodologies to the healthcare sector (S.O. a); and, a state of the art of the methodologies to address outside-in impacts resulting from the integration of raw material criticality in LCSA (S.O. b). Methodological challenges for the operationalization of this impact pathway associated with AoP Natural Resources are identified and a special focus is given to the geopolitical supply risk method, which will be a focal point in following chapters.

Chapter 3 presents the development of a novel framework to address sustainability challenges in the healthcare sector based on LCA (S.O. c). The applicability of this framework is tested by its association with previous and potential new studies in the field of healthcare sustainability. These examples will serve as a starting point for a case study presented later on in this thesis.

After the challenges to operationalize the geopolitical supply risk as a midpoint indicator in LCA were identified in Chapter 2, **Chapter 4** depicts the development and proposed application of a methodological enhancement that allows to consider recycling as a mitigating factor for supply risk (S.O. d). The method is tested with an application to materials relevant to Information and Communication Technologies (ICT) in the European Union.

Chapter 5 has as main focus the extension of the geopolitical supply risk method from a midpoint indicator in LCSA to an endpoint level indicator associated with the AoP Resources (S.O. e). A new method for quantifying the effects of supply disruption events in the price of resources is introduced and tested with a case study on Lithium-ion batteries (LIB) for the country members of the Organisation for Economic Co-operation and Development (OECD).

Chapter 6 integrates the advancements from chapters 4 and 5 by demonstrating the applicability of the methodological developments associated with the geopolitical supply risk method as a complement to environmental LCA (S.O. f). The results of the application to a case on LIB for the European Union are

compared with results for other relevant impact categories more commonly used to assess environmental impacts.

Based on the proposed framework in Chapter 3, **Chapter 7** presents an application of the geopolitical supply risk method to a resource of great importance in the healthcare sector (S.O. g). Helium is selected as a case study to demonstrate the relevance of analyzing impacts from an outside-in pathway for the healthcare sector. The results are presented from a multinational perspective.

Chapter 8 presents an integrated study of MRI scans following the LCA methodology. It focuses on the helium used in MRI machines for medical diagnosis (S.O. h). The results obtained in Chapter 7 are used as a complement to achieve an integrated assessment that contains both impact pathways relevant to the healthcare sector: inside-out and outside-in. The case study is developed from the perspective of selected countries analyzed in Chapter 7.

Finally, the hypotheses are tested and the research question is answered in **Chapter 9**. A general conclusion highlighting overcome challenges and found limitations is presented and perspectives for future work are explored.

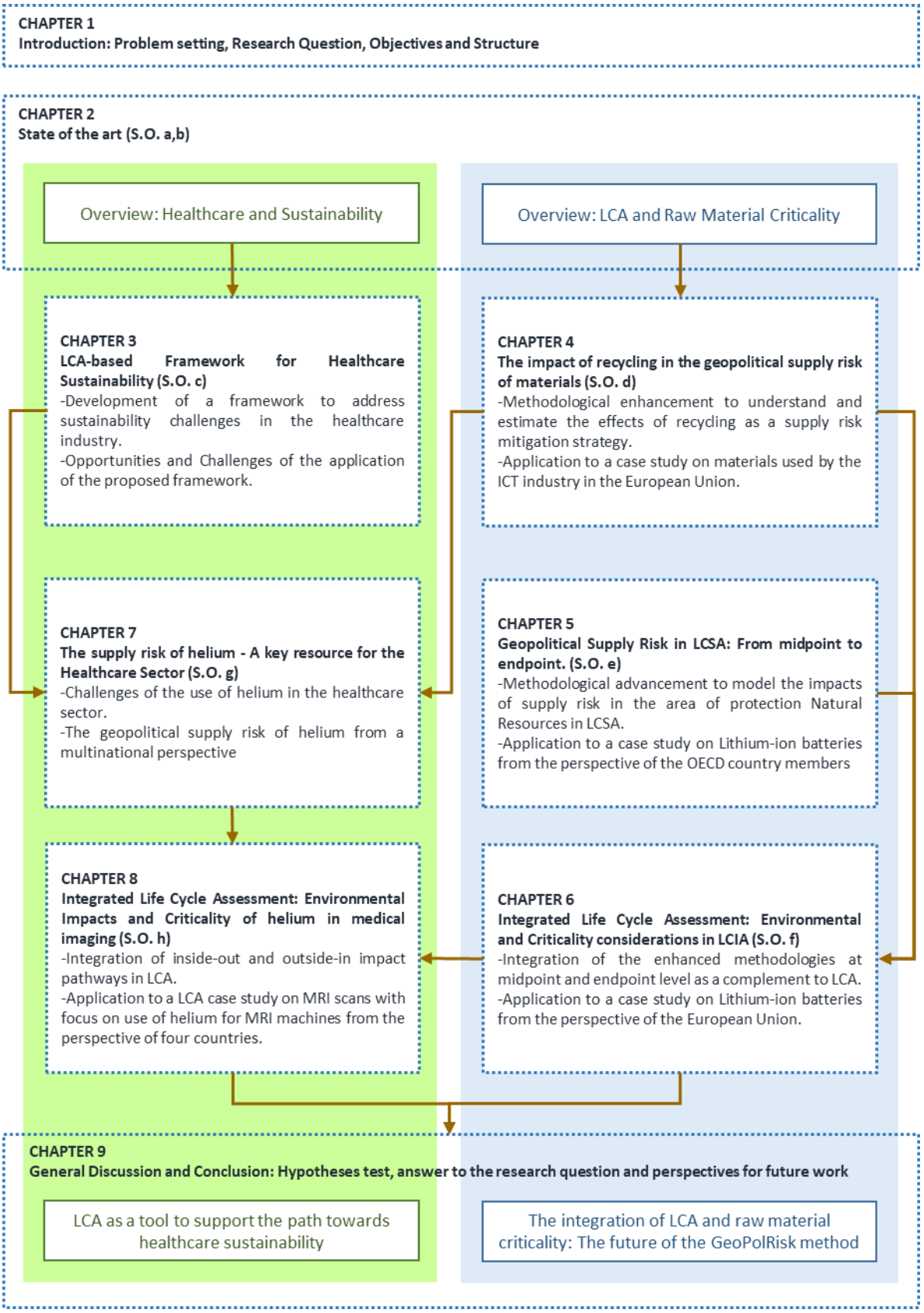


Figure 1.7 – Structure of the thesis associated to the Specific Objectives (S.O.)

Chapter 2: State of the Art

The scoping review presented in this chapter is partially based on the publication:

A. Cimprich; J. Santillán-Saldivar; C. L. Thiel; G. Sonnemann; S. B. Young (2019). Potential for industrial ecology to support healthcare sustainability: Scoping review of a fragmented literature and conceptual framework for future research. Journal of Industrial Ecology 23, 6, 1344-1352. https://doi.org/10.1111/jiec.12921.

Contribution Statement:

A. Cimprich:	Conceptualization, Methodology, Formal analysis, Investigation, Data Curation, Visualization, Writing – Original Draft
J. Santillán-Saldivar:	Conceptualization, Framework Development, Formal analysis, Investigation, Data Curation, Visualization, Writing – Review & Editing
C.L. Thiel:	Validation, Writing – Review & Editing
G. Sonnemann:	Supervision, Writing – Review & Editing
S.B. Young:	Supervision, Writing – Review & Editing, Supervision

The theoretical background related to the GeoPolRisk method in this manuscript is also featured in the publication:

J. Santillán-Saldivar; A. Koyamparambath; S. Muller; J. Villeneuve; S.B. Young; G. Sonnemann (2021) The Geopolitical Supply Risk Method. Book Chapter in: Mineral Resources in Life Cycle Assessment: New research developments and feedback from private and public stakeholders. ECO SD Annual Workshop 2020 Paris, Presses des MINES. ISBN 978-2-35671-646-0

Contribution Statement:

J. Santillán-Saldivar:	Investigation, Data Curation, Visualization, Writing – Original Draft
A. Koyamparambath:	Investigation, Writing – Original Draft
S. Muller:	Writing – Review & Editing
J. Villeneuve:	Writing – Review & Editing
S.B. Young:	Validation, Writing – Review & Editing
G. Sonnemann:	Supervision, Writing – Review & Editing

As described in Chapter 1:, the PhD thesis considers two branches. The first one is associated with the concept of healthcare sustainability and has as main objective the study, integration and application of LCA-based methodologies applicable to the healthcare sector. The second branch of the PhD thesis seeks to enhance criticality indicators to obtain a more mature outside-in impact pathway associated with the AoP Natural Resources in LCA.

The first section of this chapter provides a detailed state of the art on the application of sustainability assessment methods, with focus on the main methodological challenges for assessing healthcare systems from a life cycle perspective. It is partially based in a section of the publication entitled “Potential for industrial ecology to support healthcare sustainability: Scoping review of a fragmented literature and conceptual framework for future research”, for which the author conducted literature searches and analyzed multiple publications discussed in this chapter. Moreover, the second part of the chapter studies current methodological efforts to address outside-in impacts resulting from the integration of raw material criticality and LCA, with special focus on the Geopolitical Suppy Risk method and its readiness to address impacts on the Area of Protection Natural Resources in LCA.

2.1. Scoping Review on Healthcare and Sustainability

2.1.1. Healthcare Sustainability

Climate change has been named the number one public health issue of the 21st century (Costello et al., 2009). Estimations point to a potential loss of a quarter million lives between 2030 and 2050 directly attributable to climate change. From a healthcare perspective, the main type of conditions to increase in the nearby future because of climate change will be related to poor air quality, malnutrition, infectious diseases, limited access to water, and hazards from extreme weather events (WHO, 2009). However, 5% to 10% of greenhouse gases emissions can be associated with the healthcare sector in many developed countries around the globe (Eckelman and Sherman, 2016; NHS Sustainable Development Unit, 2016; Eckelman et al., 2018; Malik, et al., 2018).

The previously mentioned environmental impacts of healthcare are conceptualized as “inside-out” impacts: those inherent to the sector and affecting the society and environment (Porter and Kramer, 2006). On the other hand, healthcare systems are affected by other situations such as the effects of climate change (e.g. damage from extreme weather events), limited access to resources (e.g. supply disruptions of medical supplies, as seen during the COVID-19 pandemic) and other external influences. These aspects of healthcare sustainability can be conceptualized as “outside-in” impacts on healthcare.

Awareness on the environmental impacts from the healthcare sector have been increasing in the past years, but is still considered low (Sherman et al., 2020). International healthcare organisations have pointed the role of the sector in indirectly increasing the number of conditions related to sustainability issues (WHO, 2017; World Bank, 2017; Watts et al., 2017). One of the first suggestions was given by the Institute of Medicine Roundtable on Environmental Health Sciences Research and Medicine (2013), encouraging the healthcare sector to be an example by reducing its own environmental footprint and

improve planetary health. Several efforts towards healthcare sustainability made by actors in the healthcare sector have been documented.

Following the need to understand how life cycle assessment is being applied to the healthcare sector, this section is dedicated to identify the current state of the art on the topic of healthcare and sustainability; with the aim to understand the main methodological challenges for assessing healthcare sustainability from a life cycle perspective.

2.1.2. Scoping Review Methodology

Unlike typical approaches used to perform systematic reviews that focus on summarizing the collective findings on specific subjects or research questions, this review aims to map the literature associated with the topic of healthcare sustainability from an exploratory perspective. A main goal of this review is to obtain a broad picture of the work currently done on healthcare and sustainability, highlighting knowledge gaps and opportunities for future research. With this objective in mind, the development of a scoping review is proposed to study the field of healthcare sustainability.

Peters et al. (2015) developed the scoping review methodology to bring together literature in emerging disciplines. Figure 2.1 illustrates the followed methodology; in the first stage, identification, two large international databases were selected as starting point: Scopus and PubMed. The search criteria aimed to obtain results around environmental and resource-related considerations in healthcare; however, other sustainability aspects were included as part of the social and economic dimensions. Different search phrases were constructed; the main being obtained with the combination of the keywords “sustainability” and “healthcare”, along with general terms on the subject such as “environment”, “social responsibility”. Additionally, specific terms related to the studied fields were applied: (1) in the field of life cycle assessment and industrial ecology, “energy efficiency”, “carbon footprint”, “environmental management”, “waste management”, “life cycle”, “material flow analysis” among others. And (2) in the medical field, “x-ray”, “ultrasound”, “surgery”, “medical device”, among others. For the specific case of the PubMed database, which focuses on medicine and health sciences, only keywords relating to sustainability were used. In total, 134 literature searches were performed between September and November, 2017 (details are presented in Annex A).

During the screening stage, the review was limited to academic journal articles in English, published after 1987; corresponding with the publication of the Burtland report (WCED, 1987). Duplicates were eliminated from the database and over 1700 pieces of literature were identified as part of the review. For practical reasons and representing an overall limitation of the review, a stratified random sampling was conducted to reduce the numbers of articles to study; the sampling frame of 1748 articles resulted in a sample of 157 articles to be included. The list of articles that were part of the review are presented in Annex B.

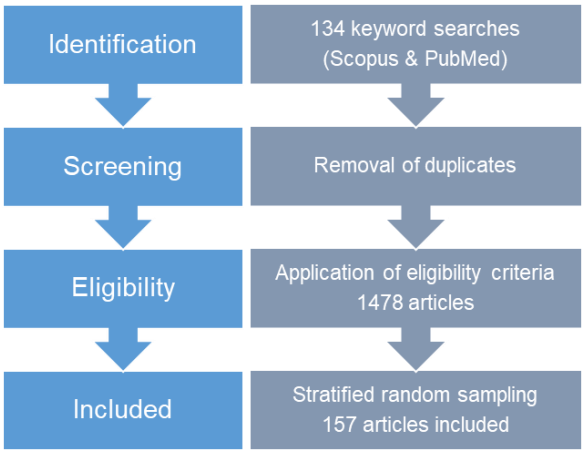


Figure 2.1 – Inclusion methodology for the scoping review

2.1.3. Literature Review - Results and Discussion

Among the general characteristics of the body of literature studied for this review, a highlight is that a 65% of items was published between 2007 and 2017. The articles are distributed in different and various journals, being the main type medical journals, followed by journals in environmental sciences; however, this fragmentation represents a new challenge when targeting appropriate audiences for dissemination.

The articles were clustered taking into consideration (1) a medical activity or resource (e.g. diagnostic procedures, therapeutic procedures, administrative services, pharmaceuticals, medical supplies) and (2) an approach to assess sustainability aspects (e.g. life cycle assessment, ecological footprint, energy efficiency). The topic of waste management is addressed in approximately 25% of the studied articles. Among these, some highlights found are related to compliance of regulatory requirements (Takatsuki 2000; Haylamicheal and Desalegne 2012; Botelho, 2013); results of surveys on best practices on waste management (Idowu et al., 2013; Ul Rahman et al., 2017; Askarian et al., 2004; Aseweh Abor and Bouwer, 2008; Saad, 2013; Thiel et al., 2017; Jovanović et al., 2016; Gupta et al., 2014) and toxicological studies on healthcare waste (Gupta et al., 2009). The visibility and direct impacts of waste from the healthcare sector are probably why this issue is highly featured in the analyzed sample.

A second highlight cluster is related to energy efficiency; two main aspects stand out: the use of heating, ventilation and air conditioning in healthcare facilities (Radwan et al., 2016; Khalil, 2012) and energy consumption for medical imaging (Burke and Stowe, 2015; Esmaeili et al., 2015). This last set of articles is the first found in the review that focus on a specific medical specialty (radiology). The interest to address concerns related to resource efficiency is evident. Climate change and greenhouse gas emissions are also topics shared by multiple articles in the sample. Carbon footprint studies on pharmaceutical production (Tvrdinić and Estapé, 2016; Markarian, 2016), anesthetics (Yasny and White, 2012) and operating room procedures (Thiel et al., 2015; Campion et al., 2012) follow a life cycle thinking approach to address “inside-out” impacts associated with specific medical products and activities. On the other hand, “outside-in” impacts are addressed in an article by Paterson et al. (2014) which focuses on climate change adaptation and resilience of healthcare facilities.

Overall, four main conclusions can be formulated from the review findings, these are illustrated in Table 2.1 as opportunities for improvement for this novel field. First, from the medical perspective, only a few areas in the field are covered; therefore, the healthcare system is understudied from a sustainability lens. Second, from a methodological perspective in the field of sustainability, there is not a unified approach to address the concerns of the sector. Life cycle assessment is used in selected articles from the review and could have the potential to support further research in the field (e.g. LCA of childbirth In the US by Campion et al., 2012; LCA of the Canadian healthcare system by Eckelman et al., 2018; LC emissions of anesthetic drugs by Sherman et al., 2012). Third, only one of the articles clearly focused on an "outside-in" impact pathway by assessing the resilience of healthcare facilities in the context of climate change (Paterson et al., 2014); therefore, further efforts need to be made to provide and/or enhance methods that support the healthcare sector (or others) when addressing "outside-in" impacts. At last, a broader systemic foundation was not found in the existing literature, an effort needs to be made to provide scholars who would like to develop research in the topic of healthcare sustainability with guidelines or a conceptual framework to support future research (Sherman et al., 2020). Proposals to address these four opportunities for improvement will be further explored in the thesis.

Table 2.1 – Identified opportunities for improvement in healthcare sustainability

	Perspective	Problem	Identified Opportunity
SCOPING REVIEW ON HEALTHCARE SUSTAINABILITY	Medicine	Only a few areas in the medical sector are studied.	Explore understudied areas in healthcare.
	Sustainability	There is not a unified approach to address sustainability concerns in the field.	Explore life cycle assessment as a method to support future research.
	Impact Pathways	Studies of impacts from the "outside-in" is almost non existent in the field.	Provide and enhance methods to address "outside-in" impacts.
	Methodological Integration	There is a lack of guidelines on how to approach research on healthcare sustainability.	Development of a conceptual framework to support future research.

2.2. Life Cycle Assessment (LCA) and Raw Material Criticality

2.2.1. LCA: An Overview

As mentioned in section 1.2, early efforts to identify and quantify environmental impacts associated with product systems were conducted in the decade of 1970. It is not until the end of the century that international organizations worked together to provide guidelines and frameworks that allow to apply the

LCA methodology on a mature and standardized way. Clear examples of the strong efforts made by international bodies are the publication of the ISO14040/44 standards on life cycle assessment as part of the environmental management family (ISO 2006a, 2006b) which provided the first consensed definition of LCA as an environmental management tool to calculate the environmental impact of products and services throughout their life cycle; and the creation of the UNEP Life Cycle Initiative (LCIni) as an organism to achieve global consensus on LCA (Sonnemann and Valdivia, 2014).

As depicted in Figure 2.2, LCAs are developed for a variety of reasons: develop new products, reduce the footprint of product systems, marketing, compliance, comparison of similar products, among others. There are four phases according to the international guidelines provided by ISO (2006a, 2006b). First, the goal and scope definition allow identifying the main objectives of the study and marking the boundaries of the analyzed system; the life cycle stages and functional unit of the study are defined in this first stage. Second, primary and secondary data is collected to form a life cycle inventory (LCI) that contains inputs and outputs along the life cycle under study. Next, an association is made between the inputs and outputs of the LCI and the impacts of the product system on the environment with the life cycle impact assessment (LCIA) phase. In parallel to the development of the three previously presented steps, the interpretation phase allows to identify limitations and make adjustments while the study is under development.

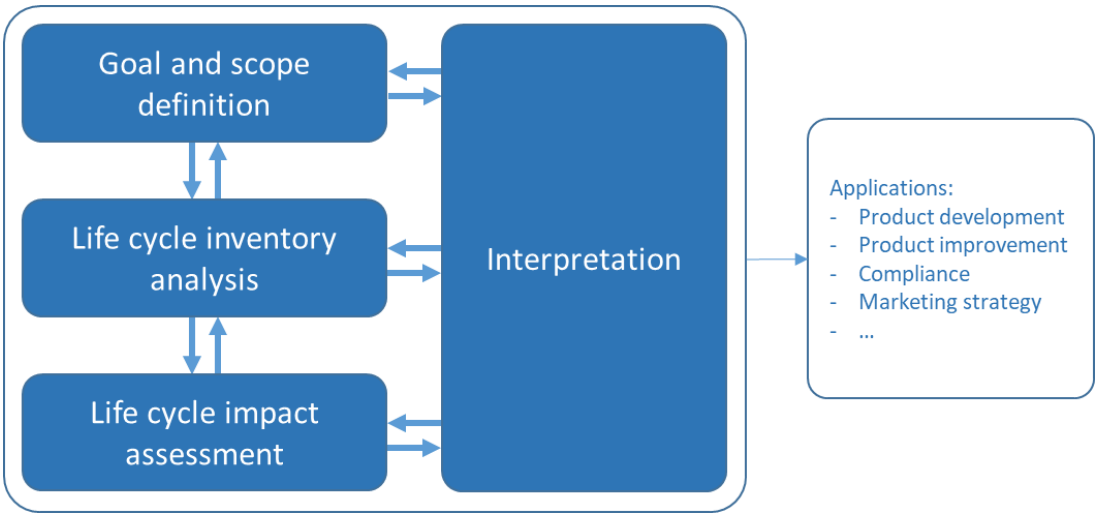


Figure 2.2 – LCA Framework
(Adapted from ISO, 2006a)

From the four mentioned phases, LCIA refers to the steps that link the inputs and outputs in a LCI with potential or tangible impacts in the environment, society or economy. Traditionally in LCA, these impacts can be associated to three AoPs: Human health, Ecosystem health and Natural Resources (JRC, 2011; Finnveden et al., 2009; Guinée et al., 2011), as illustrated in Figure 2.3. Currently available methods for LCIA provide guidelines to categorize and characterize inputs and outputs from the LCI to specific impact categories at the so-called midpoint level. The contribution of multiple impact categories at the midpoint level is then integrated and associated to one or multiple AoPs. These represent the endpoint level indicators in LCA (Jolliet et al., 2003b; Rosenbaum et al., 2018).

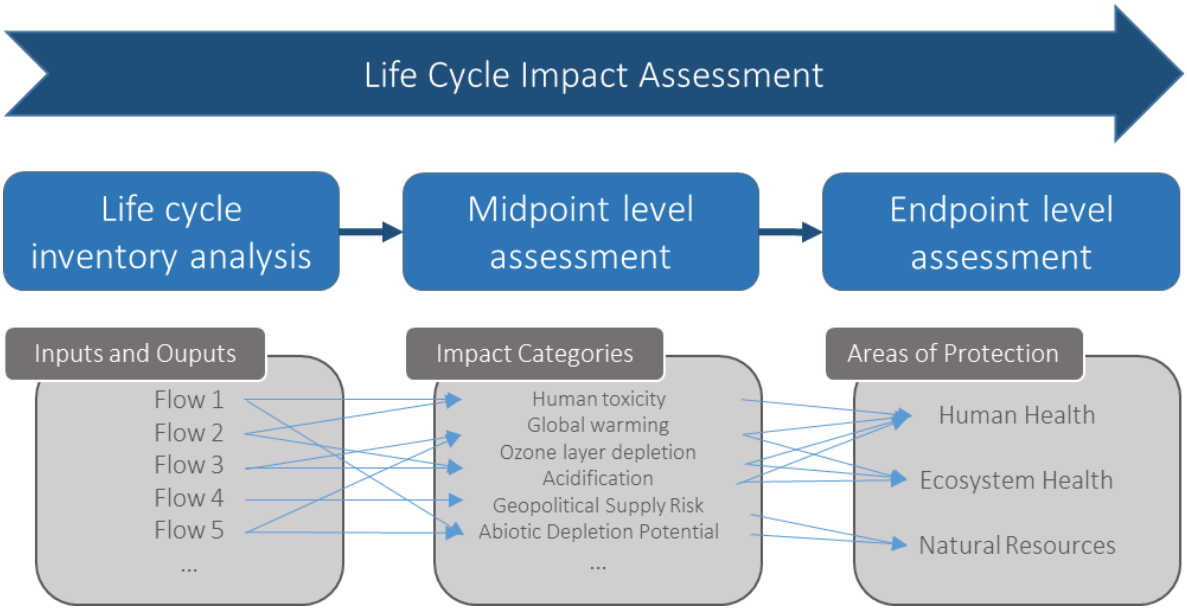


Figure 2.3 – Life Cycle Impact Assessment Framework

It is possible to say that a scientific consensus has been reached between the methods to quantify and analyze how product systems affect human health and ecosystem health. However, a misalignment has been identified among diverse LCIA methods on how to address resource use impacts (Dewulf et al., 2015; Drielsma et al., 2016a, b; Finnveden, 2005; Stewart & Weidema, 2005). This was made evident after the publication of the first Global Guidance for Life Cycle Impact Assessment Indicators, which excluded the topic of resources due to not obtaining a similar level of consensus as the other areas (UNEP, 2017). This dissonance is not only a result from multiple modeling methods, but also a consequence of a conceptual divergence on what sustainable resource extraction is and why natural resources must be protected (Sonnemann et al, 2015).

The AoP natural resources refers to all elements extracted from the environment for human use (Udo de Haes and Lindeijer, 2002); these include biotic and abiotic resources. The main goal of existing methods associated with this AoP is to quantify resource depletion due to potential intensive resource use to support human development. Current models focus on reduced availability due to geological depletion (Guinée and Heijungs, 1995; van Oers et al., 2002; van Oers and Guinée, 2016) and additional efforts required to guarantee future resource extraction (Itsubo and Inaba 2012; Ponsioen et al. 2014; Vieira et al. 2016).

However, these methods explore long-term scenarios and do not address resource accessibility considerations (Frischknecht et al. 2019). Based on this methodological gap; raw material criticality was proposed as a new perspective in LCSA to evaluate environmental, social and economic impacts related to the AoP Natural Resources with the aim to support decision-making processes (Sonnemann et al, 2015).

2.2.2. Raw Material Criticality as a complement to LCA

Based on the framework presented in Figure 1.5 (Chapter 1:); multiple motivations exist to support the integration of raw material criticality and life cycle assessment. The potential for methods to associate criticality considerations of materials to a functional unit in LCA would support decision-making processes for product design (Cimprich et al., 2017a,b). The capacity for LCA to identify hotspots in a products life cycle would allow highlighting materials with a high criticality in a life cycle inventory; with an additional opportunity to link the physical flows in the inventory to their associated criticality (Mancini et al., 2016).

Criticality assessments contain multiple dimensions for analysis such as environmental, economic and social implications (Bach et al., 2016; Graedel et al., 2012; Kolotzek et al., 2018; Schneider, 2014; Achzet and Helbig, 2013); these are already covered in LCSA through S-LCA, E-LCA and LCC from an "inside-out" perspective. However, the concept of supply risk and vulnerability to supply disruptions, which corresponds to an "outside-in" pathway, is not fully developed. The notion of supply risk in criticality assessment refers to considerations of global production concentration, country risks (e.g. political stability, development level, government type) and supply mixes (Achzet and Helbig, 2013). In terms of vulnerability to supply disruption, factors such as substitutability, recycling and stockpiling were identified as supply risk mitigating strategies worth including in criticality assessments (Hebig et al, 2016b).

Three methods based on supply risk aim to provide insights on the criticality of materials within environmental LCA; these are designed to serve as a complement to the Abiotic Depletion Potential method (ADP), used to quantify the contribution of product systems to the depletion of mineral resources (Guinée and Heijungs 1995; van Oers et al., 2002; van Oers and Guinée, 2016). First, the geopolitical supply risk method (GeoPolRisk), introduced by Gemechu et al. (2015) and subsequently extended by Helbig et al. (2016a) and Cimprich et al. (2017a,b). Then, the Economic Scarcity Potential (ESP), developed by Schneider et al. (2014); and the Integrated Method to Assess Resource Efficiency (ESSENZ), which is an extension and update of the ESP method (Bach et al., 2016). Cimprich et al. (2019b) proposed the term "product-level supply risk assessment" as a way to refer to the GeoPolRisk, ESP and ESSENZ methods, which address "outside-in" impact pathways.

The three methods for product-level supply risk assessment use proxy indicators for supply disruption and vulnerability. As a comparison, Table 2.2 summarizes the impact mechanisms that link the political stability of raw material producing countries to supply risk (midpoint level indicator in LCIA) and the potential socioeconomic impacts relevant for countries or companies manufacturing a product from an "outside-in" perspective (endpoint level indicator in LCIA).

Table 2.2 – Comparison between methods for product-level supply risk assessment. Impact mechanisms in LCIA
(Adapted from Cimprich et al., 2019)

Political (in)stability impact mechanism			GeoPolRisk	ESP	ESSENZ
Supply Risk (equivalent to LCIA midpoint)	Supply Disruption Probability	Political in(stability) of…	…trade partners	…global mining countries	…global mining countries
		⇩ Mediating factors	(+) Production concentration (+/-) Supply mix of importing country (-) Domestic Production	(+/-) Global Production Shares (+) Distance-to-target ratio >1	(+/-) Global Production Shares (+) Distance-to-target ratio >1
		Disruption of inventory flows			
	Vulnerability	⇩ Mediating Factors	(-) Substitutability	(+) Magnitude of Inventory Flow	(+) Magnitude of Inventory Flow (-) Overall global production amount
		Supply risk for…	…importing countries where a product is made	…the company purchasing the inventory flow	…the company purchasing the inventory flow
Equivalent to LCIA endpoint		⇩ Mediating factors	Not applicable	Not applicable	Not applicable
		Socioeconomic impact on country or company manufacturing a product			

As a country level measurement of political stability, the three methods consider the Worldwide Governance Indicators (WGI) developed by the World Bank (2019). The GeoPolRisk method only considers the indicator “political stability and absence of violence and terrorism” (WGI-PV); the ESP method integrates three WGIs (voice and accountability, political stability and absence of violence and terrorism, and government effectiveness). Finally, the ESSENZ method considers the previous ones, along with “regulatory quality”, “rule of law” and “control of corruption”; other variables included in the ESSENZ method aim to characterize the overall resource availability based on physical and economic considerations (reserves, feasibility of exploration, price volatility, among others).

Supply risk depends also on mediating factors that complement the risk associated with the political instability of producing countries. The GeoPolRisk method considers the supply mix of importing countries and domestic production of the country from which the supply risk is measured to achieve a weighted risk average. This value is later integrated with the global production concentration measured by the Herfindahl–Hirschman Index (HHI) (Herfindahl, 1950; Hirschman, 1945). The ESP and ESSENZ methods calculate a global weighted risk with the shares of producing countries. This is the first main difference between the methods; whereas ESP and ESSENZ provide global average characterization

factors; the GeoPolRisk method is designed to provide supply risk values for particular cases (e.g. for regions, countries or companies).

While the result indicator for the GeoPolRisk method can be directly interpreted as the mass share at constant risk of supply disruption; the ESP and ESSENZ method apply a “distance-to-target” approach (Müller-Wenk and Ahbe, 1990; Frischknecht et al., 2009): a calculated risk is compared to a “target” value and the excess indicates a high probability of supply disruption. In the GeoPolRisk method, the supply risk is independent from the magnitude of the inventory flows (Cimprich et al., 2017b); this is explained from a life cycle perspective by the fact that every input to a product system is equally necessary for the product, regardless of their amount (Peck, 2016). On the contrary, the supply risk measured with the ESP and ESSENZ methods is exacerbated proportionally to the size of the analyzed inventory flow.

Each method has an applicability in order to achieve impact assessment from the “outside-in” perspective as a complement to “inside-out” environmental LCA. However, certain limitations are shared: there is not yet a way to associate the midpoint level indicators to an impact in the AoP natural resources at the endpoint level; and, information is obtained with proxy data to quantify political stability, adding several layers of uncertainty. The ESP and ESSENZ methods could serve to obtain global average supply risk values and the GeoPolRisk method could be applied at a more granular level for regions, countries or companies.

In order for LCA to support the assessment of product systems in an integrated fashion, works needs to be done to enhance the methods for product-level supply risk assessment. As one of the suggested methods by the UNEP LCIni Task Force on LCIA methods to address natural resources (Frischknecht et al., 2019) and given the possibility to address supply risk from different perspectives, the GeoPolRisk method shows the most potential to be further developed into an endpoint level indicator to assess socioeconomic impacts associated with the AoP Natural Resources based in criticality considerations.

2.2.3. The Geopolitical Supply Risk Method

Gemechu et al. (2015) originally developed the GeoPolRisk method as a measure for the supply risk from the perspective of a country, region or company. It was designed as a midpoint indicator in LCA following the proposed integration of raw material criticality into the LCSA framework. The method focuses on the perspective of a country or region importing a raw material from multiple trade partners. It integrates (1) the global production concentration and (2) the political instability of the trade partners weighted by their corresponding supply share for the analyzed importer. The production concentration is evaluated with the HHI index and the political instability is estimated with the “political stability and absence of violence” dimension of the WGI (WGI-PV). Helbig et al. (2016a) introduced domestic production into the GeoPolRisk method to account for the local production in supply requirements. A visual representation of the dynamics that the method captures is available in Figure 2.4.

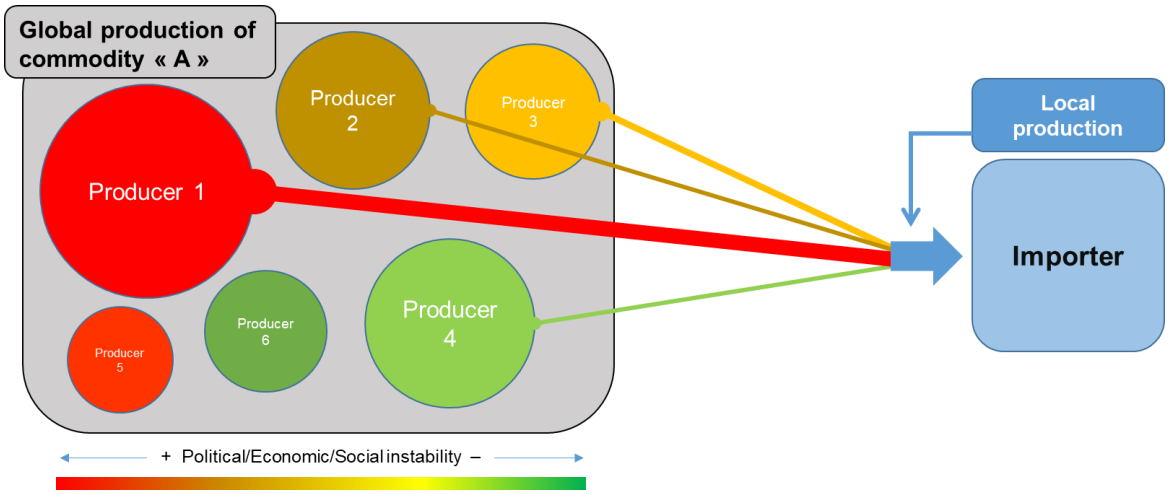


Figure 2.4 – Trade dynamics captured by the GeoPolRisk method

The formula to obtain the GeoPolRisk of a material "A" from the perspective of a country "c" in a given year is described by:

Equation 2.1..... $$GeoPolRisk_{Ac} = HHI_A * \sum_i \frac{g_i * f_{Aic}}{p_{Ac} + F_{Ac}}$$

Where:

HHI_A = Herfindahl-Hirschman Index for commodity A

g_i = Geopolitical (in)stability of country i,

f_{Aic} = Imports of commodity A from country i to country c

F_{Ac} = Total imports of commodity A to country c

p_{Ac} = Domestic production of commodity A in country c

Worldwide production information at mining and refining stages is usually obtained from the United States Geological Survey (USGS 2016, 2017, 2018). The import supply mix data is obtained from the United Nations International Trade Statistics Database – UN COMTRADE (UN, 2020) and the WGI-PV provided by the World Bank is scaled to a range from 0 to 1 (0 representing the absence of risk). The results will also be between 0 and 1; where 0 can be interpreted as the complete absence of geopolitical supply risk and 1 represents a situation in which a 100% of the material supply going to the importing country is at imminent risk of disruption.

The two components of the GeoPolRisk formula provide different components of risk. The production concentration of a raw material (measured by the HHI) gives an overview of the criticality of the commodity; while the weighted political stability provides a country-specific contribution to the supply risk. The GeoPolRisk method can be used to compare the supply risk of a commodity from the perspective of various countries.

A previous application of the GeoPolRisk method to a case study of electric vehicles (EV) serves to show the potential for the method to assess the supply risk dimension of criticality and to complement

environmental LCA. In Gemechu et al. (2016), the method was applied to materials used in electric vehicles. Among these materials, magnesium, neodymium, dysprosium and lithium have been identified as critical due to (1) the geopolitical issues in the region where they are sourced from and (2) having a hig production concentration in a few countries. The study exemplifies the application of the GeoPolRisk method under the framework of LCSA and compares the results with the midpoint indicators of a traditional environmental LCA.

The inventory data in the study includes materials, energy requirements and associated emissions throughout the analyzed life cycle stages of an EV. Although previous studies show that the use phase of an EV dominates the environmental impacts; only the resources consumed at the production stage are considered for the application. The inventory data was extracted from a publication by Hawkins et al. (2013), in which the functional unit of one EV is considered. The application focuses on the following fourteen metals: steel and iron, aluminum, copper, neodymium, zinc, lead, magnesium, boron, bronze, tin, nickel, chromium, silver and the platinum group metals. USGS and UN-COMTRADE were the main sources for the application to the year 2013. The method was applied to thirteen countries/regions: Australia, Canada, China, the EU, France, Germany, Greece, India, Italy, Japan, Norway, the UK and the USA. Partial results of the study are illustrated in Figure 2.5.

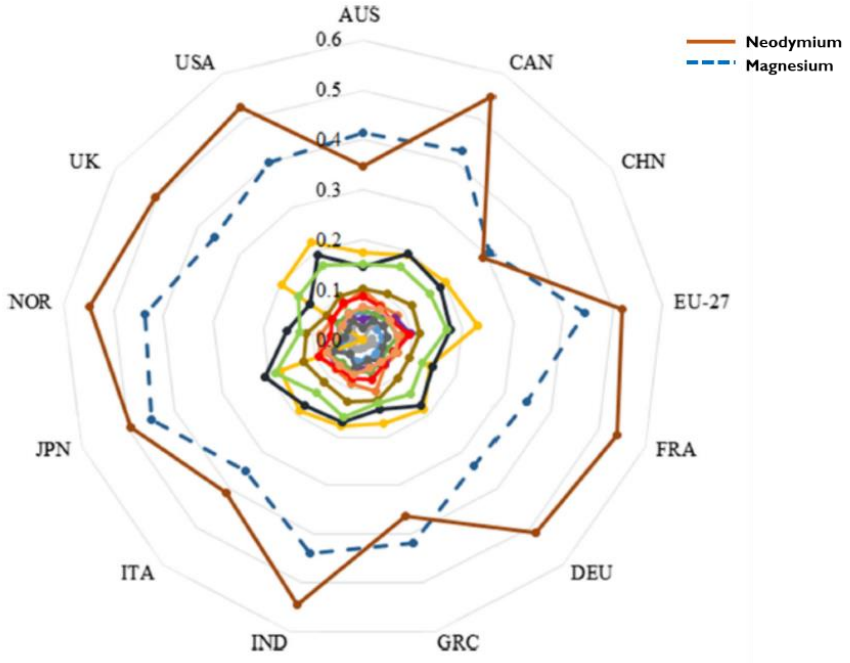


Figure 2.5 – GeoPolRisk values for 14 resources relevant to the inventory of EV in 2013
(Adapted from Gemechu et al., 2016)

As main findings, magnesium and neodymium have the highest geopolitically related supply risk from the group for most countries. Neodymium alloyed with iron and boron is used as permanent magnet in multiple applications that include wind turbines, magnetic resonance imaging (MRI) equipment and electric motors for EV. China is responsible for the 95% of neodymium supply to most of the countries; therefore contributing to the high geopolitical-related supply risk of Nd, especially from the point of view of Canada, India and Norway. Australia relies on the USA for 75% of its neodymium imports, which

translates into a lower risk than the other countries/regions because the USA is considered more geopolitically stable than China for the analyzed year. Although the USA is a producer of rare earth elements, it imports from other countries; therefore, the USA has high geopolitical-related supply risk due to the imports from China. The high GeoPolRisk value for magnesium in this study is primarily due to its high production concentration, since China accounts for 86% of global production.

From an LCA perspective, the most significant environmental impacts associated with metals are attributed to mining, extraction and refining activities. For the case of EVs, steel and iron are part of mainframe parts, doors and wheels; copper is found in wiring of electric motors and connectors; and, aluminium is utilized in the motor and other powertrain components. As presented in Figure 2.6, an E-LCA conducted using the ReCiPe midpoint method shows that aluminum and steel have the highest contribution to global warming potential and copper dominates the human toxicity and freshwater eco-toxicity midpoint indicators. E-LCA depends heavily on the mass share of the materials; therefore, copper, aluminium and steel become the resources with highest environmental impacts per functional unit. Unlike E-LCA indicators, GeoPolRisk provides a relative supply risk measure among multiple resources. The relative low contribution of magnesium and neodymium to the environmental impacts is due to their low mass requirements; however, this is not the case in the supply risk assessment. The GeoPolRisk values indicate that elements in small quantities become relevant from a criticality perspective. This case study supports the argument that the GeoPolRisk indicator complements the E-LCA, when presented together, policy makers and businesses can take more informed decisions for better product development and material management.

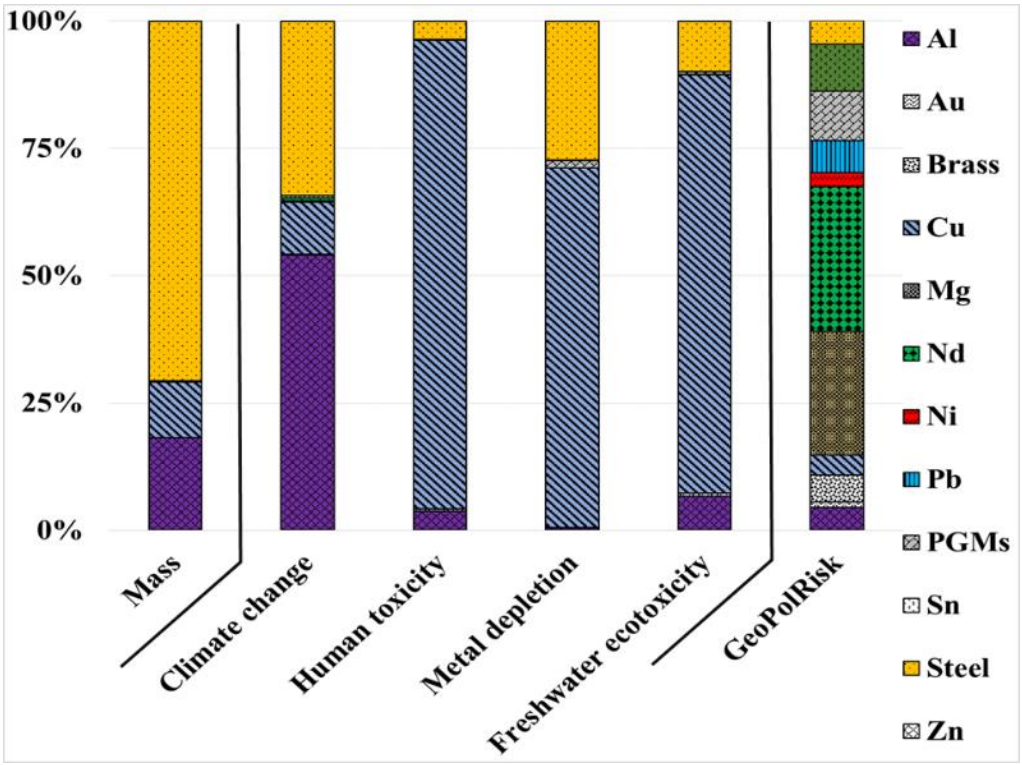


Figure 2.6 – Comparison of environmental impacts and the GeoPolRisk indicator at the midpoint level
(Adapted from Gemechu et al., 2016)

In a recent publication by the UNEP Life Cycle Initiative, life cycle impact indicators for addressing abiotic resources were comprehensively reviewed to develop recommended practices; the result of this effort was the volume 2 of the Global Guidance on Environmental Life Cycle Impact Assessment Methods (Frischknecht et al., 2019). The GeoPolRisk method was discussed and reviewed as part of the proposed methods for product-level supply risk assessment (ESP and ESSENZ). Similarities and differences between these methods were discussed in section 2.2.2.

The guidance document highlighted certain limitations in the GeoPolRisk method. First of all, it relies on not always detailed or inaccurate public data regarding production and trade patterns around the world, which represents a significant challenge when estimating the geopolitical supply risk of certain materials. In this context, the GeoPolRisk method is a snapshot in time of the supply risk of one material at the early stages of production; therefore, constant efforts need to be made to guarantee up to date values that represent the global situation of raw materials criticality.

Two main improvement opportunities are mentioned by a review on supply risk methods in LCSA (Cimprich et al., 2019b). First of all, the inclusion of recycling considerations as a supply-risk mitigation strategy and their effect in the GeoPolRisk calculations. A second main recommendation is referred to the extension of the GeoPolRisk method from a midpoint characterization factor in LCSA to an endpoint characterization factor directly related to the AoP Natural Resources. These two improvement opportunities will be further explored as part of the objectives of this PhD thesis.

Chapter 3: LCA-based Framework for Healthcare Sustainability

The work presented in this chapter is partially based on the publication:

A. Cimprich; J. Santillán-Saldivar; C. L. Thiel; G. Sonnemann; S. B. Young (2019). Potential for industrial ecology to support healthcare sustainability: Scoping review of a fragmented literature and conceptual framework for future research. Journal of Industrial Ecology 23, 6, 1344-1352. https://doi.org/10.1111/jiec.12921.

Contribution Statement:

A. Cimprich:	Conceptualization, Methodology, Formal analysis, Investigation, Data Curation, Visualization, Writing – Original Draft
J. Santillán-Saldivar:	Conceptualization, Framework Development, Formal analysis, Investigation, Data Curation, Visualization, Writing – Review & Editing
C.L. Thiel:	Validation, Writing – Review & Editing
G. Sonnemann:	Supervision, Writing – Review & Editing
S.B. Young:	Supervision, Writing – Review & Editing

As previously mentioned in Table 2.1 (Chapter 2:), there are multiple identified opportunities in the field of healthcare and sustainability: to explore understudied areas in healthcare from a sustainability lens, to investigate life cycle assessment as a method to support future research and to develop a conceptual framework that allows to integrate healthcare and sustainability aspects for future applications by academics and practitioners. This chapter develops the latter by defining and proposing a framework that allows visualizing and classifying activities related to the healthcare sector from a sustainability lens.

3.1. The Healthcare Sector

From a LCA perspective, healthcare can be seen as a system that encompasses multiple and diverse activities and flows. These activities can be directly seen when addressing a hospital environment, where doctors, nurses, technicians and other medical staff have direct contact with patients; however, countless other jobs are associated with the provision of care which are many times overlooked (Walshe and Smith, 2011). For example, a peripheral vision of the processes associated with the healthcare sector helps identify medical research and laboratory analysis as medical activities; while procurement, maintenance and food supply as non-medical support activities (De Mast et al., 2011). However, other processes such as the production of pharmaceuticals and medical devices, or the construction of healthcare facilities escape this classification. In life cycle assessment, it is possible to identify a similar behavior when categorizing specific processes as part of the life cycle inventory. The foreground system contains processes that are under the control of the decision maker carrying out the study, while the background system refers to process outside of their control (Frischknecht, 1998).

The foreground and background systems associated with healthcare provision constantly exchange resources, emissions and information. This network functions underneath a regulatory and legal context depending on the country in which the studies on healthcare sustainability are conducted. Therefore, moving forward in this manuscript, it is possible to define the healthcare sector as the group of activities in the foreground and the background that allow the provision of healthcare services to the population under a regulatory system provided by a governmental body.

As discussed in sections 1.3 and 2.1, when addressing sustainability aspects of the healthcare sector, it becomes necessary to focus not only on the so-called “inside-out” impacts to understand how the activities of the healthcare sector are affecting the environment and society, but to acknowledge how the social, environmental and economic context affect the delivery of healthcare. Based on the previous mentioned points, a first mental map for the design of an integrated framework to support research on healthcare sustainability is presented in Figure 3.1. It includes the main classification for activities in the foreground system, their connection with the background system and the regulatory context; these are linked with the “inside-out” and “outside-in” impact pathways and examples of methods to address them from a sustainability perspective.

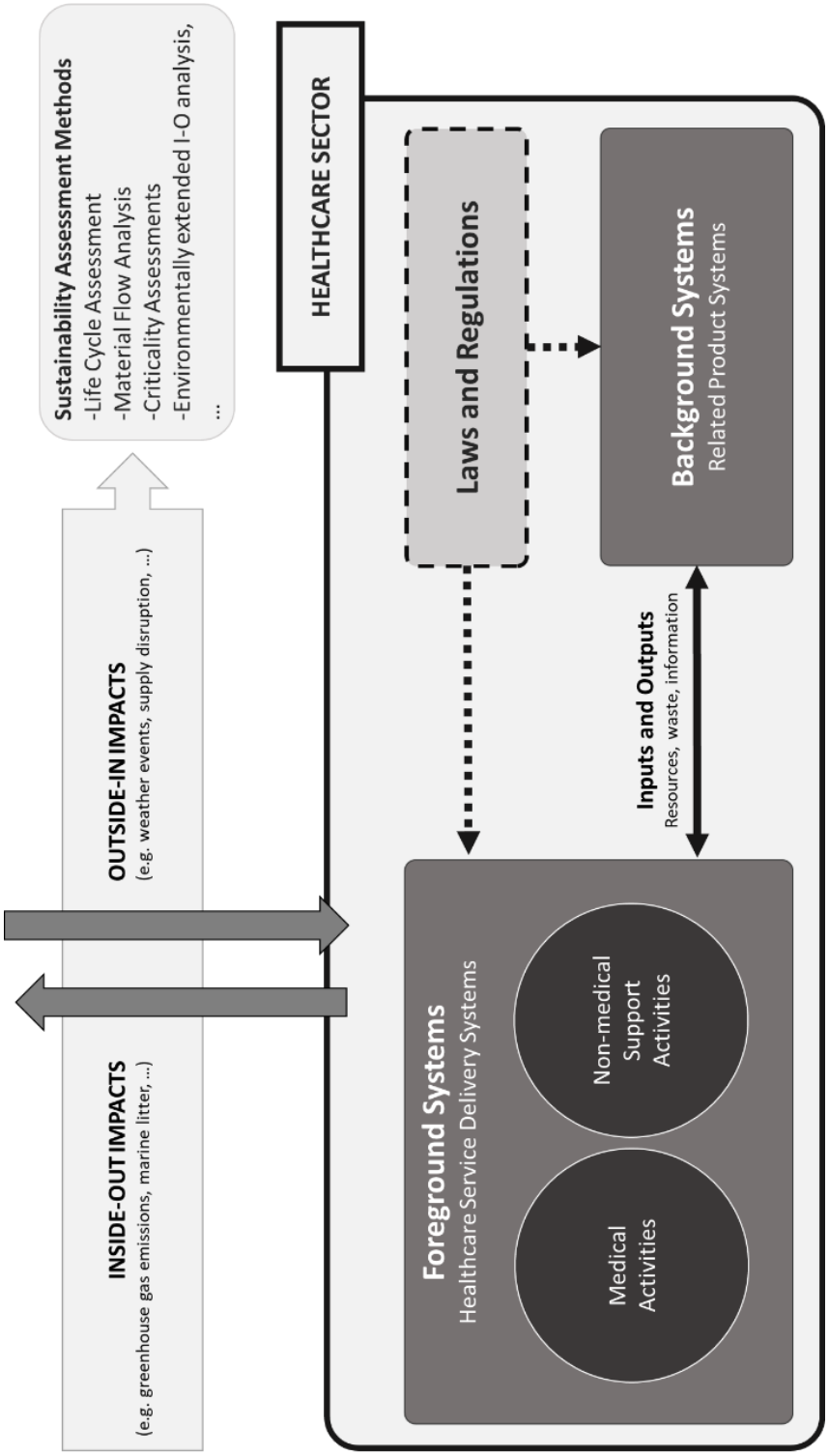


Figure 3.1 – Mental map for the integration of activities in the healthcare sector and methodologies to assess sustainability

3.2. Studying healthcare systems

With the aim to better understand the activities associated with the healthcare sector and to provide a more detailed version of the framework, it becomes necessary to explore the three main defined

classifications in Figure 3.1. A first proposed approach to the study was to list the most common medical specialties; following this train of thought and as reference for the discussion of future applications, a list of documented medical specialties by the Association of American Medical Colleges (AAMC) is presented in Table 3.1. Further discussion with experts in the field showed that all specialties behave similarly and depend on other transversal activities under a life-cycle-thinking perspective.

Table 3.1 – List of Medical Specialties
(Adapted from AAMC, 2018)

Name	Description
Allergy and Immunology	Management of disorders related to the immune system.
Anesthesiology	Medical study and application of anesthetics.
Dentistry	Prevention, diagnosis and treatment of disorders of the oral cavity.
Dermatology	Management of disorders related to the skin.
Emergency Medicine	Treatment of illnesses or injuries that require immediate attention.
Family Medicine	Comprehensive health care for people of all ages.
Internal Medicine	Prevention, diagnosis and treatment of adult diseases.
Medical Genetics	Management and study of hereditary disorders.
Neurology	Management of disorders related to the nervous system
Obstetrics and Gynecology	Care of female reproductive organs and management of pregnancy.
Ophthalmology	Management of disorders related to the optic system.
Otolaryngology	Management of disorders of the ear, nose and throat.
Pathology	Study of pathogens and diseases.
Pediatrics	Prevention, diagnosis and treatment of children diseases.
Physical Medicine - Rehabilitation	Enhancement of functional ability and quality of life.
Preventive Medicine	Study and management of measures to prevent diseases.
Psychiatry	Prevention, diagnosis and treatment of mental disorders.
Oncology	Prevention, diagnosis and treatment of cancer.
Radiology	Production and analysis of medical images for diagnosis and treatment.
Sleep Medicine	Prevention, diagnosis and treatment of sleep disorders.
Surgery	Prevention, diagnosis and treatment of conditions by manipulation of live tissue in the human body.
Urology	Prevention, diagnosis and treatment of disorders affecting the urinary and male reproductive system.

A second option to classify the activities was to use the levels of care delivery, this notation considers the complexity of patients' conditions, the level of specialty providers and the average resource requirements to provide healthcare services; therefore, it is more in line with a life-cycle-thinking perspective. This classification, as presented in Table 3.2, provides a more feasible way to address sustainability aspects and associated impacts based on the consideration of resources, time and location. However, there are still multiple medical activities that are transversal to the levels of care; therefore, additional work must be done to address these.

Table 3.2 – Levels of health care delivery
(Adapted from WHO, 2004)

Level of care	**Description**
Primary Care	Medical care required on a regular basis (e.g. routine checkups) or after the discovery of emerging mild symptoms; primary care providers are usually responsible for referring patients to specialists as needed.
Secondary Care	Specialized medical care beyond the one provided by primary care practitioners.
Tertiary Care	Further specialized care that requires specific equipment found in specialized healthcare facilities. Most complex therapeutic procedures are included in this level.
Long-term Care	Refers to services provided over a long period of time to meet the needs of patients with disabilities, chronic illnesses or in terminal state.
In-home Care	Activities directly related to the care of patients in their own homes. It includes, but is not limited to, home visits, palliative care, and specialized medicine administration.

The use of the levels of care allowed to provide categories of medical activities based on the proximity to the patient. Following previous work by Santillán-Saldivar (2017); a new layer was added to consider a business management perspective, in which all activities required to deliver healthcare to the population could be accounted for.

As seen in Figure 3.2, core medical activities can be classified based on the level of care, specialties and required resources. Ambulance Services are those dedicated to provide acute medical care outside of healthcare facilities and/or to transport patients to proper establishments to receive care. Consults refer to the acceptance of incoming patients to conduct checkups, these can be done at multiple levels of care. Diagnostic Activities are those directly aimed to understand and detect medical conditions and their severity based on parallel studies; they can be classified in Laboratory Activities (Testing of samples in a controlled environment with specific and standardized methods) and Imaging Activities (Production of medical images to represent the state of the human body).

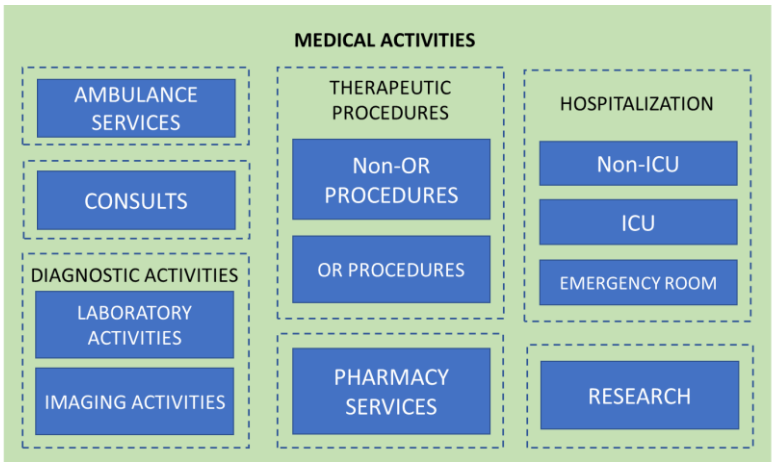


Figure 3.2 – Medical Activities (Foreground Systems)

Therapeutic Procedures can be defined as those designed to treat and cure diseases or to restore patient health. In order to account for the amount and type of resources required to perform these procedures; they have been divided in Non-OR Procedures and OR Procedures (OR: Operating Room). Non-OR procedures don't require full body anesthesia and can normally be conducted outside of the Operating Rooms, it includes rehabilitation processes. OR Procedures require a controlled and sterile environment for their optimal performance, most invasive procedures are part of this category.

Hospitalization Services are referred to the time the patients stay in healthcare facilities; they are classified based on the urgency and severity of the situation for staying in the healthcare facility. The Intensive Care Unit (ICU) is designed for patients that require close and constant monitoring due to their condition; usually specialized equipment is required. Non-ICU hospitalization is for non-critical patients; it includes, but is not limited to, recovery, surgery preparation and isolation. Also, the Emergency Room is accounted for, being designed for patients with not yet fully defined conditions; triage procedures are included in this last category. Pharmacy Services include the preparation and delivery of medicine to the patients and Research Activities involve clinical trials or other activities designed to advance medical knowledge, techniques, equipment and treatments.

Management and Administrative services are part of the Non-Medical Support Activities, these do not directly involve the treatment of patients, but are necessary to guarantee a good healthcare delivery. Administrative Activities within the healthcare systems include, but are not limited to, human resource management, financial management, information technology services, among others (Figure 3.3). On the other hand, management operations are physically related to the provision of care. Procurement refers to the management of supply chains relevant to healthcare, including acquisition and storage. Plant Operations involve construction and maintenances of facilities and equipment, taking into considerations security and safety services. Food Services are those designed to provide nourishment to patients and staff. Waste Management is directly related to the management of residues, these include effluents, solid waste and hazardous waste, among others.

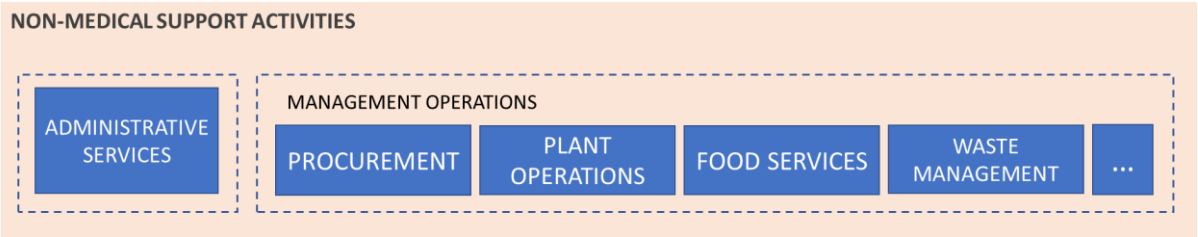


Figure 3.3 – Non-Medical Support Activities (Foreground Systems)

Healthcare delivery systems require resources to function on an optimal fashion; the Related Product Systems are those producing fixed assets, inventory items and other resources used in healthcare. This classification takes into account a life-cycle-thinking perspective, establishing these as part of the background systems in healthcare, they can be seen in Figure 3.4.

Figure 3.4 – Related Product Systems (Background Systems)

Pharmaceuticals are all the chemical products used for treatment and prevention of diseases, these include medicine, anesthetics, among others. Medical Equipment are fixed assets used for diagnosis, monitoring and treatment of medical conditions. Implants and Prosthetics are devices destined to be placed inside the body to replace body parts, deliver medication, monitor vital functions or enhance organ function. Reusable medical supplies are instrument that can be reused for diagnosis or treatment; some examples are surgical instruments, endoscopes, accessories, among others. Disposable Medical Supplies or consumables are materials, instruments or devices designed for a single use, in this category it is possible to identify syringes, masks, needles, etc.

Some other relevant related product systems are fixed assets for offices, maintenance, security, power generation, lightening; also, inventory items not related to medical activities, such as office material, laundry materials, food. In this category we can include resources as water, energy and gases necessary for the daily activities. Additionally, resources used to construct or improve facilities are included in this category.

Based on this additional information, it is possible to provide a new and enhanced version of the proposed healthcare sustainability framework originally mapped in Figure 3.1. A final version is provided in Figure 3.5 and includes all points discussed in this section; it will serve to propose and direct applications in the field of healthcare and sustainability.

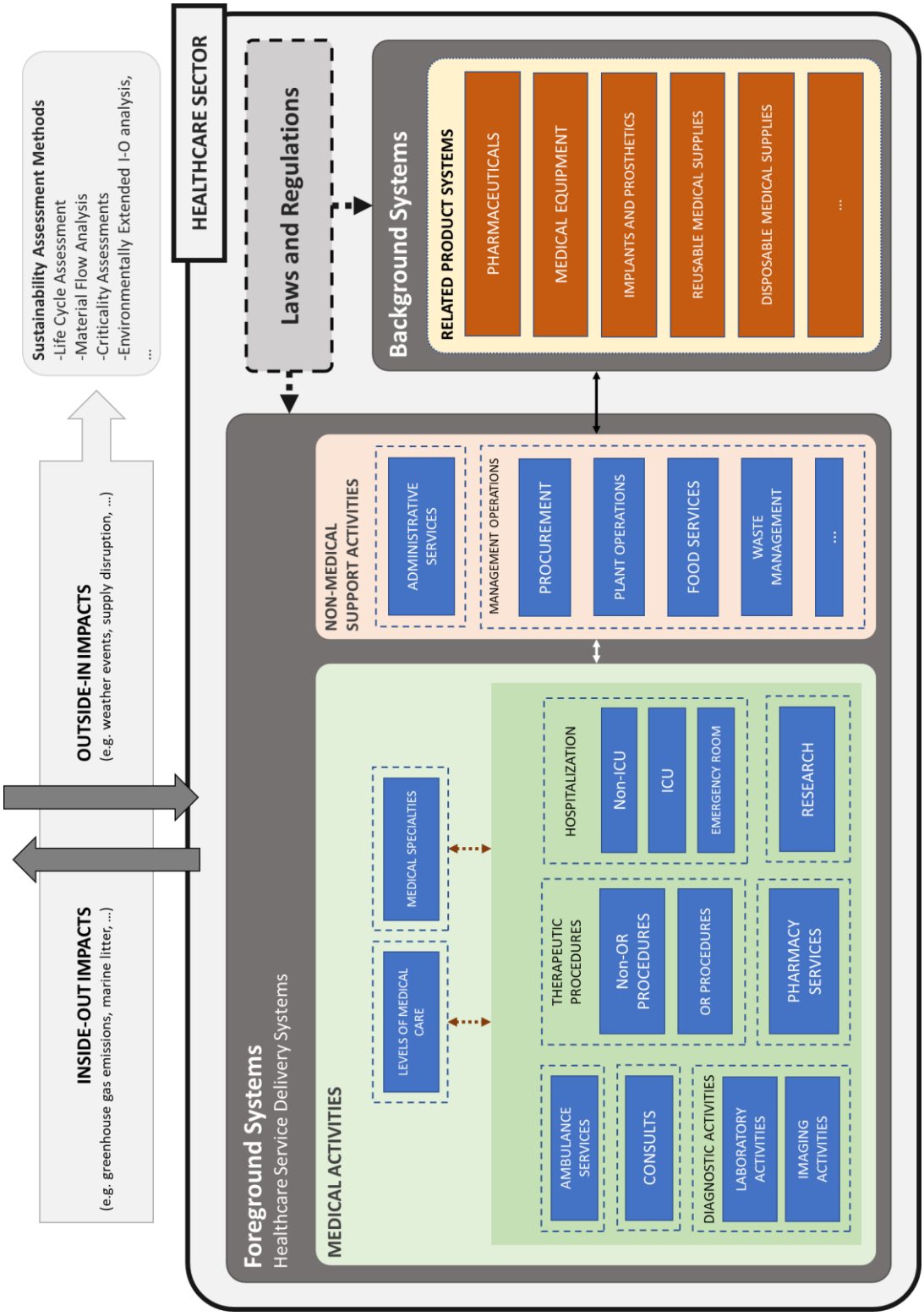


Figure 3.5 – Framework for LCA to support healthcare sustainability

3.3. Potential Applications

Based on the presented life-cycle-thinking based framework, potential applications can be proposed and mapped. The framework has the aim to help identify research gaps and to support future research on healthcare sustainability from a life cycle perspective. Along the course of the PhD, multiple alternatives to apply life-cycle based methods to the healthcare sector were explored: Identification of criticality hotspots in the life cycle of catheters required for cardiothoracic surgery; comprehensive life cycle assessment of a healthcare facility; carbon footprint of anesthetic gases used in a surgical environment and the identification of criticality hotspots in the development of medical imagery.

The feasibility for the development of two studies was analyzed for a final selection of the case study. The two proposals were established as follows: Carbon footprint of anesthetic gases used in a surgical environment; and, the integrated environmental and criticality assessment of helium used in MRI machines for medical imagery. In this section, the application of the framework to these two research proposals is presented.

3.3.1. Anesthetic gases in a surgical environment

Medical activities are diverse and numerous, among them, anesthesia delivery services are transversal and required for multiple medical specialties. The gases used for anesthetic purposes have been identified as having a significant Global Warming Potential (Sulbaek-Andersen et al., 2010) and limited studies on the delivery and use of such substances have been developed (Sherman et al., 2012; Parvatker et al., 2018). Main results showed a larger carbon footprint of gaseous anesthesia delivery (sevoflurane and desflurane) compared to intravenous anesthesia delivery (propofol); however gaseous anesthesia delivery is preferred for patient comfort and fast effect.

Under a life cycle perspective, the study and analysis of environmental impacts generated by anesthetic drugs should include the accounting and assessment of all impacts: from the extraction of raw materials to the disposal, release or final disposition of residues after their use. There are available technologies in the market designed to reduce emissions originated by the delivery of anesthetic drugs, mainly oriented to automated control of gas delivery; however, other alternatives such as gas capture are available but yet to be studied (Sherman et al., 2012; Thiel et al., 2018).

Anesthesia delivery services are transversal in healthcare services, appearing as part of the processes to be followed in therapeutic and diagnostic procedures. Reports and guides of good practices promoted by The French Society of Anesthesia and Intensive Care Medicine (SFAR) have touched the topic of green anesthesia as part of initiatives on developing a more sustainable operating room (Muret et al, 2017).

Following a life cycle perspective, the study and assessment of environmental impacts caused by the use of anesthetic drugs must include all impacts along the life of the analyzed products; focus has been

already given to production and use stages; however, an apparent gap is seen when trying to understand improvements that can be proposed to reduce the carbon footprint of anesthetics delivery to patients; especially when exploring gaseous options. Figure 3.6 shows the application of the framework to support research on healthcare sustainability to the study of anesthetics in a surgical environment.

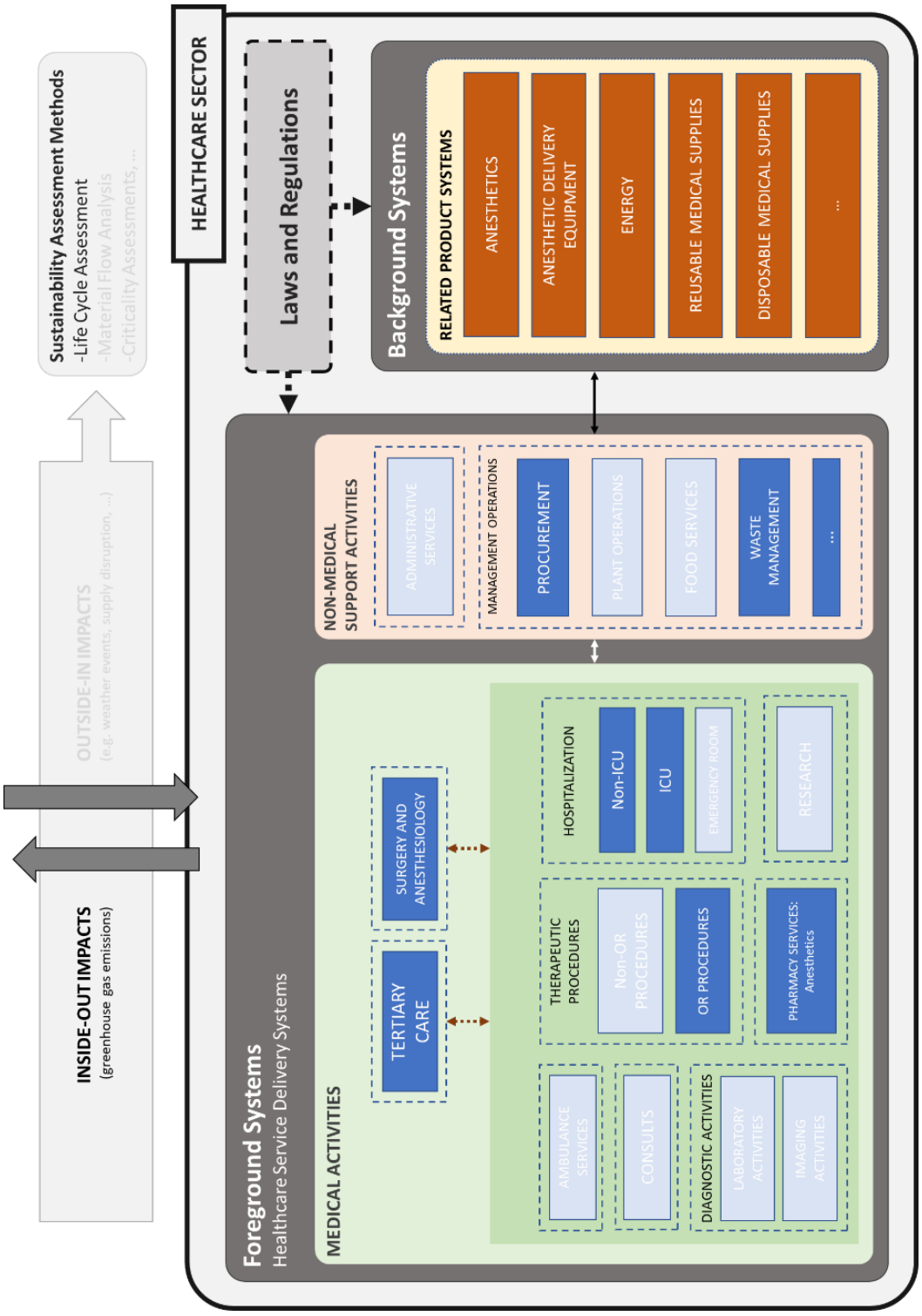


Figure 3.6 – Application of the framework for healthcare sustainability – Use of anesthetic gases in a surgical environment

The framework allows to identify the relevant aspects in the healthcare sector that will need to be explored in order to assess the carbon footprint of anesthetic gases used in a surgical environment. Focusing on the life cycle stages; multiple product systems are identified in the background (e.g. anesthetics, anesthetic delivery equipment, energy, reusable and disposable medical supplies, among others). Procurement is a non-medical support activity that will need to be assessed to identify the supply chain of selected products used for anesthetic delivery.

With focus on the medical aspect, a proposed study on this subject will involve the tertiary level of care, because specific instruments and equipment are required to deliver the service in a healthcare facility. The associated medical specialties are surgery and anesthesiology; and the involved medical activities will be Non-ICU hospitalization (Pre-operatory), OR procedures (surgery), Pharmacy services (anesthetics delivery) and ICU hospitalization (Post-operatory). Waste management will have a big role for assessing this case, since one of the main questions would be how to reduce the direct emissions of leftover anesthetic gases into the atmosphere.

Specifically, in this scenario, the addressed impacts will be those that follow an inside-out pathway and life cycle assessment is proposed as the main methodology to evaluate the carbon footprint of this system. The use of this methodological pathway would allow to identify hotspots in the life cycle that contribute to the carbon footprint and, analyze mitigating strategies to reduce emissions, especially those associated with the delivery of anesthetic gases in surgeries.

Efforts were made to take this project to fruition as part of this PhD; however, administrative requirements and conflicting schedules delayed the development of the proposal. This situation was only exacerbated by the global sanitary crisis. This case won't be further explored in this manuscript as it was preferred to move forward with the case presented in section 3.3.2 based on having a better access to data and a closer connection to the work developed as part of the component on criticality considerations in LCA for this PhD thesis.

3.3.2. Helium for medical imaging

Another transversal activity to multiple medical specialties is medical imaging. In radiology, complex machines are used to obtain images of the human body that support the diagnosis and treatment of multiple conditions. Some of the most typical imaging producing technologies are the x-rays, magnetic resonance imaging (MRI), ultrasounds and tomography. In the case of MRI machines, strong magnetic fields are used to visualize tissues in the body rich in water and lipids (Hoult and Bahkar, 1998). Most of the magnets used to create these fields require liquid helium to maintain an optimal working temperature (Weishaupt et al., 2006).

Unlike other materials used in the healthcare sector; helium is subject to two impact pathway mechanisms in terms of sustainability. First, there are environmental impacts associated to the production, delivery and use of helium for MRI machines, specially associated to the energy required to store helium at low temperatures and avoid leaks (Lvovsky et al., 2013). On the other hand, concerns

have been raised regarding potential supply risk constraints of helium (Glowacki et al., 2013), a non-renewable resource considered irreplaceable to modern science and technology (Jaffe et al., 2011). These characteristics found in helium raise questions not only about availability of the resource, but also about its accessibility; which were key points in the discussion on how to address impacts in the area of protection Natural Resources in LCA (Section 1.3).

There has not yet been a study that addresses both environmental and supply risk considerations of helium for the healthcare sector; however, helium has been the focus for limited publications on critical materials. Following a life cycle perspective, a study focused on helium should include impacts associated to the production, transport and use of helium; additionally, supply risk considerations (impacts measured from an "outside-in" perspective) should be explored to understand how external aspects not associated to the healthcare sector can affect the future delivery of care.

Figure 3.7 illustrates the application of the framework for healthcare and sustainability to support a study on the sustainability aspects of helium for the healthcare sector. It is possible to identify that liquid helium, MRI machines, energy and multiple medical devices can be associated to a case on the use of helium as background systems in LCA; being helium considered a resource with supply constraints, procurement is a relevant activity to consider.

As previously mentioned, a potential case study on the use of helium in MRI machines would be associated to imaging activities as part of diagnosis processes, which are the focus of the medical specialty of radiology. Given the requirement of complex machinery and specialized professionals, these fall under the tertiary level of care in healthcare.

The impacts that should be studied when addressing helium follow both pathways: "inside-out", for the study of emissions along the life cycle of helium and "outside-in", in close relation with the limited availability of helium. The duality when addressing the sustainability aspects of helium in the healthcare sector makes this case attractive from a research stand point. Further in this manuscript, the use of helium for medical imaging will be addressed in an integrated way, by considering both environmental assessment considerations and supply risk considerations.

However, the current indicators used in life cycle assessment are not yet fully prepared to address "outside-in" impacts; therefore, as previously discussed in section 2.2.2, product-level supply risk assessment methods need to be enhanced to provide more relevant information for decision-making processes in industry and government. Based on the maturity assessment of the existing indicators that aim to address "outside-in" impact pathways in LCA, before conducting a life cycle assessment to a case study in the healthcare sector, it becomes necessary to explore the potential of the geopolitical supply risk method to address the concerns and suggestions raised by the UNEP LCIni Task Force on LCIA methods to address natural resources (Frischknecht et al., 2019).

The following chapters will deviate from the branch of healthcare sustainability in this PhD thesis towards the exploration of raw material criticality in LCA with the objective to propose methodological

enhancements that could help position the GeoPolRisk method as a new indicator to assess the impact category supply risk in LCA.

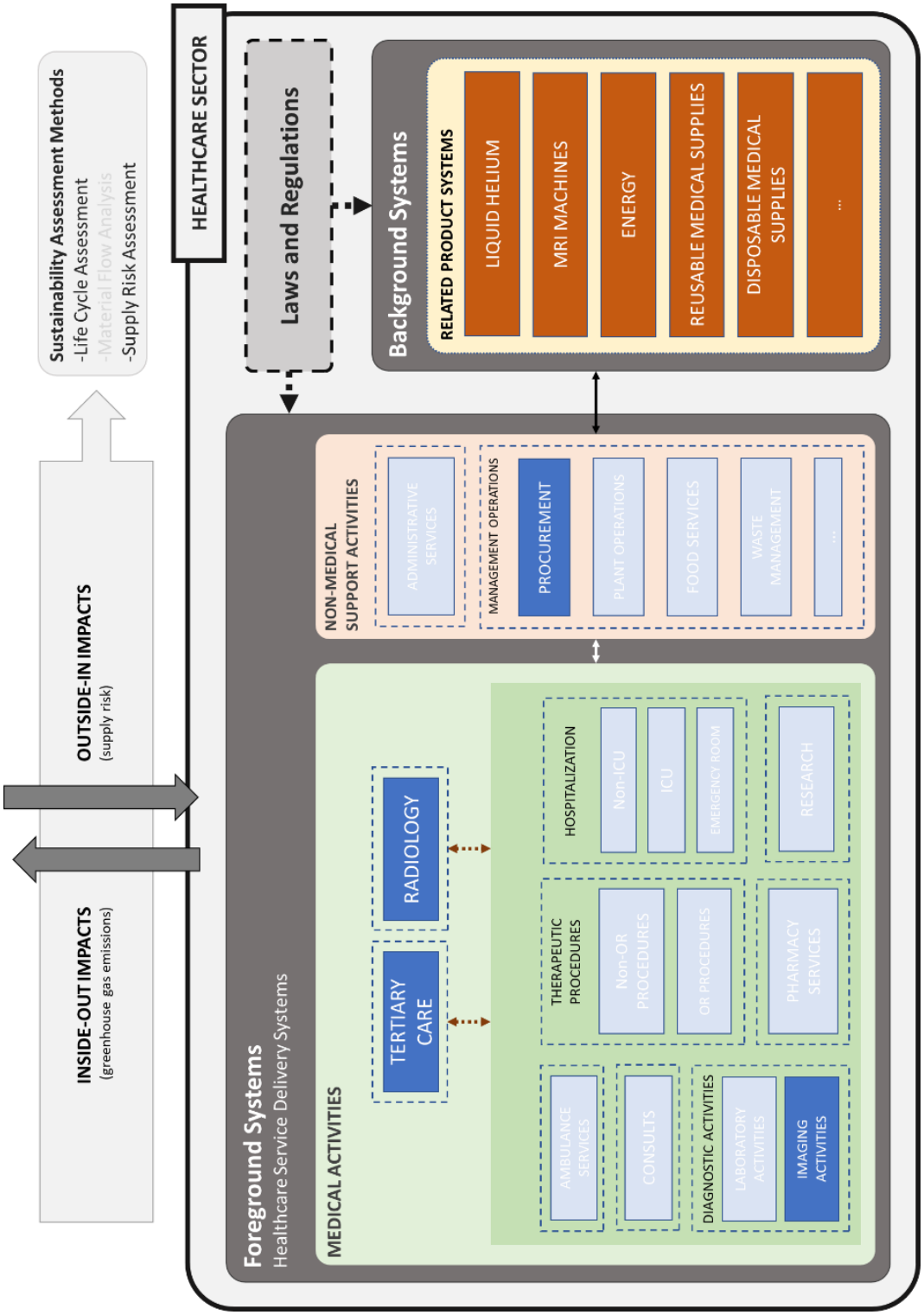


Figure 3.7 - Application of the framework for healthcare sustainability – Use of helium for medical imaging

Chapter 4: The Impact of Recycling in the Geopolitical Supply Risk of Materials

The work presented in this chapter is partially based on the publication:

J. Santillán-Saldivar; A. Cimprich; N. Shaikh; B. Laratte; S. B. Young; G. Sonnemann (2021). How recycling mitigates supply risks of critical raw materials: Extension of the geopolitical supply risk methodology applied to information and communication technologies in the European Union. Resources. Conservation and Recycling 164, 1, 105-108. https://doi.org/10.1016/j.resconrec.2020.105108

Contribution Statement:

J. Santillán-Saldivar:	Conceptualization, Methodology, Investigation, Writing - original draft
A. Cimprich:	Writing - review & editing
N. Shaikh:	Software, Data curation
B. Laratte:	Investigation, Writing - review & editing
S.B. Young:	Resources, Writing - review & editing
G. Sonnemann:	Resources, Writing - review & editing, Supervision

As previously discussed in section 2.2.1, opportunities for further development when addressing the AoP Natural Resources in LCA have been identified (Frischknecht et al., 2019). Differences in problem formulation and modelling have generated debates and confusion among LCA practitioners (Drielsma et al., 2016a, 2016b; Sonderegger et al., 2017); therefore, in 2017, the UNEP Life Cycle Initiative (LCIni) established an expert task force to review existing LCIA methods that address mineral resource use (Sonderegger et al., 2019). As a result, recommendations were formulated to support further methodological development in supply risk and to study how impacts in resources should be defined (Berger et al., 2020; Cimprich et al., 2019).

Among the analyzed methodologies, the GeoPolRisk method stands out for providing country-specific supply risk characterization factors and focusing on the geopolitical (in)stability of trade partners as a driver of supply risk; one of the main recommendations provided by the UNEP LCIni Task Force was to explore the risk-mitigating potential of recycling. In this chapter, the recommendation on assessing recycling as a risk mitigation strategy is addressed and the GeoPolRisk method is enhanced to include domestic recycling considerations.

4.1. Methodological Enhancement: Recycling as a Supply-Risk-Mitigation Strategy

The methodological proposal is based on the study of two independent effects: a “reduction effect”, which is related to an overall reduction of material requirement due to recycling; and a “redistribution effect”, which is the result of exploring changes of the import supply mix from the perspective of an analyzed country or region. In Figure 4.1 it is possible to visualize these effects on a fictive trade network for one commodity that includes one importer and four exporters with different risk profile measured by their political (in)stability. The graphic refers to a case in which the reduced requirement has the reduction of imports from country “A” as a direct consequence; in this fictive network, country “A” is both the biggest supplier and the riskiest trade partner. Inherently, a lower new requirement will contribute to a reduction of the supply risk (reduction effect); however, a second mechanism is in place when a new supply mix is visible for the importer (redistribution effect). However, the graphic shows only one ideal scenario in which the reduced requirement is taken from the riskiest partner; in reality, more considerations are in place and it’s not possible to predict how the supply mix will behave after a requirement reduction. In order to cover this limitation, two scenarios must be defined: The best-case scenario (BCS), already presented in Figure 4.1, and the worst-case scenario (WCS), in which the reduced requirement would be taken from the more stable partners.

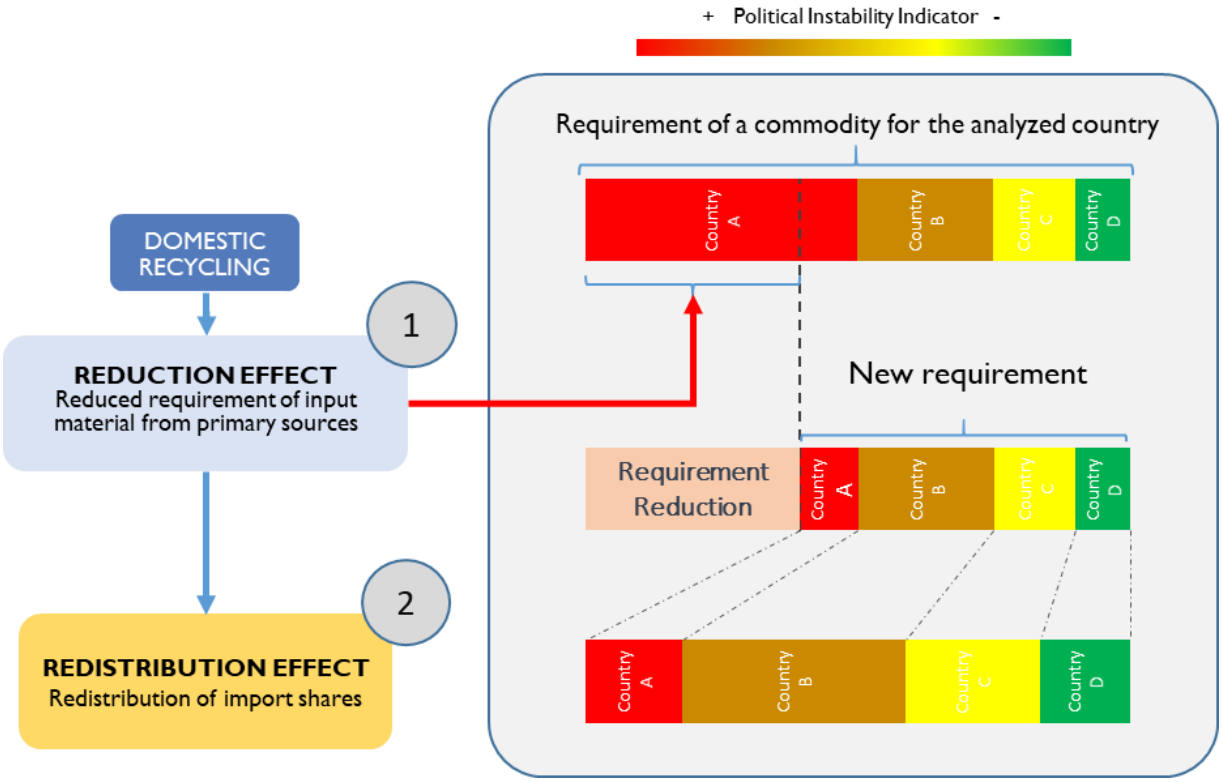


Figure 4.1 – Reduction effect and redistribution effect of domestic recycling on the supply risk of a commodity

With the described effects under consideration, the GeoPolRisk calculations will differ from the original formula presented in Equation 2.1 (Section 2.2.3). The updated version follows the structure presented in Equation 4.1.

Equation 4.1..... $$GeoPolRisk_{Ac} = HHI_A * \sum_i \frac{g_i * f^N_{Aic}}{p_{Ac} + F^N_{Ac} + R_{Ac}}$$

Where:

HHI_A = Herfindahl-Hirschman Index for commodity A

g_i = Geopolitical (in)stability of country i,

f^N_{Aic} = Redistributed Imports of commodity A from country i to country c

F^N_{Ac} = New total imports of commodity A to country c (New requirement)

p_{Ac} = Domestic production of commodity A in country c

R_{Ac} = Domestic recycling production of commodity A in country c

It is possible to define the domestic recycling production (R_{Ac}) as a percentage of the total requirement of the commodity for country A. The indicator End of Life – Recycling Input Rate (EoL-RIR), is defined as the ratio between the sum of flows of secondary material recovered from end-of-life products and reinserted into the economy through domestic recycling, and the sum of supply flows from both primary and secondary sources (European Commission, 2014).An EoL-RIR ranges from 0% to 100%, in which

0% means that recycling is non existent and 100% represents a case in which all material used in the economy is domestically recycled.

Based on these definitions, it's theoretically possible to assign a BCS and WCS values of the GeoPolRisk indicator to every EoL-RIR percentage as presented in Figure 4.2. All the potential values of the GeoPolRisk indicator as a function of the EoL-RIR will range from a best-case scenario (BCS – better supply risk improvement) to a worst-case scenario (WCS – worst supply risk improvement); capturing all possible outcomes for the specific cases. Moving forward it will be possible to see how this graphic behaves depending on the supply profile of the analyzed commodity.

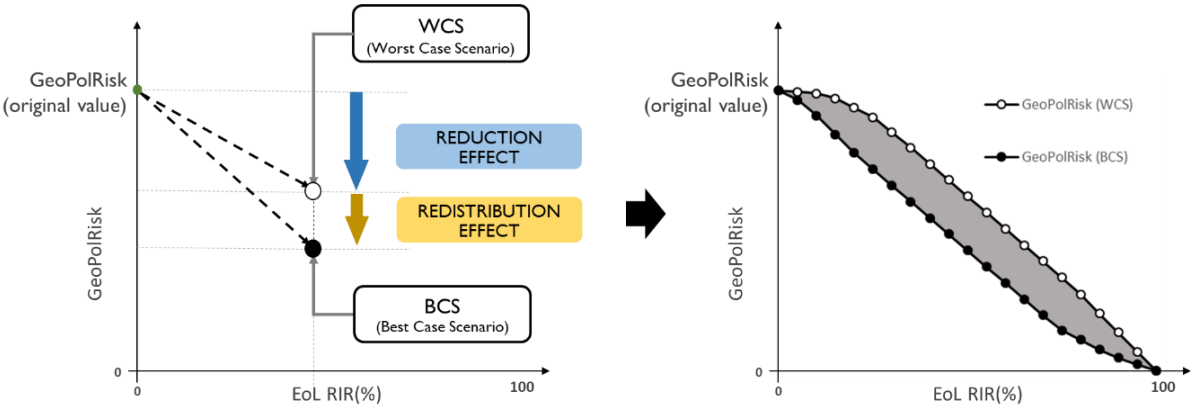


Figure 4.2 – WCS and BCS GeoPolRisk values as a function of the EoL-RIR indicator

In order to test the applicability of the enhanced GeoPolRisk method, it is required to obtain detailed trade data from the perspective of one importer for a variety of materials with reported EoL-RIR values. These pieces of information were obtained for a group of materials deemed relevant for Information and Communication Technologies (ICT) in the European Union.

4.2. The case of ICT in the European Union

The Information and Communication Technologies (ICT) sector constitutes 4.8% of the EU economy and accounts for 17% of expenditures in research and development within the EU (European Commission, 2019). The increasing use and relevance of a wide range of products in the ICT category raises questions about the amount and variety of critical raw materials needed for these applications; moreover, there are growing concerns about the potential recovery of these materials from end-of-life products in the EU (Horta, 2019). Since the GeoPolRisk method is applied at material level from the perspective of a country or region, it is possible to say that a first test application of the proposed enhancement would not only be relevant for the ICT industry, but could provide insights for other sectors that use some of all of the analyzed raw materials.

To test and demonstrate the enhanced GeoPolRisk method, a set of 13 raw materials (or groups of raw materials) was used. These materials are considered relevant for, among other things, developing and

strengthening the information and communication technologies (ICT) sector in the European Union. The complete list was obtained by crossmatching the Report on Critical Materials for the European Union (European Commission, 2017) and the raw materials listed in the report on material efficiency of the personal computers' product group (Tecchio et al. 2018). Based on data availability, the study was conducted for the year 2016.

Four main pieces of information are required to calculate the GeoPolRisk values under the extended method: production volumes of each producing country, geopolitical (in)stability of each trade partner country, import volumes from each trade partner, and domestic recycling rates for the analyzed region, in this case the EU. The geopolitical instability was measured using the country WGI-PV scores available from the World Bank (2019). These were normalized from a 0 to 1 scale as has been common practice for other previous applications of the GeoPolRisk method. The full set of re-scaled WGI-PV scores, for all countries in 2016 is provided in Annex C. Raw material production and trade data were primarily obtained from the United States Geological Survey (USGS) annual Mineral Commodity Summaries (USGS 2016, 2017, 2018) and the United Nations Comtrade Database (UN, 2020) respectively.

To fill gaps in these datasets for some raw materials (namely germanium, iridium and ruthenium), the Critical Raw Materials Factsheets from the European Commission were used (European Commission, 2017). Table 4.1 provides an overview of the data sources used to calculate the trade and production components of GeoPolRisk for the EU in 2016 (i.e., primary production by country and the import shares of each trade partner) for each raw material (or group). Grouping some raw materials – namely gallium group metals, platinum group metals (PGMs), and rare earth elements (REEs) – was necessary given data limitations.

Given the lack of data on domestic recycling of manufacturing scrap in the EU, the most recent values (i.e., from 2016) for the "end-of-life recycling input rate" (EoL-RIR) are used, available from Eurostat (2017) as a conservative estimate of the total supply of domestically recycled materials in the EU.

Previous applications of the GeoPolRisk method have been conducted using basic spreadsheet software. This approach is computationally burdensome. Especially for this case in which multiple scenarios must be analyzed. To facilitate the calculations, the author used a novel application developed on Python programming language by Shaikh (2020). Among other functionalities, this tool allows users to calculate GeoPolRisk values for a given country, sourcing a given raw material, under a range of domestic recycling rates.

Table 4.1 – Data sources (production and trade) for calculating GeoPolRisk values for the EU in 2016

Raw material	Source for production data	Source for trade data	Notes	Label used in this document
Beryllium	USGS	Comtrade	-	Beryllium
borates	USGS (boron as proxy)	Comtrade	-	Borates
cobalt	USGS	Comtrade	-	Cobalt
germanium	USGS	EC – Critical Raw Materials Fact Sheets	-	germanium
magnesium	USGS	Comtrade	-	magnesium
natural graphite	USGS	Comtrade	-	natural graphite
palladium	USGS	Comtrade	-	Palladium
platinum	USGS	Comtrade	-	Platinum
silicon metal	USGS	Comtrade	-	silicon metal
tantalum	USGS	Comtrade	-	Tantalum
gallium	USGS	Comtrade (Aggregated as Ga, Hf, In, Rh and Nb)	Zr and Rh added to the group to match available information	gallium group metals
hafnium	USGS (aggregated with zirconium)			
indium	USGS			
niobium	USGS			
iridium	EC – Critical Raw Materials Fact Sheets	Comtrade (aggregated as Ir, Os and Ru)	Os production disregarded	other platinum group metals (other PGMs)
ruthenium				
dysprosium	USGS (Aggregated as REEs and Yttrium)	Comtrade (Aggregated as REE)	Sc production added to the group to match available information	rare earth elements (REEs)
erbium				
gadolinium				
ytterbium				
neodymium				
praseodymium				
samarium				
terbium				
yttrium	USGS (aggregated with REEs)	Comtrade (Aggregated with Sc)		

The GeoPolRisk results for all 13 raw materials (or group of materials) are presented in Figure 4.3 for values of the EoL-RIR ranging from 0% to 50%; results for the full range (0-100%) are provided in Annex D. For platinum, palladium, and "other PGMs," the redistribution effect is greater than the reduction effect at the present EoL-RIR. For magnesium and cobalt, in contrast, the reduction effect is greater than the redistribution effect – to the point where the latter is indiscernible. In the case of magnesium, this result reflects the present import supply mix to the EU, which relies heavily on China and Iran as the largest trade partners, both of which are relatively unstable countries (as measured by their relatively high WGI-PV values). The case of cobalt can be explained by highly concentrated production, namely in the Democratic Republic of Congo (which has a high WGI-PV value). The magnitude of the redistribution effect mainly depends on the variation of WGI-PV values between various trade partners (see Annex C for a full set of WGI-PV values); the greater the variation, the greater the potential redistribution of the import supply mix towards more stable trade partners.

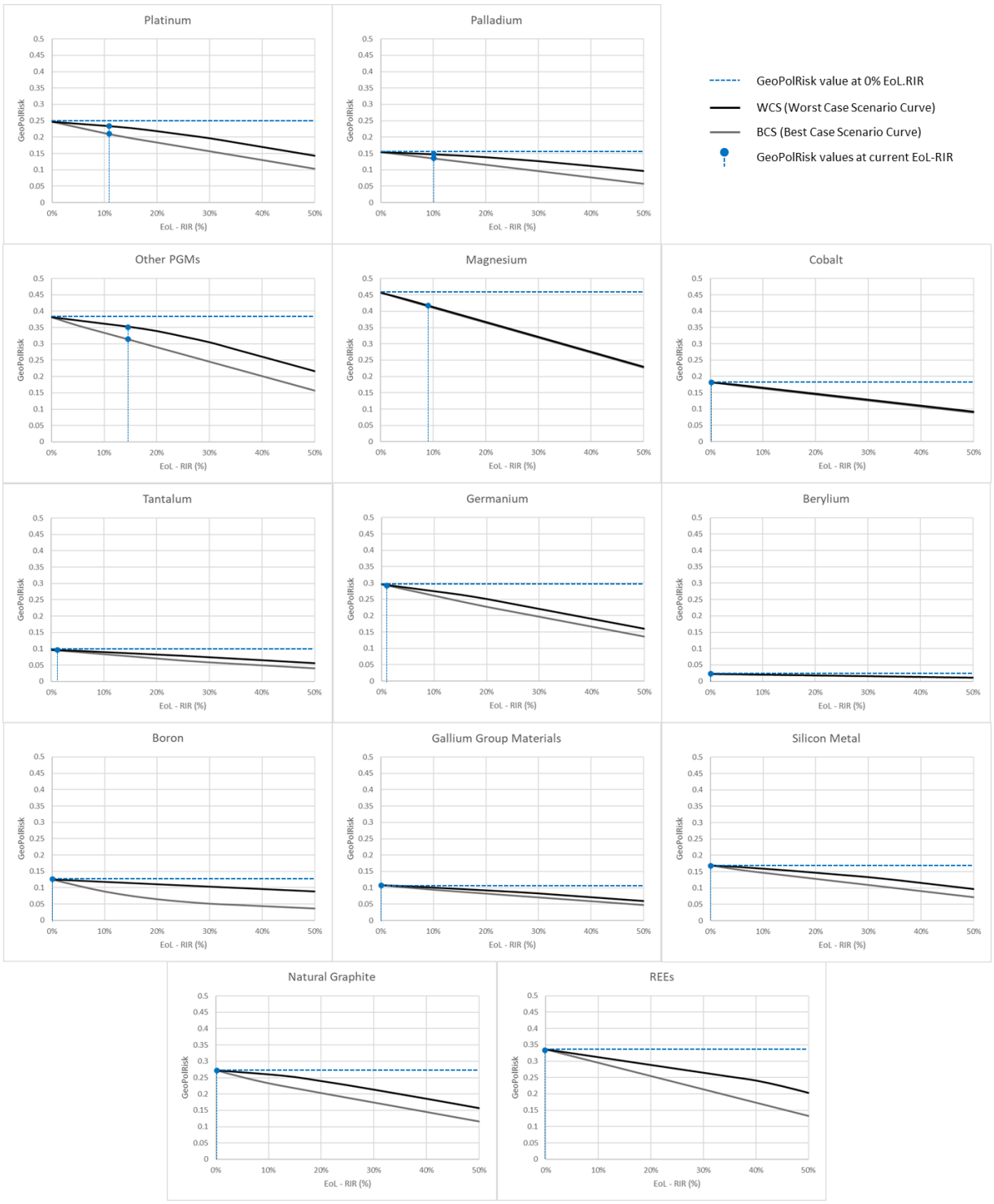


Figure 4.3 - GeoPolRisk values for 13 raw materials (or groups of materials) under a range of scenarios for the end-of-life recycling input rate (EoL-RIR) and the import supply mix

In the case of tantalum and germanium, the present EoL-RIR is low enough that neither the reduction effect nor the redistribution effect are significant – though they become increasingly significant at higher recycling rates (e.g., a 30% EoL-RIR, combined with strategic redistribution of the import supply mix, could reduce the GeoPolRisk of germanium to about 0.2, compared to the present value of 0.3). In the case of beryllium, borates, cobalt, gallium group metals, and silicon metal, the EoL-RIR is presently 0%, so the GeoPolRisk values are the same as they would be if calculated per the original method (as in

Equation 2.1). However, except for beryllium (for which production is dominated by the U.S., a relatively stable country), the results suggest that domestic recycling has significant risk-mitigating potential, especially when the import supply mix is redistributed towards more stable trading partners. Silicon metal, for example, is not currently recovered from post-consumer waste given that many of the applications of this commodity have a dissipative nature (e.g. additives in coating processes), but recycling processes are being developed for some applications (European Commission, 2017). Given data limitations, it is assumed that the EoL-RIR of natural graphite and REEs is presently 0%; nonetheless, the enhanced GeoPolRisk method enables to illustrate the potential risk mitigation that could be achieved through increased domestic recycling rates, especially when combined with redistribution of the import supply mix.

4.3. Discussion on the inclusion of recycling considerations in the GeoPolRisk method

The application of the extended GeoPolRisk method to 13 raw materials (or groups of raw materials) used for, among other things, information and communication technologies (ICT) in the European Union supports the notion – widely reflected in the literature on critical raw materials – that recycling can mitigate raw material supply risk (Erdmann & Graedel, 2011; Graedel & Reck, 2015; Gaustad et al., 2017). As in other supply risk assessment methods developed from an LCA perspective, like the Economic Scarcity Potential (ESP; Schneider et al. 2014) and ESSENZ (Bach et al. 2016), this enhancement considers that recycling can mitigate supply risk by relieving pressure on primary sourcing. However, given the regionalized nature of the GeoPolRisk indicator, another layer to the assessment is added by considering the relative geopolitical (in)stability of both primary and secondary sources. The enhanced GeoPolRisk method considers two mechanisms through which recycling can affect supply risk: first, a reduction of total imports (the “reduction effect”), and second, a potential redistribution of the import supply mix (the “redistribution effect”). Thus, to maximize risk mitigation, recycling should ideally take place domestically (or recycled materials should be imported from relatively stable countries), and the recycled material should be reinserted into the domestic economy. Importing recycled materials from foreign economies might bring environmental benefits compared to using virgin materials, but this does not maximize the mitigation of geopolitical-related supply risk. In fact, it could exacerbate supply risk if the recycled materials are imported from geopolitically unstable countries or regions. To further mitigate supply risk, the import supply mix should be considered – especially given that the redistribution effect sometimes exceeds the reduction effect.

The enhanced method is subject to several limitations in theory and practice. First, from a practical perspective, it can be difficult to obtain the necessary production and trade data with sufficient granularity for all raw materials under consideration. The UN Comtrade database, for example, often lacks an appropriate commodity code (e.g., the rare earth metals neodymium and gadolinium), or aggregates multiple commodities into a single commodity code (e.g., HS 26 15 90 for “niobium, tantalum, vanadium ores and concentrates”). Therefore, in this case, some raw materials were aggregated into groups

(namely “other PGMs,” gallium group metals, and REEs), which masks variations in supply risk between commodities within these groups.

There can also be significant uncertainty around domestic recycling rates, which are influenced by a variety of factors – including, among other things, current metal stocks, future demand, quality policies, technology restrictions, and economic feasibility (UNEP, 2013). The end-of-life recycling input rate (EoL-RIR) was used as a conservative estimate, though this value is not available for all raw materials. However, as demonstrated through the case study, the extended GeoPolRisk method can simulate what the risk-mitigating effect could be under any given recycling rate. The results of the case study suggest that increased domestic recycling rates, combined with strategic redistribution of the import supply mix, can be an effective risk-mitigation strategy. Problems of data availability and quality, though limiting in practice, do not constitute a theoretical limitation of the method itself.

The theoretical limitations of the GeoPolRisk method have been extensively discussed in earlier publications (Gemechu et al. 2015, 2016; Helbig et al. 2016a; Cimprich et al. 2017a, b) and by the Life Cycle Initiative Task Force on Mineral Resources (Cimprich et al. 2019). In particular, while the methodological advancement presented in this chapter addresses one of the main Task Force recommendations for “supply risk methods” (i.e., incorporating considerations of material recycling), the others (i.e., increased spatial resolution, improved modelling of multiple supply-chain stages and improved modelling of effects in the AoP Natural Resources) remain largely open questions.

With respect to spatial resolution, the GeoPolRisk method models supply risk as a function of commodity trading between macroeconomic units (i.e., countries or regions), whereas supply-chains actually comprise market relationships between microeconomic units (i.e., companies). The same argument applies to environmental and social sustainability aspects in supply-chains (Goldstein & Newell, 2020). With respect to modelling multiple supply-chain stages, though an extension of the GeoPolRisk method was developed for this purpose (Helbig et al. 2016a), the application of this extension was made on only (part of) a single product system (polyacrylonitrile used as a precursor for carbon fiber production); and, from an LCA perspective, it remains unclear how to link the multi-stage GeoPolRisk calculation to the functional unit of a given product.

Finally, the GeoPolRisk method can be considered equivalent to a “midpoint” approach in LCIA, as it serves to indicate (or at least give a proxy for) the relative likelihood of geopolitically-induced supply disruptions of a given raw material for a given macroeconomic unit. Further development could extend the method to an “endpoint” approach (e.g., to assess the impacts of supply disruptions as manifested in physical raw material shortages and/or price spikes) for the “natural resources” AoP in the life cycle sustainability assessment (LCSA) framework; this last potential improvement will be addressed in the next chapter.

With this enhancement, recycling considerations are assessed as strategies for criticality mitigation, as suggested by members of the International Round Table on Materials Criticality (IRTC) (Tercero-Espinoza et al., 2020) and in policy initiatives like the EU Circular Economy Plan, in which domestic recycling is highlighted as a key supply security strategy for reducing import dependency (European

Commission, 2015). Despite of the limitations, the enhancement of the GeoPolRisk method presented in this chapter directly addresses the UNEP Life Cycle Initiative Task Force recommendation to incorporate the potential risk-mitigating effects of material recycling into supply risk methods; therefore, advancing the maturity of the method for further applications.

Chapter 5: Geopolitical Supply Risk in LCSA: From Midpoint to Endpoint

The work presented in this chapter is partially based on the publication:

J. Santillán-Saldivar; T. Gaugler; C. Helbig; A. Rathgeber; G. Sonnemann; A. Thorenz; A. Tuma (2020). Design of an endpoint indicator for mineral resource supply risks in life cycle sustainability assessment: The case of Li-ion batteries. Journal of Industrial Ecology. https://doi.org/10.1111/jiec.13094

Contribution Statement:

J. Santillán-Saldivar:	Conceptualization, Methodology, Formal Analysis, Investigation, Data Curation, Writing – Original Draft
T. Gaugler:	Methodology, Formal Analysis, Investigation, Writing – Original Draft
C. Helbig:	Conceptualization, Methodology, Formal Analysis, Visualization, Writing – Original Draft
A. Rathgeber:	Validation, Writing – Review and Editing
G. Sonnemann:	Conceptualization, Supervision, Writing – Review and Editing
A. Thorenz:	Resources, Writing – Review and Editing
A. Tuma:	Supervision, Resources, Writing – Review and Editing

As discussed in section 2.2.2, raw material criticality has been proposed as a complement to environmental life cycle assessment by addressing resource accessibility as part of the LCSA framework. Moreover, resource accessibility has been accepted as an environmental impact category associated to the AoP Natural Resources in LCA; it provides the notion of a socio-economic pathway to address impacts associated with resource utilization. Product-level supply risk assessments follow this perspective by assessing outside-in impacts.

The GeoPolRisk method (Gemechu et al., 2016; Cimprich et al., 2017) has been interim recommended to quantify potential accessibility issues to raw materials related to short-term geopolitical and socioeconomic aspects. This suggestion was made by the Task Force on mineral resources of the Life Cycle Initiative hosted by UN Environment (Berger et al., 2020; Frischknecht et al., 2019). However, the accessibility issues currently addressed belong to a midpoint level in LCA and thus, so far, there has been no applicable method to associate the supply risk at midpoint level to a tangible endpoint socio-economic damage.

The current methodological challenge is to estimate a socio-economic damage through a cause-effect chain of potential geopolitical supply disruptions. Addressing damages to the AoP Natural Resources would require the inclusion of a damage factor linking supply risk to potential increased costs. Among the current efforts related to natural resources, the Abiotic Depletion Potential (ADP) method explores the contribution of a product system to the depletion of mineral resources (Guinée and Heijungs 1995; van Oers et al., 2002; van Oers and Guinée, 2016), the LIME2 (Itsubo and Inaba, 2012) method quantifies future externalities of mineral resource use, the ESSENZ method considers price volatility as an indicator that contributes to a measure of criticality (Bach et al, 2016), and the Surplus Cost Potential (SCP) explores costs increases of future resource extractions (Ponsioen et al., 2014; Vieira et al., 2016). However, these methods explore long-term scenarios and do not address accessibility considerations (Frischknecht et al., 2019). This chapter has the objective to propose and apply a novel endpoint-level indicator to address short-term socio-economic effects of geopolitical supply risk based on the GeoPolRisk method.

5.1. The Economic Impacts of Supply Disruption

It is argued that supply disruption events are linked to monetary socio-economic damage through a cause-effect chain. According to economic theory, in the case of a geopolitical tension causing a supply disruption, the supply curve shifts, meaning that less material is offered to the market for the same price (McEachern, 2011; Varian, 2014; Baumol and Blinder, 2015). Such a disruption is more likely for critical raw materials, which have more limited production, and the disruption causes undesired economic damage (Graedel and Reck, 2015). In contrast, the demand curve does not move in the case of a supply disruption event, assuming that substitution options are not immediately available and supply disruption does not affect consumption. Therefore, as illustrated in Figure 5.1, following basic economic principles the new market equilibrium after the event will be at a higher price; and the price increase will remain for as long as the supply disruption persists.

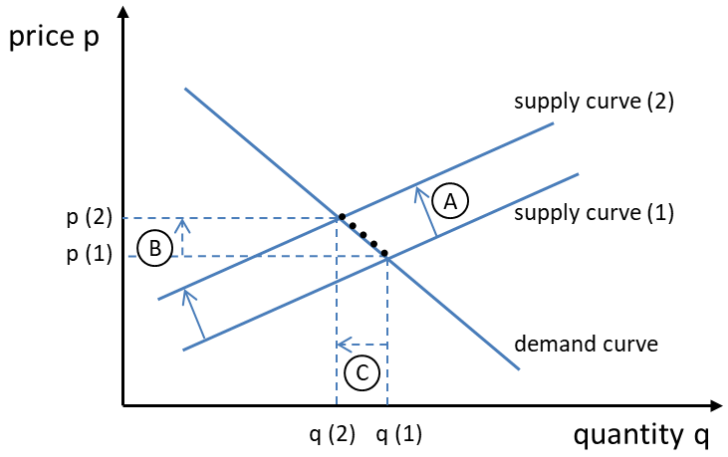


Figure 5.1 – Shift of the supply curve caused by a sudden change in available resources

Despite this cause-effect chain being plausible in theory, empirical evidence is difficult to find. As an example, price volatility indicators can be assessed as part of long-term price data series for markets (BGR, 2021); unfortunately these do not allow to observe supply and demand curves, since the equilibrium price is determined on the stock exchange (Varian 2014). Supply curves can change due to new exploration, depletion of individual mines, new extraction technologies, among other reasons that make supply relatively stable. However, the demand is strongly influenced by factors like global economic activity, monetary policy, technological changes and trade policies. This yields to the fact that most equilibrium price changes are determined by changes in the demand and only allow to derive the slope of the supply curve. Nevertheless, Fu et al. (2019) quantify long-run price elasticities, values that allow to estimate a change in price based on demand or supply changes, for three by-product metals. However, when addressing supply risk, it becomes necessary to examine events at which the raw material supply changes unexpectedly; events further studied in this chapter are unexpected and, therefore, the risk of damage in the short term is not included in the market prices (Koch and Fenili, 2013).

By looking at specific events involving sudden supply disruptions, it could be possible to estimate the slope of the demand curve. Natural catastrophes with documented effects on mining or processing activities can be addressed, since their occurrence is considered a risk for mineral production (Schnebele et al., 2019). The slope of the demand curve implies the economic damage: given a low demand slope, a reduction of the supply would cause an increase in price and, consequently, a reduction of welfare. In contrast, a high slope would imply sharply rising prices. This would result in a high wealth reduction on the demand side driven by a large consumer price increase. The “price elasticity of demand” indicates the effect of a (marginal) price change of a commodity on the requested quantity. For this calculation, the quantity and world market price changes (in percentages) are set in relation to each other as per Equation 5.1 (Varian, 2014).

Equation 5.1…… $price\ elasticity\ of\ demand = \frac{\%\ change\ in\ quantity\ q}{\%\ change\ in\ price\ p}$

Figure 5.1 illustrates this relationship: In case of a supply shortage, (A) the supply curve (1) shifts to supply curve (2) and as a result, (B) the price increases from p (1) to p (2). This leads to (C) a decline in demand from q (1) to q (2). The extent of the price increase – which corresponds to the slope of the (dotted) demand curve – results from the ratio between the change in quantity and the change in price. For the application that will be later presented in this chapter, proxies for price elasticity values will be obtained after studying the effect of short-term shortages of supply caused by natural disasters on global commodity prices.

5.2. Methodological Enhancement: GeoPolEndpoint

The proposed extension takes on previous work on the integration of criticality considerations into LCSA (Sonnemann et al. 2015) and the inclusion of supply risk as an impact category associated to the AoP Natural Resources in LCA based on social and economic considerations (Cimprich et al., 2019). As mentioned in section 2.2.3, For a given material, year and region, the GeoPolRisk method provides an indicator of the proportion of mass at risk in a life cycle taking into account the production concentration at global level and the import mix of the analyzed country or region (Cimprich et al. 2017). The novel impact pathway uses the GeoPolRisk indicator to achieve a measure of a potential increased cost due to geopolitically-driven supply disruptions. The steps and required information to obtain this new endpoint indicator (GeoPolEndpoint) for one resource, from the perspective of one importer and for one year is illustrated in Figure 5.2.

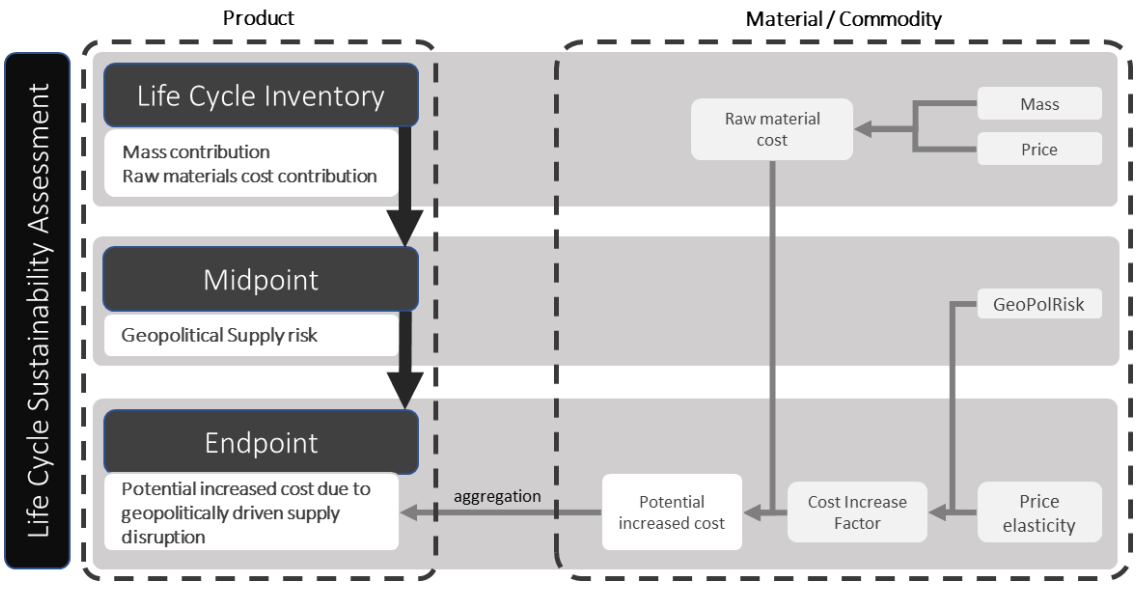


Figure 5.2 – Methodological impact pathway for the development of an endpoint indicator based on Geopolitical supply risk considerations (GeoPolEndpoint)

In LCA, the functional unit represents the service provided by the product. Given the assumption that production is still possible despite the event, the damage of a geopolitical supply shortage is equivalent to the geopolitically-driven increased costs for the production due to higher raw material costs. The result

provides a damage value in monetary units related to specific raw materials and applicable for the assessed year.

In order to develop an endpoint indicator based on the GeoPolRisk method, it becomes necessary to apply it at a larger scale because most metals are traded in a global market. As a first proof of concept, the method is applied from the perspective of the group formed by the members of the Organization for Economic Co-operation and Development (OECD). The decision on the use of the OECD members as reference group is based on its design as a global network with high impact on economic, environmental and social policies around the globe (OECD, 2019a); and for its focus on stimulating economic development and global trade (OECD, 2019b). The adjusted formula for the global fraction at risk of a commodity for a given year to be further used and referenced in this chapter is determined by:

Equation 5.2 ..... $GeoPolRisk_{OECD} = HHI * \frac{\sum_c g_c * f_{c,OECD}}{P_{OECD} + F_{OECD}}$

Where g_c is the score of the country in the WGI-PV transformed to a 0-1 scale; $f_{c,OECD}$ is the trade flow of a commodity from country c to the group of OECD countries; F_{OECD} represent the total imports of OECD countries for the commodity and P_{OECD} is the production of a commodity in the group of the OECD countries.

Based on the adjusted formula for the case of the OECD countries and the idea of implementing the concept of a price elasticity value to an endpoint-level indicator, the GeoPolEndpoint method is proposed to provide a measure of the socio economic damage to the AoP Natural Resources in LCSA. The formula for one defined resource and one year is described as follows:

Equation 5.3..... $GeoPolEndpoint_{OECD} = GeoPolRisk_{OECD} \times \varepsilon \times \bar{p} = Cost\ Increase\ Factor \times \bar{p}$

Where ε is the inverse price elasticity of the resource, which is assumed to be iso-elastic, (constant on the entire curve) (Sah and Wada, 2003) and $\bar{p}$ is the average price of a resource a in year t. The product of ε and $GeoPolRisk_{OECD}$ will be further referred as the Cost Increase Factor.

For a given resource and year, the result of this calculation is interpreted as an average cost increase of facing a sudden geopolitically-driven supply disruption per unit of mass of the material under analysis. If the supply disruption occurs, the material flow is reduced by this amount, leading to a price increase defined by the elasticity. Consequently, the measure approximates the potential loss in economic welfare of the material-processing countries facing a potential disruption. These damage factors are intended to be multiplied by the mass flows in a LCA inventory and provide a measure of the damage caused by the use of the individual resource as part of LCSA. The geopolitically-driven increased costs from all considered resources can be summed at the end for assessments at product level.

5.3. The case of Lithium-ion Batteries

Lithium-ion batteries (LIB) demand has increased steadily after the year 2000 primarily due to mobile consumer electronic devices. LIB demand growth is determined by the growing market share of electric

vehicles (Pillot, 2017). Aluminum, cobalt, nickel and copper are all used in LIB, as either current collectors or metals in cathode materials (Peters and Weil, 2016). Materials like cobalt, nickel or lithium are main contributors to supply risks of LIB (Helbig et al., 2018). For this application, it is foreseen to model the geopolitically-driven increased costs of selected materials in LIB as potential short-term increased costs on the product system of LIB due to unexpected supply disruptions.

Based on the inventory provided by Peters and Weil (2016), two types of cells of LIB will be studied: nickel-cobalt-aluminum (NCA-C) and nickel-manganese-cobalt (NMC-C) cathode active material, both with graphite anode material. NCA-C battery cells are estimated to have and energy density of 133.1 Wh/kg and NMC-C, of 130.4 Wh/kg. The most relevant materials in the inventory of these batteries are lithium, aluminum, manganese, cobalt, nickel, copper, carbon and phosphorus; however, this application will focus only on aluminum, cobalt, copper and nickel due to being the only ones for which it is possible to obtain values for price elasticity according to the method proposed in section 5.1. Table 5.1 shows the mass contribution of these four selected materials to the inventory of NCA-C and NMC-C LIB.

Table 5.1 – Mass contribution of selected materials to the LCA inventory of LIB

Material	***Mass share in NCA-C***	***Mass share in NMC-C***
Aluminum (Al)	5.8%	3.5%
Cobalt (Co)	2.0%	5.4%
Copper (Cu)	11.2%	16.5%
Nickel (Ni)	10.7%	5.4%

The supply risk, and contribution to the socio-economic impacts of these materials as part of the inventory of LIB will be analyzed for the period between the years 2015 and 2017. This period was selected due to data availability for geopolitical supply risk and for price elasticity calculations at the time of the beginning of the study. The average prices in 2017 for the four metals range in between 1.97 USD per kg for aluminum and 55.6 USD/kg for cobalt. Nickel and copper have been traded in 2017 at 10.5 USD/kg and 6.17 USD/kg, respectively. Prices refer to LME (London Metal Exchange) market prices (Thomson Reuters, 2019). The same prices are used for the calculation of price elasticity proxies, the average price values for the analyzed years are displayed in Table 5.2.

Table 5.2 – Average prices for the selected materials from 2015 to 2017

Material	***Price 2015 (USD/t)***	***Price 2016 (USD/t)***	***Price 2017 (USD/t)***
Aluminum (Al)	1,662.26	1,604.97	1,968.30
Cobalt (Co)	28,477.06	25,528.56	55,583.43
Copper (Cu)	5,503.03	4,867.39	6,173.23
Nickel (Ni)	11,877.33	9,647.89	10,469.19

5.4. Price Elasticity Data and Calculations

As previously discussed in section 5.1, to estimate the slope of the demand curve and the impact of a supply shock, it becomes necessary to focus on situations in which the supply changes due to sudden external events. Natural disasters are situations where producers are forced to reduce their capacity, because the mines or the transportation infrastructure are destroyed (Benson and Clay, 2004). For this study, it is irrelevant whether the infrastructure – which includes transport, power, and communications networks – is completely or only partially destroyed. In any case, the supply of the raw material is impaired. As a first step, natural disasters during which mines were affected are analyzed. For this purpose, the "NatCat"-database of Munich Re (2019) is used to identify the dates and the type of each disaster (e.g. earthquake and tsunami, tropical cyclone, flood and flash flood) as well as the affected country and the geographical coordinate of each natural disaster. On the other hand, the location of the mine as well as the prices of the commodities concerned are of interest. Mining data was taken from the annual Minerals Yearbook (USGS, 2016, 2017, 2018).

As previously stated, price information was obtained from the London Metal Exchange (Thomson Reuters, 2019). Only events in which more than 1% of the global mining was affected are considered. For lower affected mining volumes, it can be assumed that their possible influence on the global price is negligible. In addition, the distance between the disaster and the affected mine should not be greater than 100 kilometers measured by the great circle (longitude and latitude of event and mine). Furthermore, the focus is given to events that are followed by a price increase of the commodity affected. On the basis of these criteria, the natural disaster best fitting the criteria for each commodity is identified and the associated price changes are examined.

For this application, and following the impact pathway in Figure 5.2, we define ε as the quotient of the change in price and the change in quantity. Hence, ε is the inverse of the elasticity defined in Equation 5.1. With this approach, it is possible to identify commodity-specific disasters and the associated short-term impact measured by the inverse price elasticity of demand specific to one material (ε), which is defined as the percentage price change of the concerned metal divided by the percentage of global mining affected (Varian, 2014). Available data allows obtaining price elasticity values for aluminum, cobalt, copper and nickel, being this the main constraint for the development of the study. The selected events are displayed in Table 5.3, the table includes information on the dates of the natural disaster and the global estimated affected production.

Table 5.3 – Events affecting the supply of selected materials in the study

Commodity	***Country***	***Disaster***	***Date***	***Affected mass***
Aluminum	India	Cyclone	13/10/2014	16.94%
Cobalt	Cuba	Hurricane	04/10/2016	2.23%
Copper	Romania	Flood	04/07/2005	4.66%
Nickel	Philippines	Typhoon	05/10/2009	4.12%

For the case of aluminum, cyclone Hudhud affected 16.94% of global Bauxite supply in October 13, 2014 and the calculated ε value is 0.04. Hurricane Matthew had an impact on the production of cobalt in Cuba (global mining affected: 2.23%); the event is dated on October 4, 2016 and its associated calculated ε value is 0.81. A flood on July 4, 2005 had an impact on copper mining in Romania, accounting for 4.66% of global mining with associated 0.21 ε value. Typhoon Parma (Pepeng) crossed the Philippines on October 5, 2009, leading to a decline in nickel ore production (global mining affected: 4.12%) and an estimated value of 0.37 for ε. More details on the calculation of the price elasticities are available in Annex E.

5.5. Overall GeoPolEndpoint Results

As previously mentioned in this chapter, the proposed endpoint indicator is applied to Al, Co, Cu and Ni, four materials in the supply chain of LIB from the perspective of the group formed by the country members of the OECD. Subsequently, the obtained results at midpoint and endpoint level are compared with the inventory in order to assess the overall contribution of the four focus materials to the supply risk and to the socio-economic damage attributable to LIB.

Following Equation 5.3, the $GeoPolRisk_{OECD}$ values of the four selected raw materials are calculated for the years 2015, 2016 and 2017. The overall results can be identified in Table 5.4. More details on the GeoPolRisk calculations are available in Annex F and Annex G. In the case of aluminum, $GeoPolRisk_{OECD}$ values obtained for 2015, 2016 and 2017 are 0.023, 0.020 and 0.019 respectively. The contribution to the supply risk is attributed to the increasing participation of Russia, countries in the Middle East and China in the import shares for OECD members. Bauxite is used for the calculation of the GeoPolRisk indicator to guarantee a consistency with the elasticity values, which were calculated for an event that affected bauxite production. GeoPolRisk values could also be calculated for aluminum smelting countries, or as aggregated values for multi-stage supply chains as shown at the example of petrochemical supply chains by Helbig et al. (2016a). Results for cobalt (0.080, 0.081 and 0.097) are explained by a highly concentrated production in countries outside of the OECD, with DR Congo being the main producer with a strong and increasing participation in the global market. Additionally, the contribution from countries in the OECD decreased in the last analyzed year. The production of nickel and copper is relatively well distributed around the globe with strong participation of members from the OECD. Therefore, the supply risk of these materials is substantially lower in comparison to the first two (0.015, 0.012 and 0.014 for nickel; 0.008, 0.014 and 0.012 for copper).

Table 5.4 – $GeoPolRisk_{OECD}$ values for the analyzed materials (2015-2017)

Material	***$GeoPolRisk_{OECD}$ 2015***	***$GeoPolRisk_{OECD}$ 2016***	***$GeoPolRisk_{OECD}$ 2017***
Aluminum (Al)	0.023	0.020	0.019
Cobalt (Co)	0.080	0.081	0.097
Copper (Cu)	0.008	0.014	0.012
Nickel (Ni)	0.015	0.012	0.014

The $GeoPolRisk_{OECD}$ values and estimated Ɛ for the analyzed materials are multiplied to obtain a Cost Increase Factor, Figure 5.3 gives a graphical representation of these factors. Note that the proxy for price elasticity is calculated as a general factor for each metal and is assumed not to be dependent on the year of analysis. Aluminum and copper share cost increase factors with values that range from 0.0008 to 0.001 and 0.0017 to 0.003 respectively, followed by nickel with a range from 0.0042 to 0.0055. However, the value for cobalt ranges from 0.065 in 2015 to 0.079 in 2017. This difference in the values is further extended with the calculation of the GeoPolEndpoint factor, which results from the product of the cost increase factor and the average price of the materials.

Based on Equation 5.3, the values for socio-economic impacts associated to the geopolitical supply risk of Al, Co, Cu and Ni are calculated from the perspective of the OECD. These endpoint results are interpreted as potential increased costs and expressed in monetary units (USD) per mass (t). Cobalt shows the highest socio-economic risks for OECD countries due to geopolitical supply disruptions. Not only is cobalt most exposed to geopolitical supply disruptions because of its high production concentration and low mining volume inside OECD countries; it is also most vulnerable to supply disruptions, showing the highest positive price elasticity to a short-term event.

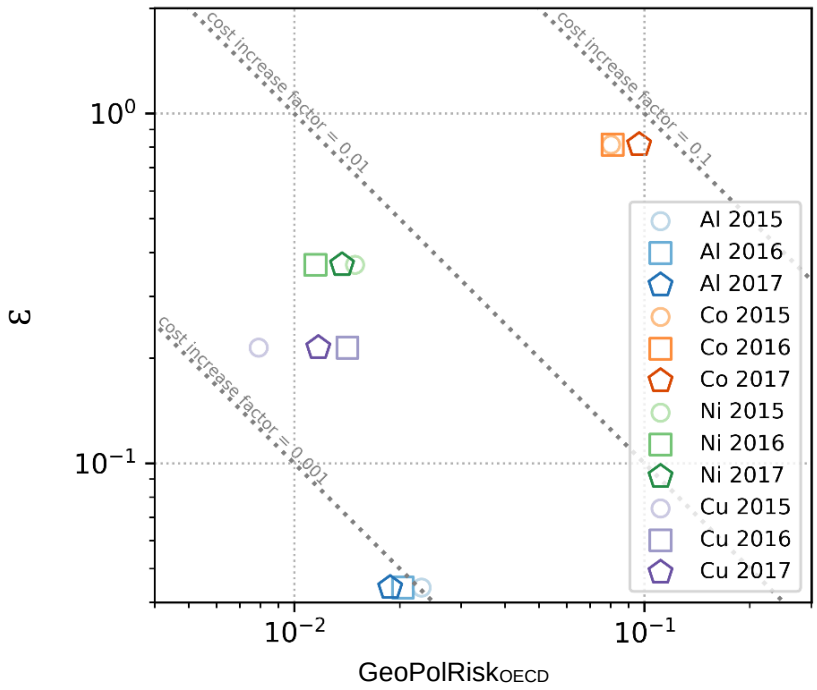


Figure 5.3 – Cost increase factors for Al, Co, Cu, and Ni in 2015, 2016 and 2017
(Plot is in a double logarithmic scale)

The smallest GeoPolEndpoint value is attributed to aluminum with a relative damage at the endpoint level of 1.69, 1.45 and 1.63 USD/t-Al (for 2015, 2016 and 2017 respectively; 1 t= 1000 kg). It is followed by copper with corresponding values of 9.33, 14.8 and 15.5 USD/t-Cu. Increased endpoint factors are obtained for nickel and cobalt, with 65.4, 41.0 and 53.0 USD/t-Ni for nickel and 1860, 1690 and 4370 USD/t-Co for cobalt. The overall socio-economic damage at endpoint level attributable to the supply risk of Al, Co, Ni, and Cu in NCA is equivalent to 1.78%, 1.83% and 3.13% of the total costs of these materials

in the battery inventory for the years 2015, 2016 and 2017 respectively. For the case of NMC, this overall contribution to the damage is higher, comparable to 3.37%, 3.48% and 5.20% of their cost. More details for these calculations are provided in Annex H.

Figure 5.4 shows the relative contribution of aluminum, cobalt, nickel and copper to the raw material costs in the battery cell and the socio-economic damage at endpoint level; this last one obtained as the product of the GeoPolEndpoint value, the mass share and energy density. From an inventory perspective, the mass share of copper and nickel is superior to aluminum and cobalt in the case of NCA. While the mass share of copper is even higher in the case of NMC, cobalt and nickel have a similar contribution in the latter case (see Table 5.1). In terms of raw materials cost, the relevance of cobalt and nickel becomes evident, especially in the year 2017 when an increase on the price of cobalt makes its cost share more dominant in the LIB inventory.

The relative contribution of the raw materials to the supply risk has remained stable over the analyzed period. However, the GeoPolRisk$_{OECD}$ indicator for cobalt emerges as a reflection of the supply chain of this material, for which a large percentage of its production is located in high risk countries. Results at endpoint level rank cobalt as of even greater importance in the assessment of socio-economic damages, representing between 82% and 92% of the total damage associated with Al, Co, Cu and Ni in NCA (values for the period between 2015 and 2017).

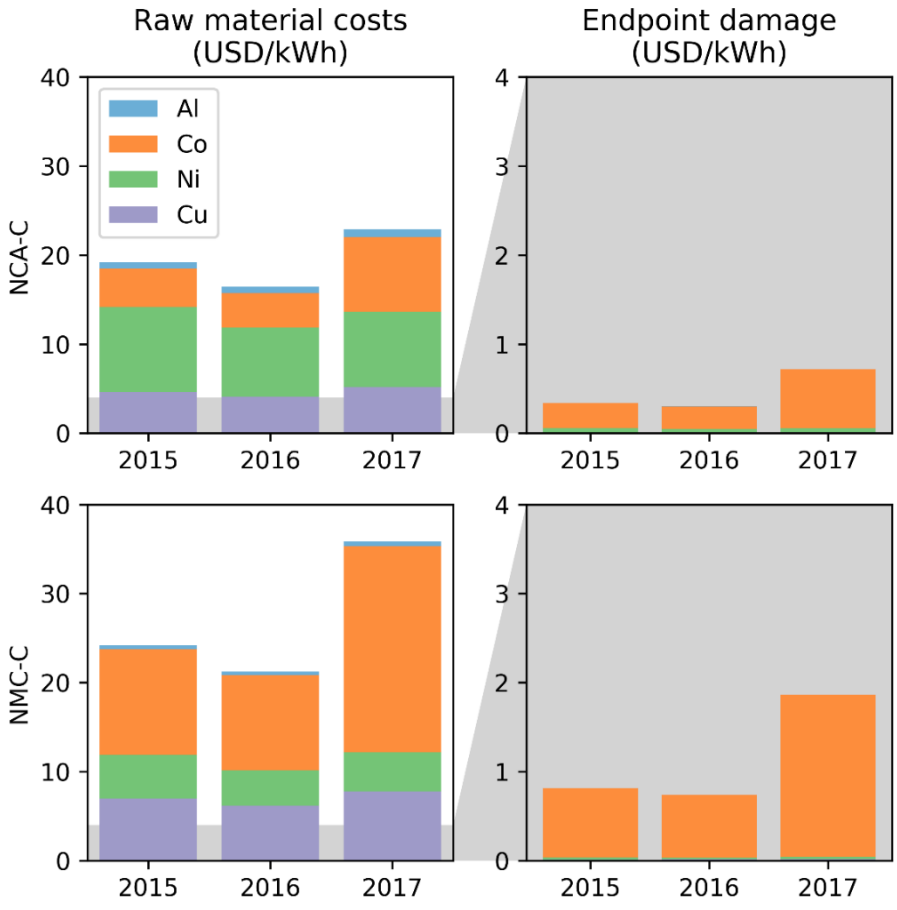


Figure 5.4 – Contribution of Al, Co, Cu, and Ni to raw material costs and endpoint damage

Nickel also plays a role in this case with a smaller share attributable to a high contribution in mass and having a relevant $GeoPolRisk_{OECD}$ value. For the case of NMC, however, the effect of cobalt displaces the contribution of the other materials, making them negligible in comparison for the case of NMC. In absolute terms, the economic impact of the use of Al, Co, Cu and Ni can be modeled as a potential increased cost of materials for the production of Li-ion batteries. In the case of NCA, this cost is calculated as 0.34, 0.30 and 0.72 USD/kWh for the years 2015, 2016 and 2017 respectively; contrastingly, the increased cost for NMC is 0.81, 0.74 and 1.86 USD/kWh. More details on these results are available in Annex H.

5.6. Discussion on the extension of the GeoPolRisk method to and Endpoint level in LCSA

As previously discussed in section 2.2.3, the GeoPolRisk method originated from the integration of criticality considerations in the LCSA framework and is designed as a regionally differentiated tool to complement environmental LCA for decision making processes based on accessibility to natural resources. The extension of the method to an endpoint indicator represents a challenge because price considerations for minerals are usually given at a global scale. Therefore, for this first application of the GeoPolEndpoint method, the selection of the OECD country members as a reference group was based on their active participation in the global economy. This decision opens an opportunity to assess the GeoPolEndpoint results from different perspectives; taking advantage of the versatility provided by the regional approach of the GeoPolRisk method, future applications could also focus on other country groups given that these could be considered to have a relevant role in global economy and trade market.

This first application of the GeoPolEndpoint method focuses on LIB. This case study was selected given the availability of information related to the estimation of price elasticity for a large portion of the materials present in the used inventories: 29.7% in the case of NCA and 30.9% for NMC. Based on the inventories, a main future challenge is the obtention of elasticity values for lithium and manganese; these, despite not being great contributors in mass, could become relevant sources of socio-economic damage when assessing supply risk or subsequent potential increased cost, similar to cobalt.

The main challenge when designing the method is the obtention of price elasticity values as these are calculated based on event studies (natural disasters); therefore, these results are not yet statistically significant. The use of a small set of datapoints forces to assume iso-elasticity of the demand function in order to apply the obtained values in the presented endpoint method (Sah and Wada, 2003). The analysis of other types of events that also cause supply disruption other than natural disasters is encouraged to study effects on the prices of commodities.

In economics, there are other indicators more widely used and more easily obtained to characterize price behavior. Specifically, price volatility (BRG, 2021) is used in the ESSENZ method to characterize price fluctuations (Bach et al, 2016); however, this is designed as a measure of dispersion and focuses on medium or long-term price variations that cannot be applied to the impact pathway presented in this

chapter. The GeoPolEndpoint aims to measure the immediate (short-term) economic damage caused by a supply disruption, rather than a measure of probability of harm happening. This makes the GeoPolEndpoint quite unique in LCA methods as an inside-out indicator associated to the AoP Natural Resources. Further work could focus on modeling socio-economic damages based on an impact pathway that considers long-term scenarios.

Some efforts have been made to develop resource scarcity indicators in LCA. Among these, examples include the ADP method for resource depletion (Guinée and Heijungs, 1995; van Oers et al., 2002; van Oers and Guinée, 2016), the LIME2 method to quantify future externalities of resource use (Itsubo and Inaba, 2012), and the SCP method for future mineral extraction costs (Ponsioen et al., 2014; Vieira et al., 2016), all focused on a long-term perspective. Unlike other methods designed to assess the increase in scarcity of resources, the GeoPolRisk method (midpoint) and the GeoPolEndpoint method (endpoint) are based on the integration of criticality considerations in LCA through the LCSA Framework (Sonnemann et al., 2015). The causes and effects of criticality considerations are analyzed in the short term; a continuous assessment of the geopolitical supply risk of raw materials is required to provide up-to-date information. Data on elasticities can be updated once relevant natural disasters are added to the respective databases, which cannot be regular due to the stochastic nature of disasters.

In this chapter, an endpoint indicator is designed to study the implications of mineral resources supply risk in the AoP Natural Resources as part of LCA and based on the GeoPolRisk method within the LCSA Framework. This enhancement addresses an area of methodological development identified in the work of the Life Cycle Initiative Task Force on Mineral Resources: linking the midpoint-level supply risk indicators to endpoint-level socio-economic damages in LCSA due to the geopolitically-driven increased costs (Berger et al., 2020; Sonderegger et al., 2020). With the developed method, it becomes possible to assess how the use of certain raw materials could have a substantial economic impact when developing new technologies; moreover, the possible shifting of burden from environmental damages, in particular in relation to climate change impacts for low carbon solutions, to new economic costs due to supply constraints is visible. It becomes evident that there is an overlap when assessing these impact pathways: geopolitical supply risk as a driver of impacts in the AoP Natural Resources in LCA and geopolitical supply risk as a link to the economical dimension in LCSA, as first mentioned in section 1.3.

Similar to other assessments of material criticality, this method faces data limitations, particularly in terms of price elasticity, primary production and commodity trading (e.g. as reflected in the focus on four key materials that represent about 30% of the mass in the inventory of LIB). Subsequent efforts should be focused on obtaining more comprehensive data on supply disruption produced by different events setting the foundations to obtain proxy price elasticity values for other relevant materials. Further applications of the method could also analyze results from different perspectives and study a procedure to better aggregate countries. Application of the GeoPolEndpoint method is encouraged for the assessment of socio-economic impacts from the point of view of the European Union, the Asia-Pacific Cooperation, or non-OECD countries, among others. An application to the European Union will be presented in the next chapter.

The method provides results based on resource supply risk and with a focus on primary production of the analyzed materials. It follows an impact pathway based on an outside-in perspective, in which the analyzed system is affected by external factors. A limitation the method carries from previous applications that study geopolitical supply risk is that potential disruptions are only analyzed at mining and refining stage; further methodological enhancements are required to determine how to assess supply risks at intermediary stages.

With the designed endpoint method, it becomes possible to quantify the effect of the use of mineral resources in the AoP Natural Resources by providing geopolitically-driven increased costs, a socio-economic indicator measured in monetary units proposed as complement to LCA and within the LCSA framework; therefore providing a new decision-making tool based on the integration of criticality considerations to life cycle sustainability assessment. This first application serves as a proof of concept in which the geopolitical supply risk is associated to the mentioned AoP; however, the main barrier for increasing its usability is the obtention of values of price elasticity linked to a wide variety of resources.

In Chapter 4:, the effect of recycling as a risk mitigation strategy is explored and a method is provided to better estimate the geopolitical supply risk taking into consideration the domestic recycling activities. A further integration of these proposed methods could serve to estimate the potential economic benefits or costs of implementing risk mitigation strategies such as recycling or substitution. The next chapter in this manuscript includes an integrated assessment that considers both approaches along with more traditionally used midpoint indicator in environmental LCA.

Chapter 6: Integrated Life Cycle Assessment: Environmental and Criticality Considerations in LCIA

The work presented in this chapter is partially based on a paper in preparation for publication:

J. Santillán-Saldivar; E. Gemechu; S. Muller; J. Villeneuve; S. B. Young; G. Sonnemann (to be submitted to the International Journal of Life Cycle Assessment) Integrated assessment of environmental and supply risk considerations for selected materials in the life cycle of Li-ion batteries.

Contribution Statement:

J. Santillán-Saldivar:	Conceptualization, Methodology, Formal Analysis, Investigation, Data Curation, Visualization, Writing – Original Draft
E. Gemechu:	Methodology, Formal Analysis, Visualization, Writing – Review and Editing
S. Muller:	Resources, Validation, Writing – Review and Editing
J. Villeneuve:	Resources, Validation, Writing – Review and Editing
S.B. Young:	Validation, Writing – Review and Editing
G. Sonnemann:	Resources, Supervision, Writing – Review and Editing

The methodological enhancements proposed and applied in chapters Chapter 4: and Chapter 5: have been developed following the original design of the GeoPolRisk method: A complement to environmental life cycle assessment based on the concerns around resource accesibility. In both case studies, results show that a perspective based on materials criticality has the potential to provide insights to support both company and policy decisions. Both efforts exist only as first applications; therefore, further work must be developed towards improving the readiness of the overall methodological impact pathway previously mentioned.

With the objective to extend the applications of this notion and to integrate both proposed improvements in chapters 4 and 5, this section compiles the outcomes of applying the GeoPolRisk method with the inclusion of recycling considerations and the GeoPolEndpoint method to the same case study, along with most commonly used midpoints and endpoints in environmental LCA.

6.1. Criticality concerns for a low-carbon transition

The efficiency of fossil fuels as energy carriers has made these the main drivers of technological development in the past century (Smil, 2016). According to Hannah and Max (2019), more than 60% of the global electricity in 2019 had its origin in a mix of coal, natural gas and petroleum. A proposed gradual change to renewable sources has been proposed by several organizations due to the severe environmental impacts of the use of fossil fuels: scientific reports show that approximately 40 billion metric tons of CO2 are released to the atmosphere on a yearly basis (IPCC 2018). The use of renewable energy has promoted innovation in the energy, transport and technology sectors, while bringing to the surface new challenges for efficient energy storage, materials demand and electronic waste management (Findlay, 2020).

A significant part of the literature on low-carbon transitions focuses on improved means for energy storage, a key element to support the increasing demand for technologies that use renewable energy sources (Sovacool et al., 2020). Batteries have been improving in efficiency with the introduction of new materials to increase energy density; however, the increased demand for these metals and minerals makes evident new problems along the supply chain: accessibility to materials and waste management (Sovacool et al., 2019). From the perspective of resources accessibility, efforts are required to understand the real and tangible costs of using critical raw materials, along with alternatives to mitigate these impacts with strategies such as recycling and substitution, as previously discussed in Chapter 4:.

Life Cycle Assessment has been used to address the environmental benefits of the use of renewable energies over fossil fuels; among these studies, the assessment of electric vehicles (EVs) represents a good example of the shift of the burden from greenhouse gases emissions from combustion of fossil fuels to other environmental impacts associated to EVs (Hawkins et al., 2012, 2013; Nordelöf et al., 2014). More specific studies focus on the batteries in EVs, recognizing them as one of the main contributors to the overall environmental impact attributed to these vehicles (Notter et al., 2010; Peters and Weil, 2016, 2017).

6.2. The readiness of LCA to address resource accessibility

As previously discussed in section 2.2, LCA focuses on three main Areas of protection (AoP) to study the impacts of the use and production of goods and services: Human health, Ecosystem health and Natural resources (Finnveden et al, 2009; Guinée et al, 2011). As a complement to environmental life cycle assessments, the concept of criticality has been introduced to assess accessibility to raw materials in relation to the AoP Natural Resources (Cimprich et al, 2019). Also, as stated in section 2.2.3, the genesis of the GeoPolRisk method is based on the integration of criticality considerations in LCA, making it recognized as a suggested midpoint indicator method by the Task Force on mineral resources of the Life Cycle Initiative hosted by UN Environment (UNEP) for quantifying "the relative potential accessibility issues to certain raw materials for a product system related to short-term geopolitical and socioeconomic aspects" (Berger et al, 2020; Frischknecht et al, 2019).

As part of the recommendations provided by UNEP, some opportunities for improvement were presented in relation to the GeoPolRisk method (Cimprich et al, 2019). The inclusion of recycling considerations as a supply risk mitigation strategy, and its subsequent effect on the GeoPolRisk indicator was already presented in Chapter 4:. In this methodological update, the domestic recycling of selected materials in the EU is analyzed to update supply risk values based on a reduced dependency from importers. The second addressed recommendation is related to extending the GeoPolRisk method from a midpoint characterization factor in LCSA to an endpoint characterization factor directly related to the AoP Natural Resources. In Chapter 5:, the GeoPolEndpoint method was also introduced, serving as a link between the supply risk of raw materials to a tangible socio-economic impact with the inclusion of price elasticity considerations to assess the effects of supply disruptions in commodity prices. In that section, an assessment from the perspective of the member countries of the OECD was conducted to obtain an estimation of the potential increased costs associated with the geopolitical supply risk of four materials in the inventory of lithium-ion batteries (LIB).

This chapter provides an integrated assessment of four key materials in the inventory of LIB based on the previously presented methodological enhancements (Chapter 4:, Chapter 5:). The GeoPolRisk method is used to address how recycling considerations mitigate the supply risk of aluminum, cobalt, copper and nickel in the European Union and how their supply risk translates into a potential economic damage related to the AoP Natural resources. These assessments at midpoint and endpoint level are presented as a complement to commonly used environmental LCA impact categories.

Similarly to Chapter 5:, this section is based on an already published LCA inventory of two types of LIB currently in the market by Peters and Weil (2016). The following section explores the feasibility of the application of the method to aluminum, cobalt copper and nickel – key materials in LIB – from the perspective of the European Union; along with the LCA methods used to assess environmental impacts

6.3. Methodology for the Integrated Assessment

In the domain of raw materials criticality and, as explored in section 2.2.3, the Geopolitical Supply Risk method was developed to calculate the supply risk of a material from the point of view of a country, region or group of countries and serves as a complement to environmental LCA. Figure 6.1 presents a LCIA framework for the integrated assessment at midpoint and endpoint level to address environmental and geopolitically-driven resource impacts.

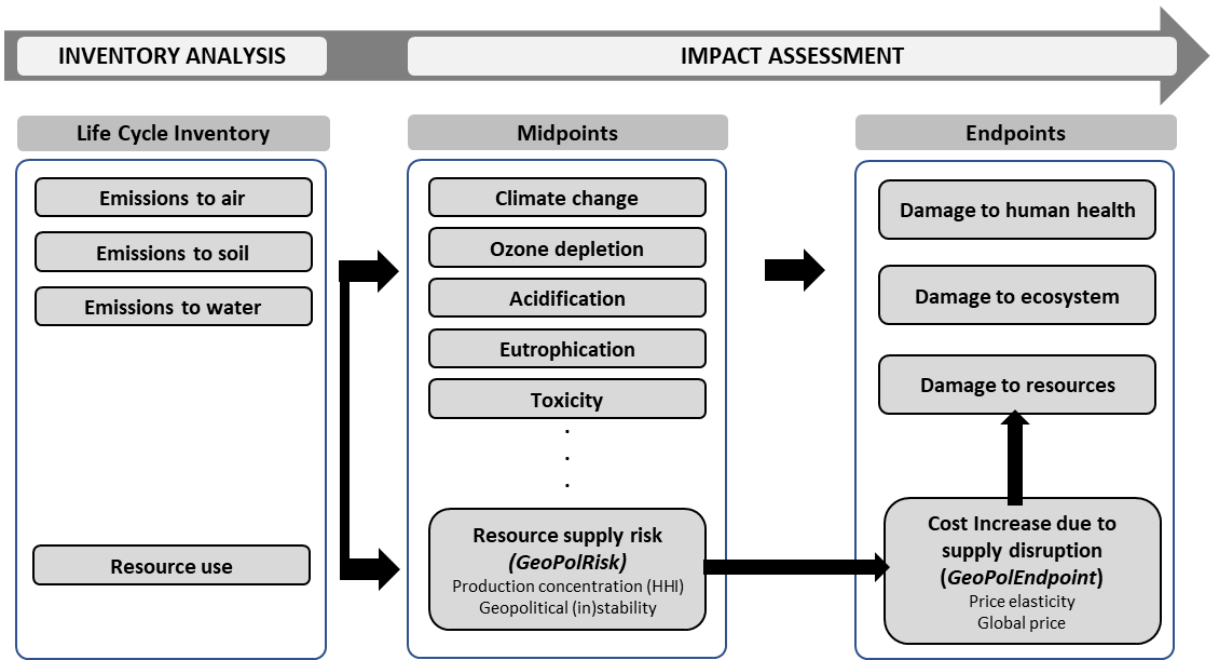


Figure 6.1 – LCIA framework for an integrated assessment based on the GeoPolRisk method

In Chapter 4:, recycling considerations are introduced as a risk mitigation strategy by modeling a requirement reduction of materials and the potential redistribution of import shares due to this reduction. Available data allowed to calculate the updated GeoPolRisk indicators for materials from the EU perspective, given that Eurostat provided values for the EoL-RIR that compile recycling information at regional level.

In Chapter 5:, the GeoPolEndpoint method was introduced to connect the supply risk of a material with the potential economic damage associated to the AoP Natural Resources in LCSA. As part of the newly introduced definitions, the term “Cost Increase Factor” is presented as the product of the supply risk (GeoPolRisk) and the inverse price elasticity; this non dimensional result is further multiplied by the average price to also obtain the GeoPolEndpoint (measured in monetary units per unit of mass). According to the discussion, the application of this formula is suggested only from the perspective of country groups with relative high influence in the global economy given that the prices of the analyzed materials are defined by the global market.

For a defined resource and year, results can be interpreted as average increased costs caused by geopolitically-driven supply disruptions. Therefore, the values are a proxy for a potential economic loss for the country/region that uses the material. By integrating these factors with the inventory information of a product, it becomes possible to measure the damage caused by the use of multiple resources in a product system.

With the two methodological limitations previously mentioned, the integrated assessment is applied to four materials in LIB: aluminum, cobalt, copper and nickel. This is taken from the perspective of the European Union for the years 2015, 2016 and 2017. The selected period is based on the available information required for the application of the enhancement proposed in Chapter 4:, finding EoL-RIR values applicable to the EU only available for 2016; moreover, the life cycle inventory data is referred to a similar period.

Two types of LIB are analyzed to obtain results at the product level: NCA-C and NMC-C (as previously introduced in section 5.3), following the inventories obtained from Peters and Weil (2016). For the GeoPolRisk and GeoPolEndpoint application, the United States Geological Survey is used as the main data source for the world-wide production in mining or refining activities (USGS, 2016, 2017, 2018). The trade data necessary to estimate the supply mixes was sourced from the United Nations International Trade Statistics Database – UN COMTRADE (United Nations, 2020). The WGI-PV is provided by the World Bank (World Bank, 2019), and rescaled from 0 to 1 (0 representing an absence of geopolitical risk) to be used in the calculations. Price information was obtained from the London Metal Exchange (LME) (Thomson Reuters, 2019) and price elasticity values are from Chapter 5:.

The environmental life cycle impacts were assessed at midpoint and endpoint level for selected impact categories. For midpoint level assessment, the CML 2001 method (Guinée et al., 2002) was used to evaluate the relative contribution of each resource to the following impact categories: acidification potential, global warming potential, depletion of abiotic resources (elements, ultimate reserves), ecotoxicity (freshwater, marine and terrestrial), eutrophication, human toxicity, ozone layer depletion and photochemical oxidation. The reasons to apply this method are the inclusion of characterization factors designed specifically for the European Union and the inclusion of the abiotic depletion potential impact category, which has been explored earlier in this thesis as one of the most common indicators to assess resource availability at midpoint level.

Similar midpoint category indicators were considered in an earlier electric vehicle case studied by Hawkins et al. (2013), and followed by Gemechu et al. (2016). This last one was the first approach towards an integrated assessment based on the GeoPolRisk indicator. Specifically, abiotic depletion evaluates the accessibility potential based on the concept of reduction in natural stock as a result of current extraction rate (Guinée and Heijungs, 1995; van Oers and Guinée, 2016) and answers questions of raw materials availability. The acidification potential refers to the increase in proton (H+) due the anthropogenic emissions of acid-base substances such as sulfur oxides, nitrogen oxides and ammonia. Eutrophication is the occurrence of excess nutrients such as nitrogen and phosphorus in aquatic or terrestrial ecosystems (Smith et al., 1999); phosphorus equivalents (PO4-3 eq.) is used to measure the

eutrophication potential in freshwater (Helmes et al., 2012). Human toxicity measures the health impacts due to exposure to chemicals released in the life cycle of a product system.

The endpoint impact assessment for this application is based on the ReCiPe method (Huijbregts et al., 2016) with a hierarchist perspective in order to include a measure of the impacts associated to the three Areas of protection previously discussed in this manuscript; this method includes the damage to resource availability measured in monetary units, similarly to the design of the GeoPoEndpoint method presented earlier in this manuscript. The environmental life cycle assessment modeling was performed using the openLCA 1.10.2 platform (GreenDelta, 2020). The Ecoinvent 3.4 database was used as a data source for the background system (Wernet et al., 2016).

The integrated assessment is based on the LIB inventories provided by Peters and Weil (2016). The study focuses on the contribution of four key materials (aluminum, cobalt, copper and nickel) to two types of batteries: those with cells with nickel-cobalt-aluminum (NCA-C) and those with nickel-manganese-cobalt (NMC-C) cathode active material, both with graphite anode material. The supply risk assessment requires a focus on a specific year and a group of countries; this study is conducted for three analyzed years: 2015, 2016 and 2017. The selected perspective is that of the European Union, in accordance with the available data for EoL-RIR obtained from Eurostat, and following the recommendation first mentioned in Chapter 5: to select a country group with significant influence and participation in the global market. Presented results will be associated to the functional unit of a tonne (1000 kg) of produced LIB.

6.4. Results of the Integrated Assessment

This section describes the values obtained for the relevant impact categories with the aim to assess the contribution of each analyzed material to the overall impacts from the environmental and the geopolitical perspective. Table 6.1 presents the GeoPolRisk values for the four analyzed materials from the perspective of the European Union between 2015 and 2017. Since these sets of results are based on the methodological enhancement that was first introduced in Chapter 4:, two values for the geopolitical supply risk from the perspective of the EU can be obtained for each combination of resource and year (BCS and WCS, given an EoL-RIR value higher than 0%). For purposes of this application, the calculations that will be further presented in this chapter will consider the simple mean of these two values; this simplification is made under the assumption that domestic recycling in the EU mitigates the supply risk by reducing the resource requirements and affecting the supply mix of the analyzed resources. A full set of the obtained values can be found in Annex I.

Table 6.1 – GeoPolRisk results for the selected materials from 2015 to 2017 (EU Perspective)

Material	***GeoPolRisk 2015***	***GeoPolRisk 2016***	***GeoPolRisk 2017***
Aluminum (Al)	0.082	0.085	0.084
Cobalt (Co)	0.108	0.132	0.168
Copper (Cu)	0.018	0.025	0.023
Nickel (Ni)	0.028	0.024	0.022

As part of the geopolitical supply risk impact pathway, at the midpoint level, copper and nickel can be considered as low-risk materials due to their relative high availability and low global production concentration, with GeoPolRisk values ranging from 0.018 to 0.025 and 0.022 to 0.028 respectively. The values for aluminum (Bauxite) vary from 0.082 in 2015 to 0.084 in 2017, with relatively no change in the analyzed period, these are mainly attributed to the supply shares for China, Russia and the Middle East. Among the studied materials, cobalt is the one with the highest GeoPolRisk values (0.108 in 2015 and 0.168 in 2017), this numbers are explained by an increasing participation of countries deemed as high-risk regions in geopolitical terms, with DR Congo being the highest contributor.

At the endpoint level, it is possible to obtain a relative economic damage in monetary units based on the GeoPolRisk indicator, prices of the materials and price elasticities associated with them; these values can be found in Chapter 5. As per Table 6.2, Aluminum and copper share relative low values, with an endpoint economic damage at material level of 6.01 to 7.29 USD and 20.59 to 29.70 USD per tonne of used material respectively. Nickel has a slightly higher value that ranges between 83.04 to 120.50 USD/t, while cobalt becomes the biggest contributor to damage with values that reach approximately 7600 USD/t in 2017. Considering the mass contribution of the four materials to the inventory of LIB, the overall damage at the endpoint level represents 2.58%, 3.08% and 5.44% of the base material costs for the case of NCA-C LIB from 2016 to 2018, while the values for NMC-C LIB in the same period are 4.63%, 5.71% and 9.04%.

Table 6.2 – GeoPolEndpoint (Damage Values) for Al, Co, Cu and Ni and their contribution in the inventory of LIB for the EU

	EndPoint Economic Damage (Material)			Endpoint Economic Damage (Product)					
	USD/t			USD/t Li-ion Battery (NCA-C)			USD/t Li-ion Battery (NMC-C)		
	2015	**2016**	**2017**	**2015**	**2016**	**2017**	**2015**	**2016**	**2017**
Aluminum	6.01	6.01	7.29	0.75	0.75	0.91	0.42	0.42	0.51
Cobalt	2502.23	2741.63	7597.36	108.35	118.71	328.97	271.24	297.19	823.55
Copper	20.59	26.02	29.70	4.96	6.27	7.16	6.78	8.56	9.77
Nickel	120.50	83.64	83.04	27.75	19.26	19.12	13.01	9.03	8.97
	Total Damage (USD/t LIB)			**141.81**	**145.00**	**356.16**	**291.45**	**315.21**	**842.80**

The previously presented values represent economic damages associated to a geopolitically-driven impact pathway, and from a LCA perspective, related to a tonne of produced LIB. Figure 6.2 shows the relative contribution of aluminum, cobalt, copper and nickel to the inventory of LIB, the geopolitical supply risk at midpoint level and the economic damage at endpoint level following the GeoPolEndpoint method.

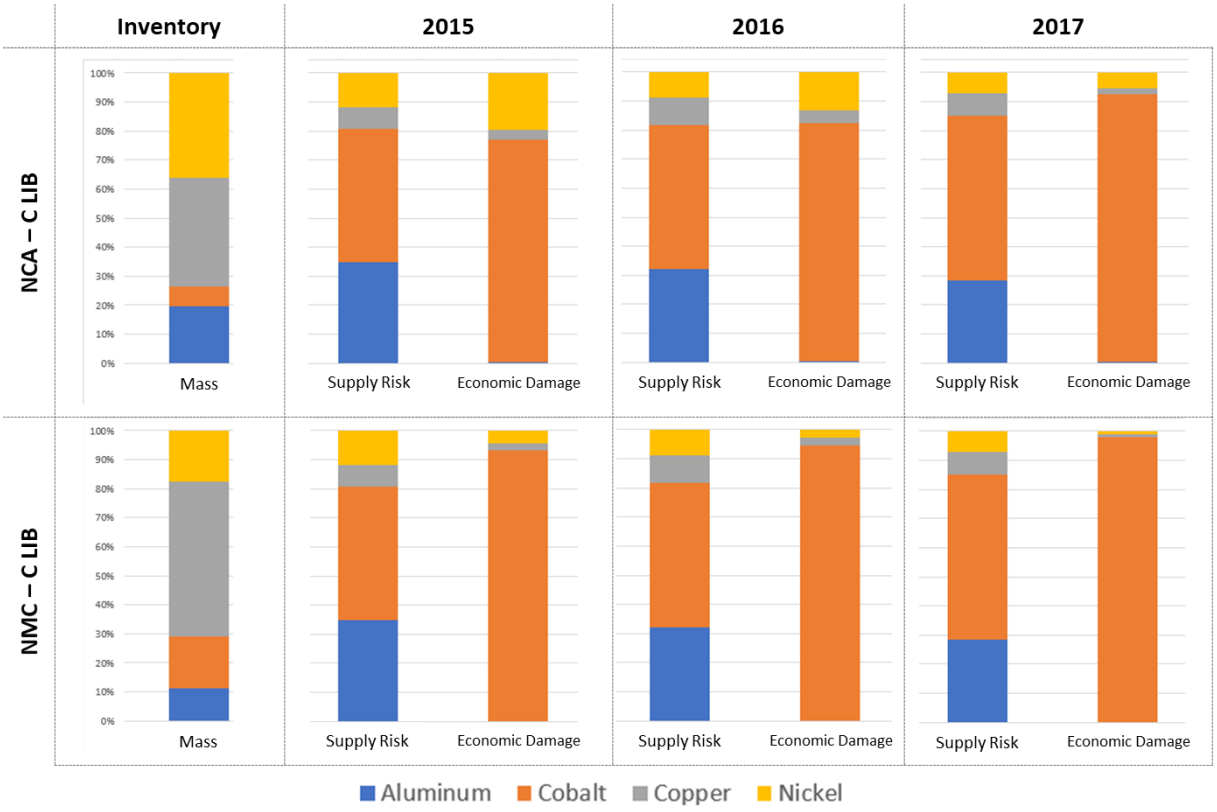


Figure 6.2 – Contribution of Al, Co, Cu and Ni to the inventory, the supply risk and the economic damage to the AoP resources of LIB from the EU perspective

Similarly to the case study in Chapter 5:, the relative contribution to the supply risk of aluminum, cobalt, copper and nickel can be considered stable over the analyzed period. However, cobalt stands out as having the highest supply risk among the analyzed materials, a reflection of its supply chain, which includes countries with perceived high geopolitical risk at the early stages (Congo and China). The transition to an endpoint level only increases the role of cobalt in the economic damages associated to resource use. Nickel appears also with a smaller share attributable to a high contribution in mass and relatively-high geopolitical supply risk. For the case of NMC-LIB, the effect of the use of cobalt displaces the contribution of other materials, making them negligible in comparison. A question remains on how these compare to other environmental impacts at midpoint and endpoint level, as described in section 6.3.

As mentioned in section 6.3, the integrated assessment at midpoint level was conducted with the CML 2001 method (Guinée et al., 2002). The overall results at this level are available in Figure 6.3, these include the contribution of the four analyzed materials to the inventory of two LIB (mass contribution; NCA-C and NMC-C), along with those corresponding to the impact categories included in the method; for comparison, these results are presented next to the supply risk, assessed with the GeoPolRisk method for the years 2015 to 2017. More details on the results are available in Annex K for further reference.

From the results in Figure 6.3, it is possible to divide the midpoint impact categories into two groups. The first group is composed by acidification and photochemical oxidation indicators, and the contribution of nickel to these impacts is higher than other resources, regardless of the mass share of this material in the inventory of LIB in both types: (a) NCA-C and (b) NMC-C; this is explained by the sulfur dioxide and nitrogen oxides emissions associated with nickel production. A second group is formed by the rest of the impact categories in the CML 2001 method; in these, the contribution to the impacts is mostly divided between copper and nickel and depends on the mass share, given the different composition between NCA-C and NMC-C LIB. The last three impact categories show similarly relevant contributions from the four materials: global warming potential, abiotic depletion potential and ozone depletion potential.

Specifically for the comparison between abiotic depletion potential and the supply risk, cobalt and aluminum gain higher visibility when using the GeoPolRisk method. This is a reflection of the supply constraints in the cobalt supply chain and the increasing participation of China and Russia in the supply mix of aluminum to the European Union during the analyzed period. Thus, the GeoPolRisk method provides another layer of assessment by highlighting barriers to the accessibility of materials rather than their overall geological availability.

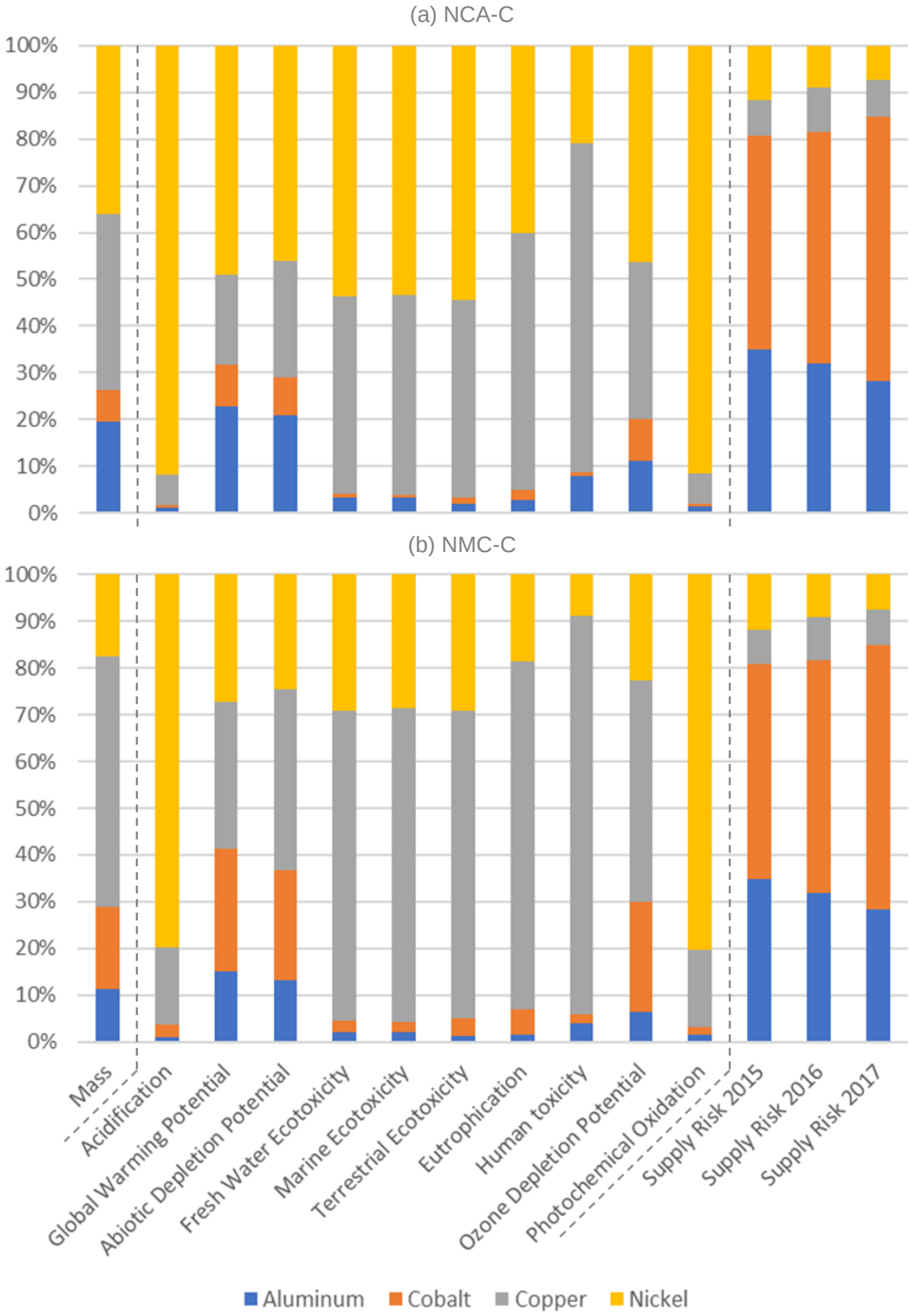


Figure 6.3 – Contribution of Al, Co, Cu and Ni to the environmental impacts at midpoint level in the integrated assessment of two types of LIB

Overall results at endpoint level can be seen in Figure 6.4; these were obtained with the ReCiPe endpoint assessment method. The graphic shows the contribution of the four analyzed materials to the inventory, the damages to the three AoPs and the socio-economic damage, this last one obtained with

the GeoPolEndpoint method for the years 2015, 2016 and 2017. Further details on these results are available in Annex L.

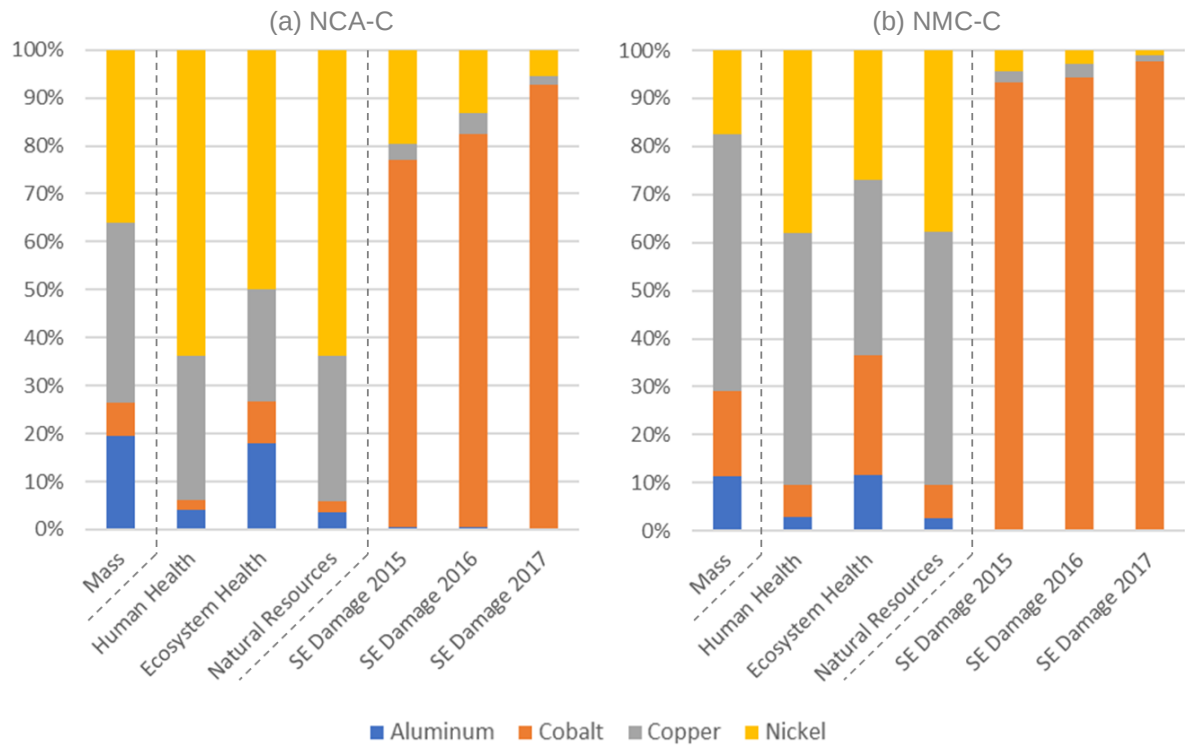


Figure 6.4 – Contribution of Al, Co, Cu and Ni to the damages at endpoint level in the integrated assessment of two types of LIB

At the endpoint level assessment, overall damages to the areas of protection human health and natural resources mostly depend on the contribution of the materials analyzed, with prevalence of copper and nickel in this specific case. Aluminum and cobalt only become relevant when assessing the damages to the AoP ecosystem health; however, a predominance of damages by copper and nickel is still visible.

A wide gap is visible between the contributions of the four materials to the damages to natural resources measured with the ReCiPe endpoint method and the contributions analyzed with the GeoPolEndpoint method. The predominance of cobalt from a geopolitical supply risk perspective is not yet captured, therefore the use of the GeoPolEndpoint offers a new perspective on how to measure the damages to the AoP natural resources.

6.5. Discussion on the integration of GeoPolRisk and GeoPolEndpoint to environmental assessments

With the presented case study, an integrated assessment based on the geopolitical supply risk method as a complement to environmental LCA was conducted. Four key materials in the inventory of LIB were the focus of the application and allowed to understand their contribution to the impacts at midpoint and endpoint level in life cycle assessment. The assessment was made for the years 2015, 2016 and 2017 from the perspective of the European Union.

The presented application demonstrates the potential use of the GeoPolRisk method (midpoint) and the GeoPolEndpoint method (endpoint) as a complement to traditional environmental life cycle assessment and following the methodological path proposed by the integration of criticality considerations into the life cycle sustainability assessment framework. As previously presented in Figure 6.1, this methodological pathway is oriented towards the assessment of damages to the area of protection natural resources, positioning its results as a part of the environmental impacts in LCA.

Multiple advantages of using the methods associated with geopolitical supply risk become evident when applying these along other more commonly used life cycle impact assessment methods. First of all, it is possible to identify once again the flexibility of the method, making it possible to tailor the results to selected years the analyzed country (in this case, region), through the consideration of its supply mix and recycling capabilities. This goes along with the idea that risk is a perception that depends on situations specific to each country, region or company that faces the risk.

Following the concept of perceived risk, the introduced methods focus on raw material accessibility as a driver of impacts in the AoP natural resources, associating an economic damage to the use of critical raw materials. This approach is different than the one followed traditionally in LCA to assess resource use damage; in this case, a comparison at midpoint level was made with the abiotic depletion potential impact category. As previously explored, the method allows to add a new layer for the assessment of impacts at midpoint level, shifting the focus from materials that are overall scarce around the globe to materials that are critical for specific economies.

At the endpoint level, a similar phenomenon occurs: the comparison is made between the results provided by the ReCiPe endpoint method and the GeoPolEndpoint method. At this stage in the impact assessment, the concept of raw material accessibility translates into a socio-economic damage measured in monetary units through geopolitical supply risk; when, typically, damages to the AoP resources under the ReCiPe method are measured as costs of future obtention of materials. Again, the introduced methodological pathway adds another layer that can support relevant stakeholders in their decision-making processes regarding the use of critical raw materials in specific technologies.

As discussed in this manuscript and mentioned in previous publications associated with the GeoPolRisk method (Cimprich et al., 2017a; Cimprich et al., 2019b; Gemechu et al., 2015; Gemechu et al., 2016; Helbig et al., 2016), the method at midpoint level did not consider the mass of the resource in the life cycle inventory as input in the calculations. This aspect is taken into account as part of the GeoPolEndpoint method providing insights on potential economic damage due to resource use.

With the presented application it is also clear that there is a methodological background that allows to further assess materials and products considering limited resource accessibility as a source of impacts. However, the methodological enhancement is not free from limitations. A first main concern is data availability, specifically when trying to understand how materials move around economies; trade databases are not always reliable or complete, preventing a 100% accuracy of the method.

Most open and available data sources focus on the mining and refining stages, the further a material moves through its life cycle, the more challenging it is to track. This is also evident when addressing recycling considerations as a supply risk-mitigating factor, as previously discussed in Chapter 4:. More work is required to identify other sources of impact associated to the accessibility to materials at further stages in their supply chain.

Specifically focusing on the GeoPolEndpoint method, its application is only valid when assessing countries or regions with a significant influence in the global economy; this limitation comes from the fact that the economic impacts are measured based on commodity prices, which are typically handled in international markets. Aditionally, the requirement of data associated with price elasticity restricts the amount of materials that can be assessed (for more information, please refer to Chapter 5:).

The flexibility of the methods comes with another challenge: constant updates. In order for the method to support further applications, it becomes necessary to construct, revise and update the information associated to global production, global trade and political (in)stability ate least on a yearly basis. As also discussed in Chapter 4:, future users could benefit from a computational tool that reduces the amount of work necessary to obtain indicators of geopolitical supply risk from multiple perspectives.

Overall, with this case study, the methodological pathway proposed by Sonnemann et al. (2015) has been demonstrated applicable with its limitations as a part of LCA and as a complement to traditional environmental assessments under the LCSA framework. The indicators associated with the geopolitical supply risk method measure a concept until now overlooked by traditional life cycle assessment: resource accessibility. Therefore, the enhanced method has the potential to support future decision-making processes when addressing potential damages associated to the AoP natural resources.

The GeoPolRisk method provides new insights that complement other methods addressing recource use in LCA; especially due to its versatility when providing information that depends on specific locations or time periods. The exploration of computational environments to facilitate the calculations and data processing is encouraged to make its application easier and more feasible for LCA practitioners.

As part of other proposed applications, and specifically focusing on the healthcare sector, the next chapter presents a case study designed to assess the supply risk of a resource with peculiar and exclusive chemical and physical properties: the case of helium. Emphasis will be made on how specific characteristics of the supply chain of this element are an opportunity to use the GeoPolRisk method as a tool to support decisions in the healthcare sector.

Chapter 7: The Supply Risk of Helium – A key Resource for the Healthcare Sector

The work presented in this chapter is partially based on a paper in preparation for publication:

A. Siddhantakar; J. Santillán-Saldivar; T. Kippes; A. Reller; G. Sonnemann; S.B. Young (to be submitted to Resources, Conservation and Recycling) The geopolitical supply risk of helium: A multinational perspective.

Contribution Statement:

A. Siddhantakar:	Conceptualization, Investigation, Data Curation, Writing – Original Draft
J. Santillán-Saldivar:	Conceptualization, Methodology, Formal Analysis, Investigation, Visualization, Writing – Review and Editing
T. Kippes:	Conceptualization, Formal Analysis, Investigation, Visualization, Writing – Review and Editing
A. Reller:	Validation, Writing – Review and Editing
G. Sonnemann:	Supervision, Writing – Review and Editing
S.B. Young:	Supervision, Writing – Review and Editing

The past three chapters have focused on enhancing and extending the GeoPolRisk method, developed to understand, analyze and measure the impacts of resource use as a complement to environmental LCA. Methodological advancements were suggested of importance for the development of integrated assessments that consider environmental impacts and criticality considerations to better inform relevant stakeholders.

The healthcare sector is no stranger to the concerns around resource accessibility for technological development. As previously mentioned in section 3.3.2, an opportunity to explore criticality considerations for helium has been identified; later in this chapter, the chemical and physical characteristics of helium are presented along the peculiarity of its supply chain. This chapter focuses on measuring and understanding the supply risk of helium from the perspective of different countries, with the objective to compare the perceived supply risk of this valuable and unusual resource for the healthcare sector.

7.1. Helium: An unusual resource

Advancements in scientific and industrial innovation during the decades leading to the XXI century have extended the range of elements in the periodic table that are studied and used to design complex materials and technologies. This growth has led to the search for new sources and the extension of extraction activities to obtain a fuller list of useful non-renewable natural resources (Chen and Graedel, 2012).

The healthcare sector provides urgent, important and technology-intensive services; it uses a wide range of elements for multiple purposes that range from the production of pharmaceuticals to the construction and maintenance of complex equipment. Among the elements relevant to the healthcare sector, helium (He) is unique for its chemical simplicity. Oddly, it is rare on earth despite being the second most abundant element in the universe (Bradshaw and Hamacher, 2013).

Helium is a consumable in healthcare facilities using magnetic resonance imaging (MRI) machines; its purpose is to cool the magnets in this equipment to extremely low temperatures due to having the lowest boiling point among all elements in the periodic table. However concerns have been raised regarding its availability for scientific, military and other uses (Hurd et al., 2012; National Research Council, 2010; Nuttall et al., 2012). Moreover, few efforts have been made to better understand, predict or improve the “use it or lose it” nature of helium supply (Hayes and McCullough, 2018).

Helium is formed from the decay of the radioactive uranium (U-238) and thorium (Th-234) in the Earth, from where helium permeates upwards through the Earth’s crust to the atmosphere, where it is subsequently lost to outer space (McKay, 1987). Some fraction of helium accumulates in the same geological formations that hold natural gas deposits, which typically contain a mixture of hydrocarbons and other gases such as nitrogen and carbon dioxide (National Research Council, 2010).

Only a very small fraction of the naturally formed helium accumulates in the Earth's crust, with an approximate ratio of accumulated over produced He equal to 10E-7 (Bradshaw and Hamacher, 2013). Helium in the atmosphere maintains an equilibrium concentration of approximately 5.2 ppm, which is assumed to have remained constant over geological time. A mass balance that estimates the amount of helium released into the atmosphere confirms that most of it has escaped to the space. This suggests a new dimension of raw material dissipation: the gas not only evades potential human use by escaping specific receiving environments in the Earth's crust, but crosses the boundaries of our planet with an estimated exit rate of 50 g per second or 1600 tonnes per year. The opportunities for future recycling once helium leaves the technosphere are practically null (Catling and Zahnle, 2009; Challoner, 2018). Due to this constraint, the production and consumption of helium is linear and results in a high rate and volume of direct loss.

Currently, the most common and efficient way to obtain helium is by separating it from natural gas. It becomes economically feasible to do this when a content of approximately 0.3% is available (Kryc, 2013; Ku and Hung, 2014; Rufford et al., 2014). As of 2020, approximately 75% of global helium supply is provided by two countries: the United States and Qatar (Kornbluth, 2015; Cockerill and Kornbluth, 2017). The US Bureau of Land Management (BLM) has played an essential role in the management of helium resources since the 1930s with its long-term artificial storage facility for crude helium, known as the US Federal Helium Reserve (Bingaman, 2017). Helium is mostly transported in its cryogenic state to increase the efficiency of this process; however this state is not naturally found on Earth. Compression processes early in the supply chain are always required (National Research Council, 2010).

The unique properties of helium give it a vital role in the development of technologies not only for the healthcare sector, but also in electronics, aerospace, military, physics research and communications applications. It may be used as a cryogenic liquid or gaseous state. As a cryogenic liquid, helium is predominantly used as a cooling agent for superconducting magnets in medical imaging (Weishaupt et al., 2006). In gas application, helium is used in welding, electronics manufacturing and leak detection.

Concerns have been raised by different sectors regarding the supply constraints associated with helium (Anderson, 2018; Bare et al., 2016; Glowacki et al., 2013; Liu, 1983; Nuttall et al., 2012; Olafsdottir and Sverdrup, 2020; Uri, 1987). Helium is considered critical for one or more energy-related technologies, been positioned among energy-critical elements as an irreplaceable and non-renewable resource to modern science and technology (Jaffe et al., 2011). The relevance of helium for the healthcare sector has also led to supply constraints among other industries who don't play such an urgent role in society (Robson, 2012; Murphy, 2019).

Given the importance of helium placed by the scientific community in modern science and industrial development (Bare et al., 2016), and the concentrated production in a small number of countries around the globe, this noble gas was identified as a critical raw material by the European Union in 2017 (European Commission, 2017), but removed from the same list in 2020 due to a decline in its economic importance (European Commission, 2020a). However, the USA remains to consider helium in their list of critical resources (USGS, 2018).

Helium has a geopolitically concentrated production; as a result, there is a need for understanding helium supply risk and its implications for relevant sectors such as healthcare, energy and research. A concerning situation during the Saudi-led embargo of Qatar in June of 2017 resulted in a short-term global supply shortage when approximately 25% of helium global supply was interrupted (Cockerill and Kornbluth, 2017). A not so different scenario is possible when the US Federal Helium Program closes in 2021, with possibilities of supply constraints (Fortier et al., 2018; Massol and Rifaat, 2016; National Research Council, 2010).

Advances in helium storage have resulted on minimum loses in early stages of the helium supply chain (Kashinath et al., 2013). However long-term storage at late stages is not common due to the characteristics of this element (Sears, 2015). This dynamic has parallels with the use-it-or-lose-it adage, meaning that a resource should be used by a particular date before it is no longer available (Cambridge University Press, 2011).

The use-it-or-lose-it dynamic is unique to helium and understanfing it is crucial to its sustainability: achieving efficient production, storage, and consumption of this non-renewable resource. Countries perceive the importance of helium supply based on their different industrial and technological needs; each country may identify this dependency on foreign sources as a strategic vulnerability for both its economy and military to adverse foreign government action, natural disasters, and other events that can disrupt supply (US Department of the Interior, 2018).

Helium is deemed critical due to its economic importance and given the likelihood and severity of potential raw material supply disruptions. As explored in section 2.2.2, the criticality aspects related to helium make it a clear example of impacts from the outside-in perspective: an impact mechanism in which external environmental or socio-economic conditions affect product systems, economic activities, corporations, among others (Porter & Kramer, 2006). Specifically, for the case of healthcare, healthcare systems are susceptible to the effects of limited accessibility to resources, and how these aspects are understudied in the medical sector.

The case of helium becomes of interest from a supply risk perspective due to its unusual supply chain; the GeoPolRisk method could provide the flexibility required for a country-specific supply risk assessment. Since previous applications of the geopolitical supply risk method have focused on metals and minerals; an opportunity appears to analyze this element as the first case in which the studied resource is traded in liquid and/or gaseous state and in its pure form as a noble gas. In the following section, the feasibility to apply the GeoPolRisk method to this case will be explored.

7.2. Applicability of the GeoPolRisk Method to the case of helium

In this section, the feasibility of applying the GeoPolRisk method to the case of helium is explored. From the literature on raw material criticality, a material is deemed critical when certain key economic sectors in a country or region are severely affected by its supply disruption and/or when the potential for the

occurrence of these supply disruptions is very high (Achzet and Helbig, 2013; Dewulf et al., 2016; Erdmann and Graedel, 2011; Graedel et al., 2012). For this study, the supply risk will be considered the defining criticality aspect for helium, since the raised concerns are referred to its supply chain rather than its economic importance (European Commission, 2020). The GeoPolRisk method is selected to assess raw material accessibility, taking into account how geopolitical aspects, such as geographical proximity, trade networks and political instability have a superior effect on supply risk than overall geological availability of resources (Sonnemann et al., 2015).

Previous applications of the GeoPolRisk method have focused on metals and minerals used for specific technologies (Cimprich et al., 2017, 2018), as also exemplified in chapters 4, 5 and 6; however as of 2021, this application will be the first one in which a resource typically traded in liquid or gaseous state is studied under this approach. The method is expected to provide significant values for the geopolitical supply risk of helium regardless given that the formula focuses on trade flows that can be measured in volume, mass and/or monetary units as long as the units and proportions remain the same over the calculations.

In order to get a comprehensive view on how different countries perceive the supply risks associated to helium, the application of the GeoPolRisk method is proposed from the perspective of ten nations: China, Japan, South Korea, Taiwan, Germany, France, the United Kingdom, Mexico, Canada, and Brazil. These countries are among the top net importers of helium, have a high level of industrial development and an advanced health care system that translates into a high density of MRI machines, one of the main indicators of high liquid helium use (OECD, 2019).

Helium transport is complex and expensive due efforts to maintain its liquid state and reduce loss rates. For this reason, importers are motivated to keep distances as short as possible; however the small number of producing countries means that transport often takes place over long distances and across regions; some examples are those countries geographically insulated such as Japan, which requires the design of long supply routes. In other cases, nations are located between producing countries such as those in the European Union (importing from Poland, Russia and Algeria) or are in direct proximity to producers, like the case of Canada, which imports from the USA.

As previously presented in Chapter 4:; the information required to apply the GeoPolRisk method are the global production, the trade flows between producing and importing countries, the political instability indicator of exporting countries and the end of life recycling rate. The global helium production is obtained from the US Geological Survey (USGS, 2016, 2017, 2018, 2019), the data used for this application is available in Annex M. The trade information for helium is extracted from the UN COMTRADE database (United Nations, 2020); the scaled WGI-PV indicator from the World Bank (World Bank, 2019) provides the political instability indicator (0: minimum risk; 1: maximum risk); and, a domestic recycling rate of 0% is assumed because it is practically impossible to recover helium from the technosphere.

An initial look at the available trade information in the UN COMTRADE database showed that multiple of the analyzed countries import helium from non-producing countries; this is explained by the existence

of countries that serve as intermediary ports between the suppliers and the consuming countries. This data limitation is overcome by allocating the flow from each intermediary port to the producing country with the biggest supply share of said redistribution location. Unlike other resources, this assumption is supported by the fact that helium is a noble gas and does not react with other elements, and is thus traded in its elementary form; therefore, no additional production processes are completed in the intermediary countries. In order to keep the consistency required for the method to be applied, flows are measured in monetary units under the assumption that price variations do not significantly impact the aggregated declared values. The full dataset used in this application is available in 2.Annex NAnnex N.

For further reference in this chapter, Figure 7.1 shows the scaled values of the WGI-PV indicator from 0 to 1 for the main exporting countries (Algeria, Australia, Poland, Qatar, Russia and the USA); these values are a reference for the contribution to the risk based on geopolitical considerations. The information was computed for the period of 2015 to 2018 with the objective to capture important developments surrounding the trade and use of helium for the analyzed countries.

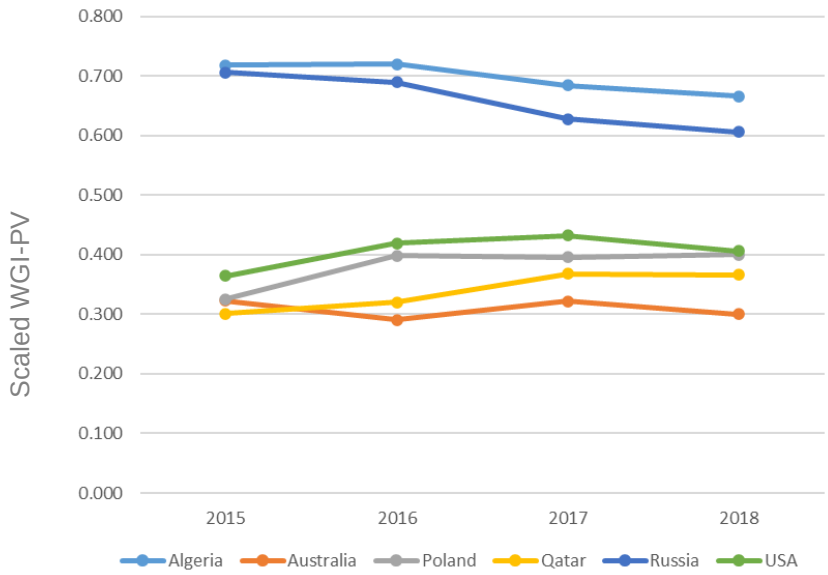


Figure 7.1 – Scaled WGI-PV index (from 0: absence of risk to 1: maximum risk) for the most important helium exporting countries.

7.3. Results for the geopolitical supply risk of helium

Figure 7.2 is a multi-part figure that contains the main findings for all the years under assessment (Part 1: 2015 and 2016, Part 2: 2017 and 2018). The visualization presented in Figure 7.2 is an amalgamation of two main components to represent the supply risk of each of the ten countries for the discussion. The first component is a Sankey diagram (SankeyMatic, 2020); in this, the width represents the quantity of helium traded from producing countries (on the left) to consuming countries (on the right). The width at the end of each flow represents the total amount of helium imported by the country measured in monetary units.

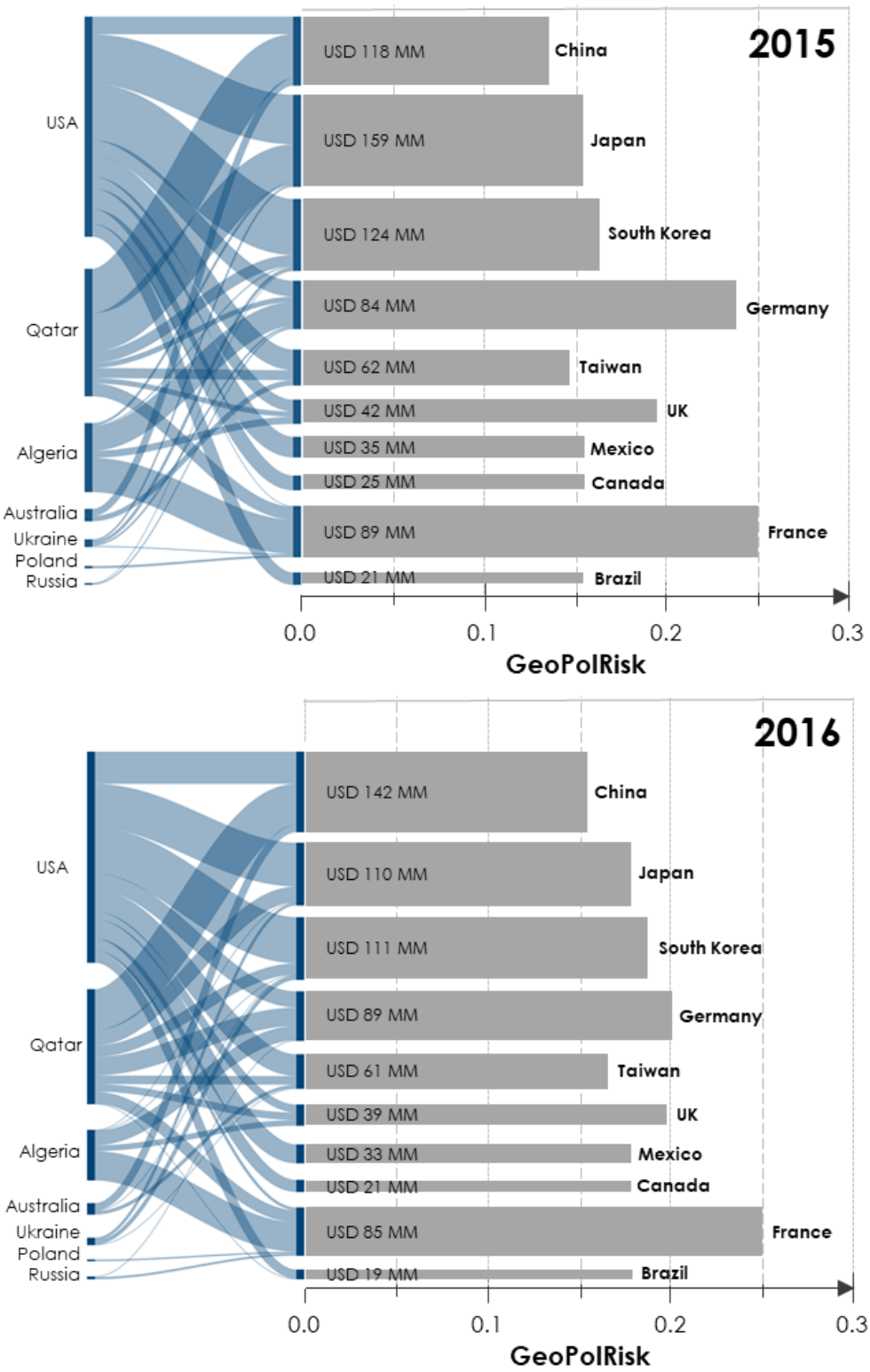


Figure 7.2 – Helium trade flows and helium GeoPolRisk for the analyzed countries (1)

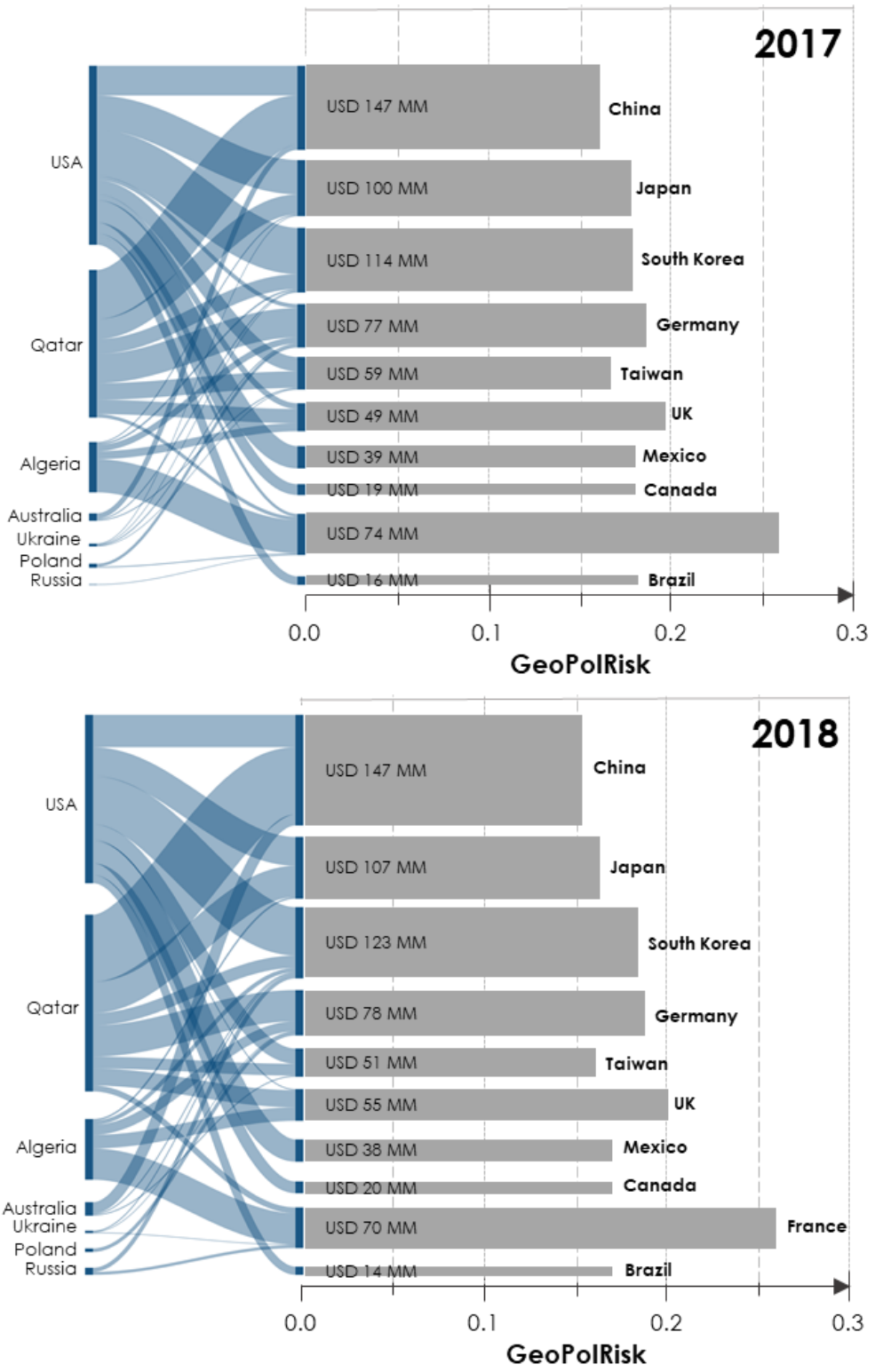


Figure 7.2 – Helium trade flows and helium GeoPolRisk for the analyzed countries (2)

The second component of each multipart figure is composed of horizontal bars coming off the end of each Sankey flow. The length of the horizontal bar represents the overall supply risk, measured from the vertical axis at the end of the Sankey flows for each importing country (this indicator ranges from 0 to 1); for this case, the horizontal axis has been cut off at 0.3 to match the calculated results for the

GeoPolRisk indicator. In this manner a proportional visual depiction of the supply mix of each importing consumer country along with a representation of the overall geopolitical supply risk of the importing country is achieved. The flows depicted in the Sankey diagram and the calculated GeoPolRisk values that correspond to these results are available in Annex O.

From Figure 7.2 it is possible to identify general trends about helium trade and helium supply risk from the perspective of the studied countries. An overall decrease in helium trade from 2015 to 2017 is observed by comparing the aggregate height of the Sankey flows across the years, however, this yearly decrease would give way to a more pointed increase from 2017 to 2018.

Qatar provides a stable increase in the flow of helium during the entire period under examination; therefore, the decrease of helium supply is attributed to a reduction in exports from the two other main producers: the USA, and Algeria. Smaller producers like Australia, Ukraine, Poland and Russia do not have a significant participation on the overall supply yet, but they may be crucial as some of these suppliers are geographically proximate to major user countries like Germany and Japan, this last one being the largest net importer in 2015, and China, which overtook Japan as the largest net importer for the years 2016-2018.

In terms of the supply mix of each importing country; in 2015 and 2016, France, which displays a consistently higher supply risk throughout as compared to other countries under consideration, relied on the imports from Algeria and Qatar, however, the overall quantities from Qatar are reduced significantly in 2017, whereas Algeria remains the leading supplier for the country throughout the study period.

Germany's overall helium imports from 2015 to 2016 fluctuate with a significant decrease in 2017 and a small increase in 2018, overall along a significant growth of the helium supply share from Qatar; this new trade level remains relatively stable in the subsequent years with a varied supply mix from all five main exporting countries. After experiencing a significant decrease in imports in 2016, Japanese imports remained relatively stable throughout the analyzed period, with Qatar and the USA as its main suppliers. Amongst all the countries considered, China has the lowest geopolitical supply risk despite relying on only two suppliers, this peculiar situation is further explored in the next section. Finally, according to the trade information, countries like Mexico, Brazil and Canada rely almost exclusively on imports from the USA; this means that the geopolitical supply risk of helium for these countries will depend mostly on the WGI-PV indicator for the USA, a country considered relatively stable for the analyzed period.

7.4. Discussion on the supply risk of helium

During the studied period, the countries with a larger traded value of helium were Qatar, the USA, Algeria, Australia and Russia. Although Qatar is not the main producer, it is a top exporter and is the primary supplier to most of the analyzed countries in the chapter. A decrease is visible in the overall helium trade flows from 2015 to 2017 with a slight increase in 2018; this last one attributable to the increasing demand in China.

Qatar is responsible for approximately 25% of the world's helium supply. In 2017, as noted above, it experienced a blockade by its neighbour countries that generated a realignment of the usual supply routes. Despite this situation, Qatar continued providing a stable flow of helium to each of the ten analyzed importing countries, but certain nations had to request more supply from other producers, for example the USA or Algeria. The countries who mostly relied in helium from Algeria had their overall supply risk indicator increased in the analyzed period, with the most notable case being France, which has an historical colonial link to this African country.

It is worth pointing out that these results are a direct reflection of using the WGI-PV indicator as a proxy of political (in)stability of the supplying countries. A limitation of this metric and the GeoPolRisk method becomes apparent. Qatar's overall low contribution to the supply risk is explained by a lower WGI-PV than the USA, indicator that arguably represents a relatively more stable political environment and less prevalence of violence within the country, despite the tense situations with neighbor nations in 2017.

Further analyzing the results, the ten countries under assessment can be clustered in three main importing groups. The first group is formed by the rapidly growing economies in Asia: China, Japan, South Korea and Taiwan; these countries rely mostly on the USA and Qatar to cover their needs. The second group of countries is in America (Brazil, Mexico and Canada) and are virtually fully dependant on the USA as a single supplier and represent the second cluster. A third group is formed by the United Kingdom, France and Germany, that each use a relatively diverse supply mix, and represent the main destination for helium from Algeria.

With the current supply mix, China shows the lowest supply risk because of its reliance on mostly Qatar and USA, the two countries with two of the lowest WGI-PV indicators; the third country that China primarily imports from is Australia, whose WGI-PV indicator is even better than Qatar's and reduces China's overall supply risk. A low supply risk in Japan is explained by the role of two companies: Taiyo Nippon and Iwatani which both have long term contracts for helium supply that is imported to Jthis nation from the USA and Qatar (Buzwair, 2013; Iwatani, 2013).

The reliance of Canada, Mexico and Brazil on the US for all of its helium supply keeps their supply risk lower than those of most analyzed countries which are reliant on Algeria and Qatar as well (United Kingdom, France and Germany). However, the indicator is slightly higher than China, South Korea and Japan, countries that benefit from Australian and Qatari supply. A question appears on how these results could vary in following periods with a potential change of the WGI-PV for the USA due to its political climate between 2018 and 2020.

Overall results of the analyzed snapshot show that for a resource such as helium, with limited number of suppliers and very much dependent on an efficient supply chain, risk management is a considerable challenge. Building networks to allow steady flows of this resource is key, as the case of Japan clearly demonstrates. Some successful strategies are those associated with the signing of long-term contracts with the most stable countries in the supply mix. As new producing countries such as Russia, Poland and the Ukraine start appearing in the mix, the overall picture might change; it is encouraged to continue this type of assessments to understand the evolution of the risk in the next years.

The use of the GeoPolRisk method allows to understand the perceived risk from the perspective of the analyzed importing countries; this further translates to potential risks for the sectors who use this element. Among them, the healthcare sector needs to rely on the adequate management of helium supply at national level and can have certain comfort on the fact that healthcare is considered a priority in most countries around the globe. However, other sectors not considered essential have already suffered from helium shortages as is the case of recreational use of helium and research (Robson, 2012; Murphy, 2019).

7.5. Discussion on the methodological outcomes of the assessment

In this chapter, the criticality of helium has been explored from the perspective of ten countries over a period of four years. Concerns around the supply of helium as a key resource to the healthcare sector remain in place with the understanding on how a complex and critical supply network can be affected and result on disruptions. As previously mentioned in section 2.2.3, the geopolitical supply risk method provides an estimation of the proportion of the required material at constant and imminent risk of supply disruption from different perspectives. In the specific case of helium, several factors become more visible when addressing such a peculiar supply network: A limited number of suppliers means that there is an increase of the Herfindahl-Hirschman Index (HHI) as an indicator for global production density; different supply mixes extend the breach of the perceived risk for three main clusters of countries; and, the effect of the WGI-PV indicator is more evident given the differences among the producing nations. The GeoPolRisk method tries to measure accessibility to materials rather than availability, highlighting how geopolitical aspects have a greater effect on supply risk than geological availability (Sonnemann et al., 2015).

One of the main contributions of this chapter is the expansion of the applicability of the GeoPolRisk method beyond metals and minerals. For this application, a raw material that is traded as a cryogenic liquid or as a gas is analyzed; also, the resource is extracted, transported and used in its most elementary form. These characteristics allow to further show the versatility of the GeoPolRisk method, allowing it to be applied to a wide range of resources and sectors.

A second contribution is the evaluation of the supply risk of a raw material that evades the general methodological definitions of dissipation, since it does not dissipate into any of the more traditionally discussed areas such as the environment, landfills or other material flows (Beylot et al., 2020; Charpentier-Poncelet et al., 2019); on the contrary, helium does not remain within the planet, from which some may think it could be retrieved and reused at a later time. This goes beyond the the possibility to obtain this resource from the tecnosphere, alternative discussed by multiple authors (Yellishetty et al., 2011; Klinglmair et al., 2014; Frischknecht, 2014; Schneider et al., 2011). These considerations make more evident the need for a sustainable and resilient supply chain.

A limitation of the use of the GeoPolRisk method for this study is that it relies on the WGI-PV scores, which are qualitative and cannot reflect a full picture of the risk level of trade partners. This is a common limitation for other methods designed to measure supply risk (Schrijvers et al., 2020). Specifically for this case study, the WGI-PV scores for Qatar reflect a relatively adequate level of political stability within the country; however, restrictions imposed by neighbouring countries were not captured by these measurement, therefore not being translated to the overall results.

Another drawback is the existence of intermediaries in the supply network between helium producers and helium consumers. As mentioned earlier in this chapter, the impacts of this limitation are mitigated by allocating flows from intermediaries to the original producers. This assumption is supported by the fact that helium is not chemically transformed along the supply chain, no extra processes are required, remaining a pure element until its use.

As exemplified with the case of Japan, global helium trade is organised between a relatively small group of private companies, which enter into joint ventures with state-owned enterprises in some countries (Buzwair, 2013; Iwatani, 2013). From a national perspective, one of the main drivers of supply risk in a market with a reduced number of suppliers is the management of the supply mix. A balance is achieved when the risk is diversified among various trade partners which are classified as politically stable countries. Is in this plane that questions on public health come into play, transforming the case of helium in a priority for multiple nations.

Sustainable management of helium supply becomes even more important due to the nature of this element. Unlike other resources, helium dissipates completely evading future recovery from the anthroposphere and escaping Earth's gravitational pull. There are several fronts to consider when managing helium supply; in preparation for the future, efforts by the sector should be directed to reduce helium losses along the supply chain, study ways to reuse helium in their main and most important applications, and guarantee a stable and low-risk supply mix.

As discussed thoroughly in Chapter 6:, supply risk is only one layer of many concerns surrounding sustainability, representing one of various environmental impacts in LCA. An assessment oriented to understand impacts of the use of resources benefits from the analysis of other midpoint indicators. In order to provide better information and tools for decision-makers in the field of healthcare sustainability, the next chapter focuses on an integrated assessment based on the results from this section and the application of the LCA methodology to the case of MRI scans from the perspective of different countries.

Chapter 8: Integrated Life Cycle Assessment: Environmental Impacts and Criticality of Helium in Medical Imaging

The work presented in this chapter is partially based on a paper in preparation for publication:

J. Santillán-Saldivar; A. Siddhantakar; T. Kippes; A. Reller; G. Sonnemann; S.B. Young (to be submitted to the Journal of Cleaner Production) Integrated life cycle assessment of MRI scans including supply risk considerations of helium use.

Contribution Statement:

J. Santillán-Saldivar:	Conceptualization, Methodology, Formal Analysis, Investigation, Data Curation, Visualization, Writing – Original Draft
A. Siddhantakar:	Formal Analysis, Investigation, Data Curation, Writing – Review and Editing
T. Kippes:	Formal Analysis, Investigation, Data Curation, Writing – Review and Editing
A. Reller:	Validation, Writing – Review and Editing
G. Sonnemann:	Resources, Supervision, Writing – Review and Editing
S.B. Young:	Supervision, Writing – Review and Editing

Chapter 7: presented the first application of the geopolitical supply risk method to helium, an element considered of importance for the healthcare sector. Additionally, the case study allowed to analyze for the first time the geopolitical supply risks associated to an element typically transported and used in liquid or gaseous state. As previously discussed, the GeoPolRisk method is designed as a complement to environmental life cycle assessments based on concerns about resource accessibility. It was demonstrated in Chapter 6: that the method and its associated enhancements provide a new layer of analysis worth considering by LCA practitioners provided relevant information is current and available.

With the objective to evaluate the overall readiness and applicability of LCA with the proposed inclusion of criticality considerations as a way to assess outside-in impacts with the GeoPolRisk method, this section presents the application of the life cycle assessment methodology to evaluate magnetic resonance imaging (MRI) scans at the midpoint level in an integrated way. This is done from the perspective of four countries (Canada, Germany, France and Japan) for the year 2018. The main focus in the assessment is on helium as one of the key elements required for this technology.

8.1. The life cycle of MRI scans: Goal and Scope

In section 3.3.2, the first approach to understanding the relevant considerations from a life cycle perspective surrounding the use of helium for medical imaging was presented. The LCA-based framework designed to support healthcare sustainability from Chapter 3: was used and one highlight of this exercise was identifying medical imaging as a key transversal activity to support the delivery of care. Among the multiple options available to produce medical images, magnetic resonance imaging (MRI) is arguably one of the most expensive and resource intensive given the use of superconducting magnets that require specific infrastructure and energy demands (Sarracanie et al., 2015; Young, 2015).

MRI allows healthcare practitioners to visualize specific anatomical structures non-invasively and without exposing patients to ionising radiation; MRI techniques produce high resolution images of the soft tissues in the body in several layers, allowing to identify anomalies, typically tumors, herniations, hemorrhages, among others. MRI machines use powerful magnets to create a magnetic field that aligns the molecules of water in the body, radio waves disturb the polarity of these molecules and a sensor identifies the time that it takes these to reposition. Essentially, the water content and the characteristics of the fluids in the body are identified, allowing to visualize any abnormalities. In some cases, contrast agents may be injected to enhance certain soft tissues (Westbrook and Talbot, 2018).

Helium is used in its liquid form as a cooling agent for the superconducting magnets used in MRI machines to maintain the temperature below -296°C and guarantee the levels of conductivity required for ideal performance. Currently, there is no alternative to helium to keep current and most common MRI machines functioning. More recent MRI equipment is designed to not consume helium and guarantee continuous operation with minimum to zero losses; this new technology is expected to be more widely used in the medium term future (Cosmus and Parizh, 2010; Notardonato et al., 2017; Laine et al., 2019).

As previously explored in Chapter 7:, concerns have been discussed about limited global helium availability (Hurd et al., 2012; National Research Council, 2010; Nuttall et al., 2012) and its accessibility in the global market due to supply constraints and specific logistics considerations (Bare et al., 2016; Glowacki et al., 2013; Olafsdottir and Sverdrup, 2020). Helium production is concentrated in few countries, making its supply chain an interesting case study from a geopolitical and an environmental sustainability perspective.

Following the work presented in the previous chapter, the application of the life cycle assessment methodology to the case of MRI scans aims to understand what are the main environmental impacts associated with the production of a medical image; special focus is given to the contributions of the helium supply chain and energy use. Specifically, potential correlations between overall impacts, energy mixes and the supply mixes of consuming countries are studied to identify hotspots along the life cycle.

The selected functional unit is one MRI scan (digitally produced in the year 2018); the assessment is conducted from the perspective of four countries that have the most MRI machines per capita yet they do not produce helium: Canada, Germany, France and Japan (OECD, 2017). For purposes of practicality, it will be assumed that scans are performed in Toronto (CA), Berlin (DE), Paris (FR) and Tokyo (JP), abbreviated by their two-letter country code. The year under assessment is 2018 considering that, at the time of the development of the study, it was the latest period for which helium production and trade information were available. Figure 8.1 shows the main inputs and outputs of the analyzed process (For further details, please refer to Annex W).

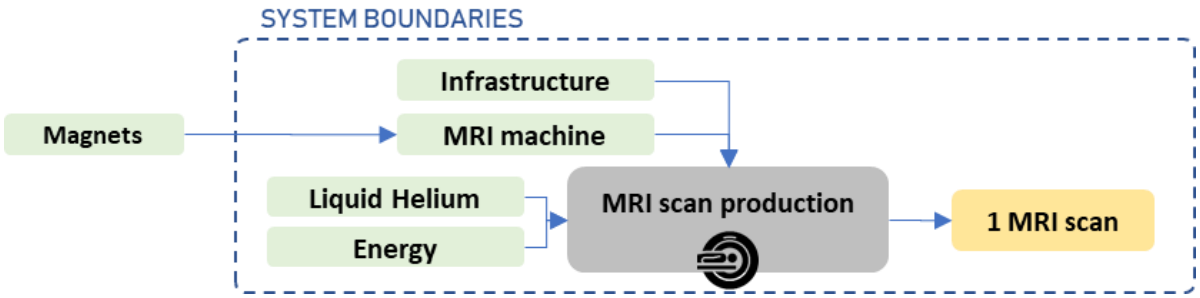


Figure 8.1 – Block diagram for MRI scan production. System Boundaries

As previously mentioned, the assessment will focus on helium as a main constraint in the supply chain. The amount of liquid helium required to provide cold for the production of one MRI scan will serve as the reference flow; this value varies according to the use scenario. As shown in Figure 8.2, the study will include three main life cycle stages associated with the helium supply chain: international helium supply, local helium distribution and helium use in MRI machines. The international helium supply considers the production of helium, local transport to port of export and international transport to the country of destination. The local distribution includes transport from the port of import to a helium transfill center, the transfill process and local transport to hospitals. Finally, the use phase considers helium consumption, energy consumption, infrastructure and MRI electronic equipment (excluding the production of magnets) (Figure 8.1).

Three scenarios of helium use and two scenarios of energy consumption are considered in order to cover a range of available levels of technology in MRI machines. The study does not include the production of natural gas that traditionally accompanies helium production. An end-of-life stage in the life cycle is not considered nor the production, transport and maintenance of magnets in the MRI machine. Supporting equipment to manage, deliver or print MRI scans is not accounted for as the study considers a system boundary after the image is digitally available in the MRI machine.

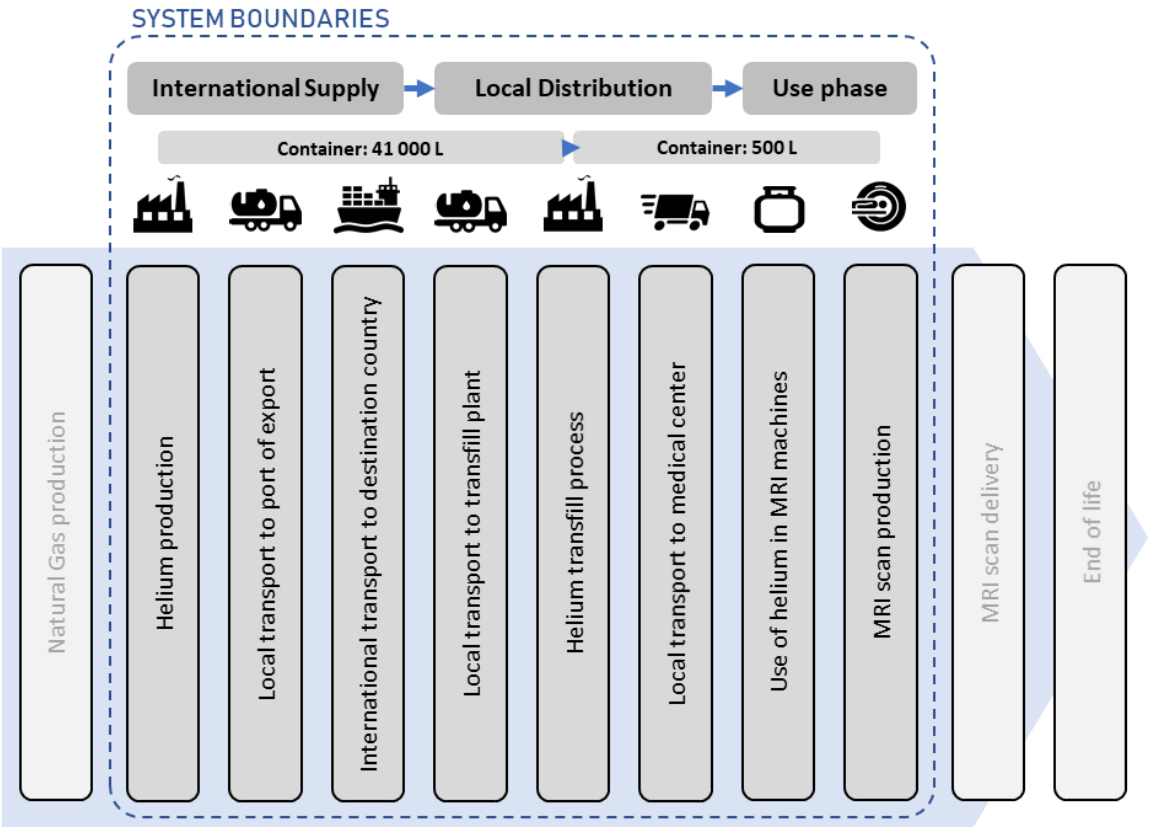


Figure 8.2 – Stages in the helium to MRI scan life cycle. System boundaries for the study

Background information was obtained from the Ecoinvent 3.4 database (Wernet et al., 2016) and the environmental life cycle assessment modeling was performed using the openLCA 1.10.2 platform (GreenDelta, 2020).The following section will present the information required to construct the life cycle inventory, as well as the impact categories used for the assessment.

8.2. Understanding the life cycle of MRI scans: Life Cycle Inventory

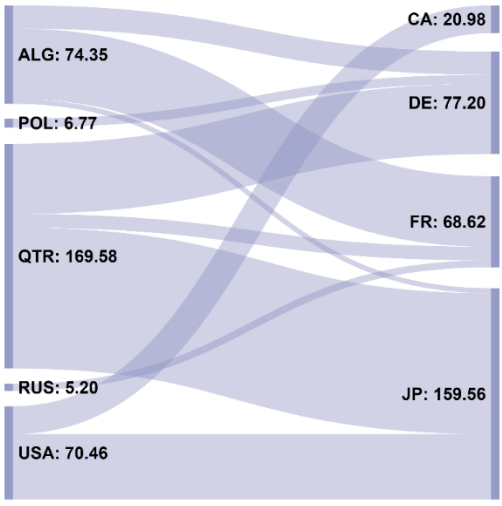
As previously illustrated in Figure 8.2, the study considers helium production as a starting point; this assessment does not take into account natural gas production. Five models of helium production are considered based on the helium producing countries relevant to the studied supply network: Algeria (ALG), Poland (POL), Qatar (QTR), Russia (RUS) and the USA (USA), abbreviated by their three-letter country code; the Ukraine was not included because it represents less than 2% of the supply in 2018.

Table 8.1 presents the parameters used to differentiate the processes modeled for the helium production stage of the life cycle. A same level of technology is assumed due to insufficient data on specific processes for each country, however, the differentiated energy mixes were included in the assessment (Detailed information is available in Annex P). Specific information for a representative plant in each producing country was also taken into account; for the specific case of the USA, the 'Liberal' plant in the State of Kansas was chosen due to being the largest one and being in a virtual average location among other helium plants in the country. The other plants were chosen due to being the most important in each of the studied exporting nations (Skidka, ALG; Odonalow, POL; Ras Laffan, QTR; Orenburg, RUS). Detailed information on the plants is available in Annex Q; the base bill of materials for the production stage is presented in Annex R.

Table 8.1 – Summary of parameters for the model of helium production

Parameter	*Status in the life cycle inventory*
Helium production technology	Assumed the same for all producing countries; contains data on energy consumption.
Efficiency of the process	Assumed the same for all producing countries (losses in the production stage).
Energy mix	Specific for each country, considers information for the year 2018 (except for Kansas, USA: 2019 as proxy).
Plant characteristics	Tailored for each plant; contains specific data on plant size, plant capacity and location in the analyzed countries.

As part of the international supply stage in the life cycle, a next step on the modelling considers local transport from the plant to the port of export. The international supply network is presented in Figure 8.3 as a Sankey diagram based on Annex S. (As mentioned above, Ukraine was excluded from the assessment). Details on the calculations for local transport in the producing countries and international transport to the importing countries are available in Annex T.



Units: millions of dollars (MM USD)

Figure 8.3 – Helium supply mix in 2018 (CA, DE, FR and JP)

Following what was presented in section 7.2, a direct transport from producing to importing country without intermediaries is assumed to simplify the model. Maximum efficiency is assumed during the international transport; containers at this stage are designed for losses of less than 1% over 60 days (Linde, 2019), period that is never surpassed in the analyzed trade network. The model considers local transportation between the port of entry in the importing country and a transfill center located in the city in which the use phase takes place. Details on this stage are available in Annex U. A transfill process in which helium is put into 500L containers is also part of the chain; these containers are delivered to medical centers for provision to MRI machines. Similar to the production stage, the transfill process is assumed of the same technology level in the four destination countries (energy and helium efficiency); however, differences associated to the local electricity mix are considered. The electricity mixes used for this model and details on the transfill process are available in Annex V. A final local transportation stage between the transfill center and the final destination is also included in the model (for further details, please refer to Annex U).

For the last analyzed stage, energy consumption, helium consumption, electronic component use and facility use were included in the model. As mentioned in section 8.1, the production, transport, use and maintenance of magnets is not considered as part of the calculations due to lack of data. Moreover, the model considers as a final output the provision of cold for the production of one MRI scan, but does not account for its management or delivery. In order to capture a range of technology levels for the MRI machines, two scenarios of energy consumption and two scenarios of helium use were considered based on estimations found in PE International (2012) and compared with experts' opinions. The details on the differences between these scenarios are presented in Table 8.2. MRI machines are assumed to have an 11.5 years lifetime working at maximum capacity (For more details, please refer to Annex W).

Table 8.2 – Parameters required to determine the analyzed scenarios for MRI scan production

Parameter	*Description*	*Values*
Country – City	Location in which the MRI scans are produced	CA: Toronto, Canada DE: Berlin, Germany FR: Paris, France JP: Tokyo, Japan
Helium use	Quantity of helium required to provide cold for MRI scan production. (Industrial expert information).	A: 380 L/y B: 1130 L/y C: 1948 L/y
Energy Consumption	Quantity of energy consumed to produce one MRI scan (PE International, 2012)	1: 13 kWh/scan 2: 15 kWh/scan

As also considered for the transfill stage, each individual electricity mix in the analyzed countries is part of the calculations for the use phase in the life cycle (for more information, please refer to Annex V). Based on the mentioned parameters, a total of 24 combinations were defined (4 countries, 2 energy

consumption levels and 3 helium use scenarios). Further details on the bill of materials for this stage are available in Annex W.

Following the above presented information in this section, the computational model in the OpenLCA software is completed according to the scope described in Figure 8.2. The 24 scenarios of the model were run following the CML impact assessment method (midpoint level); indicator results for the following impact categories were obtained: acidification, eutrophication, fresh water ecotoxicity, global warming, human toxicity, marine aquatic toxicity, ozone layer depletion, photochemical oxidation and terrestrial ecotoxicity. For resource accessibility, the results are complemented with the GeoPolRisk method applied to helium for the year 2018 from the perspective of the importing countries; helium is used as proxy due to being the main supply constraint in the analyzed supply chain, results for this last impact category are available in section 7.3.

8.3. Results of the integrated study on MRI scans

In this section, the overall results of the model will be presented. A top-down approach is followed: from general results to specific details in the analyzed system. The description of results starts with an overview of the behavior of all scenarios for MRI scan production in the four analyzed countries with the objective to identify general trends and main contributors; a next stage will focus on understanding how this contributions change depending on selected scenarios for helium consumption based on two main impact categories. Finally, a focus will be given to the international supply stage with the aim to understand the contribution of the supply mix to the global warming potential.

Figure 8.4 shows a comparison between the results on the impact categories global warming potential and ozone layer depletion potential for the scenarios A1, A2, C1 and C2 (A: low helium use, 1: low energy consumption) run for the four countries under assessment (CA, DE, FR, and JP). These two impact categories were selected for this graphic due to representing the two main trends in impact behavior at midpoint level (A full set of the overall results for the 24 scenarios is available in Annex X in the form of a colored table to identify these trends). All categories, with the exception of ozone layer depletion potential and geopolitical supply risk show significantly higher impacts for all the scenarios run for Germany and Japan compared to the results for Canada and France. Moreover, scenarios of high energy and helium consumption (C2) in Canada and France have a better environmental profile than scenarios of low energy and helium consumption (A1) in Germany and Japan.

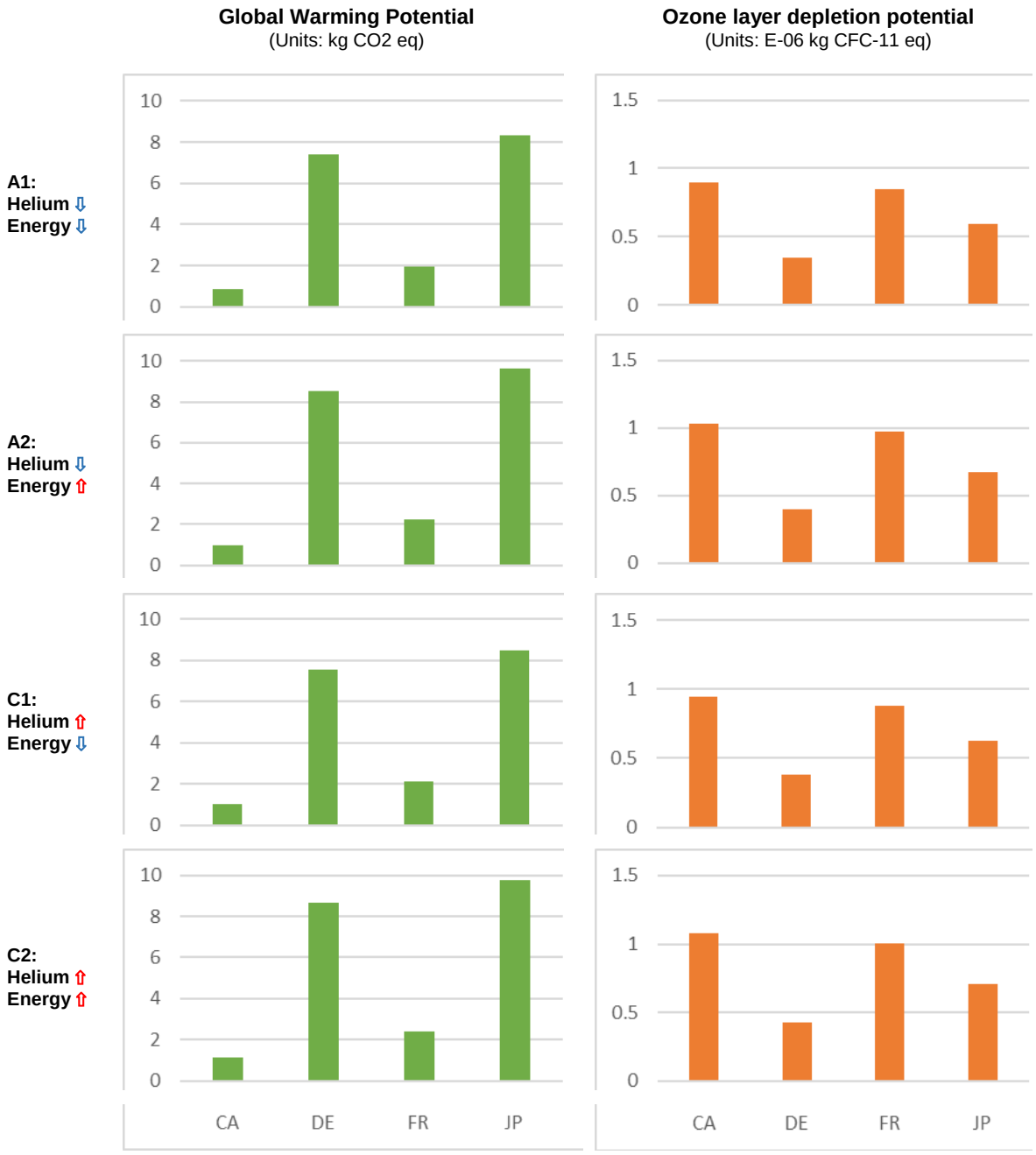


Figure 8.4 – Global warming potential and ozone layer depletion potential per scan for scenarios A1, A2, C1 and C2 from the perspective of Canada, Germany, France and Japan

In contrast, results for the ozone layer depletion potential are higher for Canada (CA) and France (FR) in all scenarios. A first early conclusion based on the behavior of these results is to identify the use phase in the life cycle as the most relevant, specially associated with the electricity profile of the countries/regions in which the MRI scans are produced. For the case of Germany and Japan, the main contributor to global warming potential (and multiple other categories) is the electricity production from coal; for the case of Canada and France, a relatively cleaner electricity mix results in lower impacts in this category. In the case of ozone layer depletion potential, the higher results for Canada and France are explained by a high percentage of electricity coming from nuclear energy, these being specifically associated with the production of uranium.

The impact category of supply risk is measured using the GeoPolRisk indicator for helium. The results do not change over the use scenarios, because they depend on the helium supply mix for the importing countries and the year of assessment (as seen in section 7.3). As reference, Figure 8.5 shows a comparison between the supply risk and the previously discussed impact categories with the results for the scenario A1 (low helium use, low energy consumption).

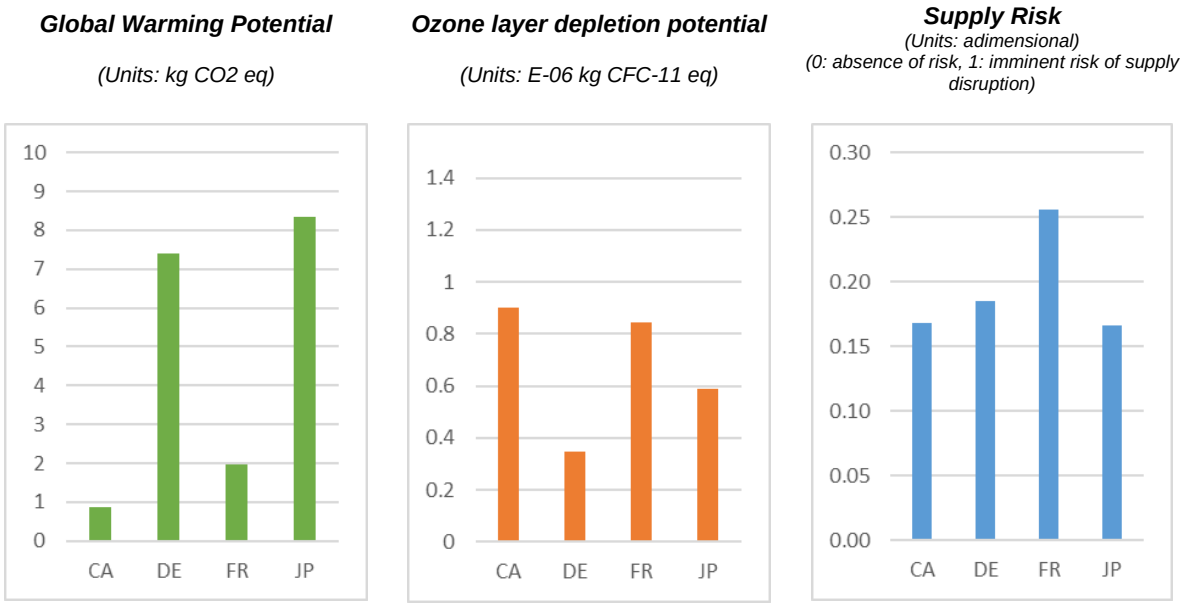


Figure 8.5 – Global warming potential and ozone layer depletion per scan for scenario A1 and helium GeoPolRisk from the perspective of Canada, Germany, France and Japan

As previously discussed in section 6.5, the use of the GeoPolRisk method provides a new layer for the assessment of impacts that is not captured with other impact assessment methods. Supply risk considerations associated with the political (in)stability of helium-supplying nations make the case of France visible: potential disruptions associated with the heavy reliance on one trade partner with a high risk profile (Algeria). This situation was not reflected by the other categories, specially considering that the electricity mix of the country in which the MRI scan is used has the highest contribution to overall impacts.

Since the electricity consumption associated with the use phase appears to be the dominant stage on the life cycle; a second layer of assessment is proposed to better understand the contribution of previous processes, namely the international supply (production and international transport) and the local distribution (refill and local transport). In Figure 8.6 it is possible to visualize the contribution of the three analyzed life cycle stages to the global warming potential impact category for the scenario C1 (high helium use and low energy consumption, selected to help visualize the role of helium supply in the impact category). The contribution associated to the international supply from the five main producing countries (ALG, POL, QTR, RUS and USA) is enhanced and compared with the supply mix of each importing country.

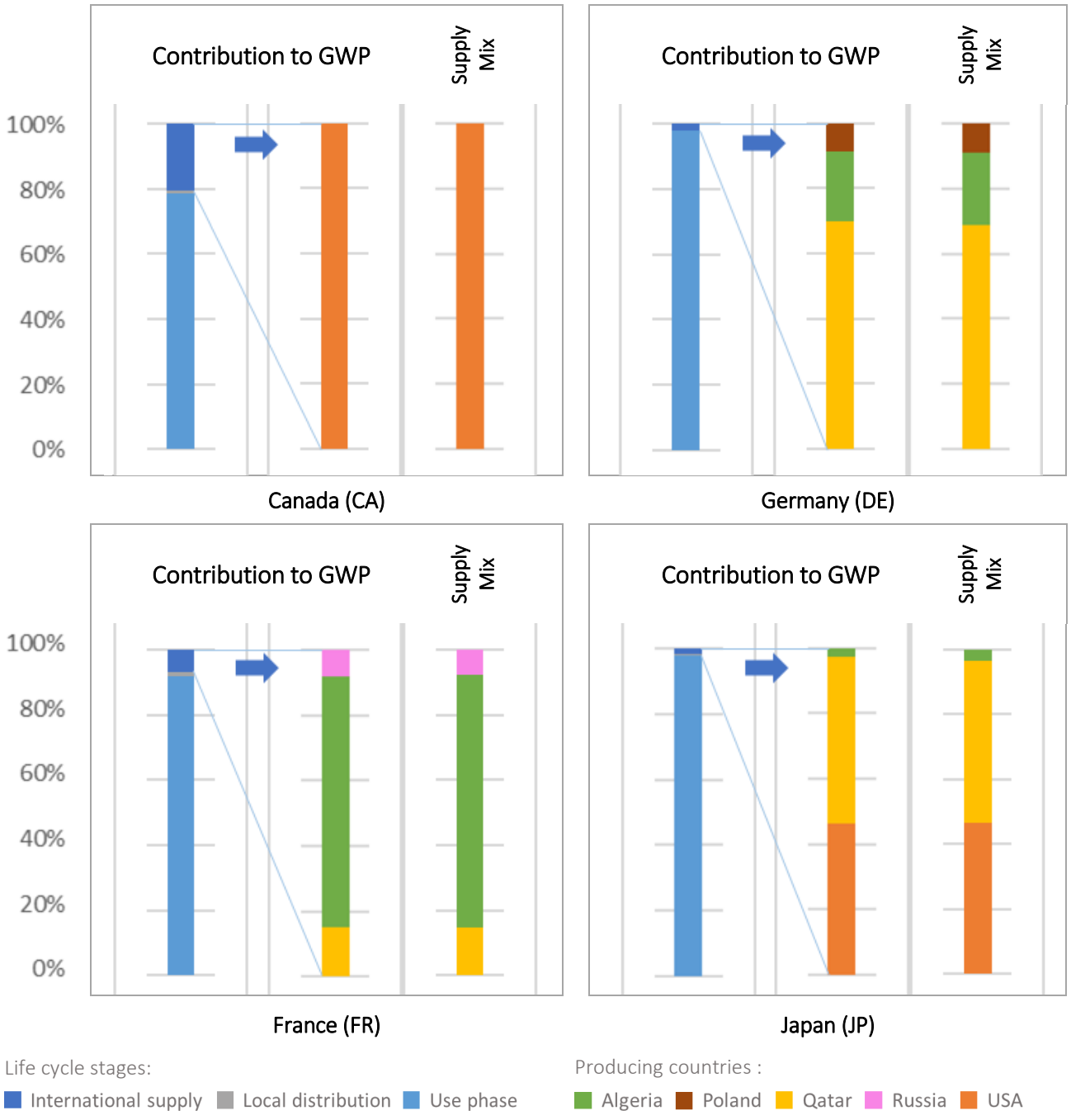


Figure 8.6 – Contribution of the main life cycle stages and the international supply mix to the impact category global warming potential under the scenario C1 for CA, DE, FR and JP

As identified above, the use phase, specifically the electricity consumption in MRI machines, is responsible for the highest proportion of contribution to the impacts in the category GWP. Figure 8.6 focuses on scenario C1 (high helium use, low energy consumption) to demonstrate that even considering higher levels of helium use (associated to losses and efficiency in the supply chain) and low levels of energy consumption, this remains the case.

In the same figure, the contribution of the international supply of helium with origin in producing countries (Algeria, Poland, Qatar, Russia and The USA) is identified. This is compared to the helium supply mix corresponding to each consuming country (Canada, Germany, France and Japan), showing that no big

differences between the percentages are captured by the model. The information presented on Figure 8.7 is the result of a further assessment with the aim to identify the absolute value of the GWP for having the equivalent to 500L of helium available in the destination country depending on its origin. The figure also contains values for the percentage of the impacts associated to international transport (from production plant to port of destination in the consuming countries).

GWP (kg CO2 eq)

		Destination			
		CA	DE	FR	JP
Origin	ALG	-	660.6	650.5	704.3
	POL	-	750.8	-	-
	QTR	-	686.6	675.7	686.6
	RUS	-	-	728.7	-
	USA	676.2	-	-	991.0
Overall		676.2	685.9	659.9	829.2

Contribution of production stage (%)

		Destination			
		CA	DE	FR	JP
Origin	ALG	-	-	-	92.0%
	POL	-	87.5%	-	-
	QTR	-	94.3%	95.8%	94.3%
	RUS	-	-	92.4%	-
	USA	95.8%	-	-	65.4%

Contribution of international transport (%)

		Destination			
		CA	DE	FR	JP
Origin	ALG	-	-	-	8.0%
	POL	-	12.5%	-	-
	QTR	-	5.7%	4.2%	5.7%
	RUS	-	-	7.6%	-
	USA	4.2%	-	-	34.6%

Figure 8.7 – GWP associated to 500L of helium available in the country of destination for the scenario C1

In the case of Japan, it is possible to identify a higher impact associated to having available helium in the country. This is explained by the international transportation stage being a big contributor to the impacts in the route USA to Japan; in this case, the transportation is responsible for over 30% of the impacts of having the equivalent to one 500L of helium available in the port of Kawasaki. With the exception of the Japanese case, the proposed model is not capable of identifying further significant differences between the international supply profiles; this is a reflection of assuming a similar model for the production of helium in the different countries of origin.

In contrast to the overall GWP associated to the production of one MRI scan in Japan and the environmental profile of helium available in the port of Kawasaki, the supply risk of helium supplied to Japan remains the lowest among the four importing countries. This is visible in Figure 8.5 and was previously discussed in section 7.4 for the period of years between 2015 and 2018. Japan might be the best ranked in terms of managing a relatively stable and continuous supply of helium; but most environmental impacts associated to their supply chain and, specially, energy consumption for MRI scan production could be addressed to improve their overall environmental profile.

An opposite case is seen for France, the GeoPolRisk indicator shows a high supply risk compared to the other analyzed countries due to its reliance on Algeria for helium supply; however its potential environmental impacts appear lower for most impact categories (with the exception of ozone layer depletion, which is associated to the use of nuclear energy). This confirms that supply risk and other more commonly used environmental impacts do not correlate and should be analyzed as complements to each other to better inform decision-making processes.

By focusing on GWP as the main category for this assessment, it is possible to see how multiple stakeholders could improve the environmental profile of MRI scans. First, energy efficiency of MRI machines should be a main concern of producers; second, medical centers using MRI equipment could focus on best practices for energy efficiency; and, third, government agencies could prioritize the transition towards a cleaner energy mix to achieve a less impactful use of this key technology in healthcare. A second layer of recommendation is associated with helium supply, promoting the study of the supply mix to mitigate its geopolitical risk.

The presented results highlight the relevance of energy consumption and the energy mix in the late stages of the life cycle, as they surpass most of the effect associated with the origin of the helium. This findings make more apparent the role of specific practices in healthcare that contribute to the carbon footprint of the sector (As previously highlighted by Eckelman et al., 2018; NHS Sustainable Development Unit, 2016; Malik, et al., 2018; Eckelman and Sherman, 2016). From an integrated perspective, healthcare is partially responsible for and being affected by climate change, making this global phenomenon a health emergency (Watts et al., 2019).

8.4. Discussion on limitations and future steps

The integrated study presented in this chapter represents a cross section of a life cycle assessment that takes into consideration geopolitical supply risk as an impact category at the midpoint level. The energy consumption at the use phase was identified as the main contributor to the impacts of MRI scan production. However, the analysis of previous stages associated to the production and international transport and the inclusion of the GeoPolRisk indicator show a new assessment level worth exploring for this case study.

From a geopolitical perspective, concerns on helium accessibility are apparent. The Japanese case shows efforts towards management of supply networks to secure reliable provision (for further details,

please refer to section 7.4). France appears among the better ranked for clean energy, but the supply risk associated to helium is the highest. Supply constraints are not visible with a traditional environmental LCA; therefore the GeoPolRisk method has the potential to support future studies interested in supply of raw materials.

The study has its limitations and further information could be extracted for future assessment. Similar analysis to the one presented in this chapter could help reveal other interesting hotspots along the life cycle for impact categories other than GWP, ozone layer depletion and supply risk. Moreover, the study focused on analyzing the contributions of the helium supply chain and the energy consumption, not accounting for important components in the MRI machine such as the magnets, or for further life cycle stages after the obtention of the digital medical image.

Early stages in the helium supply chain considered the same level of technology, energy requirement and efficiency for the production of helium in different nations, which is most likely not the case; this prevented a deeper assessment on the contributions to impacts from the international supply stage. The use of a simplified trade network, in which the resource is transported directly from point of production to point of use allowed to better understand the supply constraints associated with the commercial relations between countries. However, this impeded to better consider potential helium losses along the supply chain associated to longer transit times. Also, costs associated to helium supply were not part of the study, these could provide further insights on the decisions made by countries regarding their supply mix.

The production, trade and maintenance of magnets used in MRI machines were not considered on the study; further assessment could help better understand the impacts associated to this part of the life cycle. This would not only be worth exploring from an environmental perspective, but also from a supply risk point of view by accouting for the potential use of specific resources deemed critical (e.g. rare earth elements). Also related to the use phase, the management, storage and delivery of MRI scans were not part of the model, but it would be encouraged to include them for more information on the role that medical centers can take to mitigate impacts in late stages of the life cycle.

Considering all limitations discussed around the model, only the surface has been scratched; this chapter provides a starting point to further assess the impacts of MRI scan production. The study of further scenarios that considers a variety of production technologies, more detailed losses along the supply chain, supply costs and a temporal variable could inform medical centers and government agencies on how to work towards constructing supply mixes that not only secure helium supply, but also decrease environmental impacts.

Moreover, this case study serves as an example of the application of indicators associated to an outside-in perspective in life cycle assessment. In this specific case, the GeoPolRisk indicator allowed to obtain information that was not captured by other impact assessment methods. This shows how the integration of raw material criticality and life cycle assessment, operationalized with the GeoPolRisk method, supports decision-making processes not only in a sector as complex as healthcare, but with the potential to be applied to others.

Chapter 9: General Discussion and Conclusions

The final chapter of this thesis contains a discussion on the topics presented along the manuscript. The outcomes of each chapter are analyzed to understand the overall contribution to the main and specific objectives initially introduced. Here, the hypotheses that were formulated in Chapter 1: are tested based on the findings and results. Finally, this chapter includes conclusions and perspectives associated with the two branches in this PhD project: (1) Healthcare and Sustainability and (2) LCA and Raw Material Criticality.

9.1. Responses to the objectives

As presented in Chapter 1:, the work in this thesis was developed to answer the following research question:

How to assess environmental sustainability aspects in the healthcare sector using life cycle assessment and advancing its methodological readiness to evaluate raw material criticality in an integrated way?

Thie main objective of this thesis was defined based on the research question and is: **to provide and integrate methods to assess healthcare environmental sustainability from a life cycle perspective with focus on enhancing criticality indicators as an outside-in impact pathway associated with the AoP Natural Resources**. Following this rationale, eight specific objectives (S.O.) were completed along the chapters of this manuscript:

In Chapter 2:, a scoping review allowed to complete S.O.a: *to provide a detailed state of the art of the LCA applications in the healthcare sector while identifying the main methodological challenges for assessing healthcare systems from a life cycle perspective*. Multiple previous efforts in the field were identified; however opportunities for methodological development and further research emerged. Among these the potential to explore understudied areas in healthcare, to promote life cycle assessment as a suggested method to support the path towards healthcare sustainability, to provide and enhance methods to address outside-in impacts and to develop a conceptual framework to support research in the field. These findings became motivators for the work presented in following chapters.

Also as part of Chapter 2:, the S.O.b was completed: *to provide a detailed state of the art of the methodologies to address outside-in impacts resulting from the integration of raw material criticality and LCA while identifying the main methodological challenges for its readiness*. Following previous work developed by the UNEP Life Cycle Initiative, a review on the life cycle impact indicators for addressing abiotic resources was performed. The GeoPolRisk method was selected to assess its potential for further enhancements as a complement to LCA, specifically related to the AoP Natural Resources. Opportunities for methodological development were identified and motivated the work completed in the next chapters.

As the first chapter fully dedicated to the branch of the thesis related to healthcare sustainability, Chapter 3: follows up on previous findings and responds to the S.O.c: *to develop a framework to address healthcare sustainability from a life cycle perspective and provide its potential applications*. This section shows the rationale behind the construction of said framework and presents two cases for future application. One of these potential applications was further explored and serve as base case study for the the development of two chapters of the thesis: the case of helium for MRI scan production.

Opening the branch of LCA and raw material criticality, Chapter 4: followed up on the S.O.d: *to enhance the existing geopolitical supply risk method to include recycling considerations as a mitigation strategy*. This is a direct result from the methodological limitations previously identified. The objective was completed after proposing a methodological enhancement and testing its applicability to a case study on the supply risk of critical materials used for Information and Comunication Technologies in the European Union. This chapter also responds to recommendations provided by the UNEP Life Cycle Initiative.

Also as part of the proposed areas of improvement for the GeoPolRisk method, S.O.e was completed in Chapter 5: *to advance the scope of the geopolitical supply risk method from a midpoint level indicator to an endpoint level indicator associated to the area of protection Natural Resources*. A novel method to address potential socio-economic impacts of the use of resources was developed with the inclusion of price and proce elasticity information. A proof of concept is presented with the application of this method to selected materials in the inventory of lithium-ion batteries for the case of the country members of the OECD.

Following up on the two methodological enhancements for the GeoPolRisk method, Chapter 6: is based on their application to a case study on LIB for the European Union. With the use of the indicators based on geopolitical supply risk at midpoint and endpoint level, S.O.f is completed: *to demonstrate the added value of the geopolitical supply risk method at midpoint and endpoint level as a complement to environmental LCA with a case study*. The application allowed to identify relevant information that is not currently visible when using more traditional impact assessment methods in LCA.

Chapter 7: was developed to respond to the S.O.g: *to demonstrate the added value of the application of a method based on an outside-in impact pathway with a case study relevant to the healthcare sector*. The GeoPolRisk method is applied to the case of helium, important resource for the healthcare sector, from the perspective of the top ten helium importers in the world. This application allowed to show information that is currently only obtainable when analyzing geopolitical supply risks. This chapter starts bringing together both branches explored in the thesis: (1) Healthcare and Sustainability and (2) LCA and Raw Material Criticality.

Chapter 8: responds to S.O.h*: to demonstrate the relevance of the application of an integrated assessment based on LCA considering outside-in and inside-out impact pathways for the healthcare sector*. In this chapter, a study based on the LCA methodology of MRI scans is performed to identify hotspots along the supply chain that contribute to environmental impacts. The GeoPolRisk method was used to address supply risk as part of the outside-in impacts associated to helium use. With the study

conducted from the perspective of four countries, it was possible to verify the relevance of addressing outside-in impacts when performing environmental assessments.

9.2. Hypotheses testing

Three hypotheses were formulated to answer the research question. In this section, the hypotheses will be discussed considering the outcomes of the thesis.

Hypothesis 1: LCA is an appropriate methodology to measure environmental sustainability impacts, extending the traditional scope to include an outside-in perspective.

From the review on the state of the art, it was concluded that the LCA methodology has a high maturity level when addressing inside-out impacts for multiple sectors. This is a result of continuous work on life cycle impact assessment methods and best practices to communicate results. However, as also identified in the early chapters of the manuscript, efforts are being made to extend the application of LCA in the context of outside-in impact pathways. The UNEP Life Cycle Initiative has listed a number of methods designed to address these aspects, with multiple levels of maturity.

Overall, opportunities for further methodological development were identified. In this thesis, the Geopolitical Supply Risk method was selected for its potential based on the suggestions provided by the Task Force in charge of studying product-level supply risk assessment methods. The recommendations were addressed and new proposals were presented at midpoint and endpoint level. Certain limitations remain, especially when discussing the applicability of indicators at the endpoint level due to lack of information; however, the use of the method, associated with an outside-in impact pathway, has been proven relevant by providing new and relevant information to LCA practitioners.

Hypothesis 2: Raw material criticality has the potential to address outside-in impacts associated with the AoP Natural Resources.

In this manuscript, the work previously developed on the integration of raw material criticality in the life cycle sustainability assessment framework is followed up by the enhancement of the GeoPolRisk method. The proposed methodological advancements have been proven adequate to address impacts associated to resource use in LCA by modeling potential socio-economic damage. Therefore, raw material criticality provides a new layer for the assessment of impacts in the AoP Natural Resources in LCA. However, further work is encouraged to mainstream the use of methods associated with this impact pathway.

Hypothesis 3: Products and services related to the healthcare sector can be analyzed in an integrated manner to account for impacts from the inside-out and outside-in pathways in LCA.

The scoping literature review in this thesis allowed to identify multiple previous efforts to address concerns on healthcare sustainability with the use of the LCA methodology. As previously discussed, LCA has a high level of maturity that allows it to be used in multiple sectors to support decision-making

processes; however, outside-in impact pathways are not usually taken into account. As presented earlier in this manuscript, material criticality has been identified as a relevant topic for the healthcare sector (and several others), but a consensus on how to address it as part of life cycle assessment has not yet been achieved.

In this thesis, both inside-out and outside-in impact pathways were deemed relevant for the integrated study of a technology used in the healthcare sector. This resulted on the obtention of insights that serve as complement to each other, demonstrating that this is a methodology worth considering for future studies in the field of healthcare sustainability.

9.3. LCA as a tool to support the path towards healthcare sustainability

As illustrated by the literature presented in this manuscript, healthcare is a fast growing sector around the globe; studies have estimated that the contribution of this sector to total greenhouse gas emissions are between 5% and 10% in developed nations (Eckelman et al., 2018; Eckelman and Sherman, 2016; NHS Sustainable Development Unit, 2016; Malik, et al., 2018). Climate change, a direct consequence of human activities, has been recognized as a global health emergency; moreover, climate change itself is associated with potential supply disruptions, decrease in air quality, malnutrition, proliferation of infectious diseases, limited access to fresh water, and increase on the frequency of weather events (WHO, 2009).

The previous statements are not only a reflection of the healthcare sector being both responsible for and affected by climate change, but an example of two impact pathways: inside-out and outside-in. As explored in the scoping review, documented efforts to address environmental impacts of healthcare activities exist in the literature and most of them are focused on the inside-out pathway, addressing environmental related issues such as waste management and potential greenhouse gas emissions.

Life cycle assessment is a methodology designed to understand the environmental impacts of products and services; it has provided information to support decision-making processes in diverse sectors and it has been used to address environmental aspects of the sustainability of healthcare following an inside-out perspective. With this thesis, it is expected to contribute to the use of LCA to also address outside-in impacts relevant to the sector and to support future research on the field, as demonstrated with the application of the GeoPolRisk method to the case of helium in medical imaging. It is worth mentioning an example of the impact of supply disruptions in the healthcare sector in 2020 and 2021: the COVID-19 pandemic, which has impacted healthcare-related supply chains (pharmaceuticals, personal protective equipment) as they are facing shortages, increased costs and multiple delays (Miller et al., 2020; IDC, 2020). These cases of supply risk have not been explored in this thesis, as a multi-stage and product-specific approach in the supply chain would be required and the GeoPolRisk only considers early life cycle stages as sources of supply risk.

However, the healthcare sector is complex and involves multiple activities, materials, infrastructure, technology, personnel and services. Moreover, the levels of care and the medical specialties are factors to consider when addressing impacts from and to the sector. This manuscript presents a framework that can support future research in healthcare sustainability by compiling parameters associated to the study of impacts in healthcare activities from a life cycle perspective. In Chapter 3:, this framework was applied to two cases; a first one directed towards the environmental assessment of anesthetic gases, however further development of the proposal was interrupted due to the COVID-19 pandemic; the project remains in stand-by at the time of writing of this chapter. A second application served as a starting point for the development of an integrated assessment based on the life cycle methodology including the use of the GeoPolRisk method to the case of helium in MRI scans (Available in Chapter 7 and 8). Overall, the full potential use of this framework remains to be achieved and it is expected for this first set of applications to serve as reference for future implementation and test in other case studies for the healthcare sector.

With the development of a framework to study healthcare activities, this manuscript has addressed the environmental pillar of sustainability in healthcare. By further extending the use of the concepts of raw material criticality, this thesis also shows one possible way to analyze aspects associated to outside-in impacts in healthcare. In Chapter 7:, the criticality of helium was explored from the perspective of ten nations based on the GeoPolRisk method to follow up on this research opportunity. This allowed to identify certain hotspots related to the supply risk of helium, mostly associated with the countries of origin of said element. The results allow to extract information that would not be normally captured by the more traditionally used impact assessment methods in environmental LCA.

With the study of an integrated life cycle assessment methodology, Chapter 8: presented the case of MRI scan production in four countries (Canada, Germany, France and Japan) under different energy consumption and helium use scenarios. Following up on the previous work, the focus was given to helium as a main constraint in the studied supply chain with the objective to understand the role of helium supply in the environmental profile of MRI scans. A main outcome of this study was the finding of energy use in the MRI machines as the main contributor to the most impacts, highlighting the relevance of energy efficiency in the late stages of the life cycle and the energy mix of the countries in which the MRI scans are produced. As suspected from the results in Chapter 7:, the use of the GeoPolRisk method provides a new layer for the assessment. This is exemplified by analyzing the cases of France and Japan, MRI scans produced in France account for less environmental impacts than those produced in Japan, mainly due to the difference between the energy mixes of these countries; however, the helium supply risk for Japan is lower than the one from France because of the different helium supply mixes. A baseline for future studies is given, other aspects could be explored: different technologies of helium production, more detailed losses along the helium supply chain, costs of helium for different countries and more complex supply networks.

This integrated assessment aimed to serve as an example of the potential of LCA to support decision-making processes in the healthcare sector, even more so with the introduction of outside-in indicators that could offer complementary information usually overlooked by more traditional impact categories in life cycle impact assessment. However, work remains to be done to fully understand the implications of

healthcare activities in society, the economy and the environment; and, by extent, studying how these have a potential effect on healthcare delivery.

The development of a life-cycle based framework to support research in the field of healthcare sustainability and the first application of an outside-in indicator as part of an integrated study based on the life cycle methodology for a product in healthcare are the main outcomes in this branch of the thesis. As previously discussed, multiple opportunities for future research became evident along the manuscript; the presented framework has the potential to be further applied and tested in multiple areas, being this a reflection of the complexity and vastness of the healthcare sector. The GeoPolRisk method, an outside-in impact indicator featured in this thesis, was applied to the case of helium in medical imaging with a limited scope. Specifically for the case study, multiple materials in the life cycle of MRI scans could be further analyzed under this method, for example on rare earth elements in magnets. Moreover, supply risks at intermediate levels in the supply chain are not taken into account, future use of the method could focus not on raw materials, but also intermediate or final products such as pharmaceuticals or personal protective equipment.

The work presented here is an effort to enhance and apply the life cycle assessment methodology to the largely unexplored domain of healthcare. Only the surface has been scratched, but with this thesis it is expected to contribute to the work already done by scholars in the field of healthcare sustainability. As described above, the healthcare sector is a vast and complex system; various medical activities, technologies and products remain understudied from a life cycle perspective. Healthcare delivery is urgent and important, but the assessment of the sustainability of healthcare activities is also relevant. A next key challenge is to mainstream the use of environmental information as a new input for decision-making processes in healthcare management.

9.4. The integration of LCA and raw material criticality: The future of the GeoPolRisk method

The second branch of this PhD thesis responds to the need to enhance and extend outside-in impact indicators in LCA designed for the AoP Natural Resources. The work associated to this branch in the thesis was completed with the aim to address the suggestions provided by multiple scholars around the design and application of the GeoPolRisk methodology.

As presented in this manuscript, the GeoPolRisk method was developed as a result of the integration of raw material criticality considerations in the life cycle sustainability assessment (LCSA) framework. It was conceived both as a midpoint indicator in LCA related to potential impacts in the Area of protection Natural Resources and as a complement to environmental LCA in the economic dimension of LCSA. The method has been subject to a comprehensive review on product-level supply risk assessment indicators conducted by the UNEP Life Cycle Initiative. Opportunities for improvement were identified in said review and this thesis presents methodological enhancements to address them.

A first main suggestion relates to the use of recycling indicators in the method. The inclusion of recycling considerations allowed to model the risk-mitigation potential of recycling practices in countries or regions that use critical raw materials, which was not possible under the method up until now. A case study presented in Chapter 4: demonstrated the existence of two mechanisms through which recycling mitigates supply risk: a requirement reduction of imports (the “reduction effect”) and a potential redistribution of the supply mix (the “redistribution effect”). The enhanced method is able to capture these effects under the assumption that recycling practices take place domestically, that the recycled material is reinserted in the local economy and that the reintroduced material is usable on the same way as virgin material.

The enhanced method is still subject to limitations in theory and practice. The information required to calculate GeoPolRisk values might not be sufficient or available in the required granularity for the application; for the presented case study, certain materials had to be aggregated to match the available data. Also, the scope of the case study was limited by the availability of recycling indicators, which were obtainable only at the EU level and for a specific period of time. In order to partially overcome these challenges, simulations were made to analyze diverse recycling scenarios, which allowed to understand in which cases potential improvement opportunities could be directed towards advancing recycling technologies or towards redistributing the supply mixes of the studied materials.

All the previous work on the GeoPolRisk method has been made from a midpoint level perspective in LCA; however, a second major recommendation was to extend the scope to model potential impacts associated to the AoP Natural Resources at the endpoint level. The novel GeoPolEndpoint method was introduced in this manuscript; it serves as an indicator at the endpoint level in LCA based on the GeoPolRisk method and allows to measure the short-term impacts of resource use as a potential socio-economic damage depending on price considerations. The conception of this method allowed to associate life cycle inventory flows measured in mass units with the geopolitical supply risk, which is adimensional. The method takes a unique approach by adopting price elasticity values based on historical information for natural disasters that caused supply disruptions in the past; this allows to model potential increased costs associated to the use of critical raw materials. Limitations still exist for a widespread application of this extension, the most important being related to the availability of price elasticity values for a wider range of resources. The case study in Chapter 5: serves as a first proof of concept for this modelling process, showing a measure of potential increased costs associated to the use of four materials in specific technologies. From a LCA perspective, the method is designed to better inform about potential tangible economic impacts linked with resource use and supply risk, however more work is required from the field of economics to support the use of the GeoPolEndpoint method.

The work presented in Chapter 6: shows the kind of information that can be extracted from analyzing the supply risk of raw materials as part of an integrated life cycle assessment. Although limited due to the data constraints at both midpoint and endpoint level mentioned above, the case study allowed to show how the GeoPolRisk and the GeoPolEndpoint methods provide additional information that serve as a complement to other impact assessment methods in LCA. Further work remains to be done in order to allow these methods to be widely used by practitioners, efforts should focus on producing and

obtaining information that can support their application, namely end-of-life recycling input rates and short term price elasticities.

In order to explore the field of healthcare sustainability, an opportunity was identified in the case of helium. This element is of interest due to its peculiar characteristics: it is produced and used in its elementary form, it is transported and traded in liquid or gaseous state, and is produced by few countries around the globe. The work presented in Chapter 7: was the first application of the GeoPolRisk method to an element of these attributes. The case study allowed to measure the risk of potential supply disruptions tailored to different countries that was not possible to identify from the application of other impact assessment methods in LCA; it also helped support the integrated study on the production of MRI scans in Chapter 8:. This application is not free from limitations, a simplification of the real supply chain was considered to study the supply risk under the assumption that helium is not chemically modified along the supply chain, however this weakened the capacity of the life cycle model to quantify helium losses in the transportation stages. Also, an important potential source of supply risk for the case of MRI scan production was not considered: REE in magnets.

The highlights in this branch of the thesis respond to the suggestions made by the UNEP Life Cycle Initiative task force on natural resources around the GeoPolRisk method, specifically the inclusion of recycling as a risk-mitigation factor and the extension of the approach to allow assessments at the endpoint level with the inclusion of price and price elasticity considerations to estimate impacts associated with the AoP Natural Resources in LCA. As mentioned above, the biggest future challenges are the obtention and production of viable information to support the use of the proposed methods, namely the availability of end-of-life recycling input rates for multiple materials in various countries and regions, and the calculation of short term price elasticity values for critical raw materials. Overcoming these obstacles would help to further operationalize the GeoPolRisk and GeoPolEndpoint methods to support LCA practitioners.

Based on the current profile of the GeoPolRisk method, future work could also focus on four main areas. First, to expand the application of the method, to move from assessments at country/region level to analysis that can support decision-making processes at company or facility level. This is feasible in theory, but private partners are yet to be found for these applications. Second, the GeoPolRisk method currently focuses on the mining and refining stages to address potential supply disruptions; a previous application has explored the supply risk at different stages in the supply chain of one product (Helbig et al., 2016a), but this work has not been replicated to other applications; as previously mentioned, this could specifically contribute to the supply risk of intermediary and finished products used in the healthcare sector and made evident in the context of the COVID-19 pandemic. Third, the GeoPolRisk method relies on the WGI indicators as a measure of political (in)stability, however further exploration of other social or economic indicators could provide more insights relevant to supply risk assessments; a first approach was presented by Shaikh (2020), but further work is encouraged. Finally, with its current level of maturity, the method allows to obtain a wide range of values for geopolitical supply risk based on geographical locations and years of analysis, this information needs to be updated on a yearly basis.

The inclusion of this calculations in a software package could facilitate future studies and provide extense databases to support the development of integrated life cycle assessments.

9.5. Reflection

This PhD project was first conceived to apply life-cycle-thinking and raw-material-criticality analysis to the healthcare sector. Early stages in the project showed research opportunities on the enhancement of these to better inform decision-making processes not only in the field of healthcare sustainability, but applicable to multiple other sectors by considering outside-in impact pathways in life cycle assessment.

The enhancement of the GeoPolRisk method to include the risk mitigation potential of recycling practices allowed to understand how multiple factors can support the path towards more reliable supply chains. In the field of raw material criticality, the method can now provide new insights to inform companies and government agencies. Withstanding limitations, tangible economic impacts associated with resource use and supply risks can now be modeled with the application of the GeoPolEndpoint method, hopefully promoting the application of integrated assessments that do not focus only on environmental impacts, but also on how resource use has social and economic implications.

Mainstreaming the use of life cycle assessment and raw material criticality in the healthcare sector is a remaining challenge that can not be accomplished by one PhD project. Discussions on the topic of healthcare sustainability with medical practitioners have revealed an understanding and clear interest for studying and reducing the impacts associated with healthcare; however the urgency of daily medical tasks does not provide time and resources to address sustainability ambitions.

This situation takes us back to the phrase made popular by Mafalda, a character created by Quino in Latin-American culture: “As usual: the urgent does not leave time for the important”. Healthcare is both urgent and important, however we might not be noticing that its impacts are part of what is creating the urgency.

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ANNEXES

Annex A. Literature searches for Healthcare Sustainability Scoping Review

This annex lists all literature searches performed between September and November, 2017 in order to conduct the Healthcare and Sustainability Scoping Review. Each entry specifies the used database, the search phrase and the date of the query.

Database	Search phrase	Date
Scopus	("carbon footprint" OR "greenhouse gas*" OR "climate change" OR "global warming") AND ("diagnostic equipment" OR "diagnostic technique*" OR "computer assisted diagnos*" OR "medical technolog*" OR "medical laborator*" OR "laboratory diagnos*")	September 29, 2017
Scopus	("carbon footprint" OR "greenhouse gas*" OR "climate change" OR "global warming") AND ("diagnostic imaging" OR "x-ray*" OR radiograph* OR "computed tomography" OR ultrasound* OR "magnetic resonance imaging")	September 29, 2017
Scopus	("critical material*" OR "critical metal*" OR "critical raw material*" OR criticality) AND ("diagnostic equipment" OR "diagnostic technique*" OR "computer assisted diagnos*" OR "medical technolog*" OR "medical laborator*" OR "laboratory diagnos*")	September 29, 2017
Scopus	("critical material*" OR "critical metal*" OR "critical raw material*" OR criticality) AND ("diagnostic imaging" OR "x-ray*" OR radiograph* OR "computed tomography" OR ultrasound* OR "magnetic resonance imaging")	September 29, 2017
Scopus	("eco-efficiency" OR "energy efficiency" OR "material efficiency" OR "resource efficiency") AND ("diagnostic equipment" OR "diagnostic technique*" OR "computer assisted diagnos*" OR "medical technolog*" OR "medical laborator*" OR "laboratory diagnos*")	September 29, 2017
Scopus	("eco-efficiency" OR "energy efficiency" OR "material efficiency" OR "resource efficiency") AND ("diagnostic imaging" OR "x-ray*" OR radiograph* OR "computed tomography" OR ultrasound* OR "magnetic resonance imaging")	September 29, 2017
Scopus	("ecological footprint" OR "environmental footprint") AND ("diagnostic equipment" OR "diagnostic technique*" OR "computer assisted diagnos*" OR "medical technolog*" OR "medical laborator*" OR "laboratory diagnos*")	September 29, 2017
Scopus	("environmental management" OR "ISO 14001") AND ("diagnostic equipment" OR "diagnostic technique*" OR "computer assisted diagnos*" OR "medical technolog*" OR "medical laborator*" OR "laboratory diagnos*")	September 29, 2017
Scopus	("hazardous waste" OR "biohazard* waste" OR "waste management") AND ("diagnostic equipment" OR "diagnostic technique*" OR "computer assisted diagnos*" OR "medical technolog*" OR "medical laborator*" OR "laboratory diagnos*")	September 29, 2017
Scopus	("life cycle assessment" OR "life cycle management" OR "life cycle sustainability assessment") AND ("diagnostic equipment" OR "diagnostic technique*" OR "computer assisted diagnos*" OR "medical technolog*" OR "medical laborator*" OR "laboratory diagnos*")	September 29, 2017
Scopus	("material flow analysis" OR "material flow account*" OR "substance flow analysis") AND ("diagnostic equipment" OR "diagnostic technique*" OR "computer assisted diagnos*" OR "medical technolog*" OR "medical laborator*" OR "laboratory diagnos*")	September 29, 2017
Scopus	("responsible sourcing" OR "sustainable supply chain management") AND ("diagnostic equipment" OR "diagnostic technique*" OR "computer assisted diagnos*" OR "medical technolog*" OR "medical laborator*" OR "laboratory diagnos*")	September 29, 2017
Scopus	("water footprint" OR "water consumption") AND ("diagnostic equipment" OR "diagnostic technique*" OR "computer assisted diagnos*" OR "medical technolog*" OR "medical laborator*" OR "laboratory diagnos*")	September 29, 2017
Scopus	(Environment* OR "social* responsib*" OR "sustainable development") AND ("diagnostic equipment" OR "diagnostic technique*" OR "computer assisted diagnos*" OR "medical technolog*" OR "medical laborator*" OR "laboratory diagnos*")	September 29, 2017
Scopus	(healthcare OR "health care" OR medic*) AND sustainab*	September 29, 2017
Scopus	("carbon footprint" OR "greenhouse gas*" OR "climate change" OR "global warming") AND ("long-term care" OR "palliative care" OR "prevent* care")	September 30, 2017
Scopus	("carbon footprint" OR "greenhouse gas*" OR "climate change" OR "global warming") AND ("medical equipment" OR "medical device*" OR "medical supplies" OR "ancillary device*" OR "ancillary equipment")	September 30, 2017
Scopus	("carbon footprint" OR "greenhouse gas*" OR "climate change" OR "global warming") AND (Drug* OR pharmaceutical* OR "active pharmaceutical ingredient*" OR "medicinal ingredient*" OR vaccin*)	September 30, 2017
Scopus	("critical material*" OR "critical metal*" OR "critical raw material*" OR criticality) AND ("long-term care" OR "palliative care" OR "prevent* care")	September 30, 2017
Scopus	("critical material*" OR "critical metal*" OR "critical raw material*" OR criticality) AND ("medical equipment" OR "medical device*" OR "medical supplies" OR "ancillary device*" OR "ancillary equipment")	September 30, 2017
Scopus	("critical material*" OR "critical metal*" OR "critical raw material*" OR criticality) AND (Drug* OR pharmaceutical* OR "active pharmaceutical ingredient*" OR "medicinal ingredient*" OR vaccin*)	September 30, 2017
Scopus	("eco-efficiency" OR "energy efficiency" OR "material efficiency" OR "resource efficiency") AND ("long-term care" OR "palliative care" OR "prevent* care")	September 30, 2017

Database	Search phrase	Date
Scopus	("eco-efficiency" OR "energy efficiency" OR "material efficiency" OR "resource efficiency") AND ("medical equipment" OR "medical device*" OR "medical supplies" OR "ancillary device*" OR "ancillary equipment")	September 30, 2017
Scopus	("eco-efficiency" OR "energy efficiency" OR "material efficiency" OR "resource efficiency") AND (Drug* OR pharmaceutical* OR "active pharmaceutical ingredient*" OR "medicinal ingredient*" OR vaccin*)	September 30, 2017
Scopus	("ecological footprint" OR "environmental footprint") AND ("diagnostic imaging" OR "x-ray*" OR radiograph* OR "computed tomography" OR ultrasound* OR "magnetic resonance imaging")	September 30, 2017
Scopus	("ecological footprint" OR "environmental footprint") AND ("long-term care" OR "palliative care" OR "prevent* care")	September 30, 2017
Scopus	("ecological footprint" OR "environmental footprint") AND ("medical equipment" OR "medical device*" OR "medical supplies" OR "ancillary device*" OR "ancillary equipment")	September 30, 2017
Scopus	("ecological footprint" OR "environmental footprint") AND (Drug* OR pharmaceutical* OR "active pharmaceutical ingredient*" OR "medicinal ingredient*" OR vaccin*)	September 30, 2017
Scopus	("environmental management" OR "ISO 14001") AND ("diagnostic imaging" OR "x-ray*" OR radiograph* OR "computed tomography" OR ultrasound* OR "magnetic resonance imaging")	September 30, 2017
Scopus	("environmental management" OR "ISO 14001") AND ("long-term care" OR "palliative care" OR "prevent* care")	September 30, 2017
Scopus	("environmental management" OR "ISO 14001") AND ("medical equipment" OR "medical device*" OR "medical supplies" OR "ancillary device*" OR "ancillary equipment")	September 30, 2017
Scopus	("environmental management" OR "ISO 14001") AND (Drug* OR pharmaceutical* OR "active pharmaceutical ingredient*" OR "medicinal ingredient*" OR vaccin*)	September 30, 2017
Scopus	("hazardous waste" OR "biohazard* waste" OR "waste management") AND ("diagnostic imaging" OR "x-ray*" OR radiograph* OR "computed tomography" OR ultrasound* OR "magnetic resonance imaging")	September 30, 2017
Scopus	("hazardous waste" OR "biohazard* waste" OR "waste management") AND ("long-term care" OR "palliative care" OR "prevent* care")	September 30, 2017
Scopus	("hazardous waste" OR "biohazard* waste" OR "waste management") AND ("medical equipment" OR "medical device*" OR "medical supplies" OR "ancillary device*" OR "ancillary equipment")	September 30, 2017
Scopus	("life cycle assessment" OR "life cycle management" OR "life cycle sustainability assessment") AND ("diagnostic imaging" OR "x-ray*" OR radiograph* OR "computed tomography" OR ultrasound* OR "magnetic resonance imaging")	September 30, 2017
Scopus	("life cycle assessment" OR "life cycle management" OR "life cycle sustainability assessment") AND ("long-term care" OR "palliative care" OR "prevent* care")	September 30, 2017
Scopus	("life cycle assessment" OR "life cycle management" OR "life cycle sustainability assessment") AND ("medical equipment" OR "medical device*" OR "medical supplies" OR "ancillary device*" OR "ancillary equipment")	September 30, 2017
Scopus	("material flow analysis" OR "material flow account*" OR "substance flow analysis") AND ("diagnostic imaging" OR "x-ray*" OR radiograph* OR "computed tomography" OR ultrasound* OR "magnetic resonance imaging")	September 30, 2017
Scopus	("material flow analysis" OR "material flow account*" OR "substance flow analysis") AND ("long-term care" OR "palliative care" OR "prevent* care")	September 30, 2017
Scopus	("material flow analysis" OR "material flow account*" OR "substance flow analysis") AND ("medical equipment" OR "medical device*" OR "medical supplies" OR "ancillary device*" OR "ancillary equipment")	September 30, 2017
Scopus	("material flow analysis" OR "material flow account*" OR "substance flow analysis") AND (Drug* OR pharmaceutical* OR "active pharmaceutical ingredient*" OR "medicinal ingredient*" OR vaccin*)	September 30, 2017
Scopus	("responsible sourcing" OR "sustainable supply chain management") AND ("diagnostic imaging" OR "x-ray*" OR radiograph* OR "computed tomography" OR ultrasound* OR "magnetic resonance imaging")	September 30, 2017
Scopus	("responsible sourcing" OR "sustainable supply chain management") AND ("long-term care" OR "palliative care" OR "prevent* care")	September 30, 2017
Scopus	("responsible sourcing" OR "sustainable supply chain management") AND ("medical equipment" OR "medical device*" OR "medical supplies" OR "ancillary device*" OR "ancillary equipment")	September 30, 2017
Scopus	("responsible sourcing" OR "sustainable supply chain management") AND (Drug* OR pharmaceutical* OR "active pharmaceutical ingredient*" OR "medicinal ingredient*" OR vaccin*)	September 30, 2017
Scopus	("water footprint" OR "water consumption") AND ("diagnostic imaging" OR "x-ray*" OR radiograph* OR "computed tomography" OR ultrasound* OR "magnetic resonance imaging")	September 30, 2017
Scopus	("water footprint" OR "water consumption") AND ("long-term care" OR "palliative care" OR "prevent* care")	September 30, 2017
Scopus	("water footprint" OR "water consumption") AND ("medical equipment" OR "medical device*" OR "medical supplies" OR "ancillary device*" OR "ancillary equipment")	September 30, 2017
Scopus	("water footprint" OR "water consumption") AND (Drug* OR pharmaceutical* OR "active pharmaceutical ingredient*" OR "medicinal ingredient*" OR vaccin*)	September 30, 2017

Database	Search phrase	Date
Scopus	(Environment* OR "social* responsib*" OR "sustainable development") AND ("diagnostic imaging" OR "x-ray*" OR radiograph* OR "computed tomography" OR ultrasound* OR "magnetic resonance imaging")	September 30, 2017
Scopus	(Environment* OR "social* responsib*" OR "sustainable development") AND ("long-term care" OR "palliative care" OR "prevent* care")	September 30, 2017
Scopus	(Environment* OR "social* responsib*" OR "sustainable development") AND ("medical equipment" OR "medical device*" OR "medical supplies" OR "ancillary device*" OR "ancillary equipment")	September 30, 2017
Scopus	("carbon footprint" OR "greenhouse gas*" OR "climate change" OR "global warming") AND (Hospital* OR clinic*)	October 8, 2017
Scopus	("carbon footprint" OR "greenhouse gas*" OR "climate change" OR "global warming") AND (Implant* OR prosth*)	October 8, 2017
Scopus	("critical material*" OR "critical metal*" OR "critical raw material*" OR criticality) AND (Hospital* OR clinic*)	October 8, 2017
Scopus	("critical material*" OR "critical metal*" OR "critical raw material*" OR criticality) AND (Implant* OR prosth*)	October 8, 2017
Scopus	("critical material*" OR "critical metal*" OR "critical raw material*" OR criticality) AND (Medic* OR healthcare OR "health care")	October 8, 2017
Scopus	("critical material*" OR "critical metal*" OR "critical raw material*" OR criticality) AND (Surger* OR surgical)	October 8, 2017
Scopus	("eco-efficiency" OR "energy efficiency" OR "material efficiency" OR "resource efficiency") AND (Implant* OR prosth*)	October 8, 2017
Scopus	("eco-efficiency" OR "energy efficiency" OR "material efficiency" OR "resource efficiency") AND (Surger* OR surgical)	October 8, 2017
Scopus	("ecological footprint" OR "environmental footprint") AND (Implant* OR prosth*)	October 8, 2017
Scopus	("ecological footprint" OR "environmental footprint") AND (Surger* OR surgical)	October 8, 2017
Scopus	("environmental management" OR "ISO 14001") AND (Implant* OR prosth*)	October 8, 2017
Scopus	("environmental management" OR "ISO 14001") AND (Surger* OR surgical)	October 8, 2017
Scopus	("hazardous waste" OR "biohazard* waste" OR "waste management") AND (Implant* OR prosth*)	October 8, 2017
Scopus	("life cycle assessment" OR "life cycle management" OR "life cycle sustainability assessment") AND (Implant* OR prosth*)	October 8, 2017
Scopus	("material flow analysis" OR "material flow account*" OR "substance flow analysis") AND (Hospital* OR clinic*)	October 8, 2017
Scopus	("material flow analysis" OR "material flow account*" OR "substance flow analysis") AND (Implant* OR prosth*)	October 8, 2017
Scopus	("material flow analysis" OR "material flow account*" OR "substance flow analysis") AND (Medic* OR healthcare OR "health care")	October 8, 2017
Scopus	("responsible sourcing" OR "sustainable supply chain management") AND (Hospital* OR clinic*)	October 8, 2017
Scopus	("responsible sourcing" OR "sustainable supply chain management") AND (Implant* OR prosth*)	October 8, 2017
Scopus	("responsible sourcing" OR "sustainable supply chain management") AND (Medic* OR healthcare OR "health care")	October 8, 2017
Scopus	("water footprint" OR "water consumption") AND (Hospital* OR clinic*)	October 8, 2017
Scopus	("water footprint" OR "water consumption") AND (Implant* OR prosth*)	October 8, 2017
Scopus	("water footprint" OR "water consumption") AND (Medic* OR healthcare OR "health care")	October 8, 2017
Scopus	(Environment* OR "social* responsib*" OR "sustainable development") AND (Implant* OR prosth*)	October 8, 2017
Scopus	("critical material*" OR "critical metal*" OR "critical raw material*" OR criticality) AND (Anesth*)	October 9, 2017
Scopus	("eco-efficiency" OR "energy efficiency" OR "material efficiency" OR "resource efficiency") AND (Anesth*)	October 9, 2017
Scopus	("ecological footprint" OR "environmental footprint") AND (Anesth*)	October 9, 2017
Scopus	("environmental management" OR "ISO 14001") AND (Anesth*)	October 9, 2017
Scopus	("hazardous waste" OR "biohazard* waste" OR "waste management") AND (Anesth*)	October 9, 2017
Scopus	("hazardous waste" OR "biohazard* waste" OR "waste management") AND (Surger* OR surgical)	October 9, 2017
Scopus	("life cycle assessment" OR "life cycle management" OR "life cycle sustainability assessment") AND (Surger* OR surgical)	October 9, 2017
Scopus	("material flow analysis" OR "material flow account*" OR "substance flow analysis") AND (Anesth*)	October 9, 2017
Scopus	("material flow analysis" OR "material flow account*" OR "substance flow analysis") AND (Surger* OR surgical)	October 9, 2017
Scopus	("responsible sourcing" OR "sustainable supply chain management") AND (Anesth*)	October 9, 2017
Scopus	("responsible sourcing" OR "sustainable supply chain management") AND (Surger* OR surgical)	October 9, 2017
Scopus	("water footprint" OR "water consumption") AND (Anesth*)	October 9, 2017
Scopus	("water footprint" OR "water consumption") AND (Surger* OR surgical)	October 9, 2017

Database	Search phrase	Date
Scopus	(Environment* OR "social* responsib*" OR "sustainable development") AND (Anesth*)	October 9, 2017
Scopus	(Environment* OR "social* responsib*" OR "sustainable development") AND (Surger* OR surgical)	October 9, 2017
Scopus	"life cycle assessment" AND inhaler*	October 16, 2017
Scopus	("eco-efficiency" OR "energy efficiency" OR "material efficiency" OR "resource efficiency") AND (Hospital* OR clinic*)	November 10, 2017
Scopus	("ecological footprint" OR "environmental footprint") AND (Hospital* OR clinic*)	November 10, 2017
Scopus	("environmental management" OR "ISO 14001") AND (Hospital* OR clinic*)	November 10, 2017
Scopus	("hazardous waste" OR "biohazard* waste" OR "waste management") AND (Drug* OR pharmaceutical* OR "active pharmaceutical ingredient*" OR "medicinal ingredient*" OR vaccin*)	November 10, 2017
Scopus	("life cycle assessment" OR "life cycle management" OR "life cycle sustainability assessment") AND (Drug* OR pharmaceutical* OR "active pharmaceutical ingredient*" OR "medicinal ingredient*" OR vaccin*)	November 10, 2017
Scopus	(Environment* OR "social* responsib*" OR "sustainable development") AND (Drug* OR pharmaceutical* OR "active pharmaceutical ingredient*" OR "medicinal ingredient*" OR vaccin*)	November 10, 2017
Scopus	"green hospital*"	November 11, 2017
Scopus	"sustainable hospital*"	November 11, 2017
Scopus	("carbon footprint" OR "greenhouse gas*" OR "climate change" OR "global warming") AND (Anesth*)	November 11, 2017
Scopus	("carbon footprint" OR "greenhouse gas*" OR "climate change" OR "global warming") AND (Medic* OR healthcare OR "health care")	November 11, 2017
Scopus	("carbon footprint" OR "greenhouse gas*" OR "climate change" OR "global warming") AND (Surger* OR surgical)	November 11, 2017
Scopus	("eco-efficiency" OR "energy efficiency" OR "material efficiency" OR "resource efficiency") AND (Medic* OR healthcare OR "health care")	November 11, 2017
Scopus	("ecological footprint" OR "environmental footprint") AND (Medic* OR healthcare OR "health care")	November 11, 2017
Scopus	("environmental management" OR "ISO 14001") AND (Medic* OR healthcare OR "health care")	November 11, 2017
Scopus	("hazardous waste" OR "biohazard* waste" OR "waste management") AND (Hospital* OR clinic*)	November 11, 2017
Scopus	("hazardous waste" OR "biohazard* waste" OR "waste management") AND (Medic* OR healthcare OR "health care")	November 11, 2017
Scopus	("life cycle assessment" OR "life cycle management" OR "life cycle sustainability assessment") AND (Anesth*)	November 11, 2017
Scopus	("life cycle assessment" OR "life cycle management" OR "life cycle sustainability assessment") AND (Hospital* OR clinic*)	November 11, 2017
Scopus	("life cycle assessment" OR "life cycle management" OR "life cycle sustainability assessment") AND (Medic* OR healthcare OR "health care")	November 11, 2017
Scopus	(Environment* OR "social* responsib*" OR "sustainable development") AND (Hospital* OR clinic*)	November 11, 2017
Scopus	(Environment* OR "social* responsib*" OR "sustainable development") AND (Medic* OR healthcare OR "health care")	November 11, 2017
PubMed	"carbon footprint" OR "greenhouse gas*" OR "climate change" OR "global warming"	November 11, 2017
PubMed	"critical material*" OR "critical metal*" OR "critical raw material*" OR criticality	November 11, 2017
PubMed	"eco-efficiency" OR "energy efficiency" OR "material efficiency" OR "resource efficiency"	November 11, 2017
PubMed	"ecological footprint" OR "environmental footprint"	November 11, 2017
PubMed	"environmental management" OR "ISO 14001"	November 11, 2017
PubMed	"green chemistry"	November 11, 2017
PubMed	"green hospital*"	November 17, 2017
PubMed	"hazardous waste" OR "biohazard* waste" OR "waste management"	November 17, 2017
PubMed	"life cycle assessment" AND inhaler*	November 17, 2017
PubMed	"life cycle assessment" OR "life cycle management" OR "life cycle sustainability assessment"	November 17, 2017
PubMed	"material flow analysis" OR "material flow account*" OR "substance flow analysis"	November 17, 2017
PubMed	"medical waste" OR "hospital waste"	November 17, 2017
PubMed	"responsible sourcing" OR "sustainable supply chain management"	November 17, 2017
PubMed	"supply risk" OR "supply disruption" OR "supply restriction"	November 17, 2017
PubMed	"sustainable healthcare" OR "sustainable health care" OR "sustainable health system*"	November 17, 2017
PubMed	"sustainable hospital*"	November 17, 2017
PubMed	"water footprint"	November 17, 2017
PubMed	"water footprint" OR "water consumption"	November 17, 2017
PubMed	Environment* OR "social* responsib*" OR "sustainable development"	November 17, 2017
PubMed	Recycl* OR re-us* OR reus*	November 17, 2017

Annex B. Sample for Healthcare Sustainability Scoping Review

This annex lists all literature pieces considered for the Healthcare and Sustainability Scoping Review. Each entry specifies the authors, title of the article, name of the journal and year of publication.

#	Author(s)	Article title	Journal title	Year
1	Abor PA, Bouwer A.	Medical waste management practices in a Southern African hospital	International Journal of Health Care Quality Assurance	2008
2	Alderwick, H., Ham, C.	NHS in England embraces collaboration in tackling biggest crisis in its history: sustainability and transformation plans are being developed as competition takes a back seat	BMJ	2016
3	Al-Khatib IA.	Medical waste management in healthcare centres in the occupied Palestinian territory	Eastern Mediterranean Health Journal	2007
4	Anand, P.	Correspondence: knowledge, attitude and practice of healthcare managers to medical waste management and occupational safety practices: findings from southeast Nigeria	Journal of Clinical and Diagnostic Research	2017
5	Ard, J.L. et al.	A survey of the American Society of Anesthesiologists regarding environmental attitudes, knowledge, and organization	A & A Case Reports	2016
6	Askarian M, Vakili M, Kabir G.	Results of a hospital waste survey in private hospitals in Fars province, Iran	Waste Management	2004
7	Åström, C. et al.	Heat-related respiratory hospital admissions in Europe in a changing climate: a health impact assessment	BMJ	2013
8	Balmford, A. et al	The environmental footprints of conservationists, economists and medics compared	Biological Conservation	2017
9	Barrett, B., Charles, J.W., Temte, J.L.	Climate change, human health, and epidemiological transition	Preventive Medicine	2015
10	Bliss, L.M., Ecklund, J.M., Riley, J.B.	Recycling of renewable resources in extracorporeal circulation technology	Journal of Extra-Corporeal Technology	1995
11	Botelho, A.	The impact of regulatory compliance behavior on hazardous waste generation in European private healthcare facilities	Waste Management and Research	2013
12	Breslin, K.	EHPnet: U.S. EPA Indian environmental office	Environmental Health Perspectives	2001
13	Brown, N.J., Beattie, R.M.	The millennium development goals: taking stock as the first phase ends	Archives of Disease in Childhood	2015
14	Burke, N.P., Stowe, J.	Energy efficiency in the radiography department: an Irish perspective	Radiography	2014
15	Cetin S, Veli S, Ayberk S.	An investigation of halogens in Izmit hazardous and clinical waste incinerator	Waste Management	2004
16	Chen, M. et al.	The carbon footprints of home and in-center peritoneal dialysis in China	International Urology and Nephrology	2017
17	Chethana T et al.	Situation analysis and issues in management of biomedical waste in select small health care facilities in a ward under Bruhat Bengaluru Mahanagara Palike, Bangalore, India	Journal of Community Health	2014
18	Chiarini, A., Vagnoni, E.	Environmental sustainability in European public healthcare: Could it just be a matter of leadership?	Leadership in Health Services	2016
19	Clegg, J.C.	Influence of climate change on the incidence and impact of arenavirus diseases: a speculative assessment	Clinical Microbiology and Infection	2009
20	Cosford, P.	Partners in clime': sustainable development and climate change - what can the National Health Service do?	Public Health	2009
21	Costa TF, Felli VE, Baptista PC.	Nursing workers' perceptions regarding the handling of hazardous chemical waste	Revista da Escola de Enfermagem da U S P	2012
22	Das, P., Horton, R.	Pollution, health, and the planet: time for decisive action	The Lancet	2017
23	De Blois, J. et al.	The effects of climate change on cardiac health	Cardiology	2015
24	De Soete et al.	Challenges and recommendations for environmental sustainability assessments of pharmaceutical products in the healthcare sector	Green Chemistry	2017
25	de Souza, A.L.	Global warming and heatstroke	Indian Journal of Medical Research	2008

#	Author(s)	Article title	Journal title	Year
26	Debaveye S et al.	Human health damage modelling in life cycle assessment: a valuable addition to the evaluation of medical interventions?	Value in Health	2015
27	Derksen, J.G.M., Rijs, G.B.J., Jongbloed, R.H.	Diffuse pollution of surface water by pharmaceutical products	Water Science and Technology	2004
28	Dettenkofer, M. et al.	Environmental auditing in hospitals: first results in a University Hospital	Environmental Management	2000
29	Dhaliwal, H. et al.	A life cycle assessment of packaging options for contrast media delivery: comparing polymer bottle vs. glass bottle	International Journal of Life Cycle Assessment	2014
30	Dietert RR, Dietert JM.	The microbiome and sustainable healthcare	Healthcare	2015
31	Duputie, S., Farrington, N.	The road to a greener hospital	Irish Medical Journal	2002
32	Eckelman, M. et al.	Comparative life cycle assessment of disposable and reusable laryngeal mask airways	Anesthesia and Analgesia	2012
33	Esmaeili, A. et al.	Scope for energy improvement for hospital imaging services in the USA	Journal of Health Services Research and Policy	2015
34	Faergeman, O.	Climate change and preventive medicine	European Journal of Preventive Cardiology	2007
35	Fernando, J.	Reducing the ecological footprint of surgical hand scrub: It is time to act!	ANZ Journal of Surgery	2013
36	Fisher BE.	Dissolving medical waste	Environmental Health Perspectives	1996
37	Fitriani, I., Sangadji, S., Kristiawan, S.A.	Energy efficiency evaluation of hospital building office	Journal of Physics: Conference Series	2017
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55	Jödicke, G. et al.	Developing environmentally-sound processes in the chemical industry: a case study on pharmaceutical intermediates	Journal of Cleaner Production	1999
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59	Khalil, E.E.	Energy efficiency, air flow regime and relative humidity in air- conditioned surgical operating theatres	ASHRAE Journal	2012
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61	King, D.	Towards greener hospitals	Journal of the Royal Society of Medicine	2007
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63	Klepiszewski, K., Venditti, S., Koehler, C.	Tracer tests and uncertainty propagation to design monitoring setups in view of pharmaceutical mass flow analyses in sewer systems	Water Research	2016
64	Komilis, D., Katsafaros, N., Vassilopoulos, P.	Hazardous medical waste generation in Greece: case studies from medical facilities in Attica and from a small insular hospital	Waste Management and Research	2011
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77	Low, Y.S. et al.	Systematic framework for design of environmentally sustainable pharmaceutical supply chain network	Journal of Pharmaceutical Innovation	2016
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79	Maibach EW et al.	Do Americans understand that global warming Is harmful to human health? Evidence from a national survey.	Annals of Global Health	2015
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82	Markarian, J.	Reducing the environmental impact of manufacturing	Pharmaceutical Technology	2016
83	Martin, D.	Leading your hospital to sustainability	Health Facilities Management	2014
84	Maughan, D.L. et al.	Primary-care-based social prescribing for mental health: an analysis of financial and environmental sustainability	Primary Health Care Research & Development	2016
85	Mayers, I.	Climate change, Kyoto and the Canadian Thoracic Society	Canadian Respiratory Journal	2002
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87	McGain, F.	Why anaesthetists should no longer use nitrous oxide	Anaesthesia and Intensive Care	2007

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89	Melamed, A.	Environmental accountability in perioperative settings	AORN Journal	2003
90	Messelbeck, J., Whaley, M.	Greening the health care supply chain: triggers of change, models for success	Corporate Environmental Strategy	1999
91	Mohd Din, S.A., Nik Yahya, N.N.H., Othman, R.	Sustainable hospital for urban residents	Jurnal Teknologi (Sciences and Engineering)	2015
92	Ngwuluka, N.C., Ochekpe, N.A., Odumosu, P.O.	An assessment of pharmaceutical waste management in some Nigerian pharmaceutical industries	African Journal of Biotechnology	2011
93	Orru, H. et al	Impact of climate change on ozone-related mortality and morbidity in Europe	European Respiratory Journal	2013
94	Pallarito K.	Medical waste rules delayed	Modern Healthcare	1992
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97	Patwary, M.A. et al	Quantitative assessment of medical waste generation in the capital city of Bangladesh	Waste Management	2009
98	Picano, E.	Sustainability of medical imaging	BMJ	2004
99	Pishvaee, M.S., Razmi, J., Torabi, S.A.	An accelerated Benders decomposition algorithm for sustainable supply chain network design under uncertainty: a case study of medical needle and syringe supply chain	Transportation Research Part E: Logistics and Transportation Review	2014
100	Pungsornruk, K. et al	A renewed call for environmentally responsible anaesthesia	Anaesthesia and Intensive Care	2015
101	Radwan, A.F. et al	Retrofitting of existing buildings to achieve better energy-efficiency in commercial building case study: hospital in Egypt	AEJ - Alexandria Engineering Journal	2016
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107	Richardson, J. et al	Effect of climate change and resource scarcity on health care	Nursing Standard (Royal College of Nursing (Great Britain) : 1987)	2014
108	Roberts, J.R. et al	Integrating environmental management of asthma into pediatric health care: what worked and what still needs improvement?	Clinical Pediatrics	2016
109	Rosenblatt, W.H. et al	Case-by-case assessment of recoverable materials for overseas donation from 1318 surgical procedures	JAMA - Journal of the American Medical Association	1993
110	Ryder, M.	Pharmaceutical facility upgrades: the containment issues	Pharmaceutical Engineering	2006
111	Saad, S.A.G.	Management of hospitals solid waste in Khartoum State	Environmental Monitoring and Assessment	2013
112	Sachs JD.	High stakes at the UN on the Sustainable Development Goals	The Lancet	2013
113	Samet, K.A.	Healthier hospitals initiative. Improving sustainability and safety in healthcare.	Healthcare Executive	2011
114	Sarfaty, M. et al.	American Thoracic Society member survey on climate change and health	Annals of the American Thoracic Society	2015
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118	Schulte, M.F.	Green hospitals: improving the workplace, saving money, and healing the earth	Frontiers of Health Services Management	2008
119	Shaner-McRae, H., McRae, G., & Jas, V.	Environmentally safe health care agencies: nursing's responsibility, nightingale's legacy	Online Journal of Issues in Nursing	2007
120	Singh, R., Rustagi, N.	A mercury free health care organization: a must	Indian Journal of Public Health	2011
121	Sneyd, J.R., Montgomery, H., Pencheon, D.	The anaesthetist and the environment	Anaesthesia	2010
122	Somner, J. et al.	Ophthalmology carbon footprint: something to be considered?	Journal of Cataract and Refractive Surgery	2009
123	Soni, N.	Nosocomial infection and global warming	Current Anaesthesia and Critical Care	2005
124	Soroceanu A et al	Intraoperative waste in spine surgery: incidence, cost, and effectiveness of an educational program	Spine	2011
125	Starobin, N.	Home's where the harm is	Hospitals and Health Networks	1999
126	Stone, D.	Greening healthcare at Muskoka Algonquin Healthcare	Healthcare Management Forum	2017
127	Stott, S.A.	Anaesthesia, the environment, and our carbon footprint	Anaesthesia	2010
128	Straub, J.O.	Reduction in the environmental exposure of pharmaceuticals through diagnostics, Personalised Healthcare and other approaches. A mini review and discussion paper.	Sustainable Chemistry and Pharmacy	2016
129	Suwannee, A.	Study on waste from hospital and clinics in Phitsanulok	Online Journal of Health and Allied Sciences	2002
130	Suzuki O, Tanaka K, Watanabe N, Takeda M	Design criteria and containment evaluation for pharmaceutical containment systems in aseptic dosage form manufacturing facilities	Pharmaceutical Technology	2003
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132	Tesfahun E, Kumie A, Beyene A.	Developing models for the prediction of hospital healthcare waste generation rate	Waste Management and Research	2016
133	Thiel, C., Duncan, P., Woods, N.	Attitude of US obstetricians and gynaecologists to global warming and medical waste	Journal of Health Services Research and Policy	2017
134	Thiel, C.L. et al	Environmental impacts of surgical procedures: life cycle assessment of hysterectomy in the United States	Journal of Environmental Science and Technology	2015
135	Tomson, C., Connor, A.	Outlook: Implications of climate change for nephrology	Nature Reviews Nephrology	2015
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138	Ugwu AC.	Global climate change and body functions	Nigerian Journal of Physiological Sciences	2010
139	Ul Rahman et al.	Knowledge and attitude of nurses regarding healthcare waste management practices in a tertiary care hospitals of Lahore	Pakistan Journal of Medical and Health Sciences	2017
140	Van der Vorst, G. et al.	A systematic evaluation of the resource consumption of active pharmaceutical ingredient production at three different levels	Journal of Environmental Science and Technology	2011
141	Vidal, R. et al.	Comparison of the carbon footprint of different patient diets in a Spanish hospital	Journal of Health Services Research and Policy	2015
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144	Voudrias E. et al.	Composition and production rate of pharmaceutical and chemical waste from Xanthi General Hospital in Greece	Waste Management	2012
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148	Yasny, J.S., White, J.	Environmental implications of anesthetic gases	Anesthesia Progress	2012
149	Zheng Y.	The benefit of public transportation: physical activity to reduce obesity and ecological footprint	Preventive Medicine	2008
150	[No author name available]	China to study links between sustainable development and investment in health	International Journal of Health Care Quality Assurance	2003
151	[No author name available]	Sustainable healthcare (book review)	International Journal of Health Care Quality Assurance	2013
152	[No author name available]	ASHP guidelines on handling hazardous drugs	American Journal of Health-System Pharmacy	2006
153	[No author name available]	Climate change: How soon is now?	The Lancet	2014
154	[No author name available]	A changing climate for health	The Lancet	2005
155	[No author name available]	Global climate change and children's health	Pediatrics	2015
156	[No authors listed]	CRVS systems: a cornerstone of sustainable development	The Lancet	2015
157	[No authors listed]	Position of the American Dietetic Association: natural resource conservation and waste management	Journal of the American Dietetic Association	1997

Annex C. Re-scaled WGI scores for the year 2016

Code	Country Name	Score	Code	Country Name	Score	Code	Country Name	Score
8	Albania	0.431	288	Ghana	0.526	584	Marshall Isds	0.458
12	Algeria	0.720	296	Kiribati	0.325	585	Palau	0.310
16	American Samoa	0.261	300	Greece	0.524	586	Pakistan	0.997
24	Angola	0.563	304	Greenland	0.107	591	Panama	0.418
28	Antigua and Barbuda	0.324	308	Grenada	0.296	598	Papua New Guinea	0.601
31	Azerbaijan	0.661	316	Guam	0.365	600	Paraguay	0.472
32	Argentina	0.459	320	Guatemala	0.609	604	Peru	0.540
36	Australia	0.290	324	Guinea	0.579	608	Philippines	0.776
40	Austria	0.318	328	Guyana	0.505	616	Poland	0.399
44	Bahamas	0.305	332	Haiti	0.649	620	Portugal	0.305
48	Bahrain	0.659	340	Honduras	0.587	624	Guinea-Bissau	0.589
50	Bangladesh	0.752	344	China, Hong Kong SAR	0.350	626	Timor-Leste	0.502
51	Armenia	0.632	348	Hungary	0.369	634	Qatar	0.320
52	Barbados	0.305	352	Iceland	0.228	638	Réunion	0.437
56	Belgium	0.412	360	Indonesia	0.575	642	Romania	0.445
60	Bermuda	0.300	364	Iran	0.663	643	Russian Federation	0.689
64	Bhutan	0.275	368	Iraq	0.963	646	Rwanda	0.511
68	Bolivia	0.550	372	Ireland	0.330	659	Saint Kitts and Nevis	0.375
70	Bosnia Herzegovina	0.580	376	Israel	0.659	660	Anguilla	0.237
72	Botswana	0.301	381	Italy	0.426	662	Saint Lucia	0.296
76	Brazil	0.575	384	Côte d'Ivoire	0.682	674	San Marino	0.310
84	Belize	0.488	388	Jamaica	0.438	678	Sao Tome and Principe	0.455
90	Solomon Isds	0.399	392	Japan	0.303	682	Saudi Arabia	0.593
96	Brunei Darussalam	0.269	398	Kazakhstan	0.498	686	Senegal	0.544
100	Bulgaria	0.485	400	Jordan	0.598	688	Serbia	0.472
104	Myanmar	0.661	404	Kenya	0.771	690	Seychelles	0.353
108	Burundi	0.894	408	Dem. People's Rep. of Korea	0.636	694	Sierra Leone	0.532
112	Belarus	0.472	410	Rep. of Korea	0.467	699	India	0.691
116	Cambodia	0.458	414	Kuwait	0.510	702	Singapore	0.201
120	Cameroon	0.712	417	Kyrgyzstan	0.629	703	Slovakia	0.356
124	Canada	0.249	418	Lao People's Dem. Rep.	0.394	704	Viet Nam	0.453
132	Cape Verde	0.323	422	Lebanon	0.824	705	Slovenia	0.302
136	Cayman Isds	0.266	426	Lesotho	0.547	706	Somalia	0.971
140	Central African Rep.	0.858	428	Latvia	0.404	710	South Africa	0.528
144	Sri Lanka	0.501	430	Liberia	0.587	716	Zimbabwe	0.624
148	Chad	0.760	434	Libya	0.957	724	Spain	0.417
152	Chile	0.417	440	Lithuania	0.334	736	Sudan	0.967
156	China	0.600	442	Luxembourg	0.216	740	Suriname	0.468
170	Colombia	0.676	446	China, Macao SAR	0.217	748	Swaziland	0.598
174	Comoros	0.493	450	Madagascar	0.558	752	Sweden	0.296
178	Congo	0.604	454	Malawi	0.523	757	Switzerland	0.239
180	Congo	0.604	458	Malaysia	0.473	762	Tajikistan	0.656
188	Costa Rica	0.368	462	Maldives	0.416	764	Thailand	0.698
191	Croatia	0.367	466	Mali	0.823	768	Togo	0.534
192	Cuba	0.363	470	Malta	0.284	776	Tonga	0.316
196	Cyprus	0.379	474	Martinique	0.300	780	Trinidad and Tobago	0.443
203	Czech Republic	0.305	478	Mauritania	0.649	784	United Arab Emirates	0.387
204	Benin	0.500	480	Mauritius	0.297	788	Tunisia	0.728
208	Denmark	0.326	484	Mexico	0.626	792	Turkey	0.902
212	Dominica	0.300	496	Mongolia	0.340	795	Turkmenistan	0.538
214	Dominican Rep.	0.450	498	Rep. of Moldova	0.561	798	Tuvalu	0.217
218	Ecuador	0.517	499	Montenegro	0.445	800	Uganda	0.643
222	El Salvador	0.520	504	Morocco	0.563	804	Ukraine	0.871
226	Equatorial Guinea	0.528	508	Mozambique	0.719	807	TFYR of Macedonia	0.570
231	Ethiopia	0.824	512	Oman	0.348	818	Egypt	0.788
232	Eritrea	0.631	516	Namibia	0.358	826	United Kingdom	0.428
233	Estonia	0.365	520	Nauru	0.384	834	United Rep. of Tanzania	0.588
242	Fiji	0.316	524	Nepal	0.669	842	USA	0.420
246	Finland	0.300	528	Netherlands	0.318	850	US Virgin Isds	0.300
251	France	0.519	548	Vanuatu	0.397	854	Burkina Faso	0.673
254	French Guiana	0.390	554	New Zealand	0.196	858	Uruguay	0.287
262	Djibouti	0.625	558	Nicaragua	0.518	860	Uzbekistan	0.555
266	Gabon	0.521	562	Niger	0.721	862	Venezuela	0.705
268	Georgia	0.563	566	Nigeria	0.876	882	Samoa	0.261
270	Gambia	0.587	579	Norway	0.260	894	Zambia	0.471
276	Germany	0.364	583	FS Micronesia	0.288			

Annex D. GeoPolRisk values for 13 raw materials from the EU perspective for 2016

Assessment under a range of scenarios for the EoL-RIR and supply mix

	Beryllium		Boron		Cobalt		Gallium Group		Germanium	
EoL RIR	BCS	WCS	BCS	WCS	BCS	WCS	BCS	WCS	BCS	WCS
0%	0.023	0.023	0.125	0.125	0.182	0.182	0.107	0.107	0.296	0.296
5%	0.021	0.022	0.105	0.121	0.171	0.175	0.100	0.104	0.279	0.286
10%	0.020	0.020	0.088	0.117	0.162	0.165	0.094	0.100	0.261	0.275
15%	0.019	0.019	0.075	0.114	0.153	0.156	0.088	0.096	0.244	0.264
20%	0.018	0.018	0.065	0.110	0.143	0.147	0.082	0.092	0.227	0.251
25%	0.017	0.017	0.057	0.107	0.134	0.138	0.076	0.087	0.212	0.236
30%	0.016	0.016	0.051	0.103	0.125	0.129	0.070	0.082	0.197	0.221
35%	0.015	0.015	0.047	0.099	0.116	0.119	0.064	0.077	0.182	0.206
40%	0.013	0.014	0.044	0.096	0.107	0.110	0.059	0.071	0.166	0.190
45%	0.012	0.012	0.040	0.092	0.098	0.101	0.053	0.065	0.151	0.175
50%	0.011	0.011	0.036	0.088	0.088	0.092	0.047	0.059	0.136	0.160
55%	0.010	0.010	0.033	0.085	0.079	0.083	0.041	0.053	0.121	0.145
60%	0.009	0.009	0.029	0.081	0.070	0.074	0.035	0.048	0.106	0.130
65%	0.008	0.008	0.025	0.077	0.061	0.064	0.030	0.042	0.091	0.115
70%	0.007	0.007	0.022	0.074	0.052	0.055	0.024	0.036	0.075	0.099
75%	0.006	0.006	0.018	0.068	0.042	0.046	0.019	0.030	0.060	0.084
80%	0.004	0.005	0.015	0.060	0.033	0.037	0.015	0.024	0.045	0.069
85%	0.003	0.003	0.011	0.050	0.024	0.028	0.011	0.019	0.032	0.052
90%	0.002	0.002	0.007	0.037	0.015	0.018	0.006	0.013	0.021	0.035
95%	0.001	0.001	0.004	0.020	0.006	0.009	0.002	0.006	0.011	0.017
100%	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

	Magnesium		Natural Graphite		Palladium		Platinum		Other PGM	
EoL RIR	BCS	WCS	BCS	WCS	BCS	WCS	BCS	WCS	BCS	WCS
0%	0.457	0.457	0.273	0.273	0.154	0.154	0.246	0.246	0.382	0.382
5%	0.433	0.436	0.252	0.267	0.144	0.150	0.229	0.240	0.356	0.372
10%	0.410	0.413	0.233	0.261	0.134	0.147	0.212	0.234	0.334	0.362
15%	0.387	0.390	0.218	0.252	0.125	0.143	0.197	0.227	0.312	0.352
20%	0.364	0.367	0.203	0.240	0.115	0.138	0.183	0.218	0.290	0.339
25%	0.342	0.344	0.189	0.227	0.105	0.132	0.170	0.207	0.268	0.323
30%	0.319	0.321	0.174	0.214	0.096	0.126	0.156	0.196	0.246	0.305
35%	0.296	0.298	0.160	0.200	0.086	0.119	0.143	0.183	0.224	0.283
40%	0.273	0.275	0.145	0.186	0.076	0.111	0.130	0.170	0.201	0.261
45%	0.250	0.253	0.131	0.172	0.067	0.104	0.116	0.156	0.179	0.239
50%	0.227	0.230	0.116	0.157	0.057	0.096	0.103	0.143	0.157	0.217
55%	0.204	0.207	0.102	0.142	0.049	0.086	0.090	0.130	0.135	0.195
60%	0.181	0.184	0.087	0.128	0.042	0.077	0.076	0.116	0.113	0.172
65%	0.158	0.161	0.073	0.113	0.035	0.067	0.063	0.103	0.091	0.150
70%	0.136	0.138	0.059	0.099	0.027	0.058	0.050	0.090	0.070	0.128
75%	0.113	0.115	0.046	0.084	0.021	0.048	0.039	0.076	0.053	0.106
80%	0.090	0.092	0.033	0.070	0.015	0.038	0.028	0.063	0.038	0.084
85%	0.067	0.069	0.021	0.055	0.010	0.029	0.019	0.049	0.026	0.062
90%	0.044	0.047	0.013	0.040	0.007	0.019	0.012	0.034	0.016	0.040
95%	0.021	0.024	0.006	0.021	0.003	0.009	0.006	0.017	0.006	0.018
100%	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

	REE		Silicon Metal		Tantalum	
EoL RIR	**BCS**	**WCS**	**BCS**	**WCS**	**BCS**	**WCS**
0%	0.336	0.336	0.170	0.170	0.096	0.096
5%	0.316	0.324	0.157	0.165	0.090	0.094
10%	0.295	0.312	0.147	0.160	0.083	0.090
15%	0.275	0.300	0.138	0.154	0.077	0.086
20%	0.255	0.288	0.128	0.147	0.070	0.082
25%	0.234	0.277	0.119	0.140	0.064	0.078
30%	0.214	0.265	0.110	0.134	0.058	0.074
35%	0.194	0.253	0.100	0.125	0.054	0.070
40%	0.173	0.241	0.091	0.116	0.049	0.065
45%	0.153	0.224	0.081	0.106	0.045	0.061
50%	0.133	0.203	0.072	0.097	0.040	0.056
55%	0.112	0.183	0.063	0.088	0.036	0.051
60%	0.095	0.163	0.053	0.078	0.031	0.047
65%	0.083	0.142	0.044	0.069	0.027	0.042
70%	0.071	0.122	0.036	0.060	0.022	0.038
75%	0.059	0.102	0.029	0.050	0.018	0.032
80%	0.048	0.081	0.022	0.041	0.014	0.026
85%	0.036	0.061	0.016	0.031	0.010	0.020
90%	0.024	0.041	0.010	0.022	0.007	0.013
95%	0.012	0.021	0.004	0.012	0.003	0.007
100%	0.000	0.000	0.000	0.000	0.000	0.000

Annex E. Elasticity Calculations for Al, Co, Cu and Ni

Material	Aluminum
Event	Cyclone Hudhud (13/10/2014)
(T) Total production (t/y)	56,668,160
(D) Disrupted Production (t/y)	9,600,000
(d=100*D/T) Disrupted Production (%)	16.94%
(p) Price increase ratio	0.7465
Estimated Ɛ=p/d	0.044

Material	Cobalt
Event	Hurricane Matthew (04/10/2016)
Total production (t/y)	134,239
Disrupted Production (t/y)	3,000
Disrupted Production (%)	2.23%
Price increase ratio	1.8182
Estimated Ɛ	0.814

Material	Copper
Event	Romanian Flood (04/07/2005)
Total production (t/y)	19,319,839
Disrupted Production (t/y)	900,000
Disrupted Production (%)	4.66%
Price increase ratio	0.9962
Estimated Ɛ	0.214

Material	Nickel
Event	Typhoon Parma (05/10/2009)
Total production (t/y)	2,206,513
Disrupted Production (t/y)	91,000
Disrupted Production (%)	4.12%
Price increase ratio	1.5214
Estimated Ɛ	0.369

Annex F. HHI Calculation for Al, Co, Cu and Ni from 2015 to 2017

Year	HS Code	Commodity	World Total (kg)	Partial SumProduct Producing Countries	Total Production Squared	**HHI**
2015	2606	Bauxite (Al)	2.84E+11	1.42E+22	8.12E+22	**0.1748**
2015	810520	Cobalt	1.14E+08	4.56E+15	1.31E+16	**0.3462**
2015	7403	Copper	1.91E+10	4.59E+19	3.66E+20	**0.1255**
2015	7502	Nickel	2.12E+09	4.91E+17	4.52E+18	**0.1087**
2016	2606	Bauxite (Al)	2.66E+11	1.38E+22	7.11E+22	**0.1946**
2016	810520	Cobalt	1.09E+08	4.27E+15	1.19E+16	**0.3580**
2016	7403	Copper	1.59E+10	4.57E+19	2.55E+20	**0.1793**
2016	7502	Nickel	2.03E+09	3.93E+17	4.15E+18	**0.0947**
2017	2606	Bauxite (Al)	2.89E+11	1.57E+22	8.38E+22	**0.1874**
2017	810520	Cobalt	1.18E+08	5.50E+15	1.39E+16	**0.3947**
2017	7403	Copper	1.60E+10	4.30E+19	2.57E+20	**0.1674**
2017	7502	Nickel	1.94E+09	4.13E+17	3.77E+18	**0.1094**

Annex G.GeoPolRisk$_{OECD}$ Calculations for Al, Co, Cu and Ni (2015-2017)

YEAR: 2015	Aluminum	Cobalt	Copper	Nickel
TOTAL OECD IMPORTS (KG)	2.63E+10	8.22E+06	1.23E+09	1.55E+08
TOTAL OECD PRODUCTION (KG)	8.27E+10	1.10E+07	1.02E+10	5.33E+08
TOTAL WGI*IMPORTS (KG)	1.44E+10	4.48E+06	7.26E+08	9.46E+07
TOTAL IMPORTS + OECD PRODUCTION (KG)	1.09E+11	1.93E+07	1.14E+10	6.88E+08
HHI	0.1748	0.3462	0.1255	0.1087
GEOPOLRISK $_{OECD}$	0.0231	0.0803	0.0079	0.0149

YEAR: 2016	Aluminum	Cobalt	Copper	Nickel
TOTAL OECD IMPORTS (KG)	1.99E+10	7.75E+06	1.44E+09	1.24E+08
TOTAL OECD PRODUCTION (KG)	8.38E+10	1.04E+07	9.38E+09	5.14E+08
TOTAL WGI*IMPORTS (KG)	1.09E+10	4.12E+06	8.56E+08	7.76E+07
TOTAL IMPORTS + OECD PRODUCTION (KG)	1.03E+11	1.81E+07	1.08E+10	6.39E+08
HHI	0.1946	0.3580	0.1793	0.0947
GEOPOLRISK $_{OECD}$	0.0205	0.0812	0.0142	0.0115

YEAR: 2017	Aluminum	Cobalt	Copper	Nickel
TOTAL OECD IMPORTS (KG)	1.80E+10	8.81E+06	1.23E+09	1.13E+08
TOTAL OECD PRODUCTION (KG)	8.48E+10	9.54E+06	8.83E+09	4.23E+08
TOTAL WGI*IMPORTS (KG)	1.03E+10	4.49E+06	7.05E+08	6.71E+07
TOTAL IMPORTS + OECD PRODUCTION (KG)	1.02+11	1.83E+07	1.00E+10	5.36E+08
HHI	0.1874	0.3947	0.1674	0.1094
GEOPOLRISK $_{OECD}$	0.0188	0.0967	0.0117	0.0137

Annex H. GeoPolEndpoint Calculations for Al, Co, Cu and Ni as part of LIB (2015-2017)

	MidPoint (GeoPolRisk -OECD) 0-1			Cost Increase Factors Price %			EndPoint (Relative Damage) CostIncreaseFactor*price (USD/t)		
	GeoPolGlobal 2015	GeoPolGlobal 2016	GeoPolGlobal 2017	2015	2016	2017	GeoPolEndpoint 2015	GeoPolEndpoint 2016	GeoPolEndpoint 2017
Aluminum	0.023	0.020	0.019	0.10%	0.09%	0.08%	1.69	1.45	1.63
Cobalt	0.080	0.081	0.097	6.54%	6.61%	7.86%	1861.49	1687.15	4370.86
Copper	0.008	0.014	0.012	0.17%	0.30%	0.25%	9.33	14.78	15.49
Nickel	0.015	0.012	0.014	0.55%	0.42%	0.51%	65.43	40.96	52.96

	Cost (Raw Materials Cost per kWh)						Endpoint (Absolute Damage per kWh)					
	USD/kWh (NCA-C)			USD/kWh (NMC-C)			USD/kWh (NCA-C)			USD/kWh (NMC-C)		
	Cost Contribution 2015	Cost Contribution 2016	Cost Contribution 2017	Cost Contribution 2015	Cost Contribution 2016	Cost Contribution 2017	Socio-economic damage 2015	Socio-economic damage 2016	Socio-economic damage 2017	Socio-economic damage 2015	Socio-economic damage 2016	Socio-economic damage 2017
Aluminum	0.73	0.70	0.86	0.45	0.43	0.53	0.001	0.001	0.001	0.000	0.000	0.000
Cobalt	4.31	3.86	8.41	11.87	10.64	23.18	0.282	0.255	0.662	0.776	0.703	1.822
Copper	4.63	4.10	5.19	6.96	6.16	7.81	0.008	0.012	0.013	0.012	0.019	0.020
Nickel	9.55	7.76	8.42	4.93	4.01	4.35	0.053	0.033	0.043	0.027	0.017	0.022
Total	19.22	16.42	22.89	24.22	21.24	35.86	0.343	0.301	0.718	0.816	0.740	1.864
						Damage/Cost	1.78%	1.84%	3.14%	3.37%	3.48%	5.20%

Annex I. GeoPolRisk Values for Al, Co, Cu and Ni for the EU from 2015 to 2017

GeoPolRisk results: EU Perspective

Interpreted as portion of the overall material at iminent risk of supply

GeoPolRisk (mean)	2015	2016	2017
Bauxite (Al)	0.082	0.085	0.084
Cobalt (Co)	0.108	0.132	0.168
Copper (Cu)	0.018	0.025	0.023
Nickel (Ni)	0.028	0.024	0.022

Scale: 0 to 1

Original GeoPolRisk	2015	2016	2017
Bauxite (Al)	0.094	0.097	0.096
Cobalt (Co)	0.108	0.132	0.168
Copper (Cu)	0.040	0.061	0.057
Nickel (Ni)	0.043	0.036	0.034

Scale: 0 to 1

GeoPolRisk R - WCS	2015	2016	2017	EoL - RIR
Bauxite (Al)	0.088	0.091	0.090	12.4%
Cobalt (Co)	0.108	0.132	0.168	0.0%
Copper (Cu)	0.022	0.031	0.027	55.0%
Nickel (Ni)	0.034	0.029	0.025	33.9%

Scale: 0 to 1

GeoPolRisk R - BCS	2015	2016	2017	EoL - RIR
Bauxite (Al)	0.076	0.079	0.078	12.4%
Cobalt (Co)	0.108	0.132	0.168	0.0%
Copper (Cu)	0.013	0.019	0.018	55.0%
Nickel (Ni)	0.021	0.018	0.018	33.9%

Scale: 0 to 1

Annex J. GeoPolEndpoint and damage associated to the use of Al, Co, Cu and Ni in LIB

	Inventory		MidPoint (GeoPolRisk - EU)			Cost Increase Factors			EndPoint (Relative Damage)			Endpoint (Damage)					
	Mass %		0-1			Price %			USD/t			USD/t Li-ion Battery (NCA-C)			USD/t Li-ion Battery (NMC-C)		
	Mass NCA-C (Inventory)	Mass NMC-C (Inventory)	2015	2016	2017	2015	2016	2017	2015	2016	2017	2015	2016	2017	2015	2016	2017
Aluminum	12.50%	6.98%	0.082	0.085	0.084	0.36%	0.37%	0.37%	6.01	6.01	7.29	0.75	0.75	0.91	0.42	0.42	0.51
Cobalt	4.33%	10.84%	0.108	0.132	0.168	8.79%	10.74%	13.67%	2502.23	2741.63	7597.36	108.35	118.71	328.97	271.24	297.19	823.55
Copper	24.10%	32.90%	0.018	0.025	0.023	0.37%	0.53%	0.48%	20.59	26.02	29.70	4.96	6.27	7.16	6.78	8.56	9.77
Nickel	23.03%	10.80%	0.028	0.024	0.022	1.01%	0.87%	0.79%	120.50	83.64	83.04	27.75	19.26	19.12	13.01	9.03	8.97
Total	63.96%	61.52%							Total Damage (USD/t Li-ion Battery)			**141.81**	**145.00**	**356.16**	**291.45**	**315.21**	**842.80**

Annex K. Results of the Integrated Assessment of LIB (Midpoint)

NCA-C	Mass	Acidification	Global Warming Potential	Abiotic Depletion Potential	Fresh Water Ecotoxicity	Marine Ecotoxicity	Terrestrial Ecotoxicity	Eutrophication	Human toxicity	Ozone Depletion Potential	Photochemical Oxidation	Geopolitical Supply Risk		
	Inventory	kg SO2 eq	kg CO2 eq	kg Sb eq	kg 1,4-DB eq	kg 1,4-DB eq	kg 1,4-DB eq	kg PO4 eq	kg 1,4-DB eq	kg CFC-11 eq	kg C2H4 eq	GeoPolRisk 2015	GeoPolRisk 2016	GeoPolRisk 2017
Aluminum	12.50%	7.506E-03	1.2093	7.031E-03	0.696	2.4794	2.887E-04	1.667E-03	2.4560	3.860E-08	4.385E-04	0.08	0.085	0.084
Cobalt	4.33%	4.177E-03	0.4650	2.779E-03	0.165	0.6078	2.044E-04	1.350E-03	0.2876	3.092E-08	1.089E-04	0.11	0.132	0.168
Copper	24.10%	4.925E-02	1.0217	8.424E-03	8.793	33.4529	6.377E-03	3.353E-02	22.3344	1.150E-07	1.948E-03	0.02	0.025	0.023
Nickel	23.03%	6.926E-01	2.5983	1.560E-02	11.168	41.7278	8.178E-03	2.460E-02	6.6469	1.598E-07	2.757E-02	0.03	0.024	0.022

NMC-C	Mass	Acidification	Global Warming Potential	Abiotic Depletion Potential	Fresh Water Ecotoxicity	Marine Ecotoxicity	Terrestrial Ecotoxicity	Eutrophication	Human toxicity	Ozone Depletion Potential	Photochemical Oxidation	Geopolitical Supply Risk		
	Inventory	kg SO2 eq	kg CO2 eq	kg Sb eq	kg 1,4-DB eq	kg 1,4-DB eq	kg 1,4-DB eq	kg PO4 eq	kg 1,4-DB eq	kg CFC-11 eq	kg C2H4 eq	GeoPolRisk 2015	GeoPolRisk 2016	GeoPolRisk 2017
Aluminum	6.98%	4.191E-03	0.6753	3.926E-03	0.388	1.3845	1.612E-04	9.306E-04	1.3714	2.156E-08	2.449E-04	0.08	0.085	0.084
Cobalt	10.84%	1.046E-02	1.1641	6.958E-03	0.412	1.5215	5.117E-04	3.379E-03	0.7201	7.740E-08	2.727E-04	0.11	0.132	0.168
Copper	32.90%	6.724E-02	1.3948	1.150E-02	12.004	45.6681	8.706E-03	4.577E-02	30.4898	1.570E-07	2.660E-03	0.02	0.025	0.023
Nickel	10.80%	3.248E-01	1.2185	7.317E-03	5.237	19.5684	3.835E-03	1.153E-02	3.1171	7.495E-08	1.293E-02	0.03	0.024	0.022

Annex L. Results of the Integrated Assessment of LIB (Endpoint)

NCA-C	Mass	Human Health	Ecosystem loss	Resources	Socio-economic Damage		
	Inventory	DALY	species.yr	USD	2015 (USD)	2016 (USD)	2017 (USD)
Aluminum	12.50%	2.766E-06	1.020E-08	0.0425	0.75	0.75	0.91
Cobalt	4.33%	1.499E-06	4.863E-09	0.0258	108.35	118.71	328.97
Copper	24.10%	2.099E-05	1.318E-08	0.3515	4.96	6.27	7.16
Nickel	23.03%	4.451E-05	2.814E-08	0.7388	27.75	19.26	19.12

NMC-C	Mass	Human Health	Ecosystem loss	Resources	Socio-economic Damage		
	Inventory	DALY	species.yr	USD	2015 (USD)	2016 (USD)	2017 (USD)
Aluminum	6.98%	1.544E-06	5.693E-09	0.0237	0.42	0.42	0.51
Cobalt	10.84%	3.754E-06	1.217E-08	0.0647	271.24	297.19	823.56
Copper	32.90%	2.866E-05	1.799E-08	0.4799	6.78	8.56	9.77
Nickel	10.80%	2.087E-05	1.320E-08	0.3465	13.01	9.03	8.97

Annex M. Global Production of helium and HHI calculations (2015-2018)

As per the HHI formula; the values are calculated as follows:

HHI=(SUM of all SQUARED individual production values) / (SQUARED of total global production)

PRODUCTION MIX (million cubic meters) - USGS (2016,2017,2018,2019)

Code	12	36	616	634	643	804	842		
Year	Algeria	Australia	Poland	Qatar	Russia	Ukraine	USA	Total	HHI
2015	10	4	2	49	3	0	88	156	0.4222
2016	10	4	2	50	3	0	89	158	0.4226
2017	14	4	2	45	3	0	91	159	0.4166
2018	14	4	2	45	3	0	90	158	0.4146

Annex N. Raw helium trade database to top 10 consuming countries (2015-2018)

Exporting Country	*Net Import*	*Share*	*Importing Country*	*Year*	*Allocation to original producer*
Australia	USD 13,783.00	0.06%	Brazil	2015	Australia
Austria	USD 7,557.00	0.04%	Brazil	2015	Exclude from analysis
Canada	USD 2,098.00	0.01%	Brazil	2015	Exclude from analysis
Germany	USD 54,394.00	0.25%	Brazil	2015	Exclude from analysis
Denmark	USD 1,722.00	0.01%	Brazil	2015	Exclude from analysis
France	USD 4,907.00	0.02%	Brazil	2015	Exclude from analysis
United Kingdom	USD 3,975,621.00	18.46%	Brazil	2015	United States of America
Italy	USD 5,825.00	0.03%	Brazil	2015	Exclude from analysis
Netherlands	USD 3,928.00	0.02%	Brazil	2015	Exclude from analysis
Portugal	USD 69,139.00	0.32%	Brazil	2015	Exclude from analysis
Russia	USD 19,294.00	0.09%	Brazil	2015	Russia
United States of America	USD 17,375,767.00	80.69%	Brazil	2015	United States of America
Australia	USD 12,378.00	0.06%	Brazil	2016	Australia
Austria	USD 1,419.00	0.01%	Brazil	2016	Exclude from analysis
Germany	USD 38,303.00	0.20%	Brazil	2016	Exclude from analysis
Algeria	USD 623,995.00	3.26%	Brazil	2016	Algeria
France	USD 198,511.00	1.04%	Brazil	2016	Algeria
United Kingdom	USD 1,899,965.00	9.91%	Brazil	2016	Qatar
Israel	USD 264,641.00	1.38%	Brazil	2016	United States of America
Italy	USD 1,474.00	0.01%	Brazil	2016	Exclude from analysis
Netherlands	USD 6,998.00	0.04%	Brazil	2016	Exclude from analysis
Poland	USD 161,899.00	0.84%	Brazil	2016	Poland

Exporting Country	*Net Import*	*Share*	*Importing Country*	*Year*	*Allocation to original producer*
Portugal	USD 109,183.00	0.57%	Brazil	2016	Exclude from analysis
United States of America	USD 15,845,487.00	82.68%	Brazil	2016	United States of America
Australia	USD 12,384.00	0.08%	Brazil	2017	Australia
Austria	USD 8,063.00	0.05%	Brazil	2017	Exclude from analysis
Belgium	USD 1,399.00	0.01%	Brazil	2017	Exclude from analysis
Germany	USD 64,724.00	0.40%	Brazil	2017	Exclude from analysis
Denmark	USD 2,030.00	0.01%	Brazil	2017	Exclude from analysis
Algeria	USD 172,510.00	1.08%	Brazil	2017	Algeria
United Kingdom	USD 8,304.00	0.05%	Brazil	2017	Exclude from analysis
Italy	USD 61,806.00	0.39%	Brazil	2017	Exclude from analysis
South Korea	USD 73,180.00	0.46%	Brazil	2017	Exclude from analysis
Portugal	USD 165,538.00	1.03%	Brazil	2017	Algeria
United States of America	USD 15,456,534.00	96.44%	Brazil	2017	United States of America
Australia	USD 27,516.00	0.19%	Brazil	2018	Australia
Austria	USD 7,098.00	0.05%	Brazil	2018	Exclude from analysis
Belgium	USD 6,313.00	0.04%	Brazil	2018	Exclude from analysis
Germany	USD 42,250.00	0.29%	Brazil	2018	Exclude from analysis
France	USD 8,126.00	0.06%	Brazil	2018	Exclude from analysis
United Kingdom	USD 44,384.00	0.30%	Brazil	2018	Exclude from analysis
Italy	USD 4,996.00	0.03%	Brazil	2018	Exclude from analysis
South Korea	USD 140,407.00	0.96%	Brazil	2018	United States of America
Netherlands	USD 13,358.00	0.09%	Brazil	2018	Exclude from analysis
Portugal	USD 145,293.00	1.00%	Brazil	2018	Exclude from analysis
Russia	USD 20,778.00	0.14%	Brazil	2018	Russia
United States of America	USD 14,103,809.00	96.84%	Brazil	2018	United States of America

Exporting Country	*Net Import*	*Share*	*Importing Country*	*Year*	*Allocation to original producer*
Germany	USD 55,148.00	0.22%	Canada	2015	Exclude from analysis
France	USD 28,209.00	0.11%	Canada	2015	Exclude from analysis
United Kingdom	USD 539,039.00	2.11%	Canada	2015	United States of America
Hong Kong	USD 775.00	0.00%	Canada	2015	Exclude from analysis
Ukraine	USD 2,204.00	0.01%	Canada	2015	Ukraine
United States of America	USD 24,950,286.00	97.55%	Canada	2015	United States of America
Azerbaijan	USD 1,849.00	0.01%	Canada	2016	Exclude from analysis
China	USD 26,749.00	0.13%	Canada	2016	Exclude from analysis
Germany	USD 12,875.00	0.06%	Canada	2016	Exclude from analysis
France	USD 93,180.00	0.44%	Canada	2016	Exclude from analysis
United Kingdom	USD 24,114.00	0.11%	Canada	2016	Exclude from analysis
Ukraine	USD 7,150.00	0.03%	Canada	2016	Ukraine
United States of America	USD 21,147,005.00	99.21%	Canada	2016	United States of America
South Africa	USD 1,025.00	0.00%	Canada	2016	Exclude from analysis
Taiwan	USD 1,098.00	0.01%	Canada	2016	Exclude from analysis
Australia	USD 1,187.00	0.01%	Canada	2017	Australia
Austria	USD 6,210.00	0.03%	Canada	2017	Exclude from analysis
China	USD 16,319.00	0.08%	Canada	2017	Exclude from analysis
Germany	USD 44,422.00	0.22%	Canada	2017	Exclude from analysis
France	USD 58,375.00	0.29%	Canada	2017	Exclude from analysis
United Kingdom	USD 3,013.00	0.02%	Canada	2017	Exclude from analysis
United States of America	USD 19,680,815.00	99.34%	Canada	2017	United States of America
South Africa	USD 1,407.00	0.01%	Canada	2017	Exclude from analysis
Austria	USD 4,517.00	0.02%	Canada	2018	Exclude from analysis
Czechia	USD 26,263.00	0.13%	Canada	2018	Exclude from analysis

Exporting Country	*Net Import*	*Share*	*Importing Country*	*Year*	*Allocation to original producer*
Germany	USD 63,695.00	0.30%	Canada	2018	Exclude from analysis
France	USD 20,144.00	0.10%	Canada	2018	Exclude from analysis
Mexico	USD 2,675.00	0.01%	Canada	2018	Exclude from analysis
Netherlands	USD 2,505.00	0.01%	Canada	2018	Exclude from analysis
United States of America	USD 20,861,853.00	99.43%	Canada	2018	United States of America
Australia	USD 12,243,626.00	10.35%	China	2015	Australia
Belgium	USD 3,331.00	0.00%	China	2015	Exclude from analysis
Germany	USD 246,448.00	0.21%	China	2015	Exclude from analysis
France	USD 217,321.00	0.18%	China	2015	Exclude from analysis
United Kingdom	USD 93,468.00	0.08%	China	2015	Exclude from analysis
South Korea	USD 14,547,682.00	12.30%	China	2015	United States of America
Philippines	USD 26,626.00	0.02%	China	2015	Exclude from analysis
Qatar	USD 74,867,255.00	63.31%	China	2015	Qatar
Russia	USD 92,381.00	0.08%	China	2015	Russia
Singapore	USD 768,429.00	0.65%	China	2015	Exclude from analysis
United States of America	USD 15,142,554.00	12.81%	China	2015	United States of America
Australia	USD 12,922,166.00	9.08%	China	2016	Australia
Czechia	USD 4,195.00	0.00%	China	2016	Exclude from analysis
Germany	USD 856,435.00	0.60%	China	2016	Exclude from analysis
Fiji	USD 2,195.00	0.00%	China	2016	Exclude from analysis
France	USD 646,367.00	0.45%	China	2016	Exclude from analysis
United Kingdom	USD 107,694.00	0.08%	China	2016	Exclude from analysis
Hong Kong	USD 3,663,210.00	2.57%	China	2016	Qatar
Italy	USD 4,221.00	0.00%	China	2016	Exclude from analysis
South Korea	USD 11,043,844.00	7.76%	China	2016	United States of America

Exporting Country	*Net Import*	*Share*	*Importing Country*	*Year*	*Allocation to original producer*
Qatar	USD 66,883,416.00	47.00%	China	2016	Qatar
Russia	USD 508,410.00	0.36%	China	2016	Russia
Singapore	USD 444,290.00	0.31%	China	2016	Exclude from analysis
Ukraine	USD 165,310.00	0.12%	China	2016	Ukraine
United States of America	USD 44,895,030.00	31.55%	China	2016	United States of America
Taiwan	USD 168,897.00	0.12%	China	2016	Exclude from analysis
Undeclared	USD 2,494.00	0.00%	China	2016	Exclude from analysis
United Arab Emirates	USD 1,889,834.00	1.28%	China	2017	Qatar
Australia	USD 9,325,045.00	6.31%	China	2017	Australia
Germany	USD 62,969.00	0.04%	China	2017	Exclude from analysis
France	USD 578,081.00	0.39%	China	2017	Exclude from analysis
United Kingdom	USD 137,907.00	0.09%	China	2017	Exclude from analysis
Hong Kong	USD 2,223,644.00	1.50%	China	2017	Qatar
India	USD 131,386.00	0.09%	China	2017	Exclude from analysis
South Korea	USD 6,743,113.00	4.56%	China	2017	United States of America
Qatar	USD 80,975,650.00	54.80%	China	2017	Qatar
Singapore	USD 713,914.00	0.48%	China	2017	Exclude from analysis
United States of America	USD 44,993,436.00	30.45%	China	2017	United States of America
United Arab Emirates	USD 251,084.00	0.13%	China	2018	Exclude from analysis
Australia	USD 19,223,031.00	10.14%	China	2018	Australia
Brazil	USD 2,192.00	0.00%	China	2018	Exclude from analysis
Canada	USD 37,113.00	0.02%	China	2018	Exclude from analysis
United Kingdom	USD 23,058.00	0.01%	China	2018	Exclude from analysis
Hong Kong	USD 4,073,610.00	2.15%	China	2018	Qatar
Indonesia	USD 94,219.00	0.05%	China	2018	Exclude from analysis

Exporting Country	*Net Import*	*Share*	*Importing Country*	*Year*	*Allocation to original producer*
South Korea	USD 11,306,224.00	5.96%	China	2018	United States of America
Qatar	USD 109,657,504.00	57.82%	China	2018	Qatar
Singapore	USD 780,544.00	0.41%	China	2018	Exclude from analysis
Ukraine	USD 162,955.00	0.09%	China	2018	Ukraine
United States of America	USD 44,044,810.00	23.22%	China	2018	United States of America
Saint Barthélemy	USD 13,383.00	0.01%	France	2015	Exclude from analysis
Dominican Republic	USD 34,725.00	0.04%	France	2015	Exclude from analysis
Algeria	USD 57,615,351.00	64.49%	France	2015	Algeria
Poland	USD 4,344,509.00	4.86%	France	2015	Poland
Portugal	USD 598,104.00	0.67%	France	2015	Exclude from analysis
Qatar	USD 22,437,259.00	25.11%	France	2015	Qatar
Slovakia	USD 7,527.00	0.01%	France	2015	Exclude from analysis
Trinidad and Tobago	USD 43,764.00	0.05%	France	2015	Exclude from analysis
Ukraine	USD 2,275,406.00	2.55%	France	2015	Ukraine
United States of America	USD 1,965,152.00	2.20%	France	2015	United States of America
South Africa	USD 3,117.00	0.00%	France	2015	Exclude from analysis
United Arab Emirates	USD 148,551.00	0.17%	France	2016	Exclude from analysis
Dominican Republic	USD 30,226.00	0.04%	France	2016	Exclude from analysis
Algeria	USD 50,792,482.00	59.35%	France	2016	Algeria
Hong Kong	USD 66,457.00	0.08%	France	2016	Exclude from analysis
Poland	USD 3,277,372.00	3.83%	France	2016	Poland
Portugal	USD 343,356.00	0.40%	France	2016	Exclude from analysis
Qatar	USD 21,474,320.00	25.09%	France	2016	Qatar
Russia	USD 4,071,770.00	4.76%	France	2016	Russia
Senegal	USD 35,826.00	0.04%	France	2016	Exclude from analysis

Exporting Country	*Net Import*	*Share*	*Importing Country*	*Year*	*Allocation to original producer*
Trinidad and Tobago	USD 10,161.00	0.01%	France	2016	Exclude from analysis
Ukraine	USD 259,081.00	0.30%	France	2016	Ukraine
United States of America	USD 5,077,418.00	5.93%	France	2016	United States of America
South Africa	USD 378.00	0.00%	France	2016	Exclude from analysis
United Arab Emirates	USD 3,544,712.00	4.74%	France	2017	Qatar
Belgium	USD 74,765.00	0.10%	France	2017	Exclude from analysis
Brazil	USD 6,948.00	0.01%	France	2017	Exclude from analysis
Denmark	USD 2,984.00	0.00%	France	2017	Exclude from analysis
Algeria	USD 57,864,139.00	77.30%	France	2017	Algeria
Poland	USD 2,357,873.00	3.15%	France	2017	Poland
Portugal	USD 294,546.00	0.39%	France	2017	Exclude from analysis
Qatar	USD 3,035,923.00	4.06%	France	2017	Qatar
Russia	USD 1,987,241.00	2.65%	France	2017	Russia
Suriname	USD 10,292.00	0.01%	France	2017	Exclude from analysis
Thailand	USD 9,708.00	0.01%	France	2017	Exclude from analysis
Trinidad and Tobago	USD 6,997.00	0.01%	France	2017	Exclude from analysis
United States of America	USD 5,629,562.00	7.52%	France	2017	United States of America
Undeclared	USD 35,054.00	0.05%	France	2017	Exclude from analysis
Belgium	USD 7,690,581.00	10.91%	France	2018	Qatar
Saint Barthélemy	USD 8,444.00	0.01%	France	2018	Exclude from analysis
China	USD 533,278.00	0.76%	France	2018	Exclude from analysis
Czechia	USD 1,033.00	0.00%	France	2018	Exclude from analysis
Algeria	USD 51,536,642.00	73.11%	France	2018	Algeria
Netherlands	USD 2,446,320.00	3.47%	France	2018	Qatar
Oman	USD 67,424.00	0.10%	France	2018	Exclude from analysis

Exporting Country	*Net Import*	*Share*	*Importing Country*	*Year*	*Allocation to original producer*
Poland	USD 809,396.00	1.15%	France	2018	Poland
Portugal	USD 929,240.00	1.32%	France	2018	Algeria
Russia	USD 5,133,920.00	7.28%	France	2018	Russia
Senegal	USD 6,737.00	0.01%	France	2018	Exclude from analysis
Trinidad and Tobago	USD 11,491.00	0.02%	France	2018	Exclude from analysis
Uganda	USD 9,359.00	0.01%	France	2018	Exclude from analysis
Ukraine	USD 1,041,590.00	1.48%	France	2018	Ukraine
South Africa	USD 241,203.00	0.34%	France	2018	Exclude from analysis
Undeclared	USD 27,680.00	0.04%	France	2018	Exclude from analysis
United Arab Emirates	USD 2,024,321.00	2.39%	Germany	2015	Qatar
Belgium	USD 22,027,994.00	25.99%	Germany	2015	United States of America
Algeria	USD 13,115,212.00	15.47%	Germany	2015	Algeria
Spain	USD 27,251.00	0.03%	Germany	2015	Exclude from analysis
France	USD 28,104,028.00	33.16%	Germany	2015	Algeria
United Kingdom	USD 328,047.00	0.39%	Germany	2015	Exclude from analysis
Greece	USD 23,211.00	0.03%	Germany	2015	Exclude from analysis
Ireland	USD 54,072.00	0.06%	Germany	2015	Exclude from analysis
Luxembourg	USD 184,282.00	0.22%	Germany	2015	Exclude from analysis
Qatar	USD 6,982,134.00	8.24%	Germany	2015	Qatar
Romania	USD 57,683.00	0.07%	Germany	2015	Exclude from analysis
Russia	USD 2,583,900.00	3.05%	Germany	2015	Russia
Ukraine	USD 3,666,055.00	4.32%	Germany	2015	Ukraine
United States of America	USD 5,587,044.00	6.59%	Germany	2015	United States of America
United Arab Emirates	USD 10,412,768.00	11.69%	Germany	2016	Qatar
Belgium	USD 18,762,623.00	21.06%	Germany	2016	United States of America

Exporting Country	*Net Import*	*Share*	*Importing Country*	*Year*	*Allocation to original producer*
Algeria	USD 11,734,542.00	13.17%	Germany	2016	Algeria
France	USD 13,003,679.00	14.59%	Germany	2016	Algeria
United Kingdom	USD 309,709.00	0.35%	Germany	2016	Exclude from analysis
Ireland	USD 1,662.00	0.00%	Germany	2016	Exclude from analysis
Israel	USD 92,138.00	0.10%	Germany	2016	Exclude from analysis
Luxembourg	USD 20,543.00	0.02%	Germany	2016	Exclude from analysis
Poland	USD 629,455.00	0.71%	Germany	2016	Poland
Portugal	USD 539,142.00	0.61%	Germany	2016	Exclude from analysis
Qatar	USD 21,624,955.00	24.27%	Germany	2016	Qatar
Romania	USD 29,553.00	0.03%	Germany	2016	Exclude from analysis
Russia	USD 1,699,123.00	1.91%	Germany	2016	Russia
Sweden	USD 332,006.00	0.37%	Germany	2016	Exclude from analysis
Ukraine	USD 958,388.00	1.08%	Germany	2016	Ukraine
United States of America	USD 8,959,100.00	10.05%	Germany	2016	United States of America
United Arab Emirates	USD 6,816,839.00	8.84%	Germany	2017	Qatar
Belgium	USD 20,100,285.00	26.07%	Germany	2017	Qatar
Cyprus	USD 25,239.00	0.03%	Germany	2017	Exclude from analysis
Algeria	USD 10,418,988.00	13.51%	Germany	2017	Algeria
France	USD 907,888.00	1.18%	Germany	2017	Algeria
United Kingdom	USD 457,518.00	0.59%	Germany	2017	Exclude from analysis
India	USD 121,459.00	0.16%	Germany	2017	Exclude from analysis
Oman	USD 120,686.00	0.16%	Germany	2017	Exclude from analysis
Poland	USD 5,014,661.00	6.50%	Germany	2017	Poland
Portugal	USD 545,343.00	0.71%	Germany	2017	Exclude from analysis
Qatar	USD 23,275,526.00	30.19%	Germany	2017	Qatar

Exporting Country	*Net Import*	*Share*	*Importing Country*	*Year*	*Allocation to original producer*
Romania	USD 48,822.00	0.06%	Germany	2017	Exclude from analysis
Ukraine	USD 2,363,199.00	3.07%	Germany	2017	Ukraine
United States of America	USD 6,881,407.00	8.93%	Germany	2017	United States of America
United Arab Emirates	USD 153,275.00	0.19%	Germany	2018	Exclude from analysis
Belgium	USD 19,185,104.00	24.35%	Germany	2018	Qatar
China	USD 1,040,217.00	1.32%	Germany	2018	Qatar
Cyprus	USD 126,804.00	0.16%	Germany	2018	Exclude from analysis
Algeria	USD 10,160,622.00	12.89%	Germany	2018	Algeria
Spain	USD 33,907.00	0.04%	Germany	2018	Exclude from analysis
France	USD 5,378,258.00	6.83%	Germany	2018	Algeria
United Kingdom	USD 2,410,570.00	3.06%	Germany	2018	Qatar
Italy	USD 760,599.00	0.97%	Germany	2018	Qatar
Oman	USD 536,632.00	0.68%	Germany	2018	Exclude from analysis
Poland	USD 6,696,434.00	8.50%	Germany	2018	Poland
Portugal	USD 1,709,753.00	2.17%	Germany	2018	Algeria
Qatar	USD 29,031,038.00	36.84%	Germany	2018	Qatar
Romania	USD 5,975.00	0.01%	Germany	2018	Exclude from analysis
Ukraine	USD 1,570,679.00	1.99%	Germany	2018	Ukraine
United Arab Emirates	USD 163,240.00	0.10%	Japan	2015	Exclude from analysis
Austria	USD 10,884.00	0.01%	Japan	2015	Exclude from analysis
China	USD 22,352,748.00	14.04%	Japan	2015	Qatar
Germany	USD 219,762.00	0.14%	Japan	2015	Exclude from analysis
France	USD 4,516,104.00	2.84%	Japan	2015	Algeria
United Kingdom	USD 159,311.00	0.10%	Japan	2015	Exclude from analysis
Hong Kong	USD 18,293.00	0.01%	Japan	2015	Exclude from analysis

Exporting Country	*Net Import*	*Share*	*Importing Country*	*Year*	*Allocation to original producer*
Qatar	USD 37,279,248.00	23.42%	Japan	2015	Qatar
Russia	USD 563,228.00	0.35%	Japan	2015	Russia
Singapore	USD 5,724,847.00	3.60%	Japan	2015	Qatar
Thailand	USD 17,251.00	0.01%	Japan	2015	Exclude from analysis
Ukraine	USD 3,756,635.00	2.36%	Japan	2015	Ukraine
United States of America	USD 84,371,150.00	53.01%	Japan	2015	United States of America
Austria	USD 13,894.00	0.01%	Japan	2016	Exclude from analysis
China	USD 537,891.00	0.49%	Japan	2016	Exclude from analysis
Czechia	USD 3,260.00	0.00%	Japan	2016	Exclude from analysis
Germany	USD 545,686.00	0.49%	Japan	2016	Exclude from analysis
Spain	USD 2,138.00	0.00%	Japan	2016	Exclude from analysis
France	USD 1,361,525.00	1.23%	Japan	2016	Algeria
United Kingdom	USD 399,929.00	0.36%	Japan	2016	Exclude from analysis
Qatar	USD 22,866,320.00	20.66%	Japan	2016	Qatar
Russia	USD 25,866.00	0.02%	Japan	2016	Russia
Singapore	USD 4,050,110.00	3.66%	Japan	2016	Qatar
Thailand	USD 27,772.00	0.03%	Japan	2016	Exclude from analysis
Ukraine	USD 4,940,082.00	4.46%	Japan	2016	Ukraine
United States of America	USD 75,922,146.00	68.59%	Japan	2016	United States of America
United Arab Emirates	USD 6,639,385.00	6.59%	Japan	2017	Qatar
Austria	USD 12,807.00	0.01%	Japan	2017	Exclude from analysis
China	USD 1,378,152.00	1.37%	Japan	2017	Qatar
Czechia	USD 2,648.00	0.00%	Japan	2017	Exclude from analysis
Germany	USD 499,354.00	0.50%	Japan	2017	Exclude from analysis
France	USD 2,404,560.00	2.39%	Japan	2017	Algeria

Exporting Country	*Net Import*	*Share*	*Importing Country*	*Year*	*Allocation to original producer*
United Kingdom	USD 30,186.00	0.03%	Japan	2017	Exclude from analysis
Hong Kong	USD 21,437.00	0.02%	Japan	2017	Exclude from analysis
Qatar	USD 23,847,287.00	23.68%	Japan	2017	Qatar
Russia	USD 725,401.00	0.72%	Japan	2017	Russia
Singapore	USD 2,980,480.00	2.96%	Japan	2017	Qatar
Ukraine	USD 1,550,883.00	1.54%	Japan	2017	Ukraine
United States of America	USD 60,616,923.00	60.19%	Japan	2017	United States of America
Austria	USD 5,497.00	0.01%	Japan	2018	Exclude from analysis
China	USD 8,235,049.00	7.64%	Japan	2018	Qatar
Germany	USD 615,139.00	0.57%	Japan	2018	Exclude from analysis
France	USD 3,748,470.00	3.48%	Japan	2018	Algeria
Hong Kong	USD 15,539.00	0.01%	Japan	2018	Exclude from analysis
Poland	USD 156,691.00	0.15%	Japan	2018	Poland
Qatar	USD 36,512,304.00	33.86%	Japan	2018	Qatar
Russia	USD 659,493.00	0.61%	Japan	2018	Russia
Singapore	USD 8,008,027.00	7.43%	Japan	2018	Qatar
Ukraine	USD 672,130.00	0.62%	Japan	2018	Ukraine
United States of America	USD 49,192,743.00	45.62%	Japan	2018	United States of America
Germany	USD 67,376.00	0.19%	Mexico	2015	Exclude from analysis
United States of America	USD 35,682,530.00	99.81%	Mexico	2015	United States of America
Belgium	USD 15,450.00	0.05%	Mexico	2016	Exclude from analysis
Germany	USD 175,873.00	0.52%	Mexico	2016	Exclude from analysis
United States of America	USD 33,386,803.00	99.43%	Mexico	2016	United States of America
Belgium	USD 4,471.00	0.01%	Mexico	2017	Exclude from analysis
Germany	USD 101,813.00	0.26%	Mexico	2017	Exclude from analysis

Exporting Country	*Net Import*	*Share*	*Importing Country*	*Year*	*Allocation to original producer*
France	USD 8,308.00	0.02%	Mexico	2017	Exclude from analysis
United States of America	USD 39,269,248.00	99.71%	Mexico	2017	United States of America
Belgium	USD 30,899.00	0.08%	Mexico	2018	Exclude from analysis
China	USD 280,943.00	0.73%	Mexico	2018	Exclude from analysis
Germany	USD 100,465.00	0.26%	Mexico	2018	Exclude from analysis
India	USD 3,955.00	0.01%	Mexico	2018	Exclude from analysis
Netherlands	USD 2,290.00	0.01%	Mexico	2018	Exclude from analysis
United States of America	USD 38,164,145.00	98.92%	Mexico	2018	United States of America
Australia	USD 943,439.00	0.76%	South Korea	2015	Australia
Austria	USD 3,914.00	0.00%	South Korea	2015	Exclude from analysis
Belgium	USD 1,075.00	0.00%	South Korea	2015	Exclude from analysis
Czechia	USD 7,933.00	0.01%	South Korea	2015	Exclude from analysis
Germany	USD 480,935.00	0.39%	South Korea	2015	Exclude from analysis
France	USD 2,788,355.00	2.23%	South Korea	2015	Algeria
United Kingdom	USD 1,260,954.00	1.01%	South Korea	2015	United States of America
Hong Kong	USD 989,763.00	0.79%	South Korea	2015	Exclude from analysis
Japan	USD 160,918.00	0.13%	South Korea	2015	Exclude from analysis
Netherlands	USD 1,064.00	0.00%	South Korea	2015	Exclude from analysis
New Zealand	USD 3,493.00	0.00%	South Korea	2015	Exclude from analysis
Qatar	USD 18,817,152.00	15.07%	South Korea	2015	Qatar
Russia	USD 1,022,395.00	0.82%	South Korea	2015	Russia
Singapore	USD 177,898.00	0.14%	South Korea	2015	Exclude from analysis
Thailand	USD 374,324.00	0.30%	South Korea	2015	Exclude from analysis
Ukraine	USD 5,495,535.00	4.40%	South Korea	2015	Ukraine
United States of America	USD 92,308,724.00	73.94%	South Korea	2015	United States of America

Exporting Country	*Net Import*	*Share*	*Importing Country*	*Year*	*Allocation to original producer*
Australia	USD 1,027,893.00	0.92%	South Korea	2016	Australia
Austria	USD 4,903.00	0.00%	South Korea	2016	Exclude from analysis
Belgium	USD 1,090.00	0.00%	South Korea	2016	Exclude from analysis
Czechia	USD 13,250.00	0.01%	South Korea	2016	Exclude from analysis
Germany	USD 333,537.00	0.30%	South Korea	2016	Exclude from analysis
France	USD 1,320,304.00	1.18%	South Korea	2016	Algeria
United Kingdom	USD 426,825.00	0.38%	South Korea	2016	Exclude from analysis
Japan	USD 353,953.00	0.32%	South Korea	2016	Exclude from analysis
Netherlands	USD 16,650.00	0.01%	South Korea	2016	Exclude from analysis
Norway	USD 2,275.00	0.00%	South Korea	2016	Exclude from analysis
Qatar	USD 20,540,523.00	18.37%	South Korea	2016	Qatar
Russia	USD 310,932.00	0.28%	South Korea	2016	Russia
Singapore	USD 882,585.00	0.79%	South Korea	2016	Exclude from analysis
Ukraine	USD 7,051,506.00	6.31%	South Korea	2016	Ukraine
United States of America	USD 79,521,446.00	71.12%	South Korea	2016	United States of America
United Arab Emirates	USD 7,476,943.00	6.51%	South Korea	2017	Qatar
Australia	USD 2,698,901.00	2.35%	South Korea	2017	Australia
Austria	USD 4,207.00	0.00%	South Korea	2017	Exclude from analysis
Czechia	USD 4,630.00	0.00%	South Korea	2017	Exclude from analysis
Germany	USD 73,528.00	0.06%	South Korea	2017	Exclude from analysis
France	USD 3,173,496.00	2.76%	South Korea	2017	Algeria
United Kingdom	USD 12,644.00	0.01%	South Korea	2017	Exclude from analysis
Indonesia	USD 351.00	0.00%	South Korea	2017	Exclude from analysis
Italy	USD 3,178.00	0.00%	South Korea	2017	Exclude from analysis
Japan	USD 699,714.00	0.61%	South Korea	2017	Exclude from analysis

Exporting Country	*Net Import*	*Share*	*Importing Country*	*Year*	*Allocation to original producer*
Netherlands	USD 12,868.00	0.01%	South Korea	2017	Exclude from analysis
Norway	USD 2,827.00	0.00%	South Korea	2017	Exclude from analysis
Qatar	USD 17,058,135.00	14.85%	South Korea	2017	Qatar
Russia	USD 395,347.00	0.34%	South Korea	2017	Russia
Singapore	USD 1,667,718.00	1.45%	South Korea	2017	Qatar
Turkey	USD 897.00	0.00%	South Korea	2017	Exclude from analysis
Ukraine	USD 1,124,376.00	0.98%	South Korea	2017	Ukraine
United States of America	USD 80,368,220.00	69.96%	South Korea	2017	United States of America
Undeclared	USD 102,178.00	0.09%	South Korea	2017	Exclude from analysis
Antarctica	USD 28,012.00	0.02%	South Korea	2018	Exclude from analysis
Australia	USD 2,775,073.00	2.25%	South Korea	2018	Australia
Austria	USD 1,745.00	0.00%	South Korea	2018	Exclude from analysis
Belgium	USD 3,191.00	0.00%	South Korea	2018	Exclude from analysis
Switzerland	USD 1,735.00	0.00%	South Korea	2018	Exclude from analysis
Czechia	USD 7,413.00	0.01%	South Korea	2018	Exclude from analysis
Germany	USD 37,965.00	0.03%	South Korea	2018	Exclude from analysis
France	USD 6,952,642.00	5.63%	South Korea	2018	Algeria
United Kingdom	USD 8,136.00	0.01%	South Korea	2018	Exclude from analysis
Japan	USD 936,495.00	0.76%	South Korea	2018	Exclude from analysis
Netherlands	USD 33,981.00	0.03%	South Korea	2018	Exclude from analysis
Qatar	USD 19,897,224.00	16.10%	South Korea	2018	Qatar
Russia	USD 7,099,938.00	5.75%	South Korea	2018	Russia
Singapore	USD 1,354,056.00	1.10%	South Korea	2018	Qatar
Turkey	USD 942.00	0.00%	South Korea	2018	Exclude from analysis
Ukraine	USD 2,738,429.00	2.22%	South Korea	2018	Ukraine

Exporting Country	*Net Import*	*Share*	*Importing Country*	*Year*	*Allocation to original producer*
United States of America	USD 81,629,991.00	66.06%	South Korea	2018	United States of America
South Africa	USD 7,142.00	0.01%	South Korea	2018	Exclude from analysis
Undeclared	USD 63,743.00	0.05%	South Korea	2018	Exclude from analysis
United Arab Emirates	USD 784,473.00	1.84%	United Kingdom	2015	Qatar
Belgium	USD 8,892,865.00	20.91%	United Kingdom	2015	United States of America
Switzerland	USD 36,899.00	0.09%	United Kingdom	2015	Exclude from analysis
Algeria	USD 326,231.00	0.77%	United Kingdom	2015	Algeria
France	USD 10,959,532.00	25.76%	United Kingdom	2015	Algeria
Portugal	USD 969,279.00	2.28%	United Kingdom	2015	Algeria
Qatar	USD 8,825,881.00	20.75%	United Kingdom	2015	Qatar
Tunisia	USD 1,137.00	0.00%	United Kingdom	2015	Exclude from analysis
Ukraine	USD 10,232.00	0.02%	United Kingdom	2015	Ukraine
United States of America	USD 11,732,135.00	27.58%	United Kingdom	2015	United States of America
United Arab Emirates	USD 717,210.00	1.84%	United Kingdom	2016	Qatar
Belgium	USD 5,026,414.00	12.89%	United Kingdom	2016	United States of America
France	USD 10,724,294.00	27.49%	United Kingdom	2016	Algeria
Ghana	USD 186,878.00	0.48%	United Kingdom	2016	Exclude from analysis
Portugal	USD 266,653.00	0.68%	United Kingdom	2016	Exclude from analysis
Qatar	USD 12,387,322.00	31.76%	United Kingdom	2016	Qatar
United States of America	USD 9,699,353.00	24.86%	United Kingdom	2016	United States of America
United Arab Emirates	USD 7,022,850.00	14.05%	United Kingdom	2017	Qatar
Belgium	USD 5,408,881.00	10.82%	United Kingdom	2017	Qatar
Denmark	USD 5,731.00	0.01%	United Kingdom	2017	Exclude from analysis
France	USD 14,131,157.00	28.26%	United Kingdom	2017	Algeria
Portugal	USD 127,962.00	0.26%	United Kingdom	2017	Exclude from analysis

Exporting Country	*Net Import*	*Share*	*Importing Country*	*Year*	*Allocation to original producer*
Qatar	USD 12,834,574.00	25.67%	United Kingdom	2017	Qatar
Singapore	USD 61,533.00	0.12%	United Kingdom	2017	Exclude from analysis
United States of America	USD 10,402,935.00	20.81%	United Kingdom	2017	United States of America
United Arab Emirates	USD 15,042,267.00	27.22%	United Kingdom	2018	Algeria
Belgium	USD 9,305,752.00	16.84%	United Kingdom	2018	Qatar
France	USD 7,745,443.00	14.01%	United Kingdom	2018	Algeria
Hong Kong	USD 20,367.00	0.04%	United Kingdom	2018	Exclude from analysis
India	USD 456,410.00	0.83%	United Kingdom	2018	Exclude from analysis
Italy	USD 546,961.00	0.99%	United Kingdom	2018	Qatar
Japan	USD 3,747.00	0.01%	United Kingdom	2018	Exclude from analysis
Oman	USD 88,659.00	0.16%	United Kingdom	2018	Exclude from analysis
Poland	USD 280,919.00	0.51%	United Kingdom	2018	Poland
Portugal	USD 533,921.00	0.97%	United Kingdom	2018	Algeria
Qatar	USD 19,143,413.00	34.64%	United Kingdom	2018	Qatar
Singapore	USD 18,503.00	0.03%	United Kingdom	2018	Exclude from analysis
Uruguay	USD 1,440.00	0.00%	United Kingdom	2018	Exclude from analysis
United States of America	USD 2,079,045.00	3.76%	United Kingdom	2018	United States of America
Australia	USD 9,076,778.00	14.41%	Taiwan	2015	Australia
Belgium	USD 1,448.00	0.00%	Taiwan	2015	Exclude from analysis
China	USD 1,012,105.00	1.61%	Taiwan	2015	Qatar
Czechia	USD 11,154.00	0.02%	Taiwan	2015	Exclude from analysis
Germany	USD 11,825.00	0.02%	Taiwan	2015	Exclude from analysis
France	USD 246,573.00	0.39%	Taiwan	2015	Exclude from analysis
Japan	USD 966,365.00	1.53%	Taiwan	2015	United States of America
South Korea	USD 1,200,521.00	1.91%	Taiwan	2015	United States of America

Exporting Country	*Net Import*	*Share*	*Importing Country*	*Year*	*Allocation to original producer*
Qatar	USD 15,273,016.00	24.25%	Taiwan	2015	Qatar
Singapore	USD 1,191,512.00	1.89%	Taiwan	2015	Qatar
Ukraine	USD 822,086.00	1.31%	Taiwan	2015	Ukraine
United States of America	USD 33,179,684.00	52.67%	Taiwan	2015	United States of America
Undeclared	USD 1,124.00	0.00%	Taiwan	2015	Exclude from analysis
Australia	USD 6,219,780.00	10.09%	Taiwan	2016	Australia
Belgium	USD 6,896.00	0.01%	Taiwan	2016	Exclude from analysis
Czechia	USD 18,453.00	0.03%	Taiwan	2016	Exclude from analysis
Germany	USD 8,959.00	0.01%	Taiwan	2016	Exclude from analysis
France	USD 101,135.00	0.16%	Taiwan	2016	Exclude from analysis
United Kingdom	USD 1,068.00	0.00%	Taiwan	2016	Exclude from analysis
Japan	USD 925,786.00	1.50%	Taiwan	2016	United States of America
South Korea	USD 1,598,082.00	2.59%	Taiwan	2016	United States of America
Netherlands	USD 1,111.00	0.00%	Taiwan	2016	Exclude from analysis
Qatar	USD 15,736,227.00	25.52%	Taiwan	2016	Qatar
Singapore	USD 380,968.00	0.62%	Taiwan	2016	Exclude from analysis
Ukraine	USD 1,054,003.00	1.71%	Taiwan	2016	Ukraine
United States of America	USD 35,609,650.00	57.75%	Taiwan	2016	United States of America
United Arab Emirates	USD 9,474,181.00	15.89%	Taiwan	2017	Qatar
Australia	USD 2,858,725.00	4.80%	Taiwan	2017	Australia
China	USD 228,093.00	0.38%	Taiwan	2017	Exclude from analysis
Czechia	USD 4,356.00	0.01%	Taiwan	2017	Exclude from analysis
Germany	USD 4,565.00	0.01%	Taiwan	2017	Exclude from analysis
United Kingdom	USD 3,731.00	0.01%	Taiwan	2017	Exclude from analysis
Japan	USD 580,912.00	0.97%	Taiwan	2017	United States of America

Exporting Country	*Net Import*	*Share*	*Importing Country*	*Year*	*Allocation to original producer*
South Korea	USD 1,483,268.00	2.49%	Taiwan	2017	United States of America
Qatar	USD 19,629,080.00	32.93%	Taiwan	2017	Qatar
Russia	USD 76,916.00	0.13%	Taiwan	2017	Russia
Singapore	USD 733,929.00	1.23%	Taiwan	2017	Qatar
Ukraine	USD 1,601,386.00	2.69%	Taiwan	2017	Ukraine
United States of America	USD 22,934,099.00	38.47%	Taiwan	2017	United States of America
Australia	USD 2,933,318.00	5.73%	Taiwan	2018	Australia
Belgium	USD 1,138.00	0.00%	Taiwan	2018	Exclude from analysis
China	USD 90,800.00	0.18%	Taiwan	2018	Exclude from analysis
Czechia	USD 2,984.00	0.01%	Taiwan	2018	Exclude from analysis
Germany	USD 1,767.00	0.00%	Taiwan	2018	Exclude from analysis
United Kingdom	USD 2,135.00	0.00%	Taiwan	2018	Exclude from analysis
Indonesia	USD 24,674.00	0.05%	Taiwan	2018	Exclude from analysis
Japan	USD 457,164.00	0.89%	Taiwan	2018	United States of America
South Korea	USD 1,405,447.00	2.75%	Taiwan	2018	United States of America
Netherlands	USD 3,411.00	0.01%	Taiwan	2018	Exclude from analysis
Qatar	USD 20,581,905.00	40.20%	Taiwan	2018	Qatar
Russia	USD 175,049.00	0.34%	Taiwan	2018	Russia
Ukraine	USD 613,486.00	1.20%	Taiwan	2018	Ukraine
United States of America	USD 24,895,769.00	48.63%	Taiwan	2018	United States of America
South Africa	USD 6,857.00	0.01%	Taiwan	2018	Exclude from analysis

Annex O.Allocation of supply mixes and GeoPolRisk calculations (2015-2018)

Year 2015

Adjusted Supply Mix	Algeria	Australia	Poland	Qatar	Russia	Ukraine	USA	Total	Weighted WGI	GeoPolRisk	Net Import
China	0.00%	10.47%	0.00%	64.05%	0.08%	0.00%	25.40%	100.00%	0.320	**0.135**	USD 118,249,121.00
Japan	2.85%	0.00%	0.00%	41.22%	0.36%	2.37%	53.21%	100.00%	0.362	**0.153**	USD 159,152,701.00
South Korea	2.27%	0.77%	0.00%	15.34%	0.83%	4.48%	76.30%	100.00%	0.389	**0.164**	USD 124,837,871.00
Germany	49.02%	0.00%	0.00%	10.71%	3.07%	4.36%	32.84%	100.00%	0.564	**0.238**	USD 84,765,234.00
Taiwan	0.00%	14.47%	0.00%	27.86%	0.00%	1.31%	56.35%	100.00%	0.348	**0.147**	USD 62,994,191.00
United Kingdom	28.83%	0.00%	0.00%	22.61%	0.00%	0.02%	48.53%	100.00%	0.452	**0.191**	USD 42,538,664.00
Mexico	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%	100.00%	0.364	**0.154**	USD 35,749,906.00
Canada	0.00%	0.00%	0.00%	0.00%	0.00%	0.01%	99.99%	100.00%	0.364	**0.154**	USD 25,575,661.00
France	65.00%	0.00%	4.90%	25.31%	0.00%	2.57%	2.22%	100.00%	0.590	**0.249**	USD 89,338,297.00
Brazil	0.00%	0.06%	0.00%	0.00%	0.09%	0.00%	99.85%	100.00%	0.365	**0.154**	USD 21,534,035.00

Year 2016

Adjusted Supply Mix	Algeria	Australia	Poland	Qatar	Russia	Ukraine	USA	Total	Weighted WGI	GeoPolRisk	Net Import
China	0.00%	9.22%	0.00%	50.36%	0.36%	0.12%	39.93%	100.00%	0.359	**0.152**	USD 142,318,174.00
Japan	1.25%	0.00%	0.00%	24.66%	0.02%	4.53%	69.55%	100.00%	0.419	**0.177**	USD 110,696,619.00
South Korea	1.20%	0.94%	0.00%	18.71%	0.28%	6.42%	72.44%	100.00%	0.433	**0.183**	USD 111,807,672.00
Germany	28.18%	0.00%	0.72%	36.50%	1.94%	1.09%	31.58%	100.00%	0.478	**0.202**	USD 89,109,386.00
Taiwan	0.00%	10.17%	0.00%	25.74%	0.00%	1.72%	62.37%	100.00%	0.389	**0.164**	USD 61,662,118.00
United Kingdom	27.82%	0.00%	0.00%	33.99%	0.00%	0.00%	38.19%	100.00%	0.469	**0.198**	USD 39,008,124.00
Mexico	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%	100.00%	0.420	**0.177**	USD 33,578,126.00
Canada	0.00%	0.00%	0.00%	0.00%	0.00%	0.03%	99.97%	100.00%	0.420	**0.177**	USD 21,315,045.00
France	59.79%	0.00%	3.86%	25.28%	4.79%	0.30%	5.98%	100.00%	0.587	**0.248**	USD 85,587,398.00
Brazil	4.33%	0.07%	0.85%	10.00%	0.00%	0.00%	84.76%	100.00%	0.422	**0.178**	USD 19,164,253.00

Adjusted Supply Mix	Algeria	Australia	Poland	Qatar	Russia	Ukraine	USA	Total	Weighted WGI	GeoPolRisk	Net Import
China	0.00%	6.38%	0.00%	58.22%	0.00%	0.00%	35.40%	100.00%	0.388	0.162	USD 147,774,979.00
Japan	2.40%	0.00%	0.00%	34.80%	0.72%	1.55%	60.53%	100.00%	0.424	0.177	USD 100,709,503.00
South Korea	2.78%	2.37%	0.00%	22.99%	0.35%	0.99%	70.52%	100.00%	0.427	0.178	USD 114,880,158.00
Germany	14.95%	0.00%	6.62%	66.24%	0.00%	3.12%	9.08%	100.00%	0.439	0.183	USD 77,097,860.00
Taiwan	0.00%	4.81%	0.00%	50.25%	0.13%	2.70%	42.10%	100.00%	0.407	0.169	USD 59,613,241.00
United Kingdom	28.38%	0.00%	0.00%	50.74%	0.00%	0.00%	20.89%	100.00%	0.471	0.196	USD 49,995,623.00
Mexico	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%	100.00%	0.432	0.180	USD 39,383,840.00
Canada	0.00%	0.01%	0.00%	0.00%	0.00%	0.00%	99.99%	100.00%	0.432	0.180	USD 19,811,748.00
France	77.75%	0.00%	3.17%	8.84%	2.67%	0.00%	7.56%	100.00%	0.626	0.261	USD 74,860,744.00
Brazil	2.14%	0.08%	0.00%	0.00%	0.00%	0.00%	97.78%	100.00%	0.437	0.182	USD 16,026,472.00

Year 2017

Adjusted Supply Mix	Algeria	Australia	Poland	Qatar	Russia	Ukraine	USA	Total	Weighted WGI	GeoPolRisk	Net Import
China	0.00%	10.20%	0.00%	60.35%	0.00%	0.09%	29.37%	100.00%	0.371	0.154	USD 189,656,344.00
Japan	3.50%	0.00%	0.15%	49.22%	0.62%	0.63%	45.90%	100.00%	0.400	0.166	USD 107,821,082.00
South Korea	5.68%	2.27%	0.00%	17.36%	5.80%	2.24%	66.67%	100.00%	0.433	0.180	USD 123,577,853.00
Germany	22.13%	0.00%	8.59%	67.26%	0.00%	2.02%	0.00%	100.00%	0.446	0.185	USD 78,799,867.00
Taiwan	0.00%	5.74%	0.00%	40.31%	0.34%	1.20%	52.40%	100.00%	0.390	0.162	USD 51,195,904.00
United Kingdom	42.65%	0.00%	0.51%	53.03%	0.00%	0.00%	3.80%	100.00%	0.496	0.205	USD 55,266,847.00
Mexico	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%	100.00%	0.406	0.168	USD 38,582,697.00
Canada	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%	100.00%	0.406	0.168	USD 20,981,652.00
France	75.40%	0.00%	1.16%	14.57%	7.38%	1.50%	0.00%	100.00%	0.618	0.256	USD 70,494,338.00
Brazil	0.00%	0.19%	0.00%	0.00%	0.15%	0.00%	99.66%	100.00%	0.406	0.168	USD 14,564,328.00

Year 2018

Annex P. Energy mixes for the assessed helium producing countries

Energy source	*Algeria* *National 2018* *Source: IEA, 2020*	*Poland* *(National 2018)* *Source: IEA, 2020*	*Qatar* *(National 2018)* *Source: IEA, 2020*	*Russia* *(National 2018)* *Source: IEA, 2020*	*USA* *(Kansas, 2019)* *Source: IEA, 2020*
Nuclear	-	-	-	18.35%	18.00%
Coal	-	78.28%	-	15.96%	33.00%
Oil	0.49%	1.06%	-	0.72%	0.25%
Natural Gas	98.49%	7.44%	100.00%	47.32%	7.00%
Hydroelectric	0.16%	1.40%	-	17.31%	0.25%
Wind	0.01%	7.53%	-	0.05%	41.00%
Solar	0.86%	0.18%	-	0.05%	0.25%
Biofuels	-	3.80%	-	0.12%	0.25%
Waste	-	0.31%	-	0.12%	-

Annex Q.Helium plant information for assessed helium producing countries

Country	*Algeria*	*Poland*	*Qatar*	*Russia*	*USA*
Company	Air Products	POGC	RasGas	GazProm	Air Products
Location	Skidka	Odolanow	Ras Laffan	Orenburg	Seward County, KS
Latitude	36.8780	51.5886	25.8927	36.8780	37.1597
Longitude	6.9466	17.6486	51.5452	6.9466	-100.7662
Area (m2)	12 000	12 000	15 000	30 000	15 000
Capacity (MM m3/year)	17	2.5	55	2.8	8.1

Sources: USGS, 2016; USGS, 2017; Google, n.d.

Annex R. Base bill of materials for helium production

Flow	*Category*	*Amount*	*Unit*	*Provider*
building, hall	Construction of buildings	DEPENDS ON SPECIFIC CASE	m2	building, hall
Electricity mix Hellium	Electricity Mix	125.98	kWh	**DEPENDS ON COUNTRY (Annex P)**
EUR-flat pallet	Manufacture of wooden containers	1.92E-3	Item(s)	EUR-flat pallet
helium	Manufacture of basic chemicals	66.66	kg	helium purification | helium
sheet rolling, chromium steel	Manufacture of basic iron and steel	0.47	kg	sheet rolling, chromium steel

Output: refined helium equivalent to the content of 1 DEWAR available for local transport to port of export

1 container and 1 pallet are used for the full life span of the DEWAR (reused)

Country	***Algeria***	***Poland***	***Qatar***	***Russia***	***USA***
m2/Dewar	4.11E-3	2.57E-2	2.85E-3	6.42E-2	3.95E-3

Annex S. Helium supply mix in 2018 (CA, DE, FR and JP)

The table does not consider the contribution from the Ukraine; for further details, please refer to Annex O.

Importer	Exporter	MM USD	Contribution
Canada (CA)		**20.98**	
	USA	20.98	***100.00%***
Germany (DE)		**77.20**	
	Algeria	17.43	***22.37%***
	Poland	6.77	***7.89%***
	Qatar	53.00	***69.74%***
France (FR)		**68.62**	
	Algeria	53.15	***77.94%***
	Qatar	10.27	***14.71%***
	Russia	5.20	***7.35%***
Japan (JP)		**106.31**	
	Algeria	3.77	***2.86%***
	Qatar	53.06	***50.48%***
	USA	49.48	***46.67%***

Annex T. Distances associated with transportation for international supply

Local transport: From plant to port of export in the producing country

Transported weight: 272.17 kg (helium and container, associated to 1 DEWAR of 500L)

Country	*Origin*	*Destination*	*Distance*	*Type of transport*	*Process in Ecoinvent*
Algeria	Skidka	Skidka	1 km	Road	Transport, freight, lorry 3.5-7.5 metric ton, EURO5
Poland	Odolanow	Gdansk	380 Km	Road	Transport, freight, lorry 3.5-7.5 metric ton, EURO5
Qatar	Ras Laffan	Ras Laffan	1 Km	Road	Transport, freight, lorry 3.5-7.5 metric ton, EURO5
Russia	Orenburg	Vladivostok	8000 Km	Road	Transport, freight, lorry 3.5-7.5 metric ton, EURO5
USA	Seward County	Long Beach	1800 Km	Road	Transport, freight, lorry 3.5-7.5 metric ton, EURO5

International transport: Between countries

Transported weight: 272.17 kg (helium and container, associated to 1 DEWAR of 500L)

Origin	*Destination*	*Distance*	*Type of transport*	*Process in Ecoinvent*
Skidka (Algeria)	DE (Hamburg)	4 000 Km	Sea	transport, freight, sea, transoceanic ship
Skidka (Algeria)	FR (Marseille)	750 Km	Sea	transport, freight, sea, transoceanic ship
Skidka (Algeria)	JP (Kawasaki)	18 000 Km	Sea	transport, freight, sea, transoceanic ship
Poland (Gdansk)	DE (Hamburg)	670 Km	Road	Transport, freight, lorry 3.5-7.5 metric ton, EURO5
Qatar (Ras Laffan)	DE (Hamburg)	12 500 Km	Sea	transport, freight, sea, transoceanic ship
Qatar (Ras Laffan)	FR (Marseille)	9 000 Km	Sea	transport, freight, sea, transoceanic ship
Qatar (Ras Laffan)	JP (Kawasaki)	12 500 Km	Sea	transport, freight, sea, transoceanic ship
Russia (Vladivostok)	FR (Marseille)	4 700 Km	Road	Transport, freight, lorry 3.5-7.5 metric ton, EURO5
USA (Seward County)	CA (Niagara Falls)	2 400 Km	Road	Transport, freight, lorry 3.5-7.5 metric ton, EURO5
USA (Long Beach)	JP (Kawasaki)	9 000 Km	Sea	transport, freight, sea, transoceanic ship

Annex U. Distances associated with transportation for local distribution

Local transport: From port of import to transfill center in destination country

Transported weight: 272.17 kg (helium and container, associated to 1 DEWAR of 500L)

Country	*Origin*	*Destination*	*Distance*	*Type of transport*	*Process in Ecoinvent*
Canada (CA)	Niagara Falls	Toronto	130 Km	Road	Transport, freight, lorry 3.5-7.5 metric ton, EURO5
Germany (DE)	Hamburg	Berlin	300 Km	Road	Transport, freight, lorry 3.5-7.5 metric ton, EURO5
France (FR)	Marseille	Paris	800 Km	Road	Transport, freight, lorry 3.5-7.5 metric ton, EURO5
Japan (JP)	Kawasaki	Tokyo	20 Km	Road	Transport, freight, lorry 3.5-7.5 metric ton, EURO5

Local transport: From transfill center to final destination in destination city

Transported weight: 272.17 kg (helium and container, associated to 1 DEWAR of 500L)

Loss of 2% assumed from previous stage

Distance calculated with the formula: 2*sqrt(area of city) (distance corresponds to 2 trips)

Country	*City*	*Area*	*Distance*	*Type of transport*	*Process in Ecoinvent*
Canada (CA)	Toronto	630.2 Km2	50.2 Km	Road	Transport, freight, lorry 3.5-7.5 metric ton, EURO5
Germany (DE)	Berlin	891.8 Km2	59.7 Km	Road	Transport, freight, lorry 3.5-7.5 metric ton, EURO5
France (FR)	Paris	105.4 Km2	20.5 Km	Road	Transport, freight, lorry 3.5-7.5 metric ton, EURO5
Japan (JP)	Tokyo	622 Km2	49.9 Km	Road	Transport, freight, lorry 3.5-7.5 metric ton, EURO5

Annex V. Electricity mixes for the assessed helium importing countries (CA, DE, FR and JP)

Energy source	Canada (Ontario 2018) Source: CER-REC, 2020	Germany (National 2018) Source: IEA, 2020	France (National 2018) Source: RTE, 2019	Japan (National 2018) Source: IEA, 2020
Nuclear	60.00%	11.82%	47.51%	6.25%
Coal	-	37.16%	2.26%	32.62%
Oil	1.00%	0.81%	2.58%	4.99%
Natural Gas	3.00%	12.97%	9.14%	36.38%
Hydroelectric	26.00%	3.75%	19.20%	8.51%
Wind	7.00%	17.10%	11.37%	0.72%
Solar	2.00%	7.12%	6.42%	6.03%
Biofuels	1.00%	6.95%	1.52%	2.07%
Waste	-	2.06%	-	2.19%
Geothermal	-	0.03%	-	0.24%

Base bill of materials for helium transfer

Flow	*Category*	*Amount*	*Unit*	*Provider*
building, hall	Construction of buildings	0.025	m2	building, hall
Electricity mix Hellium	Electricity Mix	117.94	kWh	**DEPENDS ON COUNTRY**

Output: refined helium equivalent to the content of 1 DEWAR available for local transport to final use destination

Annex W. Base bill of materials for MRI scan production

Flow	*Category*	*Amount*	*Unit*	*Provider*
building, hall	Construction of buildings	2.58E-8	m2	building, hall
Electricity mix Hellium	Electricity Mix	**DEPENDS ON SCENARIO (1 or 2)**	kWh	**DEPENDS ON COUNTRY (Annex V)**
Electronic Component	Special purpose machinery	4.71E-6	Item(s)	Special purpose machinery
Helium, medical grade	Helium, available for consumption in medical setting	Reference Flow **DEPENDS ON SCENARIO (A, B or C)**	dewar(s) (500L container)	**DEPENDS ON COUNTRY (Annex S)**

Functional Unit **1 MRI SCAN**

Duration of a scan

From: PE International (2012)

Exam	Head	Spine	Abdomen	Knee	Angio	Average (min	Average (h)
Duration (min)	32.87	27.08	35.13	25.63	21.52	**28.45**	**0.47**

Lifetime of an MRI machine

From: (GE, 2017)

	years	days	hours
Lifetime	11.5	4197.5	100740

# of MRI scans in a lifetime

scans/machine	212481.8
machine/scan	4.71E-06

scans/year	18476.7

Energy Consumption

	Low	High
	Scenario 1	**Scenario 2**
Cons. (kWh/scan)	13.0000	15.0000

Helium consumption (Industrial Expert Information) - Average capacity and 3 helium loss scenarios

	Low	Medium	High
	Scenario A	**Scenario B**	**Scenario C**
loss rate (L/y)	389	1130	1948
loss rate (dewar/y)	0.778	2.26	3.896
cons. (dewar/scan)	4.21E-05	1.22E-04	2.11E-04

Annex X. Results at midpoint level for the 24 scenarios of MRI scan production

Scenario		Unit	kg SO2 eq	kg PO4--- eq	kg 1,4-DB eq	kg CO2 eq	kg 1,4-DB eq	kg 1,4-DB eq	kg CFC-11 eq	kg C2H4 eq	kg 1,4-DB eq	GeoPolRisk (0->1)
Helium use	Energy Consumption	Country	Acidification	Eutrophication	Fresh water aquatic ecotoxicity	Global Warming	Human toxicity	Marine aquatic toxicity	Ozone layer depletion	Photochemical Oxidation	Terrestrial Ecotoxicity	Supply Risk 2018
A	1	CA	4.26E-03	1.70E-03	0.53	0.87	1.19	1404.7	9.00E-07	2.12E-04	2.73E-03	0.168
A	1	DE	2.03E-02	1.25E-02	2.56	7.40	3.08	12509.6	3.46E-07	7.85E-04	7.74E-03	0.185
A	1	FR	9.07E-03	2.67E-03	0.69	1.98	1.39	2240.3	8.44E-07	4.29E-04	3.40E-03	0.256
A	1	JP	2.68E-02	1.17E-02	2.17	8.35	2.97	10688.6	5.90E-07	1.18E-03	6.84E-03	0.166
A	2	CA	4.78E-03	1.81E-03	0.56	0.98	1.28	1499.3	1.04E-06	2.36E-04	2.95E-03	0.168
A	2	DE	2.33E-02	1.43E-02	2.91	8.51	3.47	14312.9	3.96E-07	8.97E-04	8.73E-03	0.185
A	2	FR	1.03E-02	2.92E-03	0.76	2.26	1.52	2464.0	9.71E-07	4.86E-04	3.73E-03	0.256
A	2	JP	3.08E-02	1.33E-02	2.46	9.61	3.34	12211.9	6.78E-07	1.36E-03	7.69E-03	0.166
B	1	CA	4.57E-03	1.79E-03	0.54	0.95	1.22	1471.7	9.21E-07	2.32E-04	2.85E-03	0.168
B	1	DE	2.06E-02	1.26E-02	2.58	7.46	3.11	12574.0	3.62E-07	8.03E-04	7.82E-03	0.185
B	1	FR	9.34E-03	2.74E-03	0.71	2.05	1.42	2300.3	8.61E-07	4.46E-04	3.49E-03	0.256
B	1	JP	2.71E-02	1.18E-02	2.18	8.41	2.99	10751.2	6.06E-07	1.20E-03	6.91E-03	0.166
B	2	CA	5.10E-03	1.89E-03	0.58	1.06	1.31	1566.3	1.06E-06	2.56E-04	3.06E-03	0.168
B	2	DE	2.36E-02	1.43E-02	2.93	8.58	3.50	14377.3	4.12E-07	9.15E-04	8.81E-03	0.185
B	2	FR	1.06E-02	2.99E-03	0.77	2.33	1.55	2524.1	9.88E-07	5.04E-04	3.81E-03	0.256
B	2	JP	3.11E-02	1.34E-02	2.47	9.67	3.36	12274.5	6.93E-07	1.37E-03	7.77E-03	0.166
C	1	CA	4.94E-03	1.88E-03	0.56	1.05	1.26	1550.0	9.44E-07	2.55E-04	2.98E-03	0.168
C	1	DE	2.10E-02	1.27E-02	2.60	7.54	3.14	12649.3	3.80E-07	8.23E-04	7.91E-03	0.185
C	1	FR	9.65E-03	2.82E-03	0.73	2.12	1.45	2370.5	8.81E-07	4.66E-04	3.59E-03	0.256
C	1	JP	2.75E-02	1.19E-02	2.20	8.48	3.02	10824.4	6.24E-07	1.22E-03	7.00E-03	0.166
C	2	CA	5.46E-03	1.99E-03	0.60	1.16	1.35	1644.6	1.08E-06	2.79E-04	3.20E-03	0.168
C	2	DE	2.40E-02	1.44E-02	2.95	8.65	3.53	14452.6	4.30E-07	9.35E-04	8.90E-03	0.185
C	2	FR	1.09E-02	3.07E-03	0.79	2.40	1.58	2594.2	1.01E-06	5.24E-04	3.91E-03	0.256
C	2	JP	3.15E-02	1.35E-02	2.49	9.74	3.39	12347.6	7.12E-07	1.40E-03	7.86E-03	0.166