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Exploring the adoption of voluntary sustainability initiatives in mining battery minerals

by Bernardo Mendonça Severiano

Thesis submitted in fulfilment of the requirements for the degree of

Doctor of Philosophy

under the supervision of Prof. Dr. Damien Giurco and Dr. Stephen A. Northey

University of Technology Sydney
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CERTIFICATE OF ORIGINAL AUTHORSHIP

I, Bernardo Mendonça Severiano, declare that this thesis is submitted in fulfilment of the requirements for the award of Doctor of Philosophy in the Institute for Sustainable Futures at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

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Bernardo Mendonça Severiano

21st of July 2025

Sydney, Australia

Whoever teaches learns in the act of teaching, and
whoever learns teaches in the act of learning.

(Paulo Freire)

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THESIS FORMAT AND LIST OF PAPERS

This thesis is presented as a **thesis by compilation**, as outlined in Section 10.1.2 of the UTS Graduate Research School (GRS) Thesis Preparation and Submission Procedures.

The thesis comprises a coherent body of work structured as a combination of chapters and published/publishable papers. These components are integrated to form a unified narrative, with linking text and preambles to establish logical connections between chapters and papers.

Published/publishable works included in this thesis:

1. **Drivers and Barriers of Voluntary Sustainability Initiatives in Mining Raw Materials for Batteries**. Bernardo Mendonca Severiano, Stephen A. Northey, Damien Giurco

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3. **Mining Industry Networks and Diffusion of Innovations in the Battery Minerals Sector.** Bernardo Mendonca Severiano, Stephen A. Northey, Damien Giurco

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4. **Life cycle assessment of battery minerals to 2040: contribution of voluntary sustainability initiatives.** Bernardo Mendonca Severiano, Stephen A. Northey, Carina Harpprecht, Damien Giurco

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DECLARATION OF CONTRIBUTION

For each included paper, the candidate's role in conceptualisation, data collection, analysis, writing, and revision is explicitly stated. The undersigned authors agree that the nature and extent of the contributions to the work were as follows:

Table 1. Declaration of contributions related to study 1.

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ABSTRACT

In transitioning toward cleaner energy systems, lithium-ion batteries have become critical to decarbonising transportation and stationary energy storage. Yet the extraction of critical battery minerals, including lithium, nickel, manganese, and cobalt, gives rise to substantial environmental and social challenges. In addition to government regulations, Voluntary Sustainability Initiatives (VSIs) have been proposed as one possible mechanism to address these challenges. Despite bold claims, their adoption remains poorly understood, the mechanisms of diffusion are not very well explored, and their true capacity to mitigate impacts is unclear.

This thesis examines the role of VSIs in fostering more sustainable mining practices by minimising environmental impacts while ensuring future resource availability, particularly by reducing carbon footprints, managing waste responsibly, conserving water, and restoring land after operations. This work focuses on how and why these initiatives are adopted, the extent to which they diffuse, and their potential to reduce environmental burdens along the battery mineral supply chain. A multi-method framework is employed, beginning with a thematic analysis that synthesises key drivers (e.g., stakeholder pressure, reputational benefits) and barriers (e.g., smelters as pinch points, lack of standardisation) influencing mining companies' decisions to engage with VSIs. Building on this work, a participatory system dynamics approach, grounded in group-model building leverages system variables and archetypes hinting at unintended consequences within this system. To better understand pathways to widespread adoption, a network analysis clarifies how national industry associations and transnational institutes can facilitate the diffusion of sustainability practices. Finally, a prospective life cycle assessment (pLCA) quantifies the potential for VSI-influenced operational improvements to curtail environmental emissions, such as Sulfur Dioxide to air, and its respective curtailment to localised environmental impacts (e.g. particulate matter emissions decreasing air quality).

By integrating stakeholder insights with quantitative modelling, this research pinpoints critical strategies for both expanding and strengthening VSI uptake in the battery minerals sector. In particular, the prospective life cycle assessment shows that site-specific measures, such as air pollution controls and filtering membranes, can reduce localised harms (e.g., particulate matter formation, human toxicity) by up to 75–90% at certain process stages. Yet these potential gains depend on strong accountability from third-party regulators and industry associations. Without it, VSIs risk deteriorating into greenwashing tools. Transnational associations therefore have a central responsibility to promote established environmental mitigation methods and enforce transparent reporting mechanisms, ensuring that the sustainability claims of VSIs are justified through process-level improvements that translate into localised impact. In this light, these findings suggest that combining process-specific interventions under the umbrella of voluntary sustainability initiatives, backed by transparent reporting mechanisms and multi-stakeholder accountability, is crucial to making battery mineral extraction more sustainable and aligning the sector with sustainability goals.

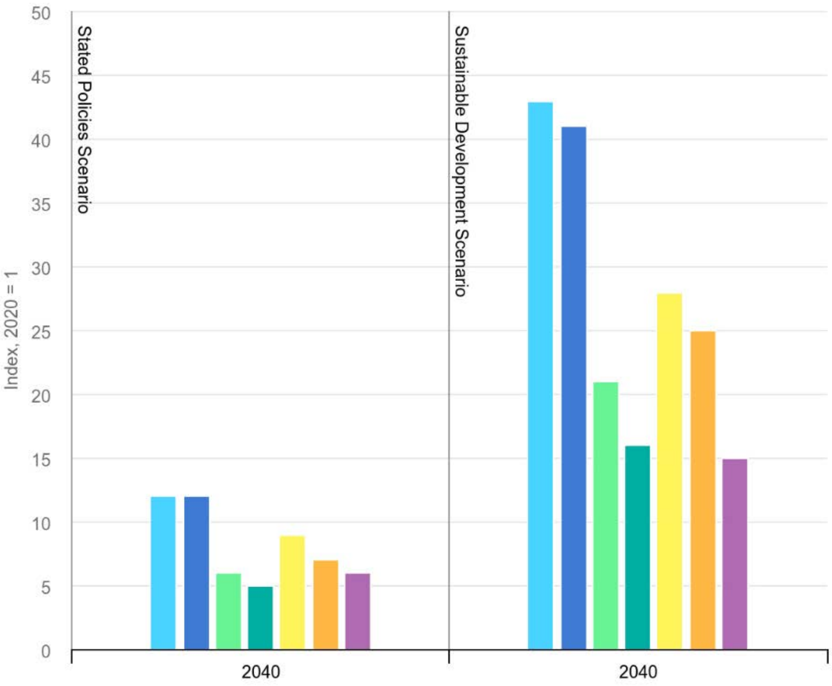
1 INTRODUCTION

1.1 Motivation and overview of problem space

Battery minerals, particularly lithium, nickel, cobalt, and manganese, are a critical foundation for the global clean energy transition, underpinning the rapidly growing battery industry for both electric mobility, including personal vehicles, public transportation, heavy vehicles, and even two- and three-wheelers, and stationary energy storage (Habib et al., 2020). While battery electric vehicles (BEVs) avoid direct (tailpipe) greenhouse gas (GHG) emissions, the upstream emissions associated with battery and vehicle manufacturing can be significant, particularly from raw material extraction and refining. Moreover, a range of environmental and social impacts are associated with the extraction of battery minerals. Managing these embodied emissions, alongside the wider environmental and social consequences of mining, is therefore a key sustainability challenge for the battery supply chain (IEA, 2020b).

Central to the expanding use of batteries are lithium-ion batteries (LIBs), which currently dominate the energy storage market due to high energy density, long cycle life, and declining costs. Although competing chemistries, such as lithium iron phosphate (LFP), are entering the market, nickel-manganese-cobalt (NMC) batteries dominate due to their optimal balance of energy density, safety, and longevity, making them indispensable in electric vehicles (Nitta et al., 2015). Across various forecasts, the demand for NMC batteries is projected to grow exponentially. However, the rapid growth in demand for BEVs and, consequently, LIBs has led to an unprecedented increase in the demand for battery minerals. Under the current *Stated Policies Scenario* (SPS), certain battery minerals could see a 5 to 12-fold increase in demand, and meeting more ambitious climate goals could require up to a 40-fold increase for minerals like lithium and nickel (**Figure 1**). As demand rises, supply security concerns increase, especially since these minerals are often concentrated in resource-rich geographies in the global south (Riofrancos, 2023), overlapping with environmental, social, and governance (ESG) risks that have become critical considerations in the supply of battery materials (Lèbre et al., 2020). These concerns particularly focused on lithium-ion cathode materials due to their high relative cost (20% of a LIB), often composed of lithium (Li), nickel (Ni), manganese (Mn), and cobalt (Co) in varying quantities, depending on battery chemistry (Habib et al., 2020; Murdock et al., 2021; Nitta et al., 2015).

Figure 1. Mineral demand growth from new EV sales. Results presented for 2040. Adapted from (IEA, 2021).



Even though the mineral extraction of battery minerals is vital for the clean energy transition, the concerns around raw material extraction are extensive. The environmental impacts of mining activities, ranging from land-use change (Sonter et al., 2018), water quality degradation (Kemp et al., 2010), air pollution (Franks et al., 2013), and biodiversity loss (Sonter et al., 2018), are widely documented. Equally significant are the social impacts of mining operations, which include inadequate consultation with local and Indigenous communities, labour rights violations, risks of child labour, and forced displacement (Kara, 2023). These factors combined have made mining a complex investment to de-risk (*Environmental, Social, and Governance: The ESG Risk Atlas: Sector and Regional Rationales and Scores*, 2020). Recent cases of poor management of tailings, including the recent catastrophes of Mount Polley (Canada), Samarco and Brumadinho (Brazil) (Innis & Kunz, 2020), have contributed to increased scrutiny and the need to demonstrate effective infrastructure and Environmental, Social and Governance (ESG) risk management. These observed impacts of mining and the potential for further localised environmental impacts with new mining developments have contributed to the mining sector being exposed to reputational risk and challenges to social licence, as exemplified by the cancellation of Rio Tinto's Jadar mining project (Undisciplined environments, 2023). Furthermore, mining activities for battery minerals are often concentrated in a limited number of countries, such as Chile, Argentina, and Australia for lithium, and the Democratic Republic of Congo for cobalt, creating vulnerabilities in supply security (Hund et al., 2020). Lastly, these supply chains often involve multiple stages of processing, with minerals being refined and manufactured into battery components, which creates difficulties for transparency and provenance tracking (Vasilyev et al., 2022). Addressing these challenges is essential to ensuring that the extraction of battery minerals are carried out sustainably, by minimising environmental impact from greenhouse gas (GHG) emissions arising from energy-intensive mining and processing activities, biodiversity loss and social disruption due to land use change, water depletion and pollution, waste related contamination, and air pollution, while ensuring that mineral resources remain available for future generations (IEA, 2021).

In response to these multifaceted risks, governments and international bodies have introduced various regulatory and policy initiatives designed to enhance accountability and traceability in mineral supply chains. One example is the Dodd-Frank Act (2010) Section 1502, which obligates companies listed on U.S. stock exchanges to disclose their use of certain minerals originating in the Democratic Republic of Congo (DRC) or adjoining countries (SEC, 2010). Another example is the *OECD Due Diligence Guidance for Responsible Supply Chains of Minerals from Conflict-Affected and High-Risk Areas (OECD, 2011)*, which provides practical guidelines for establishing mineral provenance and custody throughout the supply chain, enabling companies to meet new regulatory requirements and address growing stakeholder expectations. Additional product passport requirements, such as the European Union battery passport, further aim to ensure material provenance and ESG performance along mineral supply chains (Parliament, 2023). Despite these top-down regulations, enforcement can remain challenging where local governance is weak, or jurisdiction is limited. In such contexts, Voluntary Sustainability Initiatives (VSIs) can complement or even exceed legal requirements by encouraging higher standards of environmental stewardship and social responsibility (Franken et al., 2020; Rutovitz et al., 2020).

Although they can operate alongside or in conjunction with formal regulations, VSIs often seek to go beyond legal requirements, encouraging higher standards of environmental stewardship and social responsibility through multi-stakeholder governance structures (Rutovitz et al., 2020). Sometimes referred to as *Voluntary Sustainability Initiatives'* (Potts et al., 2018; Rutovitz et al., 2020), *'Voluntary Sustainability Standards'* (Franken et al., 2020), *'Sustainability Schemes'* (Kickler & Franken, 2017), and *'Sustainability Standard Systems'* (Erdmann & Franken, 2022), they originated in response to growing pressures from investors, regulators, and civil society for companies to address the adverse impacts of their operations while aligning with stakeholder expectations, through a multi-stakeholder governance system (Erdmann & Franken, 2022; Franken & Schütte, 2022a).

This thesis focuses on voluntary sustainability initiatives that apply specifically to mining operations producing key battery minerals used in the precursor cathode active materials of lithium-ion batteries. It examines *why* entities would adopt such initiatives, *to what extent* such initiatives can help mitigate environmental impacts, and *how* such initiatives can spread across the globe. As the battery sector continues its transformation, fostering sustainable supply chains for battery materials will be key to mitigating environmental impacts and ensuring a resilient pathway to decarbonization. In the next subsection, we'll explore these voluntary sustainability initiatives as a background context to the subsequent publications presented in this work.

1.2 Evolution of Voluntary Sustainability Initiatives (VSI) in Mining

Voluntary sustainability initiatives are not unique to mining. In fact, they have a much longer history with other industries. The adoption and efficiency of VSIs in other industries is well established and includes commodities such as tea, cocoa, forestry, and coffee, with non-governmental organisations pushing for VSI creation, diffusion, and adoption over 30 years ago (Voora et al., 2019). Agricultural industries have long documented the advantages of implementing certification schemes, with some advantages mentioned being cost reductions, as is the case for export companies that implement the ISO 14001 environmental certification (Bellesi et al., 2005). Unlocking market access can also play a role in adopting certifications and standards (Su et al., 2015). To that extent, VSIs have been widely adopted in some commodity supply chains. In the case of cocoa, for instance, the rate of annual growth of standard-compliant production has surpassed the growth of non-standard-compliant production (Voora et al., 2019), and consumer-facing product labelling is already present in agricultural sectors (having as examples Fairtrade and Rainforest Alliance).

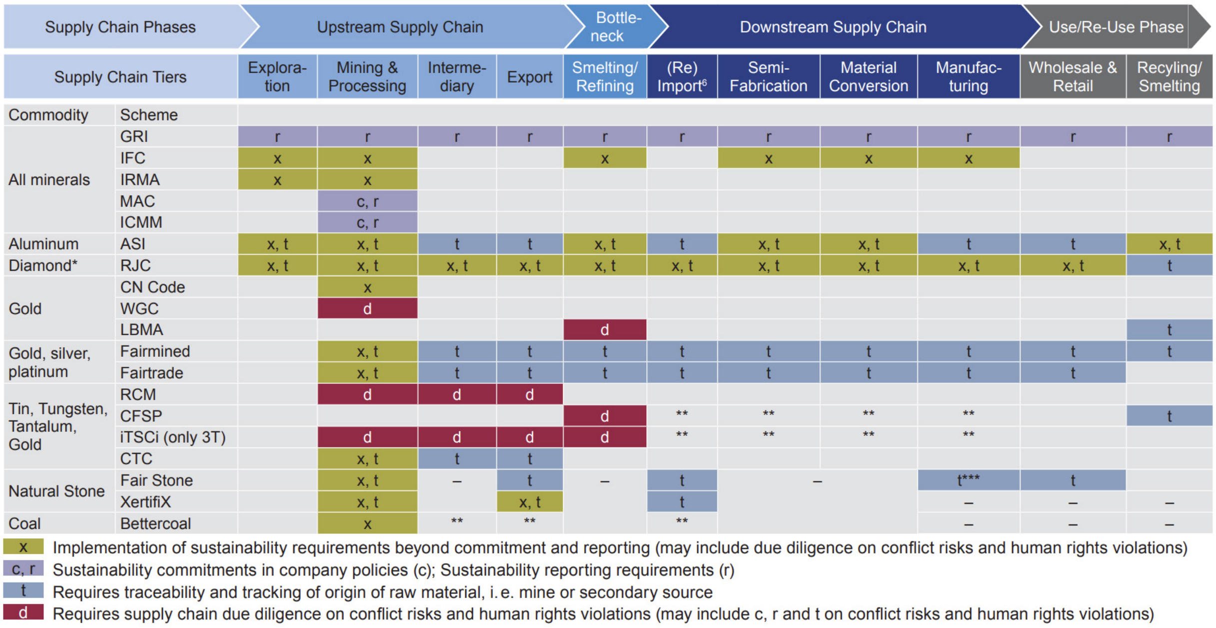
Early discussions on self-regulatory frameworks for mining trace back to the 1990s, coinciding with the rise of Corporate Social Responsibility (CSR) and heightened public awareness of environmental and social conflicts in mining. Initiatives such as the establishment of the International Council on Metals and the Environment (ICME), under the auspices of the Mining Association of Canada (MAC), marked the beginning of formal self-regulatory efforts for the sector, with a code of conduct for environmental management (Bomsel et al., 1996). Over time, these efforts have expanded to include comprehensive self-regulatory mechanisms at both national industry and firm levels, aimed at improving social and environmental performance indicators due to external control and scrutiny, with some self-regulatory efforts involving very specific actions that serve to reduce externalities for the mining industry (Peck & Sinding, 2003).

This era laid the groundwork for the later emergence of more robust, multi-stakeholder sustainability standards in the mining sector. These non-state market-driven systems have proliferated to address problems that span global areas and potential for impact, such as environmental impacts from mining (Bernstein & Cashore, 2007). These systems are not legitimised by default but can achieve the acceptance of shared rule by a community as appropriate and justified (Bernstein, 2004, p. 142). Non-state market-driven governance shifts authority away from traditional state regulation toward market-based instruments such as certifications, adopted voluntarily. These instruments, driven by market demand and buyer preference, create incentives for firms to adopt sustainable practices, thereby establishing authority and legitimacy through market dynamics rather than state influence. The legitimacy and adoption of these governance systems occur across the supply chain, as economic actors at each point of exchange choose to abide by the rules inherent in this system, reinforcing its authority throughout the production process (Cashore, 2002).

One of the first VSIs for the mining industry was first documented in 1992, with the Whitehorse Mining Initiative (WMI), led by a group of Canadian companies and representatives from civil society, under the leadership of MAC (WMI, 1994). The WMI efforts were oriented towards promoting a common vision among stakeholders respecting the future of the industry, the main areas addressed involved finance/taxation, environment, land-access, and workforce (UN DESA, 1999). Regarded as a successful endeavour in demonstrating the potential of multistakeholder collaboration (Potts et al., 2018, p. 11), WMI inspired other global initiatives like the Extractive Industries Transparency Initiative (EITI) in 2002, which leveraged government and other actors in mineral supply chains to guide demand, capacity, and commitments among producing countries. Other initiatives, such as Towards Sustainable Mining (TSM) from 2004, also under the leadership of MAC, have focused on mine-level commitments such as community relationships, biodiversity conservation, and tailings management (TSM, 2024), designed to meet the rising demand for responsible, industrial-scale mining, operating as a generic multi-commodity initiative.

Within the mining sector, the development of VSIs shows an upward trend, with the proliferation of standards being published. A comparative study done by the German Federal Institute for Geosciences and Natural Resources (BGR) mapped more than 50 Sustainability Standards Systems that are applicable to the mineral sector (Kickler & Franken, 2017). These vary significantly regarding the number of sub-issues addressed, the extent of requirements, and the specificity, as showcased in Figure 2, adapted from the previously mentioned study from BGR. For the context of this thesis, the certification schemes evaluated by Kickler and Franken (2017) applicable to battery minerals are covered under the ‘All minerals’ commodity category, such as the global schemes aimed towards large-scale mining, like the International Council on Mining and Metals (ICMM) Sustainable Development Framework (ICMM, 2023), the Initiative for Responsible Mining Assurance (IRMA) (IRMA, 2018a), the Global Reporting Initiative (GRI) Reporting Principles and Standards (GRI, 2023), and the International Finance Corporation (IFC) Environmental and Social Performance Standards (IFC, 2012). Moreover, significant advancements have been made in developing standards and certifications tailored to battery minerals. Industry organisations and multi-stakeholder platforms have increasingly focused on materials used specifically in batteries, such as the *Battery Passport* (Global Battery Alliance, 2024), the Nickel Mark (The Nickel Institute, 2024), and the *Guidance on determining the product carbon footprint of lithium products* (International Lithium Association, 2024). Furthermore, the Responsible Minerals Initiative (RMI) has dedicated focus to cobalt since 2017, with a range of tools and resources made available, such as the *Responsible Minerals Assurance Process* (RMAP), providing independent third-party assessments, and a *Conformant Cobalt Refiners* assessment report (Responsible Minerals Initiative, 2024).

Figure 2. Scheme requirements along the mineral supply chain. Reproduced from (Kickler & Franken, 2017). GRI = Global Reporting Initiative; IFC = International Finance Corporation; IRMA = Initiative for Responsible Mining Assurance; MAC = Mining Association of Canada; ICMM = International Council on Mining and Metals; ASI = Aluminium Stewardship Initiative; RJC = Responsible Jewellery Council; CN Code = Cyanide Code; WGC = World Gold Council; LBMA = The London Bullion Market Association; RCM = Regional Certification Mechanism; CFSP = Conflict-Free Smelter Program; iTSCi = ITRI Tin Supply Chain Initiative; CTC = Certified Trading Chains.



Supply Chain Phases		Upstream Supply Chain				Bottle-neck	Downstream Supply Chain				Use/Re-Use Phase	
Supply Chain Tiers		Explora-tion	Mining & Processing	Interme-diary	Export	Smelting/ Refining	(Re) Import⁶	Semi-Fabrication	Material Conversion	Manufac-turing	Wholesale & Retail	Recyling/ Smelting
Commodity	Scheme											
All minerals	GRI	r	r	r	r	r	r	r	r	r	r	r
	IFC	x	x			x		x	x	x		
	IRMA	x	x									
	MAC		c, r									
	ICMM		c, r									
Aluminum	ASI	x, t	x, t	t	t	x, t	t	x, t	x, t	t	t	x, t
Diamond*	RJC	x, t	x, t	x, t	x, t	x, t	x, t	x, t	x, t	x, t	x, t	t
Gold	CN Code		x									
	WGC		d									
	LBMA					d						t
Gold, silver, platinum	Fairmined		x, t	t	t	t	t	t	t	t	t	t
	Fairtrade		x, t	t	t	t	t	t	t	t	t	
Tin, Tungsten, Tantalum, Gold	RCM		d	d	d							
	CFSP					d	**	**	**	**		t
	iTSCi (only 3T)		d	d	d	d	**	**	**	**		
	CTC		x, t	t	t							
Natural Stone	Fair Stone		x, t	–	t	–	t	–		t***	t	
	XertifiX		x, t		x, t		t			–	–	–
Coal	Bettercoal		x	**	**		**			–	–	–

x	Implementation of sustainability requirements beyond commitment and reporting (may include due diligence on conflict risks and human rights violations)
c, r	Sustainability commitments in company policies (c); Sustainability reporting requirements (r)
t	Requires traceability and tracking of origin of raw material, i. e. mine or secondary source
d	Requires supply chain due diligence on conflict risks and human rights violations (may include c, r and t on conflict risks and human rights violations)

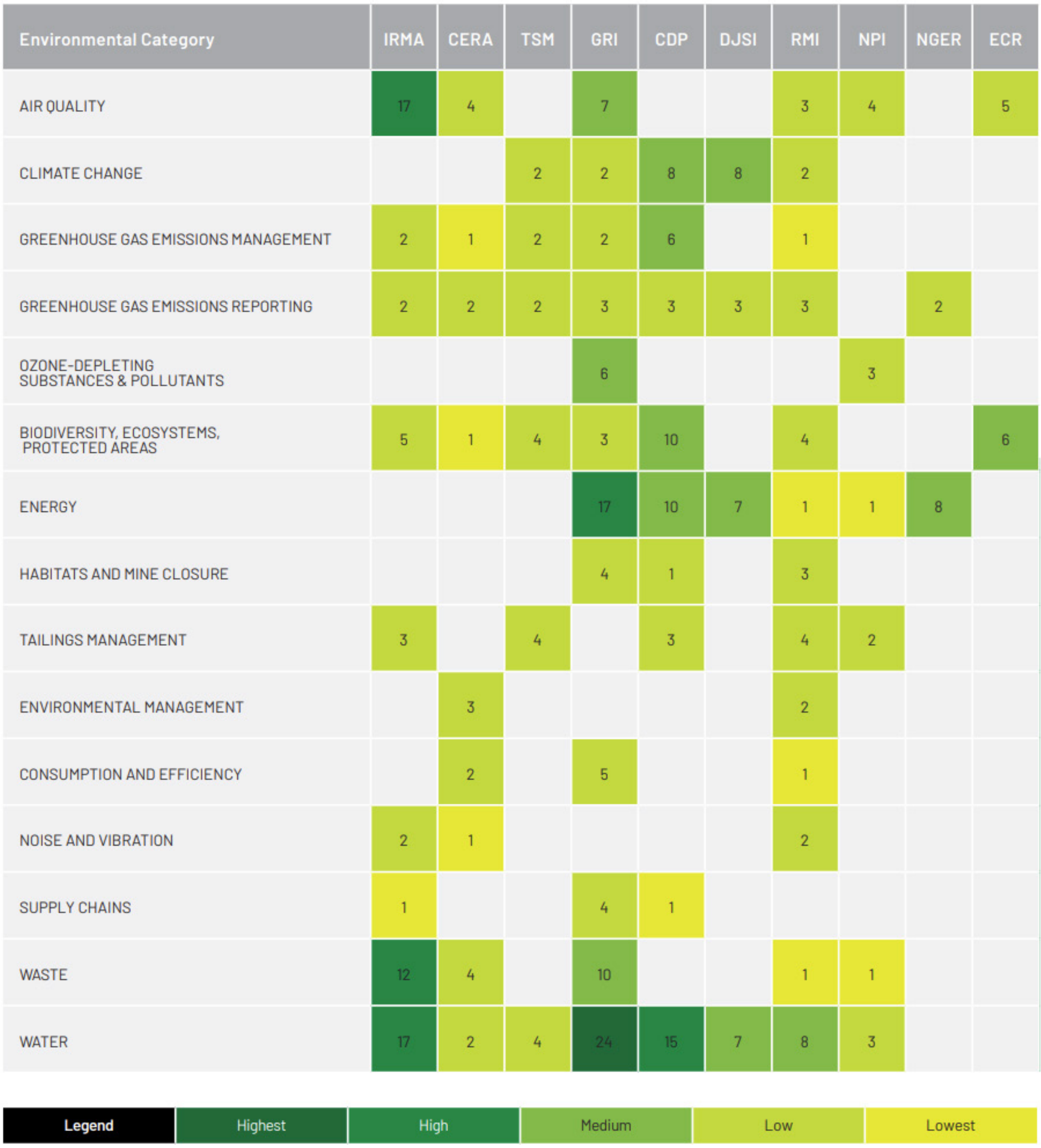
More than just a proliferation in the publication of standards, there's been a proliferation in the adoption of such standards. A case in point is the Towards Sustainable Mining (TSM) standard, which will be covered in more detail in **Chapter 5**. Spearheaded by the Mining Association of Canada (MAC), it was launched in 2004, with their second administrative body (Finnish Network for Sustainable Mining) adopting it in 2015 (Franken & Schütte, 2022a). Since then, as of writing this thesis, the standard has been adopted by 12 national mining chambers across the globe (TSM, 2024). Nevertheless, the distinct characteristics inherent to the mining sector and to battery supply chains present unique aspects. The past decades have seen increasing expectations for sustainable sourcing and transparency in these sectors, focusing more on social aspects such as workers' rights and human rights due diligence, and to a lesser extent, on environmental concerns such as reducing carbon emissions (Franken & Schütte, 2022a).

Despite such progress, scholars remain uncertain about the principal drivers that lead to VSI adoption. In some instances, national authorities have endorsed VSI frameworks to rebuild confidence after environmental or social crises. An example happened in Finland, where the government's endorsement of a third-party accountability framework after the 2012 Talvivaraa dam failure aimed to restore public confidence. This instance highlights the complex nature of public conflicts, which often involve a range of issues (such as leaks, odour, water pollution) leading up to a crisis (Franken et al., 2020; Sairinen et al., 2017; yle, 2012). Such cases are far from being isolated incidents. In fact, environmental conflicts related to mining operations are alarmingly widespread. According to the Environmental Justice Atlas, nearly one in five environmental justice conflicts worldwide are related to *Mineral Ores and Building Materials Extraction* (EJ Atlas, 2023).

Figure 3. Instances of documented environmental conflicts between local communities and mineral ores and building materials' extraction operations. From the global atlas of environmental justice (EJ atlas, 2023).

Despite decades of development, the long-term impact and uptake of these initiatives remain uncertain and often vary by commodity and geography. Although broad adoption might suggest industry commitment, authors have questioned the sustained, long-term sustainability across these sectors, leading to criticism about greenwashing. The focus on short-term impacts without acknowledging longer-term changes might serve immediate corporate interests to discredit established reporting requirements (Franken & Schütte, 2022a). Reporting requirements can also vary significantly regarding the number of sub-issues addressed, the extent of requirements, and the specificity, as showcased by **Figure 4**. Lastly, the governance structure of such standards systems also varies significantly, with some being industry-led (e.g., ICMM), Others being industry-led with structured stakeholder engagement (e.g., TSM), and some being non-industry initiated, but industry inclusive (e.g., IRMA) (Erdmann & Franken, 2022).

Figure 4. Heatmap of ESG categories considered by each VSI. Reproduced from Langdon et al. (2021). ECR=Environmental Compliance Reporting, NPI=National Pollutant Inventory, NGER=National Greenhouse and Energy Reporting, IRMA=The Initiative for Responsible Mining Assurance, CERA=The Certification of Raw Materials, TSM=Towards Sustainable Mining, GRI=Global Reporting Initiative, CDP=Carbon Disclosure Project, DJSI=Dow Jones Sustainability Index, RMI=Responsible Mining Index.



Environmental Category	IRMA	CERA	TSM	GRI	CDP	DJSI	RMI	NPI	NGER	ECR
AIR QUALITY	17	4		7			3	4		5
CLIMATE CHANGE			2	2	8	8	2			
GREENHOUSE GAS EMISSIONS MANAGEMENT	2	1	2	2	6		1			
GREENHOUSE GAS EMISSIONS REPORTING	2	2	2	3	3	3	3		2	
OZONE-DEPLETING SUBSTANCES & POLLUTANTS				6				3		
BIODIVERSITY, ECOSYSTEMS, PROTECTED AREAS	5	1	4	3	10		4			6
ENERGY				17	10	7	1	1	8	
HABITATS AND MINE CLOSURE				4	1		3			
TAILINGS MANAGEMENT	3		4		3		4	2		
ENVIRONMENTAL MANAGEMENT		3					2			
CONSUMPTION AND EFFICIENCY		2		5			1			
NOISE AND VIBRATION	2	1					2			
SUPPLY CHAINS	1			4	1					
WASTE	12	4		10			1	1		
WATER	17	2	4	24	15	7	8	3		

Some authors have speculated that the adoption of voluntary standards is a key indicator of *early mover status* (Dashwood, 2012), providing firms with cooperative relations with government regulators and greater flexibility in the enforcement of existing environmental regulations (Potoski & Prakash, 2005). Critics argue this leniency might undermine VSI's legitimacy by allowing companies to bypass stringent enforcement, thereby reducing VSI's legitimacy, limiting its success (Tröster & Hiete, 2018). These initiatives are increasingly adopted by companies seeking to differentiate themselves in competitive markets, comply with customer expectations, and meet the growing demand for sustainable products (Amnesty International, 2017a; Franken et al., 2020), with pressure by downstream consumer-facing companies being one of the strongest drivers to responsible mineral developments, second only to regulation (*Voluntary Responsible Mining Initiatives A Review*, 2015). Moreover, community relations and development, under the umbrella of CSR, can be deployed to de-escalate crises, becoming purely transactional approaches to community relations and mining (Kemp & Owen, 2013).

Voluntary initiatives represent a tool, within a toolbox, to drive a just and sustainable transition in mineral extraction and supply chains, ensuring that the green energy revolution does not perpetuate existing inequalities or create new injustices, which remains to be seen. Some authors also consider VSIs to be the “second best option”, being useless in front of total conformity with national and international laws, regulations, and standards (Franken et al., 2012). As the mining sector grapples with rising social and environmental expectations, questions of legitimacy, effectiveness, and equity remain open. These tensions are especially evident in battery mineral supply chains, where extraction contributes less than 1% of a battery’s total value (Wills et al., 2018). Additionally, the complexity is compounded in the sector by the vast number of suppliers involved. For example, Panasonic, a leading EV battery manufacturer, works with over 10,000 suppliers globally (Panasonic, 2021), affecting a company’s capability to properly engage with deep suppliers. Junior mining companies, in particular, are more vulnerable to supply chain volatility and have less influence on sourcing practices due to their dependency on suppliers (Kalaitzi et al., 2019). Lastly, the structural relations of power and modes of governance that voluntary initiatives belong to have been criticised for potentially undermining national regulations, particularly in the global south. Critics argue that certification schemes may serve corporate interests while neglecting deeper social or environmental reforms through *regulatory capture,* where industrial interests are overly represented (Blackman, 2008).

It's important to stress that the broad adoption of VSIs does not guarantee sustained, long-term sustainability across this sector. The focus on short-term impacts without acknowledging longer-term changes might serve immediate corporate interests to discredit established reporting requirements (Franken & Schütte, 2022a). Moreover, assessing the legitimacy of VSIs is complex, being defined by their ability to solve a problem, behavioural effectiveness, market diffusion, and their constitutive effectiveness, which are industry-, commodity-, and geography-specific (Tröster & Hiete, 2018). As the goods move from the global south to the global north, transnational governance plays a critical role across these layers.

Multi-tiered supply chain initiatives, such as the ones needed in the lithium-ion battery supply chain, fundamentally rely on the effective communication of information, from raw material sourcing to product end-use, with emerging technologies and process innovations, like material fingerprinting and decentralised ledger technologies, enhancing this communication, particularly in supply chain traceability (Vasilyev et al., 2022). These advancements could strengthen the role of VSIs in not only mitigating social and environmental impacts but also in highlighting positive developments (IRMA, 2018a). In the next subsection, the current state of VSI adoption within the battery minerals sector will be explored, establishing a foundation for the more in-depth thematic analysis presented in **Chapter 3**.

1.3 VSIs and battery minerals – Research directions and research gap

Building on the previous sub-section, understanding the role of VSIs in the lithium-ion battery supply chain requires navigating a complex and interdisciplinary landscape. This landscape spans diverse subject areas, methodological approaches, and data sources, calling for integrative and transdisciplinary research approaches. Notably, the body of literature on VSIs in mining is relatively young, being only a few decades old (Tröster & Hiete, 2018), and while it discusses several mined commodities, specific coverage of battery minerals such as lithium, nickel, manganese, and cobalt is considerably sparser (Franken et al., 2020; Langdon et al., 2021). This section consolidates key insights from the broader VSI literature to demonstrate how existing research on mining-related VSIs intersects with, but also leaves important gaps in, the context of battery minerals. This is particularly the case in terms of adoption drivers and effectiveness. The discussion thus illustrates why the mining-for-batteries domain remains underexplored and how this thesis builds upon and extends existing knowledge.

Overall, academic studies on Voluntary Sustainability Initiatives (VSIs) have tended to cluster around a few key themes (Table 5). First, several scholars have focused on conceptual and theoretical foundations. Early works by Paton (2000) and Croci (2005) conceptualised VSIs as tools that extend beyond mere regulatory compliance, emphasising their potential to promote economic efficiency, equity, and transparency, where VSIs can be either complements or substitutes to formal regulation, depending on whether they arise in anticipation of stricter laws or to fill regulatory gaps. Whilst research by Bellesi et al. (2005) laid the groundwork for understanding how VSIs such as ISO14001 can reduce costs and facilitate market access, concepts that would later be applied within mining contexts.

Other works have focused on the implementation and practical challenges in mining, Schiavi and Solomon (2006) highlighted a recurring disconnect between the reputational benefits of voluntary sustainability initiatives and their actual environmental performance. Mueller et al. (2009) stated that frequent supplier turnover in a global supply chain can erode the effectiveness of certification systems, requiring consistent auditing practices. This is corroborated by studies such as the one done by Stark & Levin (2011), in which the potential for greenwashing through certification was flagged, describing the use of aggregated data to indicate misleading compliance. Other researchers, such as Fonseca et al. (2013), called for integrative approaches, notably lifecycle thinking and system dynamics, to address to complexities of managing environmental and social risks throughout the mining value chain.

Another persistent theme centres on the drivers, legitimacy, and adoption dynamics. Studies by Mori Junior and Franks (2016), as well as Dyck et al. (2019), examine how stakeholder pressure and shareholder proposals can influence the uptake of VSIs. Yet, as Young et al. (2010) caution, managing deep suppliers across multi-tier supply chains introduces significant complexity. Along similar lines, Franken et al. (2020) highlight how the desire for market access, especially in critical mineral sectors like lithium and cobalt, can drive firms to adopt sustainability standards, although such adoptions also entail financial burdens that haven’t been extensively analysed.

More recently, scholars have paid considerable attention to the effectiveness of standards. Comparative analyses by Kickler & Franken (2017), as well as Potts et al. (2018), underscore significant discrepancies among different VSI schemes in terms of their scope, transparency, and stakeholder engagement. Tröster and Hiete (2018) evaluate the degree to which initiatives such as IRMA, TSM, and ICMM align with stakeholder needs, noting that capacity-building and the stringency of requirements often determine their credibility. In a similar vein, Sauer and Seuring (2019) show that many firms adopt VSIs to satisfy regulatory or investor expectations, reducing uncertainty and legitimising supply-related consistency claims within a multi-tiered supply chain, emphasising the tension between risk management and genuine long-term improvements.

Table 5. Non-exhaustive and broadly representative list of studies looking at voluntary sustainability initiatives in general, for mining, and inclusive of battery minerals

Theme	Representative Studies	Author (Year)	Key Insights
Conceptual & Theoretical Foundations	Voluntary environmental initiatives and sustainable industry	Paton (2000)	Explored private or public efforts to improve corporate environmental performance beyond legal requirements. Included an overview of such initiatives through the lenses of *environmental effectiveness, economic efficiency, equity, transparency, openness to participation by third parties,* and the *effect of industry behaviour*.
	The Economics of Environmental Voluntary Agreements	Croci (2005)	Described VSIs as advanced policy tools that have intrinsic relationships with regulation, being either *substitute, integrative, anticipatory,* or *applicative.*
	Comparative Advantage: The Impact of ISO 14001 Environmental Certification on Exports	Bellesi et al. (2005)	Agricultural industries have long documented the advantages of implementing certification schemes, with some advantages mentioned being cost reductions.
Implementation & Practical Challenges in Mining	Voluntary Initiatives in the Mining Industry: Do They Work?	Schiavi and Solomon (2006)	Analysed the demonstrated effectiveness of VSIs in terms of reputation and communication with stakeholders. Identified a challenge in attributing a demonstrated effect on environmental performance solely from VSIs.
	The Contribution of Environmental and Social Standards Towards Ensuring Legitimacy in Supply Chain Governance	Mueller et al. (2009)	An analysis of the adoption of four VSIs (ISO14001, SA8000, FLA, and FSC) states that rapid changes of suppliers in global supply chains erode the effectiveness of certification systems, requiring consistent auditing standards
	Benchmark Study of Environmental and Social Standards in Industrialised Precious Metals Mining	Stark and Levin (2011)	Identified the potential for greenwashing in certification through the use of aggregated data to indicate compliance. Analysis specific to precious metals
	Measuring what? A comparative anatomy of five mining sustainability frameworks	Fonseca et al. (2013)	Described a mainly retrospective temporal orientation of mining VSIs. Suggested that it is necessary to have experimentation with timeframes, integration, life cycle thinking, and system dynamics
Drivers, Legitimacy & Adoption Dynamics	Principles for responsible metals supply to electronics	Young et al. (2010)	Performed a literature review on CSR incorporation across stages of production of electronics, inclusive of how metals are mined, traded, and used. Concluded that certain VSIs, when adopted by manufacturers, have the power to increase awareness towards deep suppliers.
	Sustainability certification schemes: evaluating their effectiveness and adaptability	Mori Junior et al. (2016)	Identified 8 key components affecting the effectiveness of VSIs (sustainability awareness; market access; management systems and productivity; social, environmental, and economic impacts; monitoring outcomes; competition, overlapping, and interoperability; stakeholder participation; and accountability and transparency).
	Do institutional investors drive corporate social responsibility? International evidence	Dyck et al. (2019)	Analysed the influence of shareholder proposals to adopt sustainability standards, and negative and positive screening
	Jumping the Chain: How Downstream Manufacturers Engage with Deep Suppliers of Conflict Minerals	Young et al. (2019)	Described the phenomenon of “jumping the chain”, regarding the management of “deep suppliers” by top-tier firms that want to increase their supply-chain due diligence.

	Voluntary sustainability initiatives: An approach to make mining more responsible?	Franken et al. (2020)	Analysed 20 VSIs, including those applicable to all mineral resources. Based on a previous study by Cook & Mitchell (2014) regarding 3TG, concluded that while traceability schemes can provide market access, the financial burden of additional costs for producers is still highly debated. Also, it added a focus to renewable energy technologies, inclusive of lithium, nickel, and rare earth minerals, and that they need to be addressed more by these initiatives.
	Current trends in addressing environmental and social risks in mining and mineral supply chains by regulatory and voluntary approaches	Franken and Schütte (2022a)	A consolidated review of a range of VSIs adopted in the past decades. Emphasised the risk-management approach taken by most companies to address expectations related to regulators, investors, and downstream buyers. Stated how many companies have successfully adopted due diligence procedures and effectively increased the supply-chain transparency. Reiterated that short-term financial gains can undermine effective sustainability risk management, potentially leading to severe social and environmental consequences (e.g., tailings dam failures).
Effectiveness of Standards	Sustainability Schemes for Mineral Resources: A Comparative Overview	Kickler and Franken (2017)	Assessed 19 mineral sustainability schemes. Analysed schemes that targeted the mining and processing stage (e.g., IRMA), or the entire supply chain (e.g., Fairtrade). Developed a consolidated framework of sustainability issues, covering 86 mining-relevant sustainability criteria.
	Standards and the extractive economy	Potts et al. (2018)	Analysed 15 different sustainability standards applicable to the minerals' Covered expectations created by downstream agents, invariably affecting the response of the mining sector, which in turn adapts to requirements. Clearly stated the challenge of a "one-size-fits-all" approach.
	Success of voluntary sustainability certification schemes – A comprehensive review	Tröster and Hiete (2018)	Reviewed 226 studies covering certification schemes. Mainly published from 2002 to 2017. The most discussed factors influencing the problem-solving capacity of certification schemes are the quality of requirements and capacity-building measures. For diffusion, key factors include characteristics of adopting entities and governmental influences.
	Do voluntary sustainability certification schemes in the sector of mineral resources meet stakeholder demands? A multi-criteria decision analysis	Tröster and Hiete (2019)	Used a multi-criteria decision analysis method to evaluate if VSIs meet stakeholder demand. Showcased that certifications such as IRMA, TSM, and ICMM are lacking a degree of demand met in comparison to other VSIs applied to the mineral sector. Moreover, the degree of demand met across stakeholders also varies significantly across *supply-chain actors, civil society, governmental organisations,* and others.
	The complementing role of sustainability standards in managing international and multi-tiered mineral supply chains	Sauer (2021)	Focus on sustainability standards and certifications, acting as a way to reduce uncertainty and legitimise supply-related consistency claims within a multi-tiered supply chain, as the commodities move through downstream buyers.

A focused examination of the scientific literature, specifically looking at VSIs and battery minerals, reveals an even wider literary gap. Systematic searches in the Web of Science database, targeting the intersection of voluntary sustainability initiatives and the aforementioned key raw materials, returned no results (**Table 6**). This finding is noteworthy since it suggests a notable gap in the academic literature regarding the integration of voluntary sustainability initiatives in the context of mineral extraction for lithium-ion batteries, especially since a range of industry reports have been published with explicit focus on *'Voluntary Sustainability Initiatives'* (Potts et al., 2018; Rutovitz et al., 2020), *'Voluntary Sustainability Standards'* (Franken et al., 2020), *'Sustainability Schemes'* (Kickler & Franken, 2017), and *'Sustainability Standard Systems'* (Erdmann & Franken, 2022).

Furthermore, when broadening the search to include more general sustainability terms (ESG, CSR, and Environmental Stewardship), the literature remained limited, with no publications prior to 2009 and little evidence of cross-referencing or integration among studies (see **Figure 5**). It is important to note, however, that before this period, related concepts were discussed, however under different terminology, such as sustainable development and corporate sustainability. The apparent gap in the literature thus reflects a shift in language and framing. Not only this, but our analysis of the publication dataset highlighted a significant variance in the number of scientific subjects (**Figure 6**), highlighting diverse research subjects and intensity over the years**.** Using the *All Science Journal Classification* (ASJC) codes (Scopus, 2023)*,* the subject of “Management, Monitoring, Policy and Law” emerged as the most frequently represented category (19 publications), followed closely by “Economics and Econometrics” and “Geography, Planning and Development.” Among these categories, “Renewable Energy, Sustainability and the Environment” not only accounted for a significant number of publications but was also the most consistently represented over the years, spanning nine distinct publication periods. Therefore, the exploration of this topic will strategically expand existing literature into adjacent domains, leveraging integrative research methods such as system dynamics (**Chapter 4**), network theory (**Chapter 5**), and lifecycle thinking (**Chapter 6**), to create a more comprehensive understanding of the field. As illustrated in **Figure 7**, incorporating a range of studies such as Lèbre et al. (2019), Owen and Kemp (2013), Ali et al. (2017), Watari, Nansai, Nakajima, et al. (2021), van den Brink et al. (2020) into the original literature review considerably enhances its connectivity. Readers will observe how several of these studies feature in the four publications presented in **Chapters 3–6**, effectively showcasing the transdisciplinary approach of this work.

Table 6. Queries encompassing broader sustainability terminology were conducted on the Web of Science database. Filtered to encompass to minerals used in cathode active materials (lithium, nickel, manganese, and cobalt). Query performed on the 21st of November 2023.

Themes	**Web of Science Query**	**Results**
Lithium-Ion Batteries; Voluntary Initiatives; Supply-chain	TS=("lithium ion" OR "lithium-ion" OR "electric vehicle*") **AND** TS=("supply chain*" OR "value chain*") **AND** TS=("Voluntary Sustainability Initiatives" OR "Voluntary Sustainability Standards" OR "Sustainability Schemes" OR "Sustainability Standard Systems")	0
Lithium-Ion Batteries; Voluntary Initiatives;	TS=("lithium ion" OR "lithium-ion" OR "electric vehicle*") **AND** TS=("Voluntary Sustainability Initiatives" OR "Voluntary Sustainability Standards" OR "Sustainability Schemes" OR "Sustainability Standard Systems")	0
Battery Minerals; Voluntary Initiatives; Supply-chain;	TS=("lithium" OR "Nickel" OR "Manganese" OR "Cobalt") **AND** TS=("supply chain*" OR "value chain*") **AND** TS=("Voluntary Sustainability Initiatives" OR "Voluntary Sustainability Standards" OR "Sustainability Schemes" OR "Sustainability Standard Systems")	0
Battery Minerals; Voluntary Initiatives;	TS=("lithium" OR "Nickel" OR "Manganese" OR "Cobalt") **AND** TS=("Voluntary Sustainability Initiatives" OR "Voluntary Sustainability Standards" OR "Sustainability Schemes" OR "Sustainability Standard Systems")	0
Battery Minerals; Voluntary Initiatives; Supply-chain;	TS=("battery mineral*") **AND** TS=("supply chain*" OR "value chain*") **AND** TS=("Voluntary Sustainability Initiatives" OR "Voluntary Sustainability Standards" OR "Sustainability Schemes" OR "Sustainability Standard Systems")	0
Battery Minerals; Voluntary Initiatives;	TS=("battery mineral*") **AND** TS=("Voluntary Sustainability Initiatives" OR "Voluntary Sustainability Standards" OR "Sustainability Schemes" OR "Sustainability Standard Systems")	0
Energy Transition Minerals; Voluntary Initiatives; Supply-chain;	TS=("energy transition mineral*") **AND** TS=("supply chain*" OR "value chain*") AND TS=("Voluntary Sustainability Initiatives" OR "Voluntary Sustainability Standards" OR "Sustainability Schemes" OR "Sustainability Standard Systems")	0
Energy Transition Minerals; Voluntary Initiatives;	TS=("energy transition mineral*") **AND** TS=("Voluntary Sustainability Initiatives" OR "Voluntary Sustainability Standards" OR "Sustainability Schemes" OR "Sustainability Standard Systems")	0

Figure 5. Yearly distribution of publications (left), and interconnectedness of citations (right). Generated with research rabbit on 16th of December 2024.

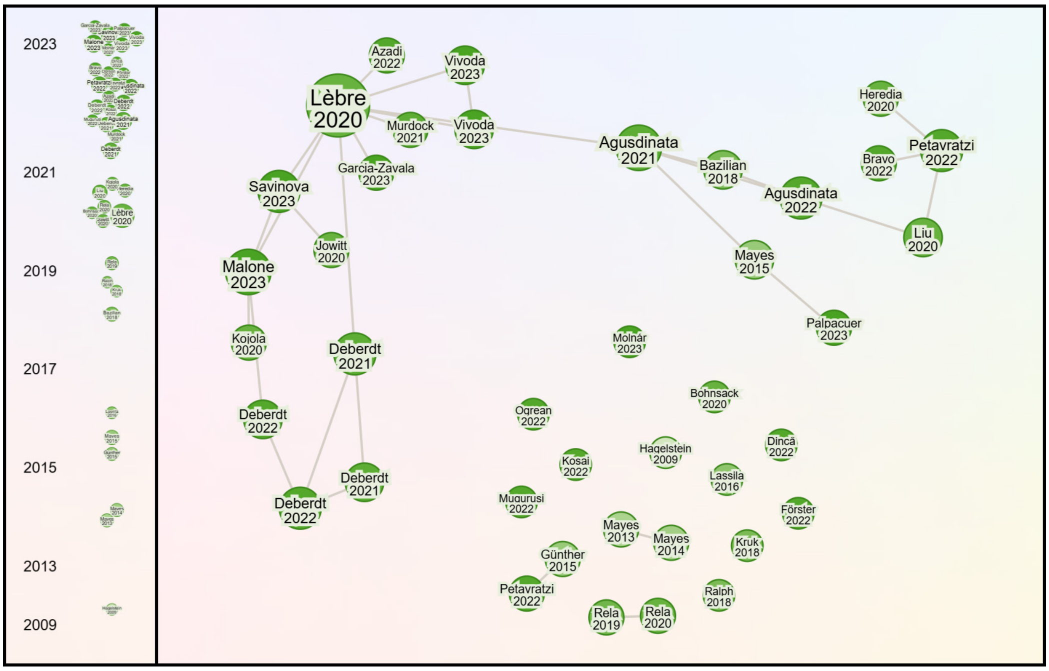


Figure 6. Distribution of publications targeting the intersection of key raw materials for lithium-ion batteries (lithium, nickel, manganese, and cobalt), and ESG, CSR, and Environmental Stewardship themes. The same publication can be labelled across different categories (e.g. the sole publication from 2009 falls under 4 different categories). Publications in blue refer to nickel, in green refer to lithium, and in yellow refer to cobalt. Publications in grey have no specific mention of either compound.

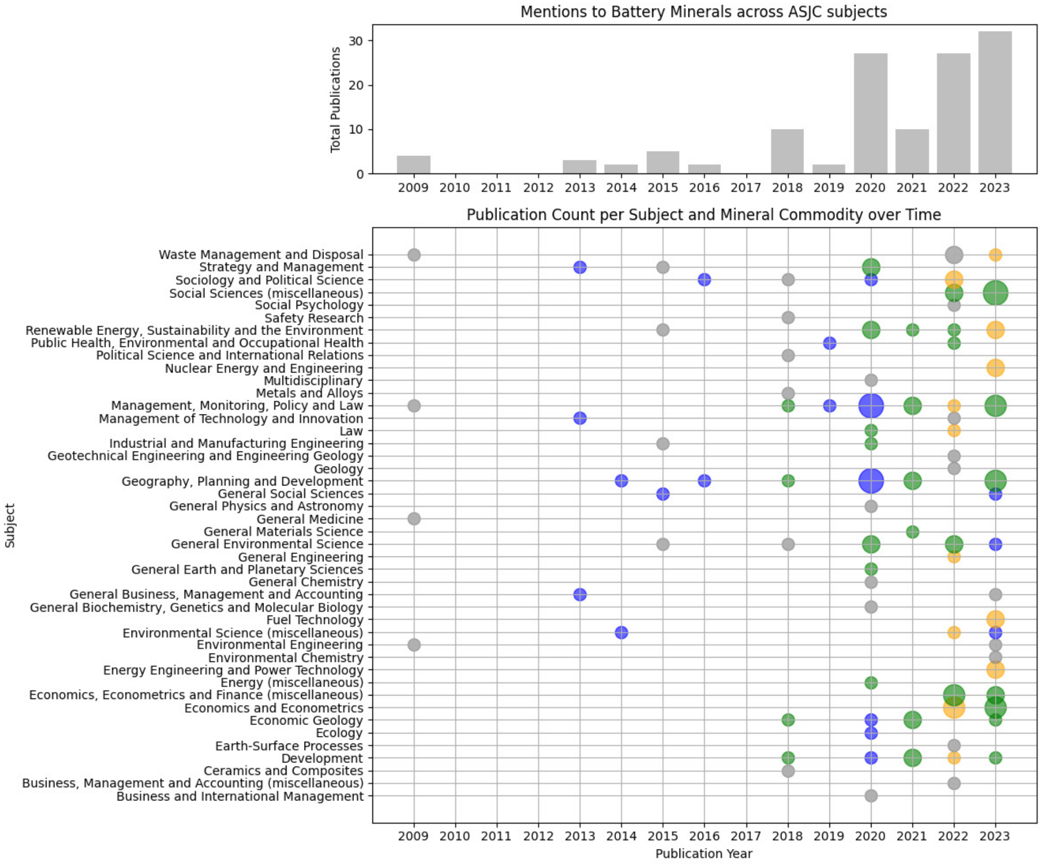
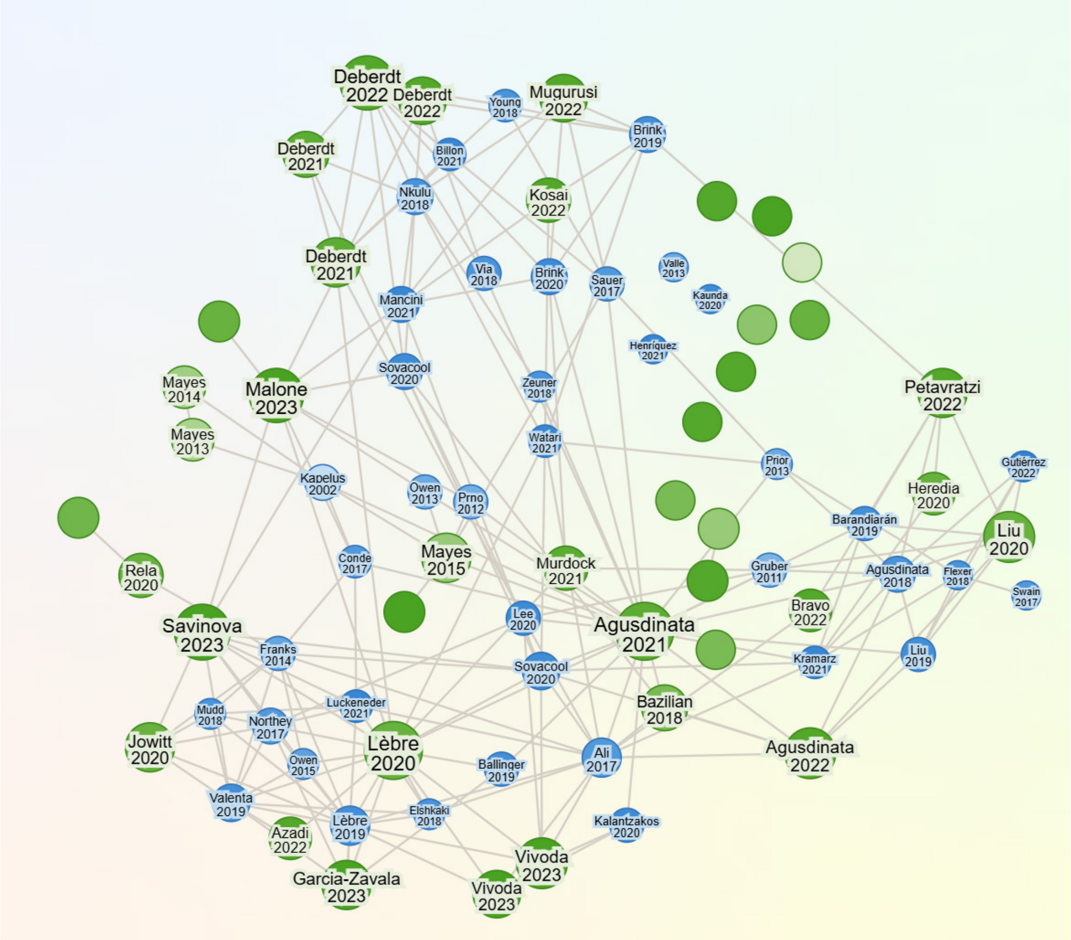


Figure 7. The same network presented in Figure 5 and Figure 6, inclusive of selected works that can significantly increase the network integration.

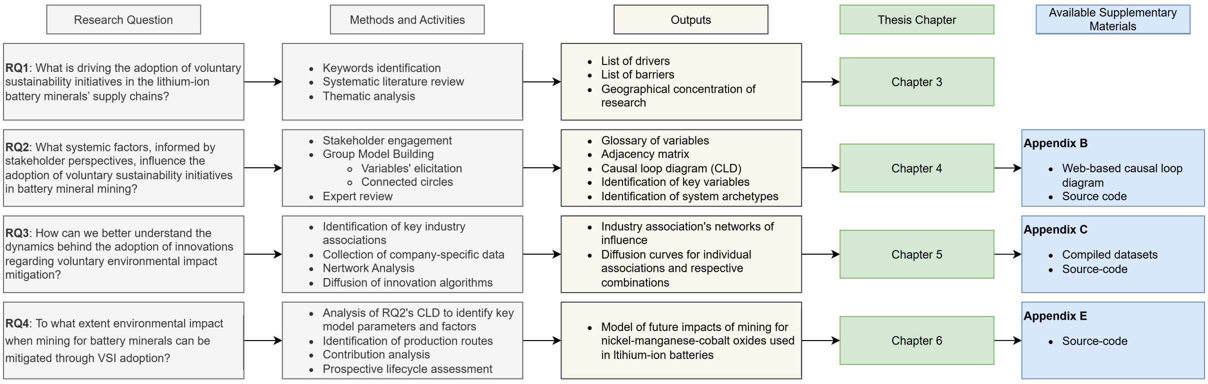


Taken together, this initial review reveals a field in which VSI adoption in mining is documented to an extent but lacks specificity when it comes to battery minerals. Although recent industry reports and broader sustainability scholarship mention voluntary initiatives that cover battery minerals, there is limited scholarly analysis of how such initiatives are adopted and evaluated specifically for lithium, nickel, manganese, and cobalt mining. With growing demand for these battery minerals, understanding how VSIs might address environmental and social risks, what are the drivers to their adoption, and the pathways for their diffusion becomes both important and timely. This thesis will cover an extensive literature review throughout a thematic analysis in **Chapter 3**. Nonetheless, we can foreshadow that this is a field that has not coalesced into a cohesive narrative, with lingering questions pertaining to *"why would companies adopt these schemes"*, *"how do these achieve proliferation across the industry"*, and *"to what extent they can mitigate environmental impacts"*, to name a few. These questions, which come naturally from the scientific literature, are better crafted and methodologically aligned under **Chapter 2**, which will describe the integrative methods applied to each research question individually, to bridge a specific scientific gap from within a specific scientific field, whilst still moving the understanding of VSIs for batteries forward.

1.4 Thesis overview

This thesis is presented as a compilation of four core articles, preceded by introductory and methodological chapters (Chapters 1 and 2) and followed by a concluding chapter (Chapter 7), as illustrated in Figure 8. Some journal articles are already published (Chapters 3, 4, and 5), and another is in the process of publication (Chapter 6). Considering the relative independence and length of the text, references are presented at the end of each chapter. The introduction of concepts and the description of the studied area may repeatedly appear in the articles because they needed a minimum of independent contextualisation at the time of publication. Nonetheless, internal cross-references are made and can lead to a cohesive reading. At the beginning of the chapters containing the journal articles (Chapters 3, 4, 5, and 6), the contributions and agreement of the co-authors are presented.

Figure 8. Schematic overview of thesis. Details on research questions and methods adopted will be presented in Chapter 2



Research Question	Methods and Activities	Outputs	Thesis Chapter	Available Supplementary Materials
RQ1: What is driving the adoption of voluntary sustainability initiatives in the lithium-ion battery minerals' supply chains?	• Keywords identification • Systematic literature review • Thematic analysis	• List of drivers • List of barriers • Geographical concentration of research	Chapter 3	
RQ2: What systemic factors, informed by stakeholder perspectives, influence the adoption of voluntary sustainability initiatives in battery mineral mining?	• Stakeholder engagement • Group Model Building ○ Variables' elicitation ○ Connected circles • Expert review	• Glossary of variables • Adjacency matrix • Causal loop diagram (CLD) • Identification of key variables • Identification of system archetypes	Chapter 4	**Appendix B** • Web-based causal loop diagram • Source code
RQ3: How can we better understand the dynamics behind the adoption of innovations regarding voluntary environmental impact mitigation?	• Identification of key industry associations • Collection of company-specific data • Nertwork Analysis • Diffusion of innovation algorithms	• Industry association's networks of influence • Diffusion curves for individual associations and respective combinations	Chapter 5	**Appendix C** • Compiled datasets • Source-code
RQ4: To what extent environmental impact when mining for battery minerals can be mitigated through VSI adoption?	• Analysis of RQ2's CLD to identify key model parameters and factors • Identification of production routes • Contribution analysis • Prospective lifecycle assessment	• Model of future impacts of mining for nickel-manganese-cobalt oxides used in ltihium-ion batteries	Chapter 6	**Appendix E** • Source-code

2 METHODOLOGY

Investigating how Voluntary Sustainability Initiatives (VSIs) are adopted, diffused, and how they can mitigate environmental impacts in the lithium-ion battery supply chain poses a complex challenge. Multiple actors operate at different steps of the supply chain and respond to distinct incentives. Further complicating this landscape are the social, environmental, and economic trade-offs that accompany battery mineral extraction in various geographic, regulatory, and market contexts. A single methodological approach would be too limiting to capture the complex interactions among local communities, corporate governance structures, global market pressures, and shifting regulatory frameworks. Consequently, this thesis adopts a multi-method approach that integrates qualitative and quantitative analyses, encompassing:

- A systematic thematic analysis of the literature (Chapter 3)
- A participatory systems approach (Chapter 4)
- Network theory and diffusion modelling (Chapter 5)
- Prospective life cycle assessment (Chapter 6)

The sections below outline the overall rationale and fit of each method for answering the four main research questions presented in **Table 7**. A deeper description and detailed methodological steps can be found within each “methods” section of each paper (Chapters 3, 4, 5, and 6).

Table 7. Research questions, their corresponding chapters, methodological approaches, and outputs.

Chapter	Research Question	Methodology	Outputs
3	What is driving the adoption of voluntary sustainability initiatives in the lithium-ion battery minerals' supply chains?	Thematic Analysis	● Systematic literature review ● Thematic coding ● System boundaries identification ● Synthesis of drivers and barriers
4	What systemic factors, informed by stakeholder perspectives, influence the adoption of voluntary sustainability initiatives in battery mineral mining?	System Dynamics Modelling	● Systems map and structure ● Systems variables ● Workshops to elicit variables. ● Reinforcing and balancing feedback loops from focus workshops ● Causal Loop Diagram ● Definition of archetypes for high-leverage intervention
5	How can we better understand the dynamics behind the adoption of innovations regarding voluntary environmental impact mitigation?	Network analysis	● Dataset of top-producing nations' mining companies based on collaboration networks ● Model of innovation diffusion applicable to mining eco-innovations ● Mapping of potential for innovation diffusion across mining collaboration networks with active mining operations involved in lithium-ion battery supply chains
6	To what extent can environmental impact, when mining for battery minerals, be mitigated through VSI adoption?	Prospective life cycle impact assessment	● Mapping of production routes ● Stepwise approach for Scenario-based Inventory Modelling for Prospective LCA (SIMPL) ● Key factors and parameters for modelling ● Contribution analysis of key processes ● Scenario Analysis based on high leverage points impact mitigation. ● Comparative potential for impact mitigation across SSP scenarios and VSI-inspired mitigation.

2.1 Research Objective and Design

The primary objective of this thesis is:

> *Develop a combination of dynamic system models to explore the adoption, diffusion, and potential environmental impact mitigation of voluntary sustainability initiatives in the battery minerals' extractive sector.*

This overarching goal requires understanding how and why VSIs are adopted, which barriers or drivers are decisive, how innovations spread through sector-wide affiliations, and to what extent these initiatives can mitigate real environmental impacts. As shown in Table 3, each research question corresponds to one of the four core studies (published or submitted papers), each employing a distinct methodological lens while contributing to the broader aim.

In the upcoming chapters, this objective is unfolded through four main research questions (RQ1–RQ4), each addressed by a separate study (**Chapters 3–6**). **Chapter 3** aims to identify the key drivers and barriers underlying VSI adoption, thereby setting the conceptual stage for investigating broader system interactions. **Chapter 4** uses insights from stakeholder workshops to create a comprehensive systems map (a causal loop diagram), providing a structured, qualitative view of feedback loops and incorporating quantitative analyses to identify leverage points that can shape the trajectory of VSI uptake. Building on these qualitative foundations, **Chapter 5** investigates the transnational character of mining industry affiliations through network theory, clarifying the structural pathways along which environmental innovations might diffuse. Finally, **Chapter 6** introduces an explicitly quantitative lens with prospective life cycle assessment (pLCA) to examine whether and how VSI-inspired measures can drive tangible reductions in local and global environmental burdens.

In designing this multi-method framework, it was crucial to align each question with the methodological approach best suited to that inquiry. Chapter 3's thematic analysis provided a baseline understanding of the key constructs in the existing literature. Chapter 4's participatory model building emphasised collaborative engagement and the elicitation of stakeholder mental models. Chapter 5's network diffusion approach took advantage of newly compiled data on industry associations to model the structural and topographic patterns by which VSI-inspired innovations might spread. Finally, Chapter 6's prospective LCA supplied quantifiable estimates of potential impact mitigation, ensuring that the field's theorised benefits of VSIs could be benchmarked under future socio-economic and decarbonization scenarios.

2.2 Overview of methodologies used

2.2.1 RQ1: What is driving the adoption of voluntary sustainability initiatives in lithium-ion battery minerals' supply chains?

Battery mineral supply chains involve diverse stakeholder motivations, from reputational concerns (Amnesty International, 2017b), investor pressures (Dyck et al., 2019), and community conflict avoidance (Franks et al., 2014a). Moreover, previous bibliometric reviews on this topic suggest that the literature has not yet coalesced into a cohesive discourse or direction (Agusdinata et al., 2022). To systematically identify and categorise these motivations, the first study (Chapter 3) employed a systematic thematic analysis (Chun Tie et al., 2019). This approach was selected for its ability to synthesise complex, context-dependent factors from fragmented academic literature, aligning with the exploratory nature of Research Question 1. This methodology is grounded in well-established qualitative research traditions (Braun & Clarke, 2006) and is particularly suited for reviewing large bodies of scholarly work (Wohlin et al., 2022). Importantly, thematic analysis is flexible enough to incorporate changes in terminology or conceptual frames found in the academic literature on VSI uptake, aligning with the evolving nature of sustainability discourse in mining (See **Table 5**). As the first step in the thesis, the key advantage of thematic analysis is its capacity to map a broad conceptual territory ranging from local conflict drivers to investor screening criteria, providing the conceptual foundation on which subsequent methods (group-model-building and network diffusion) can build upon.

Our data collection strategy began with a structured keyword search across academic databases, combining terms related to VSIs (e.g., “Voluntary Sustainability Standards,” “Sustainability Schemes”) and battery minerals (e.g., “lithium,” “cobalt,” “energy transition minerals”). Initial queries that focused narrowly on VSI terminology yielded limited results, highlighting a critical gap in the literature. To address this, the search scope was expanded to include broader but related concepts such as Corporate Social Responsibility (CSR) and Environmental, Social, and Governance (ESG) framework. This adaptive strategy ensured the inclusion of indirect but relevant studies, reflecting the emergent and interdisciplinary nature of VSI research. A snowball search further enriched the dataset, leveraging citations from key articles to identify overlooked sources. Our thematic coding followed a hybrid deductive-inductive approach (Chun Tie et al., 2019). Deductive codes were derived from established frameworks, such as definitions of drivers as “forces motivating action” and barriers as “forces preventing action” (Khan, 2019). Inductive codes emerged iteratively during data immersion, allowing novel themes to surface.

This approach is uniquely positioned to address the fragmented and multidisciplinary literature on VSIs in battery supply chains. By systematically categorizing drivers and barriers, this method provided a foundational understanding of the socio-political, economic, and regulatory forces shaping VSI adoption, bridging gaps between siloed discourses.

2.2.2 RQ2: What systemic factors, informed by stakeholder perspectives, influence the adoption of voluntary sustainability initiatives in battery mineral mining?

While the systematic thematic analysis identified what drivers and barriers exist, the why and how they influence each other demanded a deeper systems thinking approach (Sterman, 2000). The second study (**Chapter 4**) employed a participatory approach to address Research Question 2 ("What systemic factors, informed by stakeholder perspectives, influence the adoption of voluntary sustainability initiatives in battery mineral mining?"). This methodology was selected for its capacity to integrate diverse stakeholder perspectives, map nonlinear feedback mechanisms, and identify high-leverage intervention points within complex systems (Zagonel, 2002). Making it ideal for exploring how VSI adoption trajectories emerge from interconnected social, economic, and regulatory forces.

Within our recruitment process, participants included representatives from mining companies, NGOs, lifecycle assessment practitioners, and researchers (15 participants across 12 workshops), ensuring diverse perspectives on barriers and enablers of VSI adoption. The process followed established frameworks for group model building (Zagonel, 2002) utilising two main aggregate methods: (i) Variable Elicitation, adapted from Luna-Reyes et al. (2006) (Luna-Reyes et al., 2006) to identify critical system variables (e.g., "downstream manufacturer pressure", and "host nation corruption levels") from the standpoint of the stakeholder; and (ii) Connection Circles: Workshops where stakeholders mapped causal relationships between variables, highlighting feedback loops (detailed within **Chapter 4**). This iterative, stakeholder-driven process generated 168 initial variables, refined to 54 through merging and standardisation. To work through this step, an adjacency matrix was employed to isolate the connection between no more than two variables at a time. Workshop outputs were synthesised into an aggregated causal loop diagram (CLD), a qualitative SD tool that visualises feedback loops shaping VSI adoption. The CLD revealed recurring system archetypes (Senge, 1991), detailed under the results section of this manuscript.

Group model building, combined with the analytical tools employed, is uniquely positioned to address RQ2's focus on leveraged interventions. By embedding stakeholder mental models into the CLD, this approach can surface hidden dynamics and provide a starting point for more complex quantitative models.

2.2.3 RQ3: How can the dynamics of industry adoption be characterised for voluntary initiatives aimed at reducing environmental impacts?

The third study (**Chapter 5**) applied network theory and diffusion modelling to address Research Question 3 (“How can we better understand the dynamics behind the adoption of innovations regarding voluntary environmental impact mitigation?”). This approach was selected to quantify how industry collaboration networks shape the spread of sustainability innovations among mining firms, particularly in lithium, nickel, and manganese supply chains. Network theory is uniquely suited to modelling structural pathways of information flow (Borgatti et al., 2009). Meanwhile, the concept of *diffusion of innovation* has significantly influenced our understanding of the interactions between entities leading the adoption of innovations (Rogers, 1995). Diffusion algorithms capture how innovations propagate under varying conditions, aligning with the need to identify systemic bottlenecks and accelerators in VSI adoption.

A systematic map of the global collaboration network of mining companies and industry associations was generated. Top-producing countries for lithium, nickel, and manganese were identified using the British Geological Survey’s World Mineral Statistics (2020) and USGS Mineral Commodity Summaries (USGS, 2021). National and international industry associations (e.g., International Council on Mining and Metals) were selected based on public membership data availability, with 9 national associations and 4 international associations included, covering a total of 1,258 members. We’ve proposed the application of a standardisation and harmonisation approach across datasets that included the Levenshtein distance algorithm (A Levenshtein & Vladimir Iosifovich, 1966), which is particularly well-suited to tackle word harmonisation.

Network theory and diffusion modelling were critical for three reasons. First, it allowed for a systematic structural analysis through network metrics (e.g., centrality, clustering). Second, it supported the identification of influential nodes (e.g., ICMM) and fragmented subnetworks (e.g., Ghana Chamber of Mines), explaining uneven innovation diffusion. Last, it allowed for a dynamic simulation through probabilistic thresholds (better explained within **Chapter 5**), quantifying how collaboration density and association influence shape adoption rates and scenario testing. International associations (e.g., Nickel Institute) were overlaid onto national networks to demonstrate how cross-border affiliations amplify diffusion.

2.2.4 RQ4: To what extent can environmental impact, when mining for battery minerals, be mitigated through VSI adoption?

Lastly, **Chapter 6** employs prospective life cycle assessment (pLCA) to quantify the potential environmental impact mitigation achievable through the adoption of Voluntary Sustainability Initiatives (VSIs) inspired mitigation strategies when mining for lithium, nickel, and manganese. The methodology follows the Scenario-based Inventory Modelling for Prospective Life Cycle Assessment (SIMPL) framework (Langkau et al., 2023), which systematically integrates foreground system modelling (process-specific mitigation strategies derived from stakeholder-identified leverage points in **Chapter 4**). Background system modelling (global socioeconomic and decarbonization pathways from the REMIND integrated assessment model (Baumstark et al., 2021)), and scenario combination to evaluate the cumulative effects of voluntary impact mitigation under future scenarios.

The methodological steps involved (i) production route mapping using the Ecoinvent 3.8 database (Wernet et al., 2016) to evaluate the cradle-to-gate production of nickel-manganese-cobalt (NMC) oxides; (ii) a contribution analysis of on lithium carbonate production, nickel sulfate production, and manganese sulfate production; (iii) a hotspot analysis to identify critical elementary flows (e.g., sulfur dioxide emissions to air) driving environmental impacts, prioritized for mitigation, then; (iv) foreground mitigation modelling based on six VSI-aligned mitigation technologies (e.g., air pollution control devices, green reagents); and lastly, (v) a background scenario integration using the premise tool (Sacchi et al., 2022) to transform background inventories (e.g., electricity grids) to align with Shared Socioeconomic Pathways (SSPs) (Hausfather, 2018), ensuring consistency with global decarbonization trajectories.

Prospective LCA is specially fit-for-purpose for this research question due to its ability to address the temporal and systemic complexity inherent in evaluating the potential for impact mitigation of VSIs within the context of the upcoming energy transition and decarbonisation trajectories. The method's strength lies in its capacity to model non-linear interactions between technological adoption, socioeconomic pathways, and environmental outcomes in its background (e.g., through PREMISE) whilst allowing for process-specific exploration. By using the SIMPL framework (Langkau et al., 2023), insights from **Chapter 4**'s participatory systems mapping were included, ensuring that the modelled mitigation strategies reflect priorities identified by industry stakeholders. By translating qualitative feedback, such as the connection between air pollution and community wellbeing presented in **Chapter 4,** into quantitative coefficients, pLCA bridges the gap between participatory systems thinking and empirical impact quantification.

Third, the method's scenario-based approach provides policymakers and industry actors with actionable insights into the time-sensitive viability of impact mitigation. By coupling SSP-RCP scenarios with impact mitigation, the study offers a forward-looking assessment of how VSIs can contribute to sustainability goals under different future conditions.

3 Unearthing motivation: A thematic analysis of drivers and barriers to VSI adoption in the battery minerals sector:

As the global shift toward cleaner transportation accelerates and demand for battery minerals such as lithium, cobalt, nickel, and manganese continues to rise, meeting the raw material needs for electrified mobility and renewable energy storage has become increasingly urgent (Habib et al., 2020). Yet, mining expansion often occurs in regions of the Global South, creating heightened risks of environmental harm and social injustice (Amnesty International, 2017b) and prompting new pressures for responsible sourcing and transparent governance throughout the lithium-ion battery supply chain. In response, VSIs have emerged as pivotal mechanisms to ensure more equitable value distribution and mitigate adverse impacts (see **Chapter 2**). While formative work on VSIs has substantially advanced understanding in other extractive sectors (Bellesi et al., 2005; Voora et al., 2019), and subsequent research has also narrowed key complexities in their application to multi-tiered, mineral-based supply chains (Mori Junior et al., 2016; Tröster & Hiete, 2018), further exploration was needed.

As presented in **Figure 5** and **Figure 6**, an integrative approach was necessary to better understand this rapidly evolving field. Building on industry reports that have covered initiatives relevant to the mineral sector (Erdmann & Franken, 2022; Kickler & Franken, 2017; Potts et al., 2018; Rutovitz et al., 2020) and on a broad corpus of scientific work, a thematic analysis was performed to surface the drivers and barriers to VSI adoption intrinsic to the battery mining sector. The analysis presented here illustrates that the adoption of VSIs in the battery minerals sector is influenced by an intricate interplay of geographical contexts, supply chain complexities, and varied thematic and commodity-specific factors. The findings highlight elements, such as concentrated supply regions, or the influence of downstream pressure are mentioned as playing a significant role in the adoption of VSIs by mineral producers, also dependent on the mineral and geographic setting. While these results underscore the potential for VSIs to enhance responsible sourcing and reduce reputational- and supply-risks, they also draw attention to obstacles like greenwashing, lack of legitimacy, and limited interoperability among initiatives. These identified drivers and barriers are foundational not only to this thesis but also as a publicly available integrative reference that can guide future studies. By building on previous scholarship and focusing specifically on the extraction phase of battery mineral supply chains, this work furthers the field's understanding, providing a structured basis for more effective, context-sensitive strategies in mineral resource governance.

A typeset version with minor changes of this study has been published as ***Drivers and barriers of voluntary sustainability initiatives in mining raw materials for batteries,*** *B. Mendonca Severiano, S. A. Northey, and D. Giurco, The Extractive Industries and Society (2024), Vol. 20, Pages 101552*.

Drivers and Barriers of Voluntary Sustainability Initiatives in Mining Raw Materials for Batteries

Abstract

The increasing adoption of electric vehicles (EVs) is driving demand for battery raw materials, including lithium, cobalt, nickel, and manganese. The potential for Voluntary Sustainability Initiatives to mitigate the social and environmental impacts of mine development and operation is now in focus as resource supply scales rapidly. This study examines and synthesises the drivers and barriers that influence extractive companies to voluntarily adopt sustainability initiatives, including certification and reporting, to mitigate social and environmental impacts. The methodology involved a thematic analysis of articles, initially identified through a systematic keyword search and further expanded with a snowball search technique. Thematic insights were classified and mapped against actors operating within the lithium-ion battery value chain. The research found that drivers for adopting voluntary sustainability initiatives include maintaining market access and addressing the increased need for frameworks to facilitate communication between companies and local communities. Barriers encompass short-term greenwashing undermining VSI's legitimacy, and the lack of comprehensiveness of such initiatives in regarding risk identification and risk mitigation for responsibly sourced commodities.

Keywords: Voluntary Sustainability Initiatives; Battery Minerals; Mining; IRMA; Corporate Social Responsibility

3.1 Introduction

A key strategy for reducing greenhouse gas (GHG) emissions is the electrification of the transportation sector to enable the use of low-carbon energy sources (Habib et al., 2020). Several countries and manufacturers are implementing policies to phase out internal combustion vehicles (IEA, 2020b) (Jolly, 2021). The shift towards renewable energy generation and clean energy storage is increasing the demand for minerals used in lithium-ion batteries (LIBs), creating supply concerns (Dominish et al., 2019), especially since these are often concentrated in resource-rich geographies in the global south (Riofrancos, 2023). With these concerns particularly focused on lithium-ion cathode materials due to their high relative cost (20% of a LIB), often composed of lithium (Li), nickel (Ni), manganese (Mn), and cobalt (Co) in varying quantities, depending on battery chemistry (Habib et al., 2020; Murdock et al., 2021; Nitta et al., 2015).

Overall, the mining sector is under pressure from investors, regulators, and civil society to engage in supply-chain reporting (Franken & Schütte, 2022a). The European Union (EU) has established regulations concerning batteries and waste batteries that, among other elements, define carbon footprint declarations for electric vehicle (EV) batteries and supply chain due diligence procedures (European Union (EU), 2023). Moreover, consumer-facing companies such as EV manufacturers play a significant role in gauging customer sentiment, willingness to pay, and perceived value towards products and their respective environmental and social impacts within their supply chain (Amnesty International, 2017a). Companies working directly with the extraction of battery minerals are being exposed to increased pressure to play a role in mitigating the negative impacts of mineral extraction and processing (Franken & Schütte, 2022a). An established way to enact more sustainable practices related to raw material extraction, production, and processing phases is through the adoption of Voluntary Sustainability Initiatives (VSIs), inclusive standards, and certification schemes (Franken et al., 2020). Significant advancements have been made in developing standards and certifications tailored to battery minerals. Industry organizations and multi-stakeholder platforms have increasingly focused on materials used specifically in batteries, such as the *Battery Passport* (Global Battery Alliance, 2024), the Nickel Mark (The Nickel Institute, 2024), and the *Guidance on determining the product carbon footprint of lithium products* (International Lithium Association, 2024). Furthermore, the Responsible Minerals Initiative (RMI) has dedicated focus to cobalt since 2017, with a range of tools and resources made available, such as the *Responsible Minerals Assurance Process* (RMAP), providing independent third-party assessments, and a *Conformant Cobalt Refiners* assessment report (Responsible Minerals Initiative, 2024).

This study aims to inform discussions on the adoption of VSIs by providing a systemic understanding of sustainable practices' implementation across the minerals and metals sector, focusing on lithium, nickel, manganese, and cobalt. Tröster and Hiete (2018) highlight the complexity of assessing VSI legitimacy, noting that it varies by industry, commodity, and geography. We will explore specific drivers and barriers to the adoption of voluntary practices in a mining operation, influenced by supply-chain factors intrinsic to battery supply chains, through the lens of the current green energy transition. We also elicit drivers and barriers ubiquitous to the mining sector, which in turn, also influence battery minerals. Our research advances the understanding of how voluntary initiatives can legitimize sustainable sourcing efforts amidst contested debates about corporate social responsibility (CSR) in mining operations. However, this study also critically examines how the commodification of CSR short-term greenwashing undermines VSI's credibility, which can undermine genuine sustainability efforts in raw material mining. Finally, we explore the role that VSIs might play in supporting battery and EV manufacturers in mitigating supply risk, and the challenges associated with provenance tracing.

This research employs a thematic analysis, drawing on literature from Corporate Social Responsibility (CSR), Environmental, Social, and Governance (ESG) management, Environmental Stewardship, and overall mining literature. Our objective is to answer the question: *“What factors drive or hinder the adoption of voluntary sustainability initiatives in mining operations extracting lithium, nickel, manganese, and cobalt for lithium-ion batteries?”.* The paper is structured as follows: Section 3.2 introduces the research context and foundational concepts, Section 3.3 details the methodological framework, Section 3.4 presents key findings, Section 3.5 discusses the identified drivers and barriers, and Section 3.6 concludes with final remarks and future research directions.

3.2 Background to Voluntary Sustainability Initiatives

Since the 1990s, the mining sector has increasingly adopted self-regulation and transnational governance frameworks to address the complex social, environmental, and economic challenges it faces. Initiatives such as the establishment of the International Council on Metals and the Environment (ICME), under the auspices of the Mining Association of Canada (MAC), marked the beginning of formal self-regulatory efforts for the sector with a code of conduct for environmental management (Bomsel et al., 1996). Over time, these efforts have expanded to include comprehensive self-regulatory mechanisms at both national industry and firm levels, aimed at improving social and environmental performance indicators due to external control and scrutiny, with some self-regulatory efforts involving very specific actions that serve to reduce externalities for a specific industry (Peck & Sinding, 2003). These *non-state market-driven* systems have proliferated to address problems that span global areas and have a far-from-trivial potential for impact (e.g., fisheries depletion, forest deterioration, environmental impacts from mining) (Bernstein & Cashore, 2007). These systems are not legitimised by default but can achieve “*the acceptance of shared rule by a community as appropriate and justified*”[1] (Bernstein, 2004, p. 142). *Non-state market-driven* governance shifts authority away from traditional state regulation toward market-based instruments such as certifications, adopted voluntarily. These

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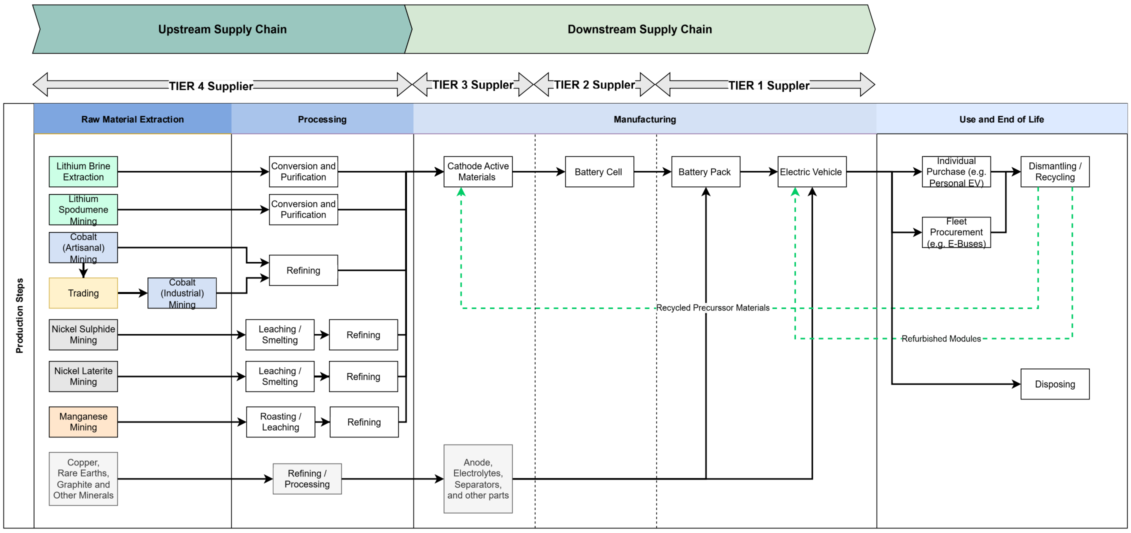
[1] The original quote from 2005 is “the acceptance and justification of shared rule by a community”, updated on Bernstein’s work from 2007.

instruments, driven by market demand and buyer preference, create incentives for firms to adopt sustainable practices, thereby establishing authority and legitimacy through market dynamics rather than state influence. The legitimacy and adoption of these governance systems occur across the supply chain, as economic actors at each point of exchange choose to abide by the rules inherent in this system, reinforcing its authority throughout the production process (Cashore, 2002).

Voluntary initiatives at a mine-site level were first documented in 1992, with the Whitehorse Mining Initiative (WMI), led by a group of Canadian companies and representatives from civil society, under the leadership of the Mining Association of Canada (MAC). The WMI efforts were oriented towards promoting a common vision among stakeholders with respect to the future of the industry. The main areas addressed involved finance/taxation, environment, land access, and workforce (UN DESA, 1999). Regarded as a successful endeavour in demonstrating the potential of multistakeholder collaboration (Potts et al., 2018, p. 11), WMI inspired other global initiatives like the Extractive Industries Transparency Initiative (EITI) in 2002, which leveraged government and other actors in mineral supply chains to guide demand, capacity, and commitments among producing countries. Other initiatives, such as the Towards Sustainable Mining (TSM) from 2004, also under the leadership of MAC, have focused on mine-level commitments, designed to meet the rising demand for responsible, industrial-scale mining, operating as a generic multi-commodity initiative.

In the years after the WMI, the landscape of voluntary initiatives grew in scope, approach, and focus. A comparative study done by the German Federal Institute for Geosciences and Natural Resources (BGR) mapped more than 50 Sustainability Standards Systems (or schemes) that are applicable to the mineral sector (Kickler & Franken, 2017). These vary significantly regarding the number of sub-issues addressed, the extent of requirements, and specificity. Global schemes aimed towards large-scale mining like the International Council on Mining and Metals (ICMM) Sustainable Development Framework (ICMM, 2023), the Initiative for Responsible Mining Assurance (IRMA) (IRMA, 2018a), the Global Reporting Initiative (GRI) Reporting Principles and Standards (GRI, 2023), the International Finance Corporation (IFC) Environmental and Social Performance Standards (IFC, 2012), cater to various mineral commodities across several geographies. Additionally, there are commodity-specific schemes for copper (Copper Mark), gold (Cyanide Code and the World Gold Council Industry Standards), aluminium (Aluminium Stewardship Initiative), and others. Lastly, the governance structure of such standards systems also varies significantly, with some being industry-led (e.g. ICMM), others being industry-led with structured stakeholder engagement (e.g., TSM), and some being non-industry-initiated, but industry inclusive (e.g., IRMA) (Erdmann & Franken, 2022). Moreover, the involvement of civil society and impacted stakeholders in the development process of these schemes can increase legitimacy, even with a longer ramp-up period. Nonetheless, despite decades of development, the long-term impact and uptake of these initiatives remain uncertain and often vary by commodity and geography. However, the broad adoption of VSIs does not guarantee sustained, long-term sustainability across these sectors, leading to criticism about greenwashing. The focus on short-term impacts without acknowledging longer-term changes might serve immediate corporate interests to discredit established reporting requirements (Franken & Schütte, 2022a). Specific to the mining industry, the adoption of voluntary standards is described as a key indicator of *early mover status* (Dashwood, 2012), providing firms with cooperative relations with government regulators and greater flexibility in the enforcement of existing environmental regulations (Potoski & Prakash, 2005), which might act against VSI legitimacy. Some authors consider VSIs to be the "second best option", being useless in front of total conformity with national and international laws, regulations, and standards (Franken et al., 2012). Moreover, community relations and development, under the umbrella of CSR, can be deployed to de-escalate crises, becoming purely transactional approaches to community relations and mining (Kemp & Owen, 2013). Assessing the legitimacy of VSIs is complex, being defined by their ability to solve a problem, behavioural effectiveness, market diffusion, and constitutive effectiveness, which are industry-, commodity-, and geography-specific (Tröster & Hiete, 2018). The EV industry, and the lithium-ion battery manufacturers by proxy, face a significant challenge when keeping a secure, responsible, and sustainable stream of minerals. Raw materials such as lithium, nickel, manganese, and cobalt are extracted from mines located in diverse regions, often in countries like Australia, Chile, Indonesia, and the Democratic Republic of the Congo. As the goods move from the global south to the global north, transnational governance plays a critical role across these layers. The multi-layered and multi-tiered aspect of this value chain is showcased in **Figure 9.**

Figure 9. Steps involved in the lithium-ion batteries' supply chain, with particular emphasis on minerals used in cathode active materials[2].



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[2] The figure maps the EV's lithium-ion batteries' supply-chain, with particular emphasis on battery minerals. Definitions of upstream and downstream steps were taken from (Erdmann & Franken, 2022) and definitions of tiers within supply chain were based on (Petavratzi & Gunn, 2023). The basic structure of the cobalt supply chain for battery manufacturing was taken from (Deberdt & Le Billon, 2022), the lithium overarching processing steps were taken from (Khakmardan et al., 2023), nickel primary production routes were taken from (Schmidt et al., 2016), and manganese supply chain steps from (Snow, 2018 routes were taken from (Schmidt et al., 2016), and manganese supply chain steps from (Snow, 2018).

The material complexity in batteries and the fact that the extraction phase accounts for only about 0.5% of a lithium-ion battery's value-added, contrast sharply with industries like coffee, where 20% of the value is added during extraction (Wills et al., 2018). Additionally, the complexity is compounded in the EV sector by the vast number of suppliers involved. For example, Panasonic, a leading EV battery manufacturer, works with over 10,000 suppliers globally (Panasonic, 2021). The complexity of battery supply chains can hinder the recognition of issues with deep suppliers. Junior mining companies, in particular, are more vulnerable to supply chain volatility and have less influence on sourcing practices due to their dependency on suppliers (Kalaitzi et al., 2019).

Whilst national adoption of standards has been implemented, the impacts of mining for battery minerals often extend beyond national borders, with demand concentrated in more affluent nations, and supply concentrated in less developed regions (Agusdinata et al., 2022). On that note, voluntary certification schemes can complement national standards when Original Equipment Manufacturers (OEMs) engage with tiered suppliers, being a way to reduce uncertainty and legitimize a claim within a multi-tiered supply chain that involves producing nations from the global south (Sauer, 2021). Well-established OEMs of a multi-tiered supply chain work towards translating their reputational risk to the minimum required standards by their suppliers (Potts et al., 2018). This is done to mitigate the reputational risk they might be exposed to due to association with the social and environmental impacts of their suppliers. Also, multi-tiered supply chain initiatives fundamentally rely on the effective communication of information, from raw material sourcing to product end-use, with emerging technologies and process innovations, like material fingerprinting (through isotope mapping) and decentralized ledger technologies (using distributed databases, such as blockchain, to securely record and verify transactions), enhancing this communication, particularly in supply chain traceability (Vasilyev et al., 2022). However, the structural relations of power and modes of governance to which voluntary initiatives belong have been criticized for potentially undermining national regulations, particularly in the global south. Critics argue that certification schemes may serve corporate interests while neglecting deeper social or environmental reforms through *regulatory capture,* where industrial interests are overly represented (Blackman, 2008).

It becomes evident that the landscape of self-regulatory frameworks within the mining sector is complex and evolving. The adoption of such VSIs might be driven by a combination of market pressures, environmental concerns, and stakeholder engagement, although there’s no consensus on the main adoption drivers. Despite their proliferation, their effectiveness is still unconfirmed. With an expectation of increased demand for battery minerals in the near future, the emphasis on analysing the landscape of VSI adoption is important and timely.

3.3 Methods

A thematic analysis was conducted to identify drivers and barriers to VSI adoption in mining operations, part of battery minerals supply chains. We performed a detailed keyword search in the literature, utilizing well-established terminologies related to voluntary sustainability in the mining sector. The selected articles were complemented by a snowball search, given the method's effectiveness in uncovering primary studies (Wohlin et al., 2022). By design, we've not included *grey literature* in the main corpus of the analysis and have kept the focus on peer-reviewed academic literature. The information within these articles was then systematically categorized into themes specifically focused on the various drivers and barriers influencing VSI adoption. The scope of this was focused on the production of lithium, nickel, manganese, and cobalt due to their critical role in manufacturing cathode active materials (Habib et al., 2020; Helbig et al., 2018).

3.3.1 Data sources and collection process

Previous bibliometric reviews suggest that the literature has not yet coalesced into a cohesive discourse or direction (Agusdinata et al., 2022). Initial keyword searches were guided by common terminology identified in relevant reports, such as *'Voluntary Sustainability Initiatives'* (Potts et al., 2018; Rutovitz et al., 2020), *'Voluntary Sustainability Standards'* (Franken et al., 2020), *'Sustainability Schemes'* (Kickler & Franken, 2017), and *'Sustainability Standard Systems'* (Erdmann & Franken, 2022). To analyse the battery minerals supply chain, we've combined this with themes such as 'lithium-ion battery', 'battery minerals', 'energy transition minerals', and the mineral names (e.g., lithium). A total of 16 systematic queries were used, and the combinations are described in **Table 8** and in the supplementary material. Queries were conducted on the 23rd of November 2023.

The first 8 queries (all focused on VSIs) yielded no results. This finding is significant since it suggests a notable gap in the academic literature regarding the integration of VSIs in the context of mineral extraction for lithium-ion batteries. It seems that there's a lack of focused and integrative studies that combine such themes. Therefore, this research highlights a critical area of future exploration. After an initial screening of the literature, extra keywords were added to the query to broaden the scope of the research by incorporating alternative, yet related, terminologies. Keywords such as *'Corporate Social Responsibility'* (and '*CSR'*), *'Environmental, Social, and Governance'* (and *'ESG'*), and *'Environmental stewardship'* were included. These yielded significantly more results, as detailed in **Table 9.**

Table 8. List of themes explored in an initial document selection. Each row represents a combination of key terms. Y = Yes; N = No. ESG = Environmental, Social, and Governance. CSR = Corporate Social Responsibility. ES = Environmental Stewardship.

Voluntary Initiatives	**Sustainability Terminology (ESG/CSR/ES)**	**Supply-chain**	**Lithium-ion Batteries**	**Lithium / Nickel / Cobalt / Manganese**	**Battery Minerals**	**Energy Transition Minerals**	**Results**
Y	N	Y	Y	N	N	N	0
Y	N	Y	N	Y	N	N	0
Y	N	Y	N	N	Y	N	0
Y	N	Y	N	N	N	Y	0
Y	N	N	Y	N	N	N	0
Y	N	N	N	Y	N	N	0
Y	N	N	N	N	Y	N	0
Y	N	N	N	N	N	Y	0
N	Y	Y	Y	N	N	N	11
N	Y	Y	N	Y	N	N	16
N	Y	Y	N	N	Y	N	0
N	Y	Y	N	N	N	Y	0
N	Y	N	Y	N	N	N	40
N	Y	N	N	Y	N	N	82
N	Y	N	N	N	Y	N	1
N	Y	N	N	N	N	Y	0

Table 9. Queries encompassing broader sustainability terminology, whilst still narrowed to minerals used in cathode active materials (lithium, nickel, manganese, and cobalt).

Themes	Web of Science Query	Results
Lithium-Ion Batteries; Broader Sustainability Terminology; Supply-chain	TS=("lithium ion" OR "lithium-ion" OR "electric vehicle*") **AND** TS=("supply chain*" OR "value chain*") **AND** TS=("Corporate Social Responsibility" OR "CSR" OR "Environmental, Social, and Governance" OR "ESG" OR "Environmental stewardship")	11
Lithium-Ion Batteries; Broader Sustainability Terminology;	TS=("lithium ion" OR "lithium-ion" OR "electric vehicle*") **AND** TS=("Corporate Social Responsibility" OR "CSR" OR "Environmental, Social, and Governance" OR "ESG" OR "Environmental stewardship")	40
Battery Minerals (specific); Broader Sustainability Terminology; Supply-chain;	TS=("lithium" OR "Nickel" OR "Manganese" OR "Cobalt") **AND** TS=("supply chain*" OR "value chain*") **AND** TS=("Corporate Social Responsibility" OR "CSR" OR "Environmental, Social, and Governance" OR "ESG" OR "Environmental stewardship")	16
Battery Minerals (specific); Broader Sustainability Terminology;	TS=("lithium" OR "Nickel" OR "Manganese" OR "Cobalt") **AND** TS=("Corporate Social Responsibility" OR "CSR" OR "Environmental, Social, and Governance" OR "ESG" OR "Environmental stewardship")	82
Battery Minerals (generic); Broader Sustainability Terminology;	TS=("battery mineral*") **AND** TS=("Corporate Social Responsibility" OR "CSR" OR "Environmental, Social, and Governance" OR "ESG" OR "Environmental stewardship")	1

3.3.2 Data analysis framework

This purposive sampling initially yielded 150 results. After the removal of duplicates, 111 articles had their abstracts analysed for thematic alignment, of which 69 were excluded for not aligning thematically with mining or mineral supply-chain (e.g. *“Application of three-phase Current Source Converter in Power Battery Testing System for Electric Vehicles”* or *“X-Ray Diffraction of Thin Polycrystalline Lithium-Fluoride Films with Silver Nanoparticles on Amorphous Substrates”*), leaving 42 relevant documents. Further analysis and a snowball search expanded this to include 125 additional articles, reports, and company statements. Of these, 30 were relevant, bringing the total count to 72 documents for analysis. Company-specific reports and grey literature are outside the scope of this work, and it’s been suggested as complementary as part of an expanded future study.

A thematic analysis was then performed, being a widely used methodology that involves both deductive and inductive approaches, outlined as a set of theme-building procedures (Braun & Clarke, 2006), stimulating knowledge building with a constant comparative method (Guest et al., 2012). The process follows a systematic guideline which involves *(i) Data Collection; (ii) Initial Coding; (iii) Intermediate Coding;* and *(iv) Advanced Coding* (Chun Tie et al., 2019), as described in Table 10.

After the coding process, the codes were clustered into sub-categories of **drivers** and **barriers,** with all the results being presented in ***Section 3.4*** and discussed in ***Section 3.5***. Drivers have been defined as ‘*things that motivate people to want to take action’*; and barriers as ‘*things that prevent people from taking action*’ (Khan, 2019). Within the context of this study:

i. **Drivers**: Internal or external forces that are responsible for the uptake of Voluntary Sustainability Initiatives at a mining operation involved in the extraction of lithium, nickel, or manganese, or cobalt.

ii. **Barriers:** Internal or external forces that demotivate companies or prevent them from engaging with Voluntary Sustainability Initiatives at a mining operation involved in the extraction of lithium, nickel, manganese, or cobalt.

The references are provided in the *supporting Information.* A descriptive overview of the data collection methods and analytical framework used in this research can be found in **Figure 10**.

Figure 10. Descriptive methodological overview and coding process leading to the identification of drivers and barriers, and how information is referenced.

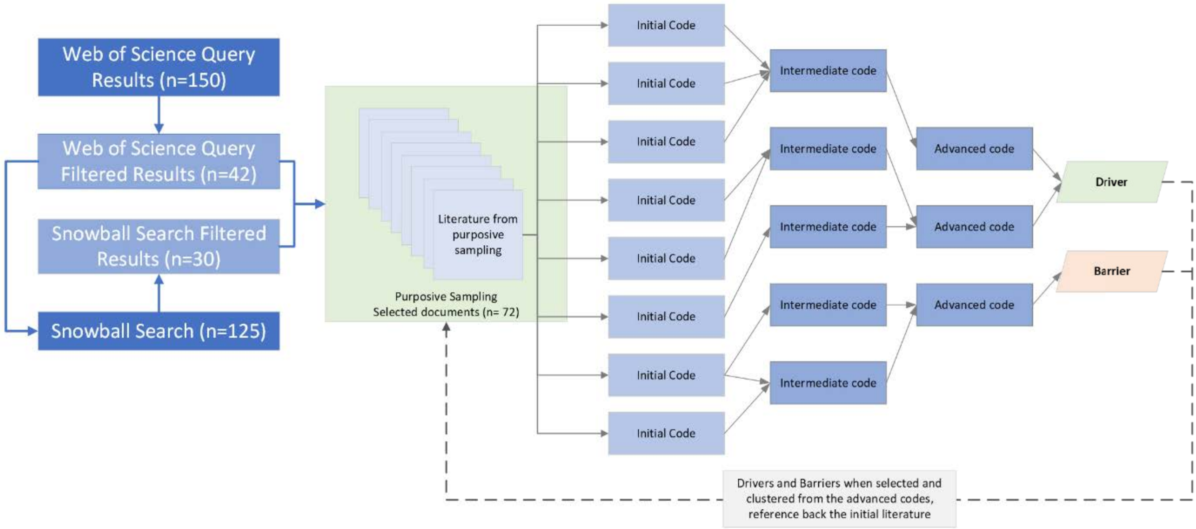


Table 10. Research design steps of a thematic analysis. Adapted from (Chun Tie et al., 2019)

Thematic analysis Step	**Description**
Purposive Sampling	Purposive sampling is the first step and directs the collection and/or generation of data. The researcher purposively selects data sources that can be supportive of answering the research questions. Moreover, this data collection process from secondary literature can be supplemented by a snowball search.
Initial coding	This is a procedure for developing categories of information. The purpose of this step is to start the process of fracturing the data collected with purposive sampling and to incidentally find similarities and patterns in the data.
Intermediate coding	Intermediate coding is a procedure for interconnecting the categories. At this research stage, core categories become more evident, and some relationships between categories are refined.
Advanced coding	Advanced Coding is a procedure for connecting the categories. During this last step, theoretical integration is pursued. Concepts were integrated in pursuit of a substantive theory.

3.4 Results

We initially analysed the coverage of selected battery minerals against their thematic and commodity-focused filters. This analysis provided an initial thematic overlap between the themes and the selected minerals, as shown in **Figure 11 (A)**. A detailed paper-by-paper breakdown is available in the supplementary material. Additionally, we mapped individual mentions of battery minerals against their combined themes, as showcased in **Figure 11 (B).** In terms of spatial and research focus, a significant portion of published research originates from Australia, followed by the United States and Canada. Most publications concentrated on the producing countries of lithium, nickel, and cobalt, as presented in Figure 12**.**

Figure 11. (A) Thematic overlap between research themes and battery minerals; (B) Distribution of mentions to individual battery minerals across a combination of research themes.

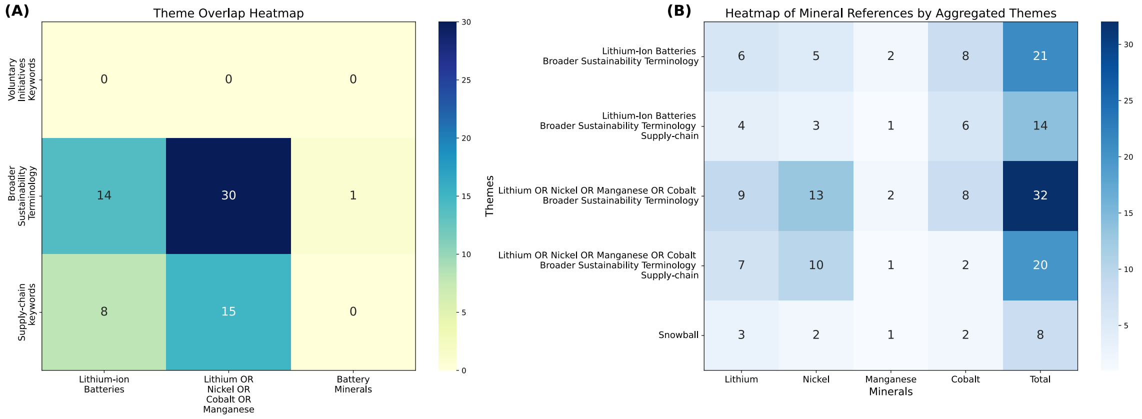
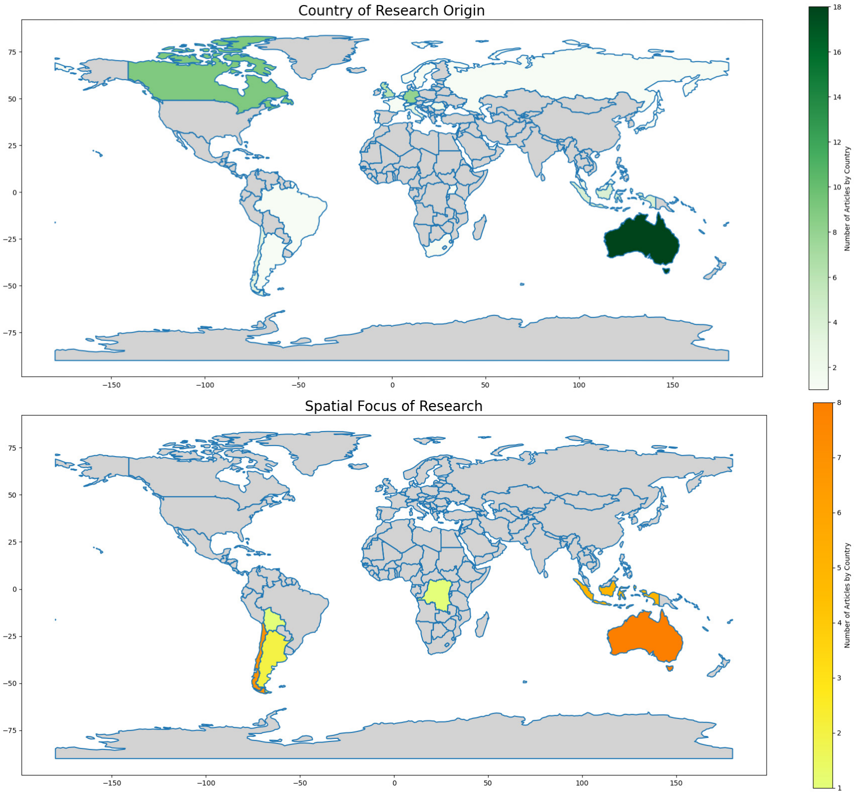


Figure 12. Geographic distribution of author affiliations (above) and spatial focus of analysis (below).



When compiling a list of drivers and barriers from the surveyed literature, we focused on identifying those cited both with and without the inclusion of "supply-chain" as a keyword, as detailed in Table 9. A mapping of the drivers common to both sets of literature - those found using the "supply-chain" keywords and those found without - is represented in **Figure 13** (for drivers) and **Figure 14** (for barriers). For both images, the leftmost grouping combines the themes found in the literature surveyed under the 'supply-chain' filter, and on the rightmost grouping, the themes found in the literature surveyed without the 'supply-chain' filter. In the middle, we can see the themes that are common to both categories. A detailed breakdown of the sources in which the drivers and barriers were found, and how many works include such drivers and barriers, can be found in the supplementary material. **Table 11** and **Table 12** provide further descriptions and references for these drivers and barriers, organized by the number of sources that discuss them. These factors are often geography-specific as well as mineral-specific, supporting an analytical framework on the success of VSIs, such as the one proposed by Tröster and Hiete (2018). For example, the concentration of cobalt supply in the Democratic Republic of Congo has led auto manufacturers to implement responsible sourcing initiatives (Malone et al., 2023) in response to client and investor concerns (Deberdt & Billon, 2021). To expand on these insights, we also analysed drivers and barriers without the supply-chain filter, focusing on mining operations not explicitly associated with the extraction of lithium, nickel, cobalt, or manganese. The most frequently cited factors, not already covered in **Table 11** and **Table 12**, are presented in **Table 13** and **Table 14.**

Figure 13. Sankey diagram of drivers that were commonly found both in literature queried with supply-chain keywords and literature queried without such keywords. The leftmost grouping (dark blue) combines the drivers found in the literature surveyed under the 'supply-chain' filter, and on the rightmost grouping (orange), the drivers found in the literature surveyed without the 'supply-chain' filter. In the middle, all the drivers that are shared amongst these two groups.

Figure 14. Sankey diagram of barriers that were commonly found both in literature queried with supply-chain keywords and literature queried without such keywords. The leftmost grouping (dark blue) combines the barriers found in the literature surveyed under the 'supply-chain' filter, and on the rightmost grouping (purple), the barriers found in the literature surveyed without the 'supply-chain' filter. In the middle, all the barriers that are shared amongst these two groups.

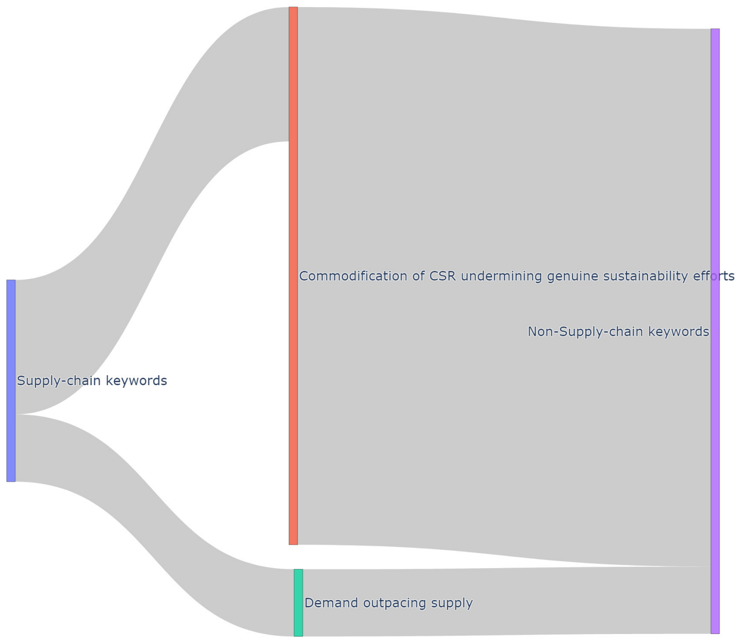


Table 11. Drivers influencing the voluntary adoption of ESG, CSR, and environmental stewardship practices in lithium, nickel, manganese, or cobalt mining operations. These have been compiled as representative of the overlap between drivers extracted from the literature queried with supply-chain keywords and without such keywords. N = Count of the total number of sources that included the driver.

Driver	**Description**	**Specific Mentions**	**Selected References**	***N***
Increased need for frameworks on company-community communication	Lithium, nickel, and cobalt projects are often located in high-ESG risk areas. These regions face significant challenges due to inadequate social participation and heightened geopolitical risks (Jowitt et al., 2020). Social conflicts have been reported in various locations, such as lithium mining in the Lithium Triangle (Liu & Agusdinata, 2020), nickel mining in Indonesia (Hudayana et al., 2020) and New Caledonia (Lassila, 2016), and cobalt mining in both the United States (Malone et al., 2023) and the Democratic Republic of the Congo (DRC) (Savinova et al., 2023). These conflicts are frequently attributed to insufficient engagement with local communities and stakeholders	• Lithium • Nickel • Cobalt	(Agusdinata et al., 2022; Malone et al., 2023; Petavratzi & Gunn, 2023; Ralph & Hancock, 2018; Savinova et al., 2023; Zainuddin Rela et al., 2020)	21
Supply chain disruption risk management	In the context of battery minerals, being part of multi-tiered supply chains, the risk of disruption is prominent. Sustainability standards and certifications might act to reduce uncertainty and legitimize claims by mining companies to battery and EV manufacturers.	• Lithium • Nickel • Cobalt • Manganese	(Agusdinata et al., 2022; Deberdt & Le Billon, 2022; Malone et al., 2023; Mugurusi & Ahishakiye, 2022; Murdock et al., 2021; Petavratzi & Gunn, 2023; Savinova et al., 2023; Vivoda & Matthews, 2023)	13
Improved guidelines on life cycle assessment	With lifecycle assessment being chosen as the methodology for the EU Battery Regulation (European Union (EU), 2023),	• Lithium • Nickel • Cobalt	(Agusdinata et al., 2022; Mugurusi & Ahishakiye,	10

	data-intensive impact assessment will have to be put in place in mining operations.		2022; Petavratzi & Gunn, 2023)	
Increased Legitimacy of Non-State Market-Driven Initiatives Specific to Battery Components	Given the prominent role of transnational corporations in mineral extraction, the potential and limitations of state governance become apparent, especially due to the geographical concentration of battery minerals in the global south. Initiatives like the Cobalt Working Group by the Responsible Minerals Initiative and the Global Battery Alliance demonstrate the need for raising the profile of mining challenges.	• Lithium • Nickel • Cobalt • Manganese	(Agusdinata et al., 2022; Deberdt & Le Billon, 2022; Lèbre et al., 2020; Petavratzi & Gunn, 2023)	9
Downstream pressure to mitigate reputational risk	Downstream companies that are concerned with reputational damage by association might drive VSI adoption. Battery and EV manufacturers are increasing their due diligence process and supply-chain transparency to avoid reputational risk associated with low environmental performers. (Barry et al., 2012; CATL, 2021; Newbold, 2006; Potts et al., 2018)	• Cobalt	(Deberdt & Billon, 2021)	7
Geographical Concentration of Battery Minerals	The geographical concentration of battery minerals, with raw material supply centred in the global south, and manufacturing and EV demand in the global north, raises sustainability and supply chain stability concerns.	• Lithium • Nickel • Cobalt • Manganese	(Agusdinata et al., 2022; Deberdt & Le Billon, 2022; Murdock et al., 2021; Vivoda & Matthews, 2023)	7
Investment attraction	Mining activities are increasingly seen as high risk by insurers. Therefore, VSIs taking the form of certifications may give rise to benefits such as lower insurance premiums. Moreover, many institutional investors consider ESG investments to provide risk insurance and market differentiation. Moreover, Institutional investors that take into consideration E&S risk measures provided by third parties are already pushing companies towards an improvement in E&S metrics. Through exclusion, selection, and shareholder proposals, this might drive certification adoption and standards compliance.	• Lithium • Nickel • Cobalt • Manganese	(Petavratzi & Gunn, 2023; Savinova et al., 2023)	7
Consumer Awareness and Mobilization	There is some evidence that consumers of low-carbon technologies are increasingly aware that such technologies use a multitude of minerals that could cause environmental degradation and regions of mineral extraction (International Resource Panel, 2020).	• Lithium • Nickel • Cobalt	(Agusdinata et al., 2022; Deberdt & Le Billon, 2022; Ralph & Hancock, 2018)	4
Increased need to manage biodiversity impacts	The expansion of mining activities necessitates comprehensive mining plans that assess and mitigate impacts on nearby ecosystems, including long-term effects and rehabilitation strategies. Due to the proximity of mining operations to critical biodiversity preservation areas, there is an increasing need to address potential ecological disruptions.	• Lithium • Nickel • Cobalt • Manganese	(Lèbre et al., 2020; Murdock et al., 2021)	2
State-to-state commercial agreements	The potential for state-to-state commercial arrangements to replace open-markets in the case of military and energy applications might lead to requirements related to due-diligence backed by standards compliance and certifications.	• Lithium • Nickel • Cobalt • Manganese	(Heredia et al., 2020; Owen et al., 2022; Petavratzi & Gunn, 2023; Vivoda & Matthews, 2023)	2

Table 12. Barriers influencing the voluntary adoption of ESG, CSR, and environmental stewardship practices in lithium, nickel, manganese, or cobalt mining operations. These have been compiled as representative of the overlap between drivers extracted from the literature queried with supply-chain keywords and without such keywords. N = Count of the total number of sources that included the barrier.

Barrier	**Description**	**Specific Mentions**	**References**	***N***

Short-term greenwashing undermining VSI legitimacy	. Short-term greenwashing can manifest when firms adopt CSR policies primarily to meet stakeholder expectations, secure investment, or maintain their social license to operate, rather than to address significant social or environmental issues (Palpacuer & Roussey, 2023). For example, CSR practices in nickel mining in Indonesia and cobalt mining in the Congo often fail to address deep-rooted issues like land ownership.	• Nickel • Cobalt	(Deberdt, 2022; Deberdt & Le Billon, 2022; Malone et al., 2023; Palpacuer & Roussey, 2023; Zainuddin Rela et al., 2020)	15
Demand outpacing supply	In an economy where demand for a product or service outpaces supply, known as a seller's market, companies may prioritize maximizing output over adopting voluntary sustainability initiatives. The urgency to supply high-demand critical minerals can limit the willingness of companies to engage in sustainability efforts.	• Lithium • Nickel • Cobalt	(Agusdinata et al., 2023; Vivoda & Matthews, 2023)	2

Table 13. Drivers influencing the adoption of ESG, CSR, and environmental stewardship at overall mining operations that can influence mining for battery minerals. These contain the drivers most frequently mentioned (N ≥ 4) and not included in Table 11. N = Count of the total number of sources that included the driver.

Driver	**Description**	**Selected References**	***N***
Operating in complex water management contexts	The imperative to manage water resources effectively is driven by the significant environmental and socio-economic impacts observed in mining regions. In areas like Bahodopi in Indonesia (Hudayana et al., 2020) and the Salar de Atacama (Heredia et al., 2020), mining activities have led to water contamination and scarcity, respectively. The majority of lithium resources and future projects are located in areas facing medium to very high water risks (Lèbre et al., 2020), emphasizing the urgency of adopting sustainable water management strategies	(Heredia et al., 2020; Hudayana et al., 2020; Lèbre et al., 2020)	6
Onshoring of mineral extraction - Closer to consumption markets	The strategic shift to localize mineral extraction near consumption markets, notably in the U.S. through the Mineral Security Partnership (MSP), is acting to secure a steady source of critical minerals. This trend is driven by the desire to reduce dependency on foreign sources. With stricter regulatory environments and higher societal expectations, companies might be motivated to adhere to VSIs to maintain their social license to operate	(Agusdinata et al., 2022; Malone et al., 2023; Petavratzi & Gunn, 2023; Vivoda & Matthews, 2023)	5
Public campaigns by civil society and NGO calling attention to negative sustainable practices	Publications such as the one by Amnesty International (2017b) can highlight significant sustainability gaps in the mining of battery minerals, leading to increased scrutiny.	(Deberdt & Billon, 2021; Deberdt & Le Billon, 2022)	4

Table 14. Barriers hindering the adoption of ESG, CSR, and environmental stewardship at overall mining operations that can influence mining for battery minerals. These contain the barriers most frequently mentioned (N ≥ 2) and not included in Table 12. N = Count of the total number of sources that included the barrier.

Barriers	**Description**	**Selected References**	***N***
Tracing Provenance at Key Points	Smelters control information crucial to traceability which can undermine mine-site efforts when adopting VSIs, since both certified and non-certified commodities might be processed simultaneously, which due to the nature of the physical and chemical processes, might make traceability more difficult.	(Förster & Mischo, 2022; Murdock et al., 2021; Petavratzi & Gunn, 2023)	4
VSIs interoperability and Scope	There's an increasing number of VSIs in the market that might be suitable to the several industries operating in this supply chain. It's unclear how much these VSIs overlap, to what extent they are interoperable and compatible. Moreover, it's still unclear to what extent this interoperability increases environmental and social impact mitigation.	(Deberdt & Billon, 2021; Franken & Schütte, 2022a; Franken et al., 2012; Franks et al., 2013; Ghorbani & Kuan, 2017; Mori Junior et al., 2016; Potts et al., 2018; Rutovitz et al., 2020; Tröster & Hiete, 2018, 2019)	3

Limited regulatory capacity	Regulatory institutions face significant limitations in their personnel and technical capacity to promote the standard adoption and issue certifications. There's also a lack of governmental incentives and technical support during the implementation phase of standards.	(Franks et al., 2013; Owen & Kemp, 2013; Young et al., 2019)	2
Misalignment of regulatory initiatives	Local and international regulatory initiatives might be misaligned, leading to potential redundancy of efforts. Moreover, the majority of certification schemes analysed so far are not designed to interact with other governance systems. Furthermore, competing initiatives might deter the adoption of VSI in the face of other national policies.	(Barry et al., 2012; Deberdt & Billon, 2021; Franken & Schütte, 2022a; Franken et al., 2012; Mori Junior et al., 2016; Newbold, 2006; Owen et al., 2022; Sauer, 2021; Tröster & Hiete, 2018)	2

3.5 Discussion

3.5.1 Drivers

3.5.1.1 Insights on Company-Community Communication: Social License, Conflicts, and Voluntary Sustainability

The findings presented in **Table 11** underscore the critical need for comprehensive frameworks on company-community communication, especially in regions where lithium, nickel, and cobalt projects are situated, which often present high ESG risks (Lèbre et al., 2020). The social aspect of this risk assessment is evidenced by the frequent social conflicts in such regions, including lithium mining in the lithium triangle (Liu & Agusdinata, 2020), nickel mining in Indonesia (Hudayana et al., 2020) and New Caledonia (Lassila, 2016), and cobalt mining in both the United States (Malone et al., 2023) and the Democratic Republic of the Congo (DRC) (Savinova et al., 2023).

During the pre-permitting stage, when company-community conflicts are at their highest due to the proximate and imminent social and environmental impacts, such as pollution, resource competition, and lack of consent, concerns over health and safety, and the influence of external agents are particularly evident (Franks et al., 2014b). Mine-site developments being delayed, interrupted, and shut down due to public opposition are ubiquitous (Moffat & Zhang, 2014), with most of the company-community conflicts being observed during the pre-operational stages of a mine life, such as exploration, feasibility, and construction (Franks et al., 2014b). Past instances of conflict have resulted in mining operations being delayed, interrupted, or shut down (Jenkins, 2004). With recent examples being the Jadar Lithium mine project in Serbia, which had its exploration licenses revoked by the government due to strong protests (Wired, 2022), effectively limiting further exploration of the combined indicated and inferred resource of 143.5Mt at 1.80% Li20 (~2.58 Mt Li2O) (Rio Tinto, 2022), which could be relevant for future supply. Authors have discussed that the implementation of sustainability certification schemes, taking the form of VSIs, may be an effective means of improving the company-community relationship regarding environmental impact mitigation and preventing opposition to mine-site development (Tröster & Hiete, 2018). This poses an interesting reflection on the Jadar lithium mine project, since Rio Tinto is a member of ICMM, with public commitments to CSR (ICMM, 2024). It's unclear from the literature review if the adoption of VSIs is enough to avoid community opposition to a project, and more importantly, if this should even be the driving element behind VSI adoption.

Analyses of the implementation of voluntary practices related to new nickel projects in Southeast Sulawesi, Indonesia, have linked CSR practices with an effective licence to operate (Hudayana et al., 2020). Correlations between CSR implementation and community resilience were drawn (Zainuddin Rela et al., 2020), which is corroborated by previous studies that established that CSR projects contribute to economic welfare, income, employment, and asset financing (Sarmila et al., 2015). Agusdinata et al. (2023) have concluded that the nickel mining in Sulawesi contributes positively to the achievement of some SDGs, while acknowledging a need to mitigate impacts related to effects on farmland and displaced farmers.

Current perspectives view CSR primarily as a risk management tool for companies (Agusdinata et al., 2023). For example, to expedite regulatory approval due to the absence of conflict, practices such as organizing public forums, funding community events, and donating to local charities have been noted in proposed nickel mines in the United States. Additionally, risk-management strategies such as public tours of undeveloped land are used to engage local community members. The underdeveloped land showcased during tours doesn’t express the future impacts and can be a method of suppressing opposition (Kojola & McMillan Lequieu, 2020). Therefore, it’s crucial to understand the line between the adoption of VSIs from an *increased need for frameworks on company-community communication* (a mapped driver from this work), and s*hort-term greenwashing undermining genuine sustainability efforts in mining* (a barrier to the legitimacy of VSIs, affecting their adoption), further explored under the *barriers* discussion section.

3.5.1.2 Navigating Supply-Chain Pressures and VSIs

The drivers for VSI adoption span further than just its footprint. The second most frequently found driver in the literature we covered is the need to manage *supply-chain disruption risk*. Supply risk is often assessed through potential for supply reduction, increased demand, product concentration, and political risk, with all minerals described within this study (Li, Ni, Mn, and Co) presenting a high risk of supply disruption (Helbig et al., 2018). These risks are exacerbated by the geographical concentration of battery minerals, aligning regions with high ESG risks to critical points in the global supply chain (Agusdinata et al., 2022; van den Brink et al., 2020) (described under driver “*Geographical Concentration of Battery Minerals*”). Long-term supply strategies to address supply risk through cross-sector collaboration and support have been emphasized (Petavratzi & Gunn, 2023), with VSIs potentially playing a role in signalling risk management and mitigation through transparent adaptive management.

When looking at the driver *“Downstream pressure to mitigate reputational risk”*, some authors claim that the automotive industry procurement sectors are showing greater interest in responsible sourcing practices for raw materials (Rutovitz et al., 2020). Due to the potential for opposition and social impact associated with mining operations, mining companies are especially vulnerable to reputational risks (Innis & Kunz, 2020), making certification and compliance with standards an attractive potential de-risking strategy. From the literature review, several key drivers relate to environmental performance monitoring, namely: (i) *improved guidelines on life cycle assessment*, (ii) *increased need to manage biodiversity impacts*, and (iii) *operating in complex water management contexts*. The importance of monitoring environmental performance and life cycle indicators at the source of raw material extraction might be driven by legislation such as directives on corporate sustainability due diligence (European Union (EU), 2023) and battery passports (Berger et al., 2023). Article 77 of the most recent EU battery regulation requires that, by 2027, operators provide a record of all stages of the battery life cycle. Such regulation might be associated with *harder accountability*, as mentioned by Johnson and Khosravani (2024), which, although it wasn't part of the analysed literature, adds a significant amount to the discussion. An important point raised is that, although the EU's battery regulation is an obligatory form of regulation, the transnational aspect of the battery supply chain might require voluntary environmental management at the mining operation level to bridge the gap between a certain level of vagueness or over-focus on European interests.

Lastly, the incorporation of mining stakeholders in initiatives related to the responsible recycling of metals, such as the Roundtable on the Responsible Recycling of Metals (RRRM, 2023) will likely lead to increased requirements for visibility and transparency across the supply chain. These all speak to an increasingly prominent role of transnational corporations in mineral extraction. Extending on the importance of improved monitoring efforts, an author discussed the need to incorporate life cycle assessments to capture the full costs of mineral extraction (Agusdinata et al., 2022). Another author mentioned that emerging frameworks should consider that the legislation in the 'demand country' should consider the impacts of mining from the 'supplying countries' (Kosai et al., 2022). Some authors discuss that for EV consumers, information about the local impacts of mineral extractions should be factored into the life cycle cost of EV ownership (Mitropoulos et al., 2017), which is consistent with a growing body of literature looking at *telecoupling, global value chains, global production networks,* and some other associated concepts. Authors working in this field have proposed to shift mineral extraction to the regions of consumption (e.g., Europe) to improve the control and security of the supply chain (Sun et al 2019, Mateus and Martins 2020, Schmid 2020).

3.5.1.3 Insights on Investor Impact on Adoption of VSIs

Institutional investors are increasingly conscious of the environmental performance of mining companies, leading to higher environmental performance expectations (Dyck et al., 2019), with some investors using screening techniques or impact investing to incentivize adherence to certifications and standards (Barber et al., 2021). It's important to call attention to the observation that while these actions can improve the returns of specific portfolios, their overall impact on the system may be limited. Moreover, institutional investors have recently started to pay attention to responsible tailings management (Innis & Kunz, 2020) that can be covered by standards such as the *Global Industry Standard on Tailings Management* (International Council on Mining & Metals, 2020), the *Tailings Management Protocol* encompassed by the *Towards Sustainable Mining* standard (Towards Sustainable Mining, 2022), and the *Community Health and Safety* section of the *Initiative for Responsible Mining Assurance* (IRMA, 2018a). Similar to environmentally-oriented investment funds, socially responsible investment (SRI) is also growing rapidly and has been associated with *social signalling* (Bialkowski & Starks, 2016), which may influence institutional investors' future investment decisions. The number of institutional investors publicly committed to non-governmental, market-oriented responsibility initiatives is significant, with more than 5,319 signatories owning assets equivalent to U$121 trillion as of 2022 under the UN Principles for Responsible Investment (UN PRI, 2022), which requires disclosure of information on ESG integration and engagement efforts by signatories. Lastly, increased cooperation among non-governmental organisations (NGOs), governments, and companies has led to the adoption of standards as a comprehensive framework for communication in a shared language (Barry et al., 2012), with NGOs also acting as third-party certifiers and verifiers, which might provide NGOs with extended sources for funding other than corporate funding and donations.

3.5.2 Barriers

3.5.2.1 VSI Legitimacy, Greenwashing, and Feasibility.

Petavratzi and Gunn (2023) highlight a significant gap between the increased pace of developing new mining projects and the adoption of better ESG practices. Downstream entities in the EV sector, encompassing design, development, component manufacturing, and production, typically operate with a lead time exceeding 10 years for new projects. In contrast, upstream participants, responsible for extraction and processing, can face a lead time surpassing 20 years; however, this is dependent on the economics of a project, with some operations having a quick turnaround when there are clear and stable price signals. The implementation of VSIs during pre-production stages can extend their lead time, consequently delaying the inauguration of new mining operations. Also, it’s been noted that it is in the investors’ interest to minimise the mine construction time to ensure not only rapid payback of the investment made, but also to minimise the risk of the conclusions of previous studies becoming outdated and thus invalid. It remains uncertain whether improved CSR practices during feasibility analysis and community engagement can offset delays caused by community opposition and the time needed to implement VSIs.

Moreover, CSR practices have been criticised as ways to circumvent popular discontent. An example of corporate dissonance is the Weda Bay Nickel (WBN) Mine Project on Halmahera Island, Indonesia. Palpacuer and Roussey (2023) described the repression and defeat of several counter movements, also corroborated by the Environmental Justice Atlas (EJ atlas, 2023), whilst Eramet (2023) describes it as a *‘success story’*, Hudayana et al. (2020) concludes that communal conflicts can be resolved through cooperation between companies and communities through an established mechanism for compensation. Such financial compensation might be sufficient to eliminate public opposition, but no studies have shown a direct correlation with long-lasting sustainability goals.

Hence, we argue that the *social-licence-to-mitigate-risk* narrative merits criticism. While quantifying risks as an externality is a foundational part of business, and authors have made significant progress in developing this discussion (Franks et al., 2014b), significant concerns remain on the short-term approach to risk mitigation in the form of greenwashing, and how this de-legitimises sincere efforts. Predominantly, there is the tendency from businesses to perceive local communities simply as barriers to overcome, rather than recognizing them as stakeholders with legitimate concerns and local knowledge. There's also an apprehension that companies might exploit VSIs to pre-emptively suppress emerging local movements that could surface a range of environmental and social issues (Lassila, 2016; Malone et al., 2023; Palpacuer & Roussey, 2023). This has led to open-ended questions around the long-lasting effects of voluntary sustainability practices when involving local communities during a new project development. Third-party observation of local conflicts, such as the ones done across the globe by *EJ Atlas* (EJ Atlas, 2023), in Indonesia by *Jatam* (Jatam, 2023), and in South America by *Olca, Conflictos Mineros,* and OPSAL (Conflictos Mineros, 2023; Olca, 2023; OPSAL), is crucial to decentralised research and should be incorporated into the risk analysis. Further, the transparency of local opposition should not be obfuscated.

It’s also worth mentioning that the cost of implementing VSIs and adhering to certified standards can make products uncompetitive in price-sensitive markets, deterring decision-makers from adopting and maintaining VSIs due to the lack of financial incentives (Barry et al., 2012; Ndhulukula & du Plessis, 2007). This challenge is particularly acute for smallholders and junior mining companies, where the relative costs of certification are higher, and compliance demands extensive personnel and technical training (Deberdt & Billon, 2021), potentially excluding them from markets with strict import requirements (Tröster & Hiete, 2018). Therefore, the narrative in relation to the cost-effectiveness of VSIs remains to be seen. Direct costs associated with the implementation and maintenance of VSIs can impact commodity prices in a market already driven by price. Studies have linked increased adoption of social and environmental standards to improved water and/or energy usage (Dummett, 2006), minimization of operational disruptions (Franks et al., 2014b), and improved employee retention (Lodhia & Hess, 2014). However, these are counterbalanced by costs incurred from more thorough life cycle assessments (Agusdinata et al., 2022), detailed feasibility studies (Petavratzi & Gunn, 2023), and technological implementation (e.g., uptake of renewable energy) (Jowitt et al., 2020).

Ways in which these financial challenges have been overcome have been documented in Chile, where the government provided a support programme called Associated Development Programmes (PROPO) that partially funded the costs for VSI adoption. In 2002, Minera Escondida took a more active role in the project, with the provision of extra expenses not initially included, which led to a successful ISO 14001 certification for participating small and medium enterprises (Ghorbani & Kuan, 2017; Newbold, 2006). Moreover, authors have discussed that VSI interoperability has the potential to reduce costs and can amplify the outcomes achieved by individual certifications (Barry et al., 2012; Mori Junior et al., 2016; Potts et al., 2018), with notable work being done in evaluating and mapping VSI's commonalities (Langdon et al., 2021). This evolving landscape highlights the necessity for participatory research in integrating VSIs into business models, weighing their potential financial benefits against the accompanying costs, and exploring innovative strategies to mitigate financial challenges.

3.5.2.2 Tracing Provenance at Key Points

Tracing the provenance of materials within the lithium-ion battery supply chain is a technically challenging task due to the presence of multiple, overlapping supply chains and several chemical and physical transformations, as made clear by the breadth of works that mention this barrier (*"Tracing provenance at key points"* in **Table 14**). Downstream procurement sectors might face a lack of visibility into what has been certified and to what extent. Additionally, a persistent focus on immediate suppliers or *focal companies* exacerbates this challenge (Young et al., 2019), with the interface between manufacturers and higher-tier suppliers being a common theme in the literature.

Typically, manufacturers engage primarily with their direct suppliers, concentrating on ensuring these suppliers adhere to environmental and social standards (Mugurusi & Ahishakiye, 2022). Adding to these challenges, smelters often serve as critical choke points within the supply chain (Deberdt & Le Billon, 2022; Vasilyev et al., 2022), potentially disrupting the continuity of the material's chain-of-custody, thereby diminishing the effectiveness of certifications initiated at the mining stage. Moreover, there's a significant concentration of refining operations, with China refining 73% of cobalt, 59% of lithium, and 68% of nickel (Vivoda & Matthews, 2023). The European Union has implemented a regulatory approach that mandates due diligence for companies wishing to trade within its borders, specifically targeting sourcing from a list of responsible smelters and refiners (European Commission, 2021). The China Chamber of Commerce of Metals, Minerals & Chemicals Importers and Exporters also published voluntary Guidelines for Social Responsibility in Outbound Mining Investments (Ralph & Hancock, 2018), and the United States is invested in the Minerals Security Partnership, a multilateral collaboration aimed at securing critical minerals on the part of the United States (US Department of State, 2023). In addition, the introduction of the battery passport by the European Union requires that, by 2027, battery operators provide a full lifecycle record, including carbon footprints from raw material acquisition to pre-processing stages, reinforcing transparency and sustainability through market mechanisms (European Union (EU), 2023). The battery passport reflects growing expectations for supply chain transparency, and when combined with more robust lifecycle monitoring mechanisms, it may help address the challenges posed by smelters and refiners as bottlenecks in the chain of custody. Whether this increased traceability will enhance the credibility of non-state market-driven systems remains to be seen, as it pushes for stronger alignment between market incentives and sustainable sourcing.

Parallel to these regulatory approaches, blockchain technology has garnered attention in various studies as a promising solution (Deberdt & Le Billon, 2022; Mugurusi & Ahishakiye, 2022; van den Brink et al., 2019; Vasilyev et al., 2022). Its success in other industries and potential to preserve the integrity of ground-level information make it a noteworthy consideration (Deberdt & Billon, 2021). However, the effectiveness of blockchain as a decentralized ledger is contingent on the *quality* and *availability* of the data it records. Hence, its utility is maximized when implemented at the source, though it remains limited by the accuracy of the input data, a challenge that has been well-documented at the ground *level* (Deberdt & Le Billon, 2022), not to mention the challenges surrounding the discussion and definition regarding who has accessibility and visibility to the data, as it moves along the supply-chain.

Lastly, as the field of Sustainable Supply Chain Management (SSCM) moves forward and advocates for increased monitoring and traceability (Goli et al., 2023), such challenges might be addressed. Theoretical developments have been made in incorporating green procurement and regulatory frameworks into widespread institutional theory related to sustainable supply chains and influence sustainable practices such as low-carbon performance (Ali et al., 2023). As these advancements are made, the overall benchmark for sustainable supply chain is raised, and the qualitative needs related to monitoring at the source might be adhered to as part of best available practice by mining companies and operators.

3.6 Concluding remarks

As the widespread uptake of EVs continues, the demand for energy transition minerals – including lithium, nickel, manganese, and cobalt – is intensifying. These resources are mainly concentrated in resource-rich regions of the global south, where mining operations have to grapple with significant ESG challenges (Lèbre et al., 2020). Simultaneously, nations from the global north, which consume these resources in their final form, enforce stronger ESG requirements (e.g., battery passport). This situation foregrounds the complex dynamic of how OEM buyers navigate supply disruption risk and geography-specific ESG challenges while meeting trade requirements. This dynamic highlights the importance of sustainable and responsible mining practices, as governments and corporations seek to reconcile the demand with ethical and environmental imperatives, whilst securing mineral supply. VSIs emerge as potential instruments to bridge this gap, arguing they can promote more sustainable and responsible mining practices – currently concentrated in the global south – to align with the ESG demands – currently driven by consumption of the global north. However, the legitimacy of VSIs is often questioned due to instances of greenwashing disguised as corporate social responsibility.

This research contributes to the emerging body of literature on voluntary sustainability initiatives applicable to battery minerals by surfacing a range of drivers and barriers relevant to VSI adoption and market diffusion. By highlighting how specific factors prevalent in the global south—such as regulatory environments, ESG risks, and market pressures—influence the adoption of VSIs, our findings lay the groundwork for a more comprehensive understanding of the system dynamics at play. This, in turn, enriches discussions on the critical linkage between resource production in the global south and consumption in the global north. The geographical concentration of battery raw materials, along with the risk of missing energy transition deadlines due to supply disruptions of battery raw materials, has raised interest in the legitimacy of voluntary initiatives adopted at mining operations. The legitimacy of these initiatives, however, remains a contested issue in the literature, as exemplified by the opposing drivers related to the legitimacy of non-state market-driven systems sought by initiatives such as the Global Battery Alliance and the Nickel Mark, contrasted with short-term greenwashing in mining operations observed in Indonesia, Australia, New Caledonia, and the United States.

The potential drivers to voluntary sustainability are varied and multifaceted, but many include the adoption of some level of CSR to mitigate risks associated with their extraction process, mainly driven from a corporate risk-mitigation perspective. It’s important to surface that voluntary practices to achieve and maintain social license to operate are promoted by global and national industry peak bodies and business advisers (Mayes, 2015). Furthermore, sustainability standards and certifications in mining operations are increasingly relevant due to downstream reputational pressure from EV and battery manufacturers, serving to reduce uncertainty and substantiate sustainability claims. Few studies have comprehensively assessed the balance between the costs of certification and the potential reduction in direct and indirect costs. Moreover, no comprehensive study has focused on premiums related to VSI adoption, indicating a potential future research avenue. Lastly, the complexity of tracing provenance in a supply chain characterized by physical and chemical transformations and international trade has been a recurring challenge. In this context, the potential application of blockchain technology as a solution to this challenge has been highlighted in several articles.

For future research, we suggest focusing on (*i*) an expansion of this analysis to include industry and non-technical reporting; and (*ii*) conducting stakeholder interviews to verify or challenge the results informed by contemporary industry practices. Our study focuses primarily on the factors that promote the adoption of these practices. However, the enduring effectiveness of adopting VSIs requires more in-depth investigation, particularly in the context of their long-term impacts on the mining governance landscape, local populations’ quality of life, and developmental trajectories in the global south.

4 Untangling complexity: A stakeholder-driven systems map of VSI adoption in the battery minerals sector:

The previous chapter examined what the scientific literature reveals about the drivers and barriers to VSI adoption in the context of battery minerals supply chains. Within this chapter, perspectives of diverse stakeholders actively involved across this supply chain will be explored. To achieve this, well-established methods to decompose complex systems were employed, namely, *variables elicitation* and *connected circles* (Hovmand et al., 2013). These methods are effective in decomposing a complex system into its fundamental components (individual variables) and then methodically linking these variables through cause-and-effect relationships. This approach involved a series of guided workshops with industry representatives, NGOs, and academics, as well as iterative steps to construct adjacency matrices, culminating in the development of comprehensive causal loop diagrams, explained in detail within the article.

Building on this participatory foundation, this chapter utilises an iterative, systems thinking approach grounded in system dynamics (Sterman, 2000) to surface the multifaceted factors influencing VSI adoption at the battery mineral extraction stage. The result is a Causal Loop Diagram that synthesises stakeholder inputs from 12 workshops performed in 2023, and maps how regulatory drivers, trade agreements, recycling incentives, environmental concerns, and social license dynamics interact. Employing Zagonel's group-model building methodology (Zagonel, 2002), along with new analytical tools such as Structural Analysis of System Dynamics Models (Schoenenberger et al., 2021) and the Speaker-listener Label Propagation Algorithm (SLPA) (Xie et al., 2011), innovative methods for objectively identifying key variables, variable hubs, and systemic archetypes are introduced. Applications that, to the best of our knowledge, have not previously been employed in this context.

By identifying subsystems, feedback loops, and archetypal system behaviours, this modelling effort reveals how shifts in battery recycling targets, supply chain pressures, and stakeholder expectations reinforce or counteract each other, often producing complex and sometimes unintended outcomes. The presented conceptual model does not provide definitive prescriptions but offers a structured lens through which to interpret the evolving battery minerals sector. Some results have been extracted, presented, and discussed, but they are by no means exhaustive. Therefore, a glossary of variables and datasets has been provided in the supplementary material and made publicly available, which can support future system models. Moreover, the causal loop diagram, with its calculated metrics, is publicly available at:

https://kumu.io/bernardo-mendonca/cld-vsi-battery-minerals

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Investigating the Adoption of Voluntary Sustainability Initiatives when Mining for Battery Minerals: An Iterative Systems Thinking Approach

Abstract

Decarbonizing the automotive sector is leading to a significant shift towards electric vehicle (EV) adoption, underpinning the need for lithium-ion batteries, which in turn depend on the extraction of minerals such as lithium, nickel, manganese, and cobalt. To understand the complexities associated with adopting voluntary sustainability initiatives (VSI) when mining these minerals, this study leverages System Dynamics (SD) to conceptualize the perceptions between stakeholders, intrinsic motivations, and various factors across supply chain steps. This research follows an iterative process of participatory model building, engaging stakeholders through workshops to validate and refine the model, thus embodying a shared understanding of the problem space. The result of this study includes a Causal Loop Diagram (CLD), which captures the system's dynamics, describes mental models, and identifies feedback loops influencing the adoption of VSIs in mining operations. A detailed analysis of the CLD is performed to provide insights into common system patterns. This research aims to support a better understanding of factors influencing decisions regarding environmental impact mitigation in the mining sector for battery minerals. These findings offer preliminary insights that could support more informed decision-making and sustainable practices in the decarbonisation of battery supply chains.

Keywords: Voluntary Sustainability Initiatives; Mining; Systems Analysis; Battery Minerals; Causal Loop Diagram;

4.1 Introduction

The rapid growth of electric vehicles (EVs), batteries, and energy transition minerals (ETM) mining has dramatically transformed global industries, pushing technological and economic boundaries (Habib et al., 2020). As the demand for lithium-ion batteries continues to surge, so does the need for the sourcing of raw materials (IEA, 2021). This has been accompanied by a rise in concerns about environmental degradation, social impacts, and governance challenges associated with the extraction of such minerals (Lèbre et al., 2020). The potential for environmental and social impacts when mining for lithium-ion battery minerals is extensive and geographically dispersed (Agusdinata et al., 2022). Addressing these issues requires a multifaceted approach, and authors have started to examine the effectiveness, diffusion, and impact of voluntary environmental impact mitigation approaches (Franken & Schütte, 2022a).

Several elements play a role in the scale between the demand for battery minerals and the supply of such. Trade agreements, such as friendshoring, play a significant role, as they can either facilitate or hinder the flow of raw materials across borders, impacting the supply chain and availability of critical minerals (Vivoda & Matthews, 2023). Recycling of lithium-ion batteries is another critical factor, as it can reduce the demand for newly mined minerals (Harper et al., 2019). Additionally, the environmental sustainability of mineral recovery methods (e.g., hard rock versus brine for lithium, and sulfides versus laterites for nickel) involves inherent trade-offs that must be considered (Khakmardan et al., 2023). Geopolitical factors, including the stability of mining regions and the ethical considerations of mining practices, also significantly influence the development of new projects (Lèbre et al., 2020). Collectively, these factors shape the complex landscape of mining impacts for lithium-ion battery minerals and can hardly be isolated from each other.

The mining sector has seen an increase in the creation and adoption of VSIs. Since the first industry-specific initiative in 1992, more than 50 unique sustainability standards have been published (Kickler & Franken, 2017). They originated in response to growing pressures from investors, regulators, and civil society for companies to address the adverse impacts of their operations (Erdmann & Franken, 2022; Franken & Schütte, 2022a). Authors have speculated on the elements that might be associated with VSI adoption, often encompassing elements such as the financial costs of social licence (Franks et al., 2014a), future regulatory pressure (Franken & Schütte, 2022a), and the influence of institutional investors (Dyck et al., 2019), albeit not specifically targeting battery minerals. It happens that battery minerals such as lithium, nickel, manganese, and cobalt are uniquely positioned within global supply chains due to their geographic concentration, limited substitutability, and their presence in regions with high environmental and social risks (Murdock et al., 2021). Given these characteristics, VSIs offer a potentially valuable mechanism for mitigating the adverse impacts associated with battery mineral operations, yet the specific drivers behind their adoption in this context remain insufficiently understood.

This landscape is inherently complex and comprises a range of systems and systems-of-systems (SoS). Previous work has highlighted the importance of understanding the systemic aspects of industries involved in this supply chain, incorporating elements such as mining activities, community livelihoods, and regional development (Agusdinata et al., 2018). According to Agusdinata et al. (2018), this understanding is necessary to support the achievement of shared goals that might extend beyond the top priority of each actor within that system, such as minimizing environmental impacts.

To develop a stakeholder-informed qualitative model that accurately reflects the complexities of the lithium-ion battery supply chain, a group-model building (GMB) approach (Zagonel, 2002) was adopted, focused on engaging stakeholders through participatory methods. Invitations to interviews and workshops were extended to a diverse group of stakeholders central to the lithium-ion battery supply chain. These included downstream consumers such as the automotive sector, midstream actors like refiners and traders, upstream producers from mining companies, and representatives from civil society organizations, researchers, and policymakers. Using insights from the GMB approach, we synthesized a causal loop diagram, identified subsystems, and mapped system archetypes. This structured approach aims to provide a comprehensive understanding of the challenges and opportunities in the EV and battery sectors, highlighting the importance of stakeholder engagement through the process of qualitative reflection.

4.2 Materials and Methods

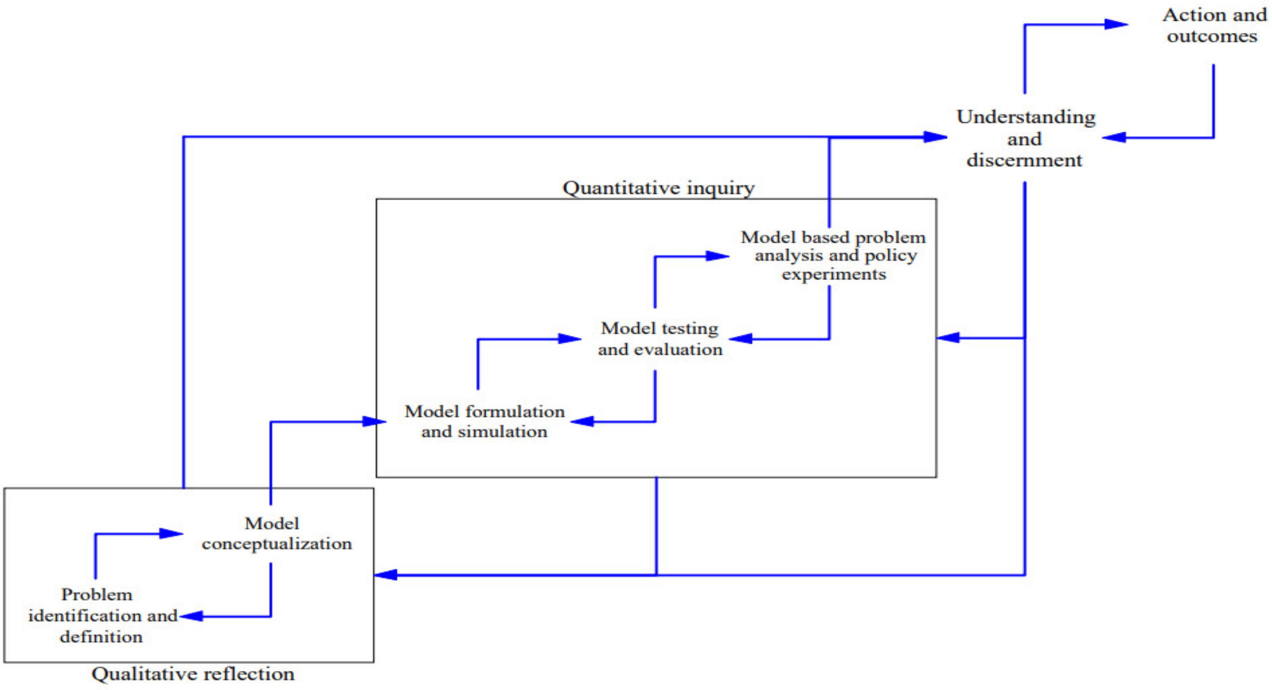
4.2.1 Overview of System Dynamics and Understanding Systems

Understanding how Voluntary Sustainability Initiatives (VSI) are adopted by battery mineral producers and their supply chains can be facilitated by participatory modelling approaches to co-create and describe mental models, employing tools such as variable-elicitation scripts, connection circles, adjacency matrices, and causal loop diagrams. These take into consideration exogenous forces and a stakeholder’s intrinsic motivation, integrating both actual (measurable or objective) and perceived (stakeholder-driven or subjective) variables spanning across several supply chain steps. With that in mind, System Dynamics (SD) is perceived as a suitable framework to understand and map mental models (Meadows, 2009), giving the researchers the power to conceptualise agents and their perception of reality, and map how their decisions and actions shape the equilibrium of said system.

System Dynamics Modelling is a problem-oriented modelling approach pioneered by Jay Forrester in the late 1950s to help decision-makers better understand industrial problems (Currie et al., 2018). The field of system dynamics is oriented towards understanding, framing, and discussing nonlinear complex systems. The use of systems thinking and systems dynamics modelling in sustainable development studies has been crucial to move researchers and practitioners beyond a linear-thinking approach and to adopt non-linear mental models (Nabavi et al., 2017). This integrative perspective takes into consideration the conceptualisation of a socio-ecological system, classified as a non-linear, unpredictable, and self-organised system behaving in a complex manner (Norberg & Cumming, 2008). Systems thinking is effective in expanding the boundaries of our mental models regarding the behaviour of complex systems (Sterman, 2000). A systems-oriented approach to problem-solving is capable of integrating social and technical aspects into a qualitative and quantitative model and of considering the complexity, feedback mechanisms, archetypes, unintended consequences, and dynamic behaviours present in the system being studied (Maani et al., 2007). This approach has been applied to support decision-making around complex problems such as the limits to exponential economic growth (Meadows et al., 2017), renewable energy technology adoption (Dhirasasna et al., 2020), and supply-chain management (Rebs et al., 2019).

The process of conceptualising a system dynamics model can include multiple distinct phases, inclusive of qualitative and quantitative inquiries, and action-oriented steps. **Figure 15** contains the steps of a system dynamics model-building exercise compiled by Aldo A. Zagonel (Zagonel, 2002), and inclusive of frameworks developed by leading authors in this space (Richardson & Andersen, 1995). The focus of our research study will be on *Problem Identification and definition,* and *Model conceptualisation*, focusing on producing a qualitative reflection or an analogue of the problem space.

Figure 15. Steps of system conceptualisation, from (Zagonel, 2002)



To better describe the relationship between a model conceptualisation and the participatory aspect of model building, a detailed description of *participatory model building* has been made under **Chapter 4.2.2**. Moreover, **Chapter 4.2.3.** describes the process of going from that to causal loop diagrams and includes the expected outcomes of this research.

4.2.2 Problem Identification and Definition Through Participatory Model Building

This study follows a participatory model-building process, which has been shown in the literature to be effective for building system understanding among diverse stakeholders (Haji Gholam Saryazdi et al., 2021; Homer, 2019; Vennix, 1999). Our study design is based on a multi-step process, initially focused on identifying the problem and conceptualising the system of interest. Sterman (Sterman, 2000) suggests that this type of process should aim to produce preliminary models as soon as possible, and then follow an iterative process that enables continual validation and re-validation of system models and behaviours. With this in mind, a participatory systems thinking approach was adopted that included the stages described in **Table 15.** As a starting point, we focused on developing a systems-level understanding related to the voluntary mitigation of environmental impacts by battery mineral producers.

Table 15. Stages included in the participatory systems thinking approach.

Stage	Process	Activities
1. Problem Identification and Definition	Stakeholder workshops	• Participants' outreach • Variables elicitation • Connection circles • Variables' consolidation • Problem identification
2. Model Conceptualisation	Researcher Review	• Key variables identification • Researcher review of variables • Weighting of most influential variables by experts • Glossary of Variables
	Validation Workshop	• Industry experts' feedback on the glossary of variables • Further development of system boundaries • Adjacency Matrix • Present initial CLD to research team
3. Qualitative Reflection and Interpretation	Researcher Review	• Interpretation of outcomes from the validation workshop • Identification of causal relationships between key variables • Iterations of CLD until Final CLD
	Researcher Interpretation	• Identification of system boundaries • Definition of variables' metrics • Identification of system archetypes

4.2.3 Participatory Model Building

This research used a combination of small groups and individual workshops to elicit system components, identify their relationships and feedback loops, and build consensus around the problem, with external stakeholder engagement being done during the *first stage, as* presented in **Table 15.** In order to identify the system components, we adopted a '*variables elicitation*' script from Luna-Reyes et al. (Luna-Reyes et al., 2006), which incorporates elements from previous participatory model-building approaches (André L. Delbecq et al., 1976; Stroebe et al., 2014; Vennix & Shields, 1997). Moreover, to better define and start conceptualising a system, we adapted a '*Connection Circle*' workshop from the works published at *Scriptapedia* by Peter Hovmand and Alison Kraus (Hovmand et al., 2013).

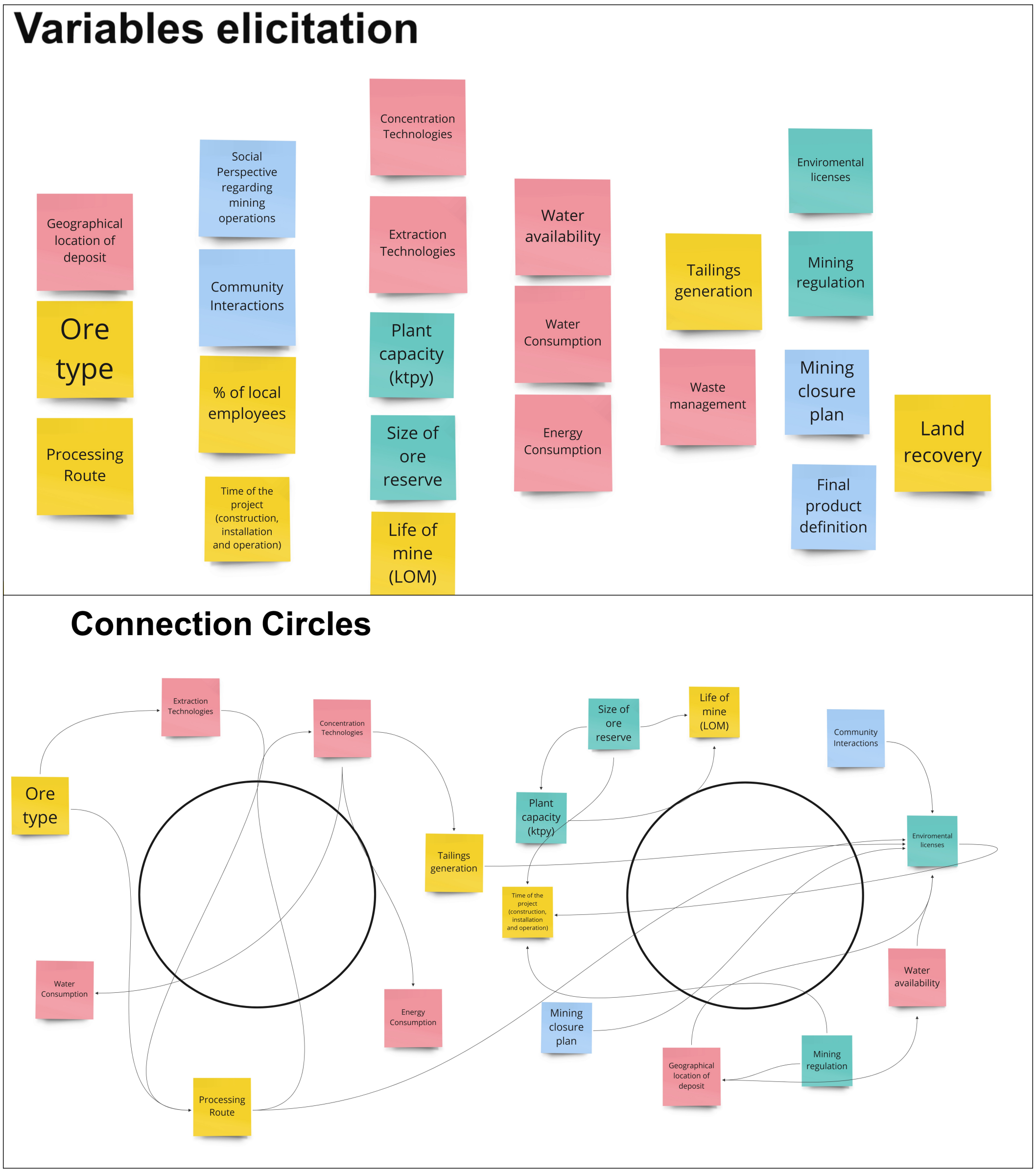
To recruit participants, we initially reached out to representatives from the Future Battery Industries CRC in Australia (Future Battery Industries CRC, 2024), along with representatives from NGOs active in battery mineral mining regions, battery-anode and battery manufacturers, industry associations, metal exchanges, and mining companies. These groups were selected to provide greater diversity in the perspectives and types of responses. We reached out to a total of 62 potential participants. This effort led to 12 workshops (individual or small group), engaging a total of 15 people (**Table 16**).

The scripts mentioned were applied to the participants described in **Table 16**. The outcome of these workshops would be: (i) a list of variables, which the stakeholders considered to be the most influential over the system (regarding the adoption of VSIs by mining companies mining for battery minerals), and (ii) at least one 'connected circle', in which the participants would connect such variables through links of causation. An example of the output of one of these workshops can be seen in **Figure 16**. A detailed script of the workshop, inclusive of workshop agenda and prompts used to discuss the system with the participants, can be found in the supplementary information.

Table 16. Profile of workshop attendees

Stakeholder Group	No	Position(s)	Location of Stakeholder
Academic and Research	1	Researcher – Production Networks and Critical Minerals	Australia
	2	Researcher – Materials Science	United Kingdom
	3	Life Cycle Assessment – Researchers (x4)	Germany
	4	Professor – Environmental Studies	United Kingdom
NGO	5	Legal Researcher – Human Rights Lawyer	Democratic Republic of Congo
Mining Operations	6	Sustainability Manager	United Kingdom
	7	General Manager	Australia / Mozambique
	8	Managing Director	Australia
	9	Engineering Manager / Executive (x2)	Australia / Vietnam
Mineral Processing	10	Head of Laboratory – Mineral Processing	Brazil
Recycling	11	Engineering Manager	Australia
Exchange	12	Head of Responsible Business	United Kingdom

Figure 16. Outcome of one of the workshops held with participants. On the top panel, a list of variables referred to by the participant as the most influential to the system. On the bottom panel, two 'connected circles' in which the participants attempt to connect them through links of causality.



Given the extended geographical network that battery supply chains entail, this research has adopted a mix of face-to-face and virtual environments. While there are certain benefits to convening in person, virtual videoconferencing platforms and online workspaces/whiteboards can be used to ensure engagement across a wider geographical area. Positive experiences in regard to online participatory system mapping have been documented, and authors consider that *"significant time and effort invested in bringing a system's mapping experience into an online environment was worth it"* (Wilkerson et al., 2020).

4.2.4 Model Conceptualisation and Construction

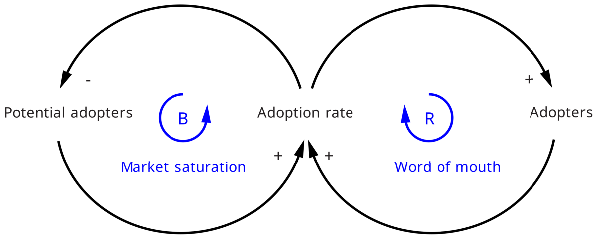
With the outcomes of the workshops in hand, this study aimed to synthesise stakeholders' perspectives into an integrated causal loop diagram (CLD). While most viewpoints were compatible, participants often emphasized distinct variables based on their expertise and context, with few participants mentioning the exact same variable as another. Rather than observing contradictions, we observed different areas of focus. Therefore, we aimed for consolidation and viewpoint integration across variables' linkages within the CLD. A CLD seeks an endogenous explanation of the system behaviour, which allows system archetypes to be identified and thoughtful policy interventions to be formulated.

Prior research identified a range of diverse drivers (e.g., the need for robust company–community communication frameworks, disruption risk management, and downstream pressure), and barriers (e.g., perceived legitimacy issues, and challenges in tracing mineral provenance) influencing VSI adoption (Mendonca Severiano et al., 2024). However, that publication was limited to a literature review on works reflective of VSI adoption by battery mineral producers, and we aim to extend this understanding through our collaborative model-building. Moreover, during the workshops conducted, stakeholder from the *mineral operations* group mentioned that each battery mineral (lithium, nickel, manganese, and cobalt) was to be addressed individually due to their idiosyncrasies and specific geography. Through our participant outreach (see previous section), we succeeded in recruiting a limited number of representatives who work closely with lithium, nickel, and cobalt operations. Unfortunately, we didn't succeed in including representatives from manganese mining operations. Consequently, while lithium, nickel, and cobalt were informed by stakeholder expertise specific to these minerals, our discussion of manganese is more generic. Whilst the number of participants that should make up a minimum sample to implement a group model building approach varies significantly, previous works have succeeded in building a CLD through GMB, with a range from five (Vennix et al., 1996) up to almost twenty (Salim et al., 2020) participants.

Transitioning from the participatory model-building process to the development of a Causal Loop Diagram (CLD) integrates a critical step in synthesizing expert judgment and stakeholder insights into a coherent, qualitative model. The authors performed an initial integration of the collection of stakeholder-generated causal loop diagrams into an aggregated causal loop diagram. Both the individual causal loop diagrams extracted from the *connected circles* workshops and the initial integration of these diagrams can be found in the supplementary material. Following the steps described in **Table 15**, an initial glossary of variables collected from the stakeholder workshop is presented to the research team. An initial list with 168 variables was iteratively merged, split, and clarified to a total of 54 unique variables. It is important to highlight that the participants' language and use of certain industry terms were not always aligned with formal technical definitions. After the workshops, the research team developed a glossary of variables to standardize key terms for clarity and consistency. This glossary explicitly relied on recognized definitions to interpret and consolidate any potential informal workshop language.

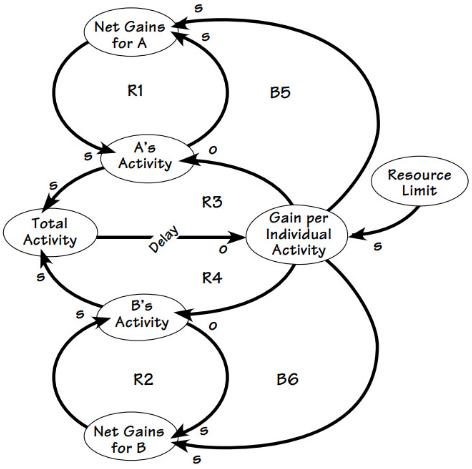
Further down the steps described in **Table 15**, a CLD is iteratively constructed, encapsulating variables and their interconnections that reflect the collective understanding of the system's dynamics. CLDs are effective in capturing the causes of dynamics within a given system, surfacing mental models of individuals and agents, and highlighting feedback that might be responsible for a specific problem (Sterman, 2000). An example of a simple causal loop diagram can be found in **Figure 17.**

Figure 17. Causal loop diagram of a new product adoption model by John Sterman (2001). Systems dynamics modelling: tools for learning in a complex world, California management review, Vol 43, no 1, Summer 2001



The construction of CLDs paves the way for an in-depth examination of emergent system archetypes, a concept introduced by Peter Senge in 1991 (Senge, 1991). These archetypes are identified as recurring patterns of behaviour over time, distilled from reinforcing and balancing feedback loops depicted in the CLDs. By mapping real-world scenarios to these archetypes – such as "Shifting the Burden," "Limits to Growth," and "Tragedy of the Commons" – we can gain insights into common dynamics that recur in many real-world systems, highlighting potential unintended consequences and interventions (Kim, 1992). An example of an archetype can be seen in **Figure 18**.

Figure 18. Example of system archetype "Tragedy of the Commons". From "The Fifth Discipline", adapted by Daniel, K. [31].



In several instances, the authors were faced with ambiguity. For example, from one of the workshops, a causal link was established between *Corruption Level in Host Nation* and *Mining Operation Accountability Level.* In that case, this link can be quite ambiguous due to elasticity. On the one hand, a country with higher levels of corruption can have an operation with *lower accountability levels.* On the other hand, it's also worth considering that increased accountability efforts might be a response to higher levels of perceived corruption. To deal with this challenge, we've disaggregated causal pathways to showcase the multiple links between them.

4.3 Results and Discussion

4.3.1 Model Conceptualisation Construction

A crucial step in conceptualising a robust system model is the transition from qualitative reflection to quantitative inquiry (Zagonel, 2002). To support future modelling efforts, we have concentrated on identifying key variables that can serve as targets for system dynamics models, presented in **Table 17**. These variables are often central to analysis, intervention, or policy implementation. Based on our initial research focus, we have extracted and mapped two main variable categories from our workshops: (i) environmental impact categories, and (ii) drivers to mitigate these environmental impacts. We identified the key environmental impacts they perceived as being: (i) water use, (ii) greenhouse gas emissions, and (iii) biodiversity loss. These impacts have been further refined to align with our current model development.

Regarding water-related impacts, from the initial participant descriptions, we expanded the interpretation of water use to better align with definitions for mine water balance variables. These have been influenced by the definition provided by the International Council on Mining and Metals' (ICMM) Water Reporting: Good Practice Guide (ICMM, 2021). Consequently, we incorporated the variables of Water Availability, Mining Operational Water Withdrawal, Ecosystem Water Demand, and Operational Water Reuse or Recycling. For biodiversity impacts, participants highlighted concerns about animal migration and biodiversity levels. The mining impacts on biodiversity are still poorly understood, and frameworks to properly understand and address these impacts across diverse pathways and spatial scales are still being developed (Sonter et al., 2018). In our CLD, we classified this variable as 'Biodiversity & Ecosystem Services', consistent with the portrait of this relationship referred to by Mace et al. (2012) and Oliver et al. (2015) and is often cited in environmental frameworks and guidelines (IRMA, 2018a). When addressing greenhouse gas emissions in our CLD, we labelled the variable "Greenhouse Gas Emissions from Extracting and Processing." This designation was influenced by the research of Manjong et al. (2021) and Azadi et al. (2020), as well as industry reports from McKinsey (Delevingne et al., 2020) and the Rocky Mountain Institute (Kirk & Lund, 2018).

In addition to this iterative qualitative reflection, we have selected key variables based on their betweenness centrality, as presented in **Table 18**. This metric measures how often an element lies on the shortest path between two other elements, indicating its role as a bridge within the network. We have also mapped variables with the highest *degree centrality* and *closeness centrality*, recognizing their roles as connectors/hubs and efficient spreaders of information, respectively (Perez & Germon, 2016). The field of structural analysis of system dynamics models is rapidly evolving (Schoenenberger et al., 2021), and we acknowledge the value of such analysis. Consequently, we have made all the relevant metrics available in the supplementary material.

Table 17. Key variables encompassing environmental impacts and drivers to impact mitigation extracted from participants' workshops and discussions

Category	Variable	Description
Environmental Impact	Water availability	The availability of water resources in the project area of influence.
	Mining Operational Water Withdrawal	Volume of water that enters the operational water system used to meet the operational water demand for mining activities.
	Ecosystem Water Demand	The volume of water needed to maintain the health and functionality of local ecosystems surrounding mining operations.
	Greenhouse Gas emissions from extracting and refining	Greenhouse gas (GHG) emissions associated with mining, mineral extraction, and processing phase of the mineral and metal value chain. Expressed in kg of CO2 equivalent.
	Biodiversity & Ecosystem Services	Biodiversity, which includes the variability among living organisms – including species, between species, and of ecosystems – underpins the benefits that humans can derive from the ecosystem (Mace et al., 2012). The ecosystem services are the outputs of ecosystem processes that provide benefits to humans (Oliver et al., 2015).
Driver to Impact Mitigation	Operational Water Reuse or Recycling	Volume of water reused or recycled in the mining operation. According to ICMM, operational water reuse and recycle is water that has been used in an operational task and is recovered and used again in an operational task, either without treatment (reuse) or with treatment (recycle) (ICMM, 2021)
	Low-Carbon Premium for Green Metal	Premium added to the mineral procurement cost when the metal has a registered carbon footprint lower than a certain threshold (measured in CO2 equivalent per tonne of output). An example can be found in the *low-carbon class 1 nickel* currently being transacted at the London Metals Exchange (LME).
	Dedicated Sustainability Team at Mining Operation	Specialized personnel who possess expertise in environmental impact assessment and mitigation. This team is responsible for implementing and maintaining environmental standards and certifications.
	Community Benefit Agreements (CBA)	"CBAs are undertakings that can be signed by project proponents, governments, and impacted communities specifying how resource development will be managed, how adverse impacts will be mitigated, and how benefits will be shared and distributed" (Gunton et al., 2021).

Table 18. Variables with the highest betweenness centrality, degree centrality, and closeness centrality

Metric	Rank	Variable	Value
Betweenness Centrality	1	Dedicated Sustainability Team at Mining Operation	0.369
	2	Battery Recycled Volume	0.366
	3	Demand for Raw Battery Minerals	0.361
	4	Mining Operation Production Volume	0.356
	5	Operational Expenditures	0.307
Degree Centrality	1	Dedicated Sustainability Team at Mining Operation	9
	2	Mining Operation Production Volume	8
	3	Operational Expenditures	8
	4	Pressure from Local Community	7
	5	Battery Recycled Volume	7
	6	Community Wellbeing	7
Closeness Centrality	1	Mining Operation Production Volume	0.323
	2	EV adoption rate	0.252
	3	Tailings Volume	0.246
	4	Battery Lifetime	0.235
	5	Demand for Raw Battery Minerals	0.221

4.3.2 Supply Chain Activities and Sub-system Boundaries

In collaboration with the participants, as detailed in **Table 16**, we co-developed the model, identifying both endogenous and exogenous variables. This process allowed us to clearly define the system boundary across several supply-chain steps and map the subsystem diagrams. Initially focused on the mining operations of battery minerals, we expanded the boundaries of the system of interest to encompass refining steps, procurement activities, end-use, and recycling. Recognizing that a sustainable low-carbon transition through electric vehicles requires a comprehensive understanding of the environmental impacts across the lithium-ion battery global supply chain (Llamas-Orozco et al., 2023), we categorized all variables according to their respective supply-chain stages.

Building on the analyses of lithium-ion battery production networks by Bridge & Faigen (Bridge & Faigen, 2022) and the supply-chain framework outlined by Sun & Hao (Sun et al., 2019), we categorized each system variable into distinct supply-chain activities: (a) Mining, (b) Refining, (c) Material component manufacturing, (d) Cell and battery manufacturing, (e) EV manufacturing, (f) EV use phase, and (g) Recycling process, with the latter two included to address the importance of closing-the-loop strategies (Öztürk et al., 2024). To improve the clarity of the causal loop diagram, these supply-chain stages were synthesized and delineated, as presented in **Table 19.**

Table 19. Supply chain steps categorised in the causal loop diagram

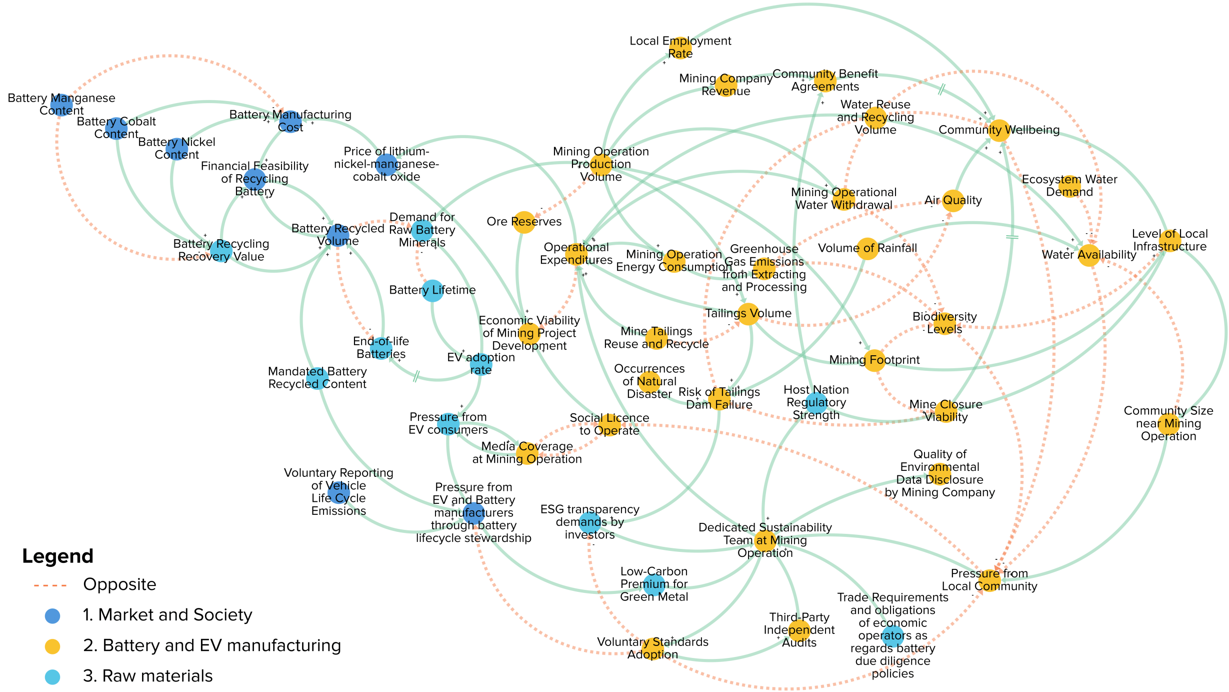
Classification	Description
Market and Society	This subsystem determines the mining requirements for lithium, nickel, manganese, and cobalt, encompassing elements related to EV use. This subsystem focuses on the influence of EV adoption rates and how this affects the demand for raw battery minerals. This subsystem also includes exogenous variables such as mandated battery recycled content and trade requirements related to battery due diligence policies.
Battery and EV manufacturing	This subsystem includes all activities related to cell and battery manufacturing, as well as EV manufacturing. It also incorporates aspects of recycling. This includes elements of battery chemistry and manufacturing costs.
Raw materials	This subsystem encompasses mining, processing, and refining activities. It includes operational elements, as well as community-related aspects such as local employment, socio-economic impacts, and stakeholder engagement. Additionally, this subsystem addresses the environmental burdens associated with mining, including land degradation, water and air pollution, and biodiversity disturbances.

4.3.3 Causal Loop Diagram

A static version of the final Causal Loop Diagram is presented in **Figure 19**. The subsystems are colour-coded for clarity: variables related to the market and society are in dark blue, those associated with battery and EV manufacturing are in light blue, and variables related to raw materials are in yellow. Additionally, a digital version can be found at

https://kumu.io/bernardo-mendonca/cld-vsi-battery-minerals.

Figure 19. Final Causal Loop Diagram. The green arrows denote a positive relationship (+), red dotted arrows reflect an inverse relationship (-). Arrows with two stripes (||) denote a delayed relationship (either positive or inverse).



The data structure was prepared and organized for use in Kumu, a relationship-mapping software [51]. In Kumu, we conducted a community detection analysis utilizing the Speaker-listener Label Propagation Algorithm (SLPA) to aid our subsystem classification (Xie et al., 2011). The identification of key variables and subsystems in systems models using social network metrics has gained some recognition (Barranquero et al., 2015; Jierui et al., 2013). However, this application is novel to the best of our knowledge. Further details on the algorithm are provided in the supplementary information. The inclusion of subsystems within the causal loop diagram is consistent with prior studies that systematically developed system dynamics models for battery minerals (Olafsdottir & Sverdrup, 2021; Sverdrup, 2016), and methodological definitions of system boundary setting (Dhirasasna et al., 2020). The community detection analysis initially identified two subsystems, which according to our judgement, can be labelled as: (i) Cost Dynamics of Recycling & Raw Materials Extraction, and (ii) Drivers to Voluntary Sustainability. Based on our expert judgment, we added a third subsystem: (iii) Social Licence to Operate & Mining. These subsystems are described in detail below.

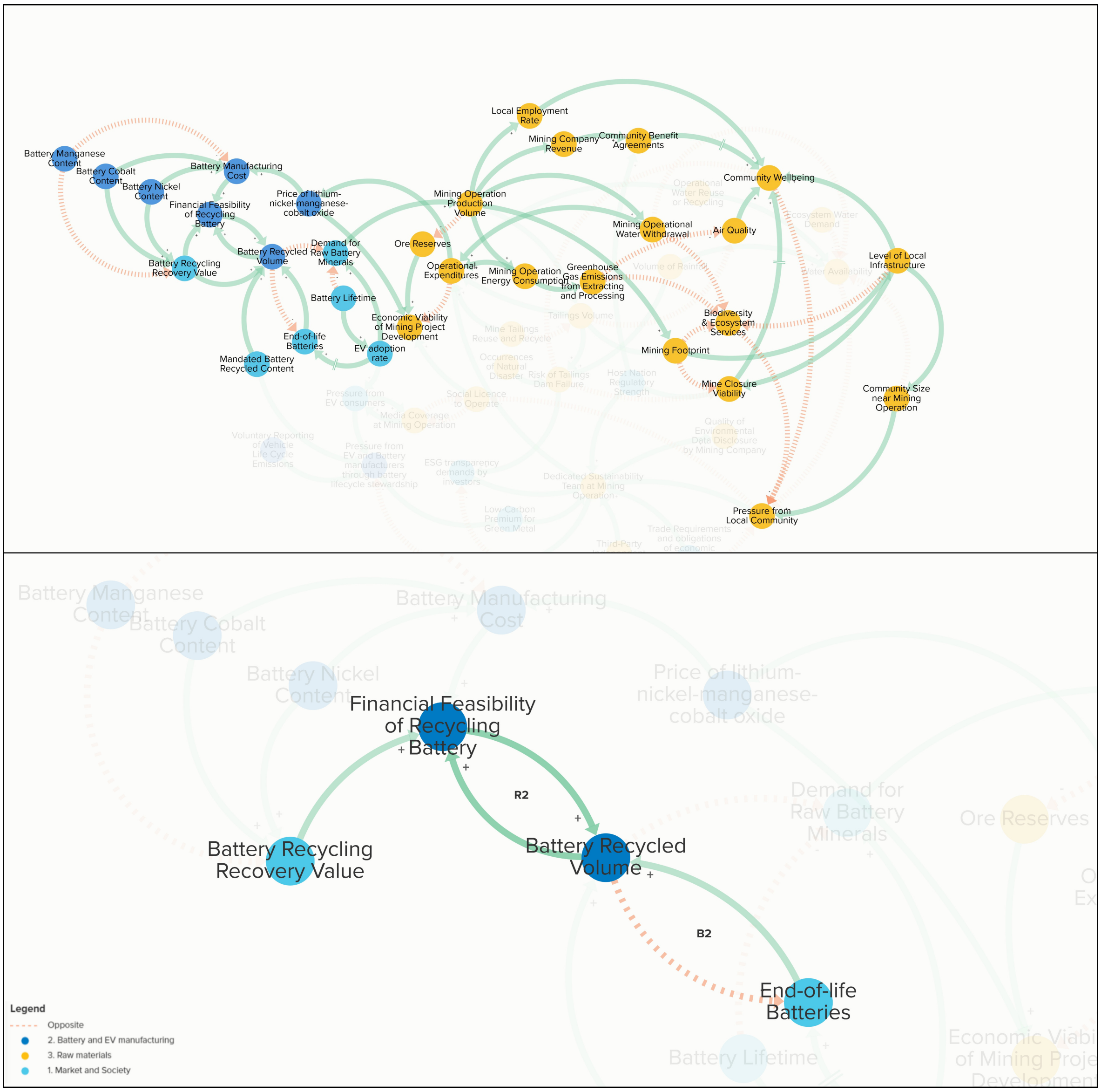
4.3.3.1 Subsystem 1: Cost Dynamics of Recycling & Raw Materials Extraction

The first cluster captures the mental models associated with the financial aspects affecting the balance between the need for minerals used in batteries and their source, between primary extraction and recycling. A dynamic, interactive version can be found in the supplementary materials, and a static version is presented within **Figure 20 (top panel)**. One of the primary insights extracted from the CLD is that an increase in *Battery Recycled Volume* is linked to a reduction in environmental impacts. The causal loop emphasizes that recycling can significantly decrease greenhouse gas emissions and water withdrawal associated with raw material extraction through reduced *Operational Production Volume*.

In the context of our CLD, this is associated with a "Limits to Success" archetype, where continuous efforts face constraints that inhibit further growth or success (Braun, 2002). Within **Figure 20 (bottom panel)** we can identify how the reinforcing loop between *Financial Feasibility of Recycling Battery* and *Battery Recycled volume* (R2 loop) is limited by the *Battery Recycling Recovery Value.* Workshop participants highlighted a clear relationship between the cobalt content in a battery and its recycling value, noting that batteries are only financially viable for recycling if they have a higher cobalt content. This is well documented in the literature, with batteries with higher cobalt content having a higher recovery value due to cobalt's economic importance and recyclability (Thompson et al., 2021). At present, for LIB recycling to be competitive, it still needs to increase its economic efficiency, with high recovery rates for materials like nickel and lithium reducing materials costs by half through recycled credits, and batteries with a lower cobalt content (e.g., NMC811) presenting decreased profits (Rezaei et al., 2025). Reducing cobalt content in battery chemistries, a trend driven by supply chain and ethical considerations, could challenge the financial viability of recycling (Harper et al., 2019)

Moreover, the *Battery Recycled Volume* is directly affected by the *Mandated Battery Recycled Content.* This is representative of frameworks such as the European Union (EU) regulation concerning batteries and waste batteries (European Union (EU), 2023). This framework introduces sustainability and safety requirements for batteries, including mandatory minimum levels of recycled content for industrial EV batteries. This directive establishes that, by 2036, EV batteries should have a minimum recycled content of (a) 26 % cobalt; (b) 85 % lead; (c) 12 % lithium; and (d) 15 % nickel. These targets are set to increase progressively, aiming to drive the recycling industry and reduce dependency on primary extraction. A connection between increased battery recycled content and potential social impacts affecting mining communities has been described under **Section 3.3.3.** The implications of the new EU rules remain unknown, with notable questions around the feasibility of meeting the EU targets. Some of these questions relate to the difficulty of achieving a high rate of recycling efficiencies, and a major challenge in meeting the cobalt target under the EU rules. This is exacerbated by an ongoing discussion on other countries implementing similar measures to promote the retention of critical minerals onshore (Zhou et al., 2024).

Figure 20. Top – Static representation of Subsystem 1: Cost Dynamics of Recycling & Raw Materials Extraction; Bottom – Segment of Subsystem 1 with a focus on the 'limits to success' archetype



From our workshops, one stakeholder argued that nickel being valued and traded as a commodity leads to limited preference amongst purchasers to value non-price-based information when procuring nickel. An example of this is the closure of Australian nickel mines (ABC News, 2024a, 2024b), at a time when Indonesian nickel operations are being opened or expanded[3] (GlobalData, 2024). Some stakeholders involved in our workshops argued that Australian nickel production has a lower ESG impact or risk than Indonesian nickel production. In their opinion, mining in a place like Indonesia has higher risks of impacting the biodiversity, combined with higher rainfall volumes, which in our final CLD has a positive

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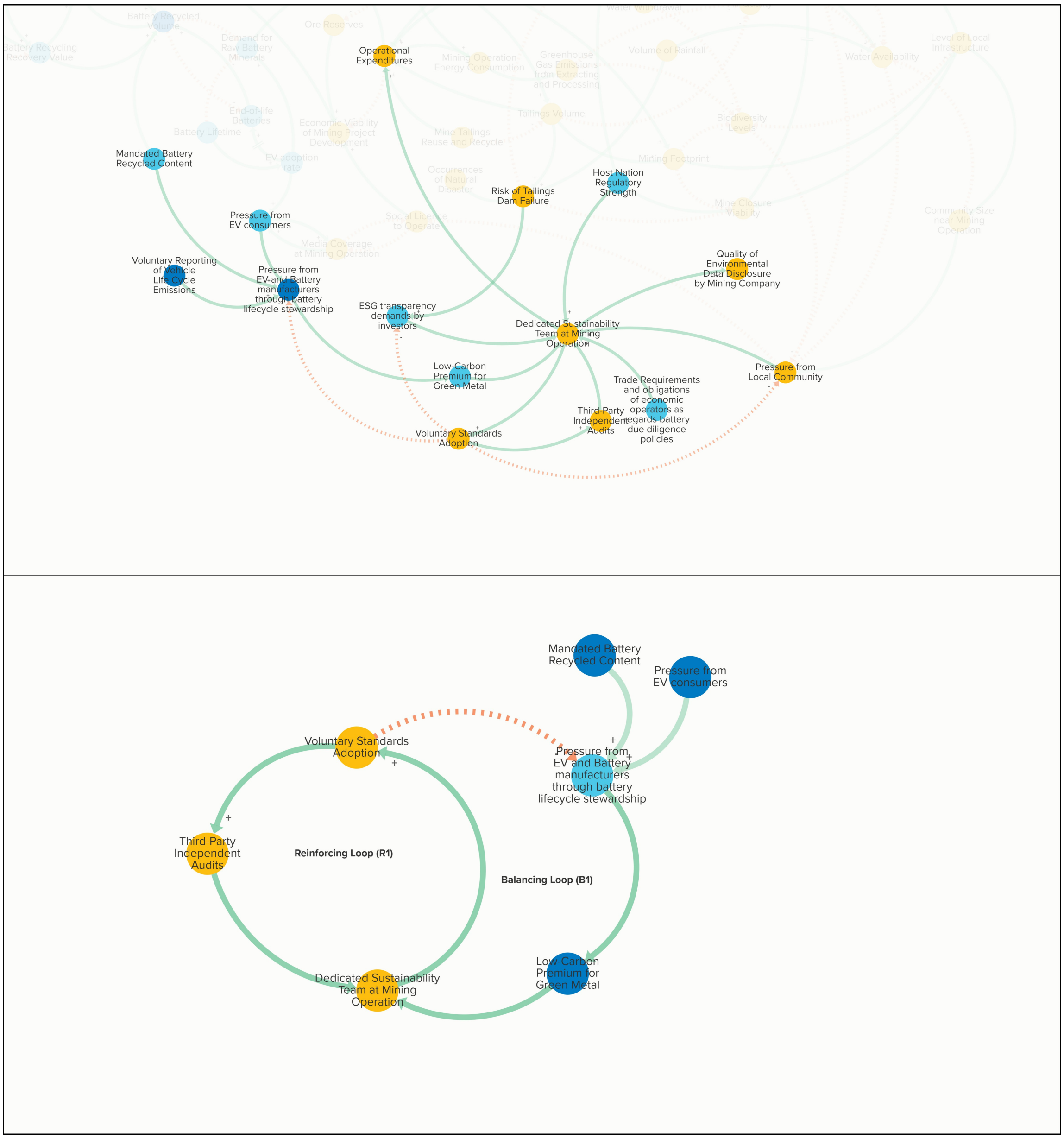
[3] Over the five years to 2022, production from Indonesia increased by a CAGR of 24% and is expected to rise by a CAGR of 13% between 2023 and 2027

relationship with *Risk of Tailings Dam Failure.* Rainfall-induced landslides are seemingly more prevalent in Indonesia than in Australia (Amarasinghe et al., 2024), which, combined with Indonesia being a biodiversity hotspot (Myers et al., 2000) can create a higher ESG risk profile for such operations. Further works that incorporate the concept of complex orebodies (Valenta et al., 2023) can draw from such insights.

4.3.3.2 Subsystem 2: Drivers to Voluntary Sustainability

The second subsystem emphasizes the variables influencing the adoption of VSIs, aggregating drivers that indirectly encourage such adoption. The CLD captures external influences, such as pressure from Original Equipment Manufacturers (OEMs), demands for ESG transparency by investors, and pressure from local communities (**Figure 21, top panel**). A notable link is the *pressure from EV manufacturers* leading to the implementation of a *low-carbon premium for green metal*. This, in turn, leads to the establishment of a *dedicated sustainability team at mining operation*, which supports the *Voluntary Standards Adoption*. One example of a *low-carbon premium for green metal* is the London Metal Exchange (LME) implementation of a low-carbon premium for the nickel market, effective March 2024. This premium applies to class 1 nickel with a registered carbon footprint lower than 20t of CO2 equivalent per tonne of output across scopes 1-3 (London Metal Exchange, 2024b). LME collaborated with *Metalshub* to determine that the Nickel Institute’s GHG Emissions Guidance is the appropriate initial method for assessing the eligible carbon threshold (London Metal Exchange, 2024a). In the long term, it is also expected that standards such as the Nickel Mark might be used to classify “green nickel” (The Nickel Institute, 2024), which might alleviate the unintended consequences of an over-focus on carbon emissions mitigation. The previously mentioned connections can be seen as part of the common archetype known as "fixes that fail" (**Figure 21**, **bottom panel**). Here, an initial fix appears to resolve the problem symptom in the short term, but unintended consequences might follow (Kim, 1992). These potential unintended consequences are still largely unexplored, but might include environmental trade-offs and an overfocus on short-term gains (Mori Junior et al., 2016). Within the co-created CLD, participants also discussed the role that the *Host Nation Regulatory Strength* has in influencing a *Dedicated Sustainability Team at Mining Operation*. Participants from operational cohorts mentioned that sustainability managers at an operational level were uncommon. Instead, mining companies typically employ environmental managers who focus on environmental monitoring, compliance, and stakeholder engagement at a higher level. Additionally, environmental impact assessments are often outsourced, further distinguishing these roles from dedicated sustainability management functions at an operational level.

Figure 21. Top – Subsystem 2 in focus; Bottom – Isolated "fixes that fail" archetype within subsystem 2



While reducing greenhouse gas (GHG) emissions is essential for mitigating climate change, an overemphasis on carbon mitigation can lead to unintended consequences such as burden shifting. To avoid such unintended consequences, it is crucial to clearly define environmental targets and understand how pursuing these targets might lead to environmental trade-offs. In the context of lithium-ion batteries, the production of lithium hydroxide (used in cathode materials) can come from lithium carbonate (from evaporation ponds) or lithium sulphate (from spodumene). These processing routes differ significantly and have distinct environmental impacts (Khakmardan et al., 2023). An overfocus on reducing carbon dioxide emissions might shift production to less energy-intensive areas, such as the lithium triangle, exacerbating water scarcity and impacting local communities and ecosystems (Sonter et al., 2020). While reducing the carbon footprint is beneficial, it necessitates careful consideration of water-related challenges. Furthermore, the adoption of multi-stakeholder initiative frameworks (MSI) has been presented as a collaborative approach to responsible mining initiatives (Sauer & Hiete, 2020). Finally, integrating voluntary standards with existing regulatory frameworks and mandatory requirements can create a more robust and coherent sustainability strategy. Some authors claim that "Certification is the second-best option. It would be useless in front of total conformity with national and international laws, regulations, and standards" (Franken et al., 2012). Unfortunately, in many regions, lax regulations or weak oversight mean that voluntary sustainability initiatives can fill critical gaps and steer companies to meet higher standards than those mandated by law. In this sense, VSIs can act as a tool of transnational governance, especially where formal legal frameworks are underdeveloped.

Lastly, from the workshops, no links were directly mentioned between VSIs and specific environmental impact mitigations, these were often achieved through the implementations of improved processes as part of the requirements for VSI adoption and certification. Upon examining standards such as Towards Sustainable Mining (TSM) (Towards Sustainable Mining, 2022) and the Initiative for Responsible Mining Assurance (IRMA) (IRMA, 2018a), it is evident that these provide coverage to the environmental impacts previously identified by the participants. Amongst others, they cover tailings management, water stewardship, biodiversity conservation, and air quality. Despite this, there is significant variation in the specificity of their requirements. For instance, under the IRMA GHG guidelines, *"4.5.3.2. The operating company shall demonstrate progress toward its greenhouse gas reduction targets."* (IRMA, 2018c). Greenhouse gas emissions are a non-local issue, with a relatively well-established measure of performance, and it's comparatively easier to measure. In contrast, the IRMA *water stewardship guidelines* are focused on an adaptive management approach of water resources due to the complexity of hydrology and water impacts surrounding mines (IRMA, 2018b). The guidelines acknowledge the trade-offs that can occur between different criteria and indicators, particularly in how companies identify potentially impacted water users and plan for 'future water uses' in the context of dynamic and site-specific water resource challenges. This is made clear by IRMA requirements related to *Water Management Context* and *Site characterisation*[4]. As an internationally oriented framework that focuses on being overarching, IRMA necessarily introduces flexibility in the interpretation and implementation of standards, leading to significant differences in how environmental impacts are managed across operations worldwide. Moreover, these standards vary significantly from each other in scope, verification methods (e.g., third-party involvement), reporting requirements, and more (Langdon et al., 2021). Consequently, a generic variable like *Voluntary Standards Adoption* needs to be specified in detail in future studies that aim to conduct quantitative inquiries, with specific links to the desired environmental impacts being measured.

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[4] IRMA Standard V1.0 (2018) criteria 4.2.1. and 4.2.2., respectively.

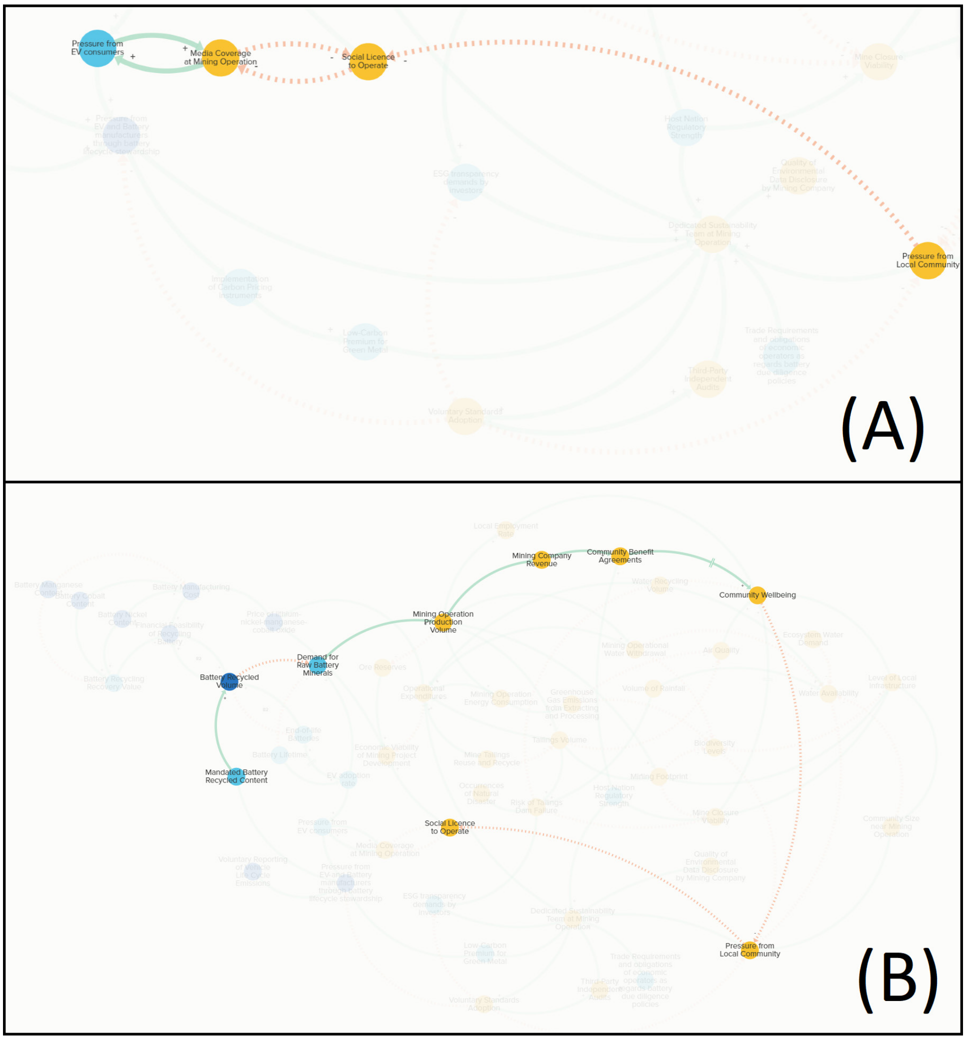
4.3.3.3 Subsystem 3: Social Licence to Operate & Mining

This subsystem captures the interrelationships between variables associated with a social licence to operate (SLO) affecting a mining operation. There is no universally accepted definition of SLO, and it is often related to terms such as corporate social responsibility, community acceptance, and reputation (Raufflet et al., 2013). An SLO encompasses environmental performance, ethical business practices, and community relationships (Jenkins, 2004). While an SLO is linked to the industry's efforts to promote and maintain development viability, it has also been used to reduce opposition rather than promote long-term development (Owen & Kemp, 2013). Based on the final CLD built from our workshops, the SLO here is a function of pressure from the local community, which is influenced by community well-being, impacts to nature, and the community size near the operation, with the size of the community near the operation being a crucial observation made by the participants. In this matter, previous studies have associated a larger community with more extensive engagement efforts (Measham & Zhang, 2019) and larger communities having more diverse and numerous concerns (Caxaj et al., 2014).

The final CLD also shows a connection between the SLO and the *viability of mining project development*, aligning with Thomson and Boutilier (Thomson & Boutilier, 2011), who describe the level of SLO as inversely proportional to the level of sociopolitical risk a company faces. This is also in line with works by Franks et al. (Franks et al., 2014b), who mapped the extent of how company–community conflict can be financially detrimental. Some authors claim that the SLO is never fully gained and represents an ongoing process, specific to the moment of the life cycle of the project in question (Kurlander, 2001). Transitioning from the CLD to a dynamic model could help quantitatively identify critical thresholds.

Moreover, the CLD shows an inverse relationship (-) between SLO and media coverage, indicating that a loss of SLO might lead to increased media attention. Here, the participants were referring to *press articles* and *media attention,* as traditional media (journals, etc.). To strengthen the quantitative inquiry, we suggest incorporating another variable as *social media sentiment,* since extensive work has been done in quantitatively linking the monitoring of social media opinion by the local community and a company's SLO over time (Xu et al., 2020). Additionally, the role of trust, contact quality, and procedural fairness, though not directly raised by workshop participants, could be unpacked under the *community well-being* variable (Moffat & Zhang, 2014). Participants described various social and environmental aspects that influence community well-being, including local employment rates and infrastructure on the social side, as well as air quality, water quality, ecosystem services, and the risk of tailings dam failures on the environmental side. While elements of environmental pollution were vaguely encompassed within the air quality and water quality variables, it is important to acknowledge that mining sites often rank among the most polluted sites worldwide. Issues such as heavy metal pollution, human health impacts, dust emissions, large-scale land pollution and degradation, acid mine drainage, and pollutant migration through water systems significantly affect local communities both directly and indirectly. Although these specific environmental pollution factors were not explicitly mentioned by our workshop participants, they are critical components of community well-being and should be disaggregated in future quantitative inquiries.

Figure 22. Selected segments of the final CLD with a focus on: (A) The reinforcing and balancing feedback loops that characterize the 'limits to success' archetype within the system, and (B)The pathway from mandated battery recycled content and a social licence to operate.



We can observe that *media coverage* is part of a reinforcing loop with *pressure from EV consumers*, as showcased in the **Figure 22 (top panel),** whilst being balanced by *Social Licence to Operate* (SLO), having *Pressure from local community* as a limiting condition to SLO (the more pressure form a local community, the less SLO that operation will have). This is an example of the "Limits to Growth" archetype, where a condition of interest – in this case, *media coverage* – initially increases but reaches a plateau due to limiting factors, inhibiting further growth (Braun, 2002). This archetype was introduced by Meadows et al. in 1972, stating that a process of accelerating growth will encounter a balancing process as the limit of that system is reached (Meadows et al., 2017). In our case, *media coverage* can rise in response to EV consumer pressure but is capped once an operation's SLO decreases, either because the mine ultimately ceases operations (eliminating further coverage) or the operation improves enough that major community concerns are no longer voiced. This archetype describes the phenomenon that *media coverage* won't keep growing indefinitely, displaying the social dynamics between community pressure and industry accountability.

Community well-being, within our CLD, is a critical driver of local community pressure on mining operations, which can lead to a loss of an SLO. This variable has been aligned with the Responsible Mining Index (RMI) to assess the extent to which companies are taking measures to respect mining-affected communities (Responsible Mining Index, 2022). Key factors in our CLD directly influencing *community well-being* include community benefit agreements (CBAs), local employment rates, infrastructure levels, mine closure viability, and the risk of tailings dam failure. Notably, *greenhouse gas emissions* negatively impact the local *biodiversity & ecosystem services,* while tailings can represent a meaningful *air quality* risk in some cases through the generation of fine dust from uncapped disposal sites. These fine dust particles can disperse over adjacent communities, indirectly affecting *community well-being*. Moreover, *biodiversity & ecosystem services* and *water availability* are inversely related to local community pressure. Additionally, it's important to discuss the relationship between greenhouse gas emissions, mining operation withdrawal, and mining footprint with *ecosystem services*. As these variables increase, the outputs of ecosystem processes that provide benefits to humans, like agriculture (ecosystem services as defined by Oliver et al. (2015)), decrease. These factors are inherently localized, both spatially and temporally, a clear example being the potential for lack of access to freshwater and agriculture by local communities bordering lithium brine operations (Roche et al., 2024). Moreover, it is important to note that under the RMI analysis, community well-being is the thematic area with the weakest performance overall, with most companies failing to systematically address socio-economic impacts, both positive and negative (Responsible Mining Index, 2022). Expanding the analysis to incorporate exogenous variables reveals that external factors can significantly influence the system.

Notably, stakeholders noted that a push toward higher recycling rates could inadvertently reduce demand for primary minerals, which is typically a positive outcome from an environmental standpoint. However, that also surfaced a potential unintended consequence through a connection between *mandated battery recycling content* and CBAs, as shown in black in **Figure 22 (bottom panel)**, since CBAs are often based on a percentage of either the value of production or a percentage of the profit of an operation (Gunton et al., 2021). This observation provides two lines of thought. First, it underscores the need to reevaluate how CBAs are paid to the local community, so they are not left disadvantaged by a shift towards a recycling-oriented sourcing economy. Secondly, increasing the mandated recycling content to a level where CBAs become insufficient can potentially lead to a loss of SLO, potentially causing mine closures or operational volatility, in turn, impacting the global market for battery minerals. Similarly, the way in which CBAs are financed and administered could help mitigate this outcome. The extent to which such changes would affect the global market can be the focus of future quantitative system models.

4.4 Conclusion and Future Directions

This study provides an initial exploration of the intricate dynamics of adopting voluntary sustainability initiatives within the context of battery minerals mining. Through a participatory model-building approach involving a small, but diverse, group of stakeholders, we mapped interconnected variables shaping VSI adoption. While the limited sample size reflects only a segment of shared mental models, the resulting causal loop diagram highlights the value of these methods. One of the main advantages of this approach is expanding individual mental models across the triangulation of knowledge. The insights that can be derived from the CLD can offer significant implications for stakeholders across the battery supply chain. This has been done through free access to the Kumu system model and can also be found in the supplementary material. Lastly, an adjacency matrix has also been provided in the supplementary material, with further references to the variables used in the CLD. We expect that the availability of a digital visualisation can support further discussion on more targeted interventions that encourage the adoption of VSIs, if such are deemed net positive. Below, we present our suggestions for future studies and the key findings and implications of the current analysis:

4.4.1 Next Steps and Future Studies

Building on the findings of this study, there's a pressing need to understand how such type of information should be translated into recommendations, and into the usefulness of such knowledge for improving the overall sustainability of the battery material sector. For instance, system modellers wanting to understand scenarios for the future require an improved understanding of how decisions affecting social license influence the potential industry expansion or environmental mitigation across the broader battery material sector. Extending our qualitative analysis into a quantified systems dynamics model would provide one pathway for modelling these interactions.

While the qualitative model provides valuable insights, it is insufficient to fully capture the dynamic behaviour of the system, as it primarily reflects the collective knowledge of stakeholders. Future work should focus on developing a quantitative system dynamics (SD) model, such as *stock-and-flow*, based on the causal loop diagram (CLD) created in this study. The analysis of loops and archetypes presented under the results section is, by no means, exhaustive, and to build upon the findings of this study, we suggest that future research should consider employing advanced analytical methods to gain deeper insights into the system dynamics. The field of structural analysis methods (SAM) of system dynamics models is rapidly evolving (Schoenenberger et al., 2021) and is becoming complementary to previously well-established tools in system dynamics.

Previous studies have developed system models that analyse the relationships between environmental impacts, their mitigation, and community trust and public opinion (Brunilde Verrier et al., 2019). These models align closely with our Causal Loop Diagram (CLD), where pressure from the local community plays a pivotal role in shaping the overall system dynamics. Moffat and Zhang (Moffat & Zhang, 2014) explored pathways to achieving a social licence to operate (SLO), emphasizing the importance of social infrastructure and community engagement. Their findings resonate with our CLD, particularly the connection between community well-being and SLO. They suggest that companies are rewarded for establishing and maintaining high-quality communication with community stakeholders, which enhances trust and supports sustainable operations. However, in our workshops, participants did not distinguish between the quantity and quality of communication, resulting in this variable not being prominently featured in our final CLD. This omission may indicate a potential oversight by the participants, especially given the extensive emphasis on company-community relationship frameworks in the literature (Mendonca Severiano et al., 2024). Our findings suggest that while community pressure is acknowledged, the specific mechanisms through which companies build and sustain trust may require further exploration to fully capture their impact on VSI adoption.

A limitation of this study is that we couldn't access representatives from manganese extractive projects, introducing a level of moderate uncertainty into our causal loop diagram. Consequently, the confidence in manganese-related feedback loops is lower and should be covered in future studies. Moreover, recruiting a diverse set of stakeholders working closely with lithium, nickel, and cobalt projects proved challenging, limiting our cohort of workshop participants to 15 across 12 sessions. Nonetheless, these representatives offered a valuable cross-section of perspectives spanning mining operations, NGOs, industry associations, and academic researchers. Also, transitioning from a qualitative reflection synthesised from a group-model building exercise such as this to a quantitative inquiry, as described by Zagonel (2002), should become commodity-specific and regionalised in order to achieve the necessary level of precision. Because a CLD is inherently a conceptual representation of stakeholders' collective perceptions, some factors may remain outside the current scope, and we envision future quantitative modelling, at which stage calibrations and sensitivity analyses can further refine and validate the diagram.

4.4.2 Key Takeaways and Implications

By translating stakeholder perceptions into standardized variables and identifying the interactions within subsystems, our research lays the groundwork for future modelling efforts and highlights critical areas for further investigation. Key findings include translating the perceived key variables by the stakeholders involved into variables that align with standard definitions, and, potentially, openly available datasets. Moreover, the identification of the subsystems' interactions is crucial for future modelling efforts. From our initial qualitative reflection, we can see that stakeholders from mining operations, NGOs, life-cycle analysts, mineral processing, and recycling were aligned with the potential for environmental impact mitigation, albeit each had its own view of how this would affect the whole system. Stakeholders identified connections between these environmental impacts and the pressures faced by local communities. Some stakeholders were aware of policies and frameworks to define such impacts from a financial standpoint, with some of them mentioning that the commodified nature of battery minerals is influential to geographic shifts in production to higher ESG risk regions. Two system archetypes were identified on the basis of the CLD, including "limits to success" and "fixes that fail".

From a policy perspective, our findings illuminate how voluntary sustainability initiatives (VSIs) can complement or fill gaps where formal regulations are insufficient or weakly enforced. Our findings highlight how global recycling mandates (such as the ones proposed by the European Union (European Union (EU), 2023) must be carefully integrated with local socio-economic considerations, suggesting a review of how CBAs are financially managed, and a potential disaggregation from operational production and profit. Policymakers could restructure CBAs to support communities transitioning away from direct mining employment, invest in alternative economic opportunities, and standardize CBAs across operations, ensuring that environmental benefits from a low-carbon economy do not come at the expense of local communities' well-being. Nationally, strengthening oversight and integrating VSIs with existing legal frameworks (e.g., mining codes, environmental regulations) could foster greater accountability.

Stakeholders emphasized that having a *Dedicated Sustainability Team at Mining Operation* is crucial when it comes to overseeing VSI implementation. While sustainability teams, often situated at corporate headquarters, are responsible for broader ESG reporting and initiative management across multiple projects, environmental managers at the mining operation level are typically responsible for environmental impact assessment and mitigation, focusing on project-specific elements. A further analysis of organizational models and effectiveness should be complementary to the understanding we currently have about a company's preconditions for successful implementation of sustainability standards (Ruokonen, 2020), such as the roles of mine management, line managers, and environmental experts, and also the importance of a mature organization with a functional management system. Additionally, the size of a company may influence the role of environmental managers within the organizational structure and affect their involvement in VSI adoption, particularly in how they connect with mining operations on a day-to-day basis.

In conclusion, our results lay the groundwork for future research to expand on this qualitative reflection. We aim to provide a critical foundation for understanding the systemic factors influencing VSI adoption in battery mineral mining. Moving forward with extensive mining operations for battery minerals will require detailed work to properly understand the implications of the increasing demand and how to mitigate spatially specific environmental impacts. Hence, a geographical and commodity-specific analysis is imperative for a transition to a quantitative inquiry.

5 Finding the links: Network diffusion of sustainability initiatives in the global battery minerals sector

The previous chapters explored why such VSIs might be adopted (**Chapter 3**), and how certain stakeholders perceive this decision-making space (**Chapter 4**). Beyond direct extraction challenges, firms must navigate complex, transnational networks of suppliers, industry associations, and regulatory bodies that influence how sustainability-focused innovations and voluntary initiatives spread. While previous studies have examined individual sustainability standards or country-level frameworks, the underlying mechanisms of innovation diffusion within the global mining sector's interconnected networks remain poorly understood. An initial understanding of this topic might come from how VSIs started, and how their adoption has been proposed in the last few decades, namely through industry associations (see **Chapter 1.2**).

This chapter addresses this gap by applying network theory to map and analyse industry associations and their member companies across leading producers of lithium, nickel, and manganese, key minerals in lithium-ion battery cathodes. The research compiles company-affiliation data from national mining associations in top-producing countries, then overlays these networks with international leadership bodies and commodity-specific associations. Further, network-based diffusion algorithms were employed to simulate how sustainability innovations (e.g., eco-innovations, voluntary sustainability standards) could propagate through networks of industries. Because each association listed members differently and was prone to typographical errors, an extensive data harmonisation process was conducted. To ensure accuracy and consistency, the *Levenshtein* distance algorithm was utilised (A Levenshtein & Vladimir Iosifovich, 1966) to effectively identify and reconcile variations in company names. This standardisation step not only enhances the reliability of our results but also provides a valuable methodological reference for future researchers grappling with similar data quality challenges.

Our findings highlight a pronounced transnational character to industry affiliation patterns, identifying both globally connected hubs and relatively isolated clusters. Notably, the integration of influential international bodies, such as the International Council on Mining and Metals (ICMM), accelerates the dissemination of sustainability-related information through these networks. Similarly, commodity-focused groups (e.g., International Lithium Association, International Manganese Institute, Nickel Institute) can serve as conduits bridging national associations and fostering more rapid diffusion of sustainability practices. By providing a structured lens on how innovations travel through multi-layered, geographically dispersed corporate networks, this chapter advances understanding of the conditions under which new ESG-focused approaches might gain traction. Lastly, all datasets built and used to build and analyse the networks have been made publicly available.

A typeset version of this study has been published as: ***Mining industry networks influence the diffusion of innovations in the battery minerals sector,*** *Mendonca Severiano et al, Environ. Res.: Infrastruct. Sustain. (2025) .*

Mining Industry Networks and Diffusion of Innovations in the Battery Minerals Sector

Abstract

The shift toward decarbonisation in the transportation sector, primarily through the adoption of electric vehicles (EVs), has significantly increased the demand for battery minerals such as lithium, nickel, and manganese. This, in turn, leads to the development of new mining operations and the expansion of existing ones. Recognising the reputational risks associated with the mining industry and the supply risks associated with transnational multi-layered supply chains, EV manufacturers are intensifying their focus on sustainability-focused innovations and responsible sourcing. However, the industry dynamics of information flows driving the adoption of these innovations and their impact on the supply chain remain largely unexplored. This study aims to address this gap by analysing the diffusion of innovations within the global mining industry, particularly in the context of selected battery mineral supply chains. Employing network theory, we compiled datasets and constructed comprehensive networks of national and international mining industry associations and their affiliated companies. We focused on the top-producing countries for lithium, nickel, and manganese, utilising network-based diffusion algorithms to model the channels potentially available for the dissemination of innovations. Our findings reveal a pronounced transnational character in these networks, with notable isolations. The inclusion of international leadership organisations in the network analysis highlighted their potential role in facilitating faster information dissemination among transnational companies. These results provide critical insights into the mechanisms of innovation diffusion in mining supply chains and underscore the significance of industry associations in influencing sustainability practices. This study contributes to a deeper understanding of the network dynamics that govern the adoption of sustainability innovations in the mining sector, offering a basis for further research.

Keywords: Battery Minerals, Critical Minerals, Network Theory, Mining, Diffusion of Innovations

5.1 Introduction

The complex environmental challenges faced in the 21st century, including environmental pollution and threats to human health, ecosystem degradation, and limited resource availability, pose a significant threat to human life and prosperity *IPCC, 2022: Summary for Policymakers* (2022). Transport systems are some of the most environmentally impactful human activities, being material-intensive and still reliant on fossil fuels, accounting for roughly one quarter of all Greenhouse Gas (GHG) emissions globally (IEA, 2020a). Although there's been significant discussion of minimising car-dependency, investment in high-quality public transport, and minimising travel overall, the remaining vehicular fleet will require significant electrification. Therefore, massive deployment of all available low-emission enabling technologies, such as Electric Vehicles (EVs), will be required if a net-zero goal is to be achieved in 2050 (*Net Zero by 2050 - A Roadmap for the Global Energy Sector*, 2021).

On a global level, international treaties such as the Kyoto Protocol and UN resolutions, including Agenda 30 that defined the UN Sustainable Development Goals, contributed to the integration of renewable energy generation and clean energy storage across sectors (Tabelin et al., 2021). On a national level, several countries have already planned to phase out or ban sales of petrol- and diesel-powered cars (*Global EV Outlook 2020 - Analysis*, 2020). To achieve the massive shift towards renewable energy generation and clean energy storage within the sector, we will see increased demand for mineral commodities such as lithium, cobalt, nickel, and rare earth elements. Most of these metals have only previously been mined in modest amounts, increasing their forecast demand (E. Dominish et al., 2019). This requires global manufacturers to rely on complex supply chains, with complex embedded potential for environmental and social impacts. For instance, one of the top three EV battery manufacturers, Panasonic, has more than 10,000 suppliers worldwide (Panasonic, 2021).

Hence, there have been significant concerns regarding the supply of battery minerals. For instance, concerns related to lithium have arisen due to the potential for extraction of lithium-rich brines in the Lithium Triangle (Argentina, Bolivia, and Chile) to contaminate water resources, alter regional hydrology, and potentially lead to water shortages and ecosystem impacts (Flexer et al., 2018). Similarly, nickel mining poses substantial environmental challenges, including high greenhouse gas emissions from energy-intensive processing (Mudd, 2010), risks associated with tailings waste management (Earthworks, 2025), and biodiversity loss in sensitive ecosystems (Sonter et al., 2020) Therefore, as downstream companies, such as battery manufacturers and consumer-facing EV manufacturers, become more preoccupied with reputational risks associated with environmental catastrophes and human rights violations, approaches to supplier engagement are becoming more standardised, with mines, smelters, refiners, and battery assemblers being scrutinised. Mining companies are being pushed to improve their raw materials extraction and processing, and are being influenced by institutional investors, regulatory entities, and civil society to engage in detailed reporting (Franken & Schütte, 2022b).

The concerns on sustainability impacts associated with mining have given rise to industry sector-specific voluntary initiatives (Potts et al., 2018), as a means of industry self-regulation, with more than 50 voluntary initiatives applicable to the mineral sector (Kickler & Franken, 2017). These initiatives vary widely in their adoption methods, with one notable approach being the engagement with national industry platforms, exemplified by the Towards Sustainable Mining (TSM) initiative, now implemented in 13 countries. The TSM approach involves a national industry platform to disseminate the standards across the companies operating in that country (not limited to mining but involved in the sector). This approach aims to enhance operational quality and public acceptance of mining activities (Franken & Schütte, 2022a).

Recent studies have underscored the importance of a network-centric approach to better understand and manage these supply risks (van den Brink et al., 2020; Yue et al., 2024). This shift in perspective necessitates more nuanced and comprehensive analyses of supply chain networks. In this study, we compiled detailed datasets of mining sector industry associations and their constituent member companies. Using this, we constructed a network representation of the sector and applied various network-based analyses to understand the potential relative rate of information or voluntary sustainability initiative, based upon different assumed network topologies and first-mover/seed nodes. This allows us to assess the potential influence that transnational networks have, through information flows, into being vectors of influence to the adoption of sustainability innovations at a mine-site level. In this study, we define innovation as operational, technological, or organizational changes that improve sustainability outcomes at mine sites. Specifically, we focus on eco-innovation practices that reduce environmental impacts, such as emissions, water use, and land disturbance (Rennings, 2000). Examples include the adoption of renewable energy systems, enhanced water recycling, or adherence to voluntary sustainability initiatives and certification schemes (Franken & Schütte, 2022a). We focus exclusively on eco-innovations for two reasons. First, environmental practices are typically codified in industry guidelines and voluntary standards (e.g., TSM's Tailings Management Protocol (Towards Sustainable Mining, 2022), ICMM's Water Reporting Guidelines (ICMM, 2021), and IRMA's Standard for Responsible Mining: Greenhouse Gas Emissions (IRMA, 2018c)), which we assume can be diffused through transnational industry networks. Second, environmental performance can be quantified more precisely, and its improvement can often be modelled from well-specified technical or process changes (e.g., energy intensity, water-use factors). Social-impact innovations (e.g., labour-rights agreements), by contrast, evolve over longer timescales and are prone to systemic, sometimes unintended, consequences that introduce substantial heterogeneity that wouldn't be covered by our methodological approach. Capturing those dynamics would require a different modelling framework and data set beyond the scope of our network-centric analysis.

5.2 Extended theory and research context

5.2.1 Network Dynamics and Sustainability Reporting in Global Mining Supply Chains

Global large-scale mining supply chains can be described as complex systems comprised of integrated facilities employing varied production techniques and being geographically distributed, dealing with a range of stakeholders such as governments, local communities, and downstream manufacturers, while managing environmental and social footprints (Pimentel et al., 2016). These operations are geographically dispersed, working in coordination, linked together by materials, information, and financial flows, which can traverse the supply chain in both forward and backward directions (Pimentel et al., 2010). With decentralised global steps within supply chains being supervised by a range of distinct stakeholders with unique managerial philosophies (Sarimveis et al., 2008), decision-making within supply chains can be far from optimal. Pimentel et al. (Pimentel et al., 2016) studied approaches for analysing mining *supply chains* overall sustainability citing that *“one of the most challenging changes in the way companies work with sustainable development is the shift of focus from their particular operations towards the improvement of the performance of their entire supply chains”,* also mentioning that the integration of impact assessment methods, multi-criteria decision analysis and mathematical optimisation can be supportive of sustainable whole life-cycle design of mining networks (Pimentel et al., 2016).

Mining companies are increasingly faced with the challenge of meeting stringent requirements from downstream stakeholders in a highly price-sensitive market, while upholding their social license to operate. In response, these companies are turning to innovations that align with these objectives (Franken et al., 2020). Eco-innovations play a pivotal role in this context, focusing on reducing the environmental footprint while maintaining economic competitiveness. Within the extractive industries, eco-innovations are defined as innovations that reduce the environmental impact or the use of resources (Rennings, 2000), through the implementation of a novel process or technology, being *“less environmentally harmful than the use of relevant alternatives”* (Kemp & Pearson, 2007). Examples in the mining industry include offsetting fossil fuels with solar energy (International Institute for Sustainable Development, 2018), fleet electrification, water recycling, and freshwater use reduction (The Intergovernmental Forum on Mining, 2018), tailings co-disposal and recycling (Edraki et al., 2014), and many more. While these have a positive impact in mitigating environmental impacts, it’s important to note that they might also reduce costs to operate, reduce risks, and increase safety (Monitor Deloitte, 2016). Such innovations are often aligned with standardised operational and reporting frameworks, enabling relatively easier cross-border transfer across mining companies operating internationally, and will be the focus of this work. In contrast, social innovations, such as Indigenous rights engagement, labour rights improvements, and community participation models, are highly context-specific, depending on localised regulatory frameworks, societal norms, and political negotiations.

The adoption of such eco-innovations by a mining company can take place through the involvement of several partners and is influenced by characteristics of the networks in which these partners operate (Green et al., 1994). Network relations are related to the formal reporting structure and formal and informal relationships among internal groups within a firm and between a firm and its industrial environment (Triguero et al., 2016), with external cooperation being an important driver of eco-innovations (De Marchi, 2012). Nuss et al. (2016) made a noteworthy contribution in bringing network theory to the analysis of mineral supply chains (Nuss et al., 2016). In their work, they've explored the assessment of supply chain risks using network analysis of product platforms, tracking the flow of materials from mineral extraction to end-use in final products (solar cells, turbine blades, batteries, and magnets). This study introduced network indicators and analysed mineral supply-chain risk with a network theory overlay, providing significant insights that have been considered in future studies covering other commodities. Additionally, van den Brink et al. (2020) have done work in incorporating network theory into the analysis of Cobalt supply chain disruption risk, providing significant insights on the network characteristics of a particular commodity supply network (van den Brink et al., 2020). Nonetheless, this work still describes a notable gap in assessing the linkages between companies from a network standpoint.

5.2.2 Diffusion of Innovations and Networks

The notion of *'diffusion of innovation'*, initially introduced in 1962 by Everett Rogers, has significantly influenced our understanding of the interactions between entities leading the adoption of innovations (Rogers, 1995). Moreover, a range of studies have been conducted around the innovation dynamics of networks, including eco-innovation through inter-firm networks (Ramkumar et al., 2022), the influence of trust and distrust in the system (Fujii, 2022), and many more. The adoption of eco-innovations holds uncertain value (Assenova, 2018) and can be considered to be more complex than conventional market-driven innovation (Goodman et al., 2017), requiring the overcoming of intra- and inter-organisational management challenges (Carrillo-Hermosilla et al., 2010). The role of networks and relationships in driving eco-innovation has been successfully demonstrated (Pellegrini et al., 2019), as well as the concept that opinion leaders who have a higher influence on other agents and have strong weighted links to other agents are found to spread information faster and increase the rates of adoption over the network (van Eck et al., 2011). Moreover, more radical eco-innovations require greater internal and external firm resources, leading to higher thresholds for adoption and diffusion due to the lower incentives and pressures for their adoption (Hasler et al., 2016).

Considering that learning involves exchanging information between actors and revising such opinions based on the opinions and behaviour of others (Chandrasekhar et al., 2016), the influence of inter- and intra-firm relationships, either through a centralised association or not, shouldn't be overlooked. Especially since the formation of collective opinions can be analysed under the lens of diffusion of innovation within a network structure (Assenova, 2018). Networks might shape how companies involved within this supply chain communicate, and how they form their opinions related to best practices, environmental and social reporting, and adoption of complex eco-innovations such as certifications, standards, and initiatives. The role of cross-industry collaborations as a way to address due diligence in complex supply chains has been explored, and the role that Industry associations have in responding to their members‘ needs to support shared learning has been analysed (OECD, 2012). Moreover, it’s been argued that mining industry associations are influential in developing standards and codes that shape the institutionalisation of corporate social responsibility (CSR) practices (Lindsay, 2011).

Networks are naturally empirical, data-driven, and interdisciplinary with a high potential for economic, managerial, and societal impact. In the efforts to describe and detail the behaviour of a complex system containing hundreds, thousands, and maybe even millions of interacting components, this study aims to increase the body of work that looks at battery minerals supply chains from that standpoint. The identification and mapping of such networks is a necessary step towards the understanding of how eco-innovations might be disseminated.

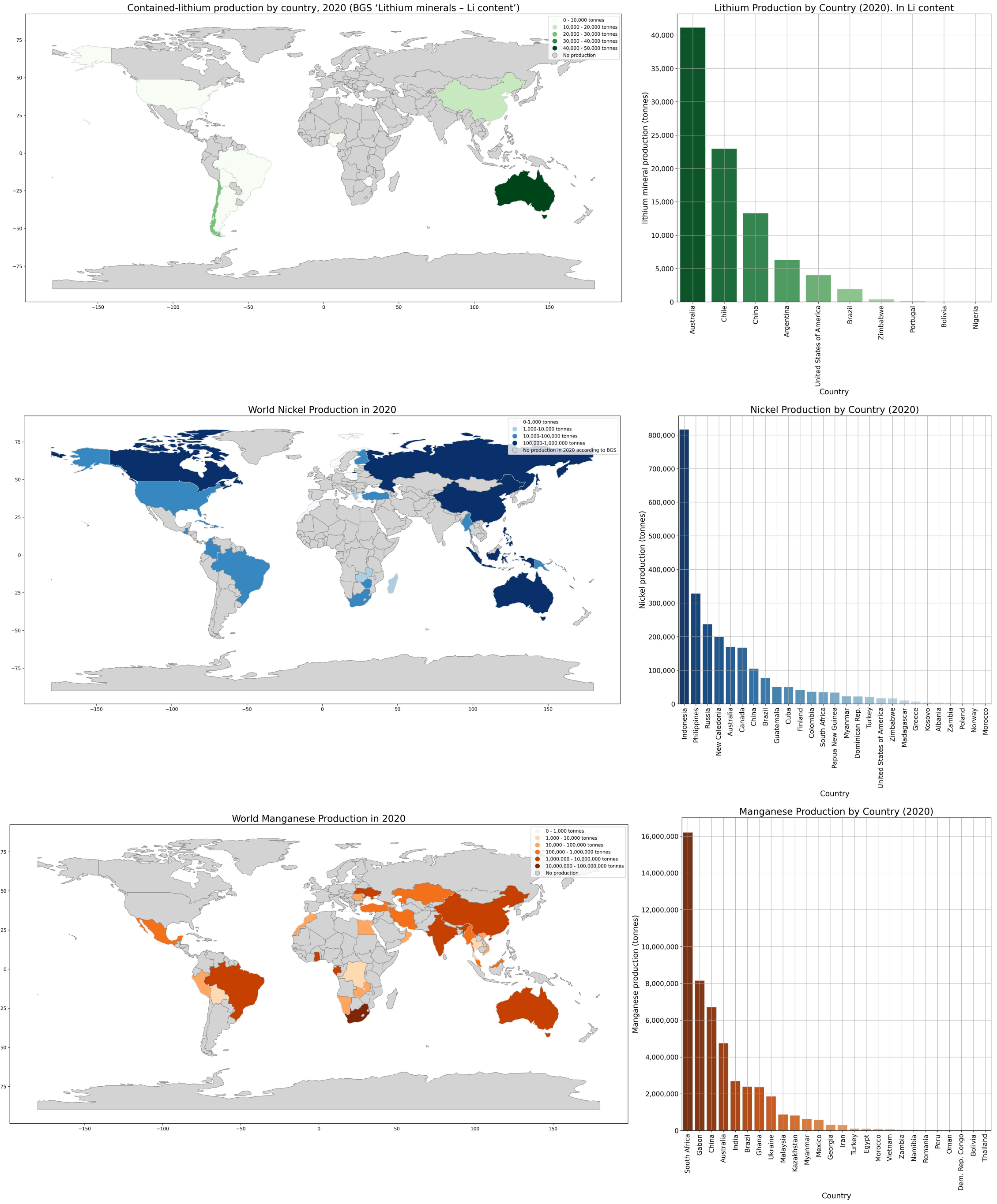
5.3 Research objectives and methods

The main objective of this research is to conduct a network-based analysis aimed at clarifying the potential relative rate of information dissemination across several industry collaboration network topologies. With this analysis, we expect to better understand the potential for eco-innovations within the battery minerals sector.

5.3.1 Selection of Primary Commodities and Industry Associations

Three primary commodities have been selected for this study due to their significance in the manufacturing process of lithium-ion battery cathodes: Lithium, nickel, and manganese. Our preliminary analysis utilised the 2020 data from the British Geological Survey’s (BGS) World Mineral Statistics database (British Geological Survey, 2023) to identify the leading producing countries for these commodities. This dataset has been cross-referenced against the nickel, lithium, and manganese *Mineral Commodity Summaries* from the United States Geological Survey (USGS, 2020a, 2020b, 2020c). This assessment yielded a list of 14 top-producing countries, which are detailed in **Table 20**. The primary producers for each of these three commodities are depicted in **Figure 23**. For lithium, we used the BGS “Lithium minerals (Li content)” parameter, which reports lithium production in terms of contained elemental lithium (t Li), allowing comparability across different mineral sources and processing routes. Where applicable, values from carbonate production were added to account for brine-based production, notably in Argentina and Chile.

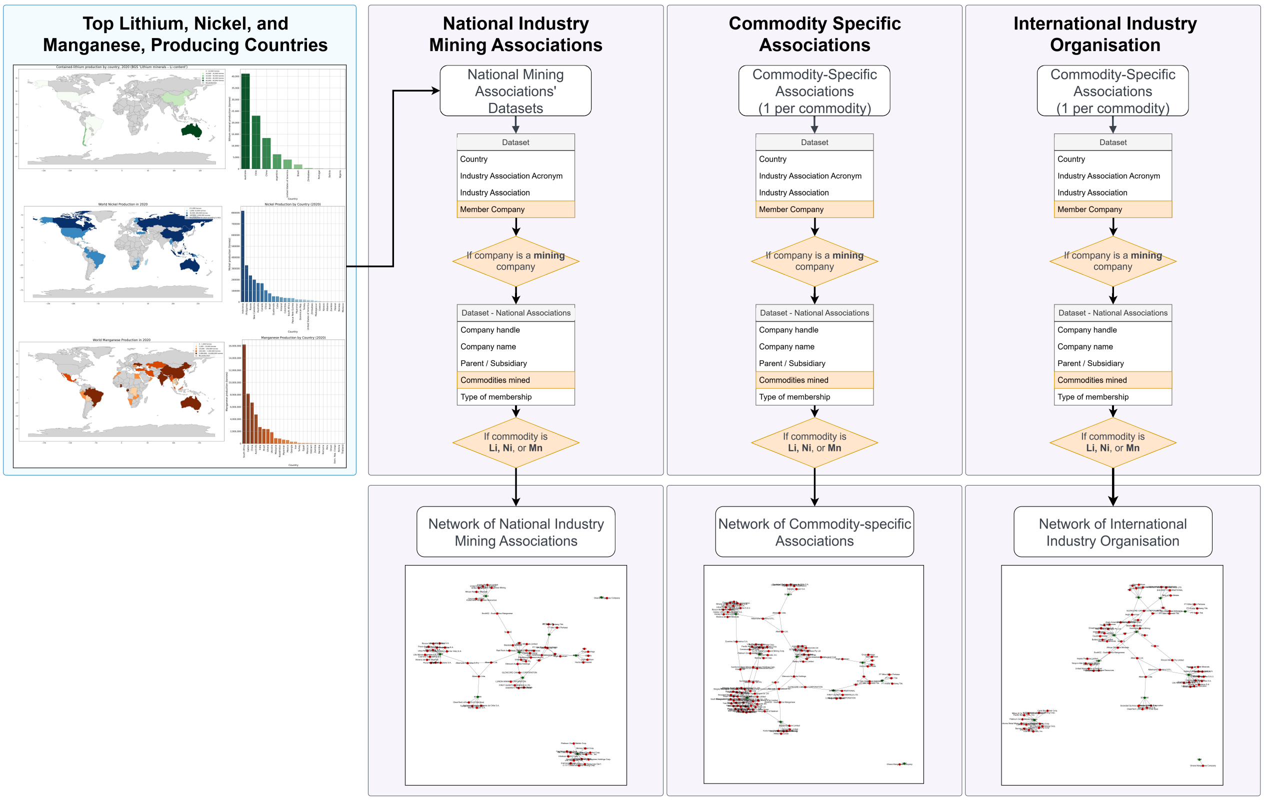
Figure 23. Identification of the top-producing countries of lithium, nickel, and manganese. From 2020, data from the British Geological Survey's Mineral Commodity Summaries



For each of these top producers, we identified their respective national-level mining industry association, with one association being selected per country, with these being detailed in **Table 20**. A criterion for the inclusion of an industry association was the availability of a public list of member companies. Public information was notably absent for China, Russia, Gabon, India, and New Caledonia. Two national-level industry associations were considered for China. The *Global Mining Association of China* (GMAC) website was accessed, but no membership data was found. Similarly, the *China Chamber of Commerce of Metals, Minerals and Chemicals Importers and Exporters* (CCCMC) website had no public information on associated members. Importantly, Russia and China were significant producers of nickel in 2020, accounting for approximately 9.6% and 4.3% of global production, respectively. No significant mining industry association could be found for Russia and Gabon. For India, the Federation of Indian Mineral Industries has been considered, but no public data was available related to its members. As for New Caledonia, as an ultramarine territory of France, a national-level industry association representative of France was considered, but no public information was found on that matter.

In the case of the nine qualifying countries, we compiled an extensive list of operational members of their respective industry associations. These companies were systematically categorised based on their association membership, with a detailed collection of attributes for each. These attributes included the type of membership held, the specific industry sector of operation, and the commodities mined (when relevant), as described in **Figure 24**.

Figure 24. Graphical representation of the data collection process and the dataset creation of national and regional industry associations and company membership



In addition to the national industry bodies, we considered one international leadership association and three commodity-specific associations to assess their role in shaping the global network and its potential influence on adoption practices. These include the International Council on Mining and Metals (ICMM), the International Lithium Association (ILiA), the International Manganese Institute (IMnI), and the Nickel Institute. Membership in these associations is contingent upon a formal admission process and adherence to various performance commitments.

Table 20. National mining industry associations in the leading nickel, lithium, and manganese producing countries. This table also includes international leadership associations and commodity-specific associations.

Country	National Level Mining Industry Association	Acronym	# of members
Australia	Minerals Council of Australia	MCA	124
Argentina	Cámara Argentina de Empresarios Mineros	CAEM	151
Brazil	Instituto Brasileiro de Mineração	IBRAM	161
Canada	Mining Association of Canada	MAC	100
Chile	Sociedad Nacional de Minería de Chile	SONAMI	115[5]
Ghana	Ghana Chamber of Mines	GCM	95
Indonesia	Indonesia Mining Association	IMA	90
Philippines	Chamber of Mines of the Philippines	COMP	72
South Africa	Minerals Council South Africa	MCSA	77
International	International Council on Mining and Metals	ICMM	65
International	International Lithium Association	ILiA	68
International	International Manganese Institute	IMnI	123
International	Nickel Institute	NI	17

5.3.2 Standardisation of Company Names

In our methodology, we collected descriptive information for each company within the associations. This data comprised company names, locations of mining operations, and the commodities mined. These names were sourced from public documents, stock exchanges, press releases, and mining databases, noting that the format of these names was not standardized across sources. To standardise the company names, a four-step process was conducted. Step 1 included the removal of common corporate suffixes (e.g., S.A., PLC, Ltd., AG) from the names. A comprehensive list of the removed suffixes is available in the supporting information. Subsequently, we manually corrected typographical errors and filled in missing values in the company names. We then applied the *Levenshtein distance* algorithm to assess the similarity between names. This measure identifies the minimum number of edits needed to transform one string into another, providing a quantitative basis for comparing string sequences. At last, another round of manual corrections was performed to ensure accuracy.

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[5] For SONAMI, individuals haven't been included (Personas Naturales and Honorarios)

The *Levenshtein distance* is a method for measuring the difference between two sequences of strings (names, sentences, etc.) defined as the minimum number of edit operations to transform one string into another (A Levenshtein & Vladimir Iosifovich, 1966). This algorithm is widely used in information theory to quantify the difference between two sequences, and therefore can be used to identify similarities between strings that should be the same but might be typed differently (Peter Christen, 2006). The distance (number of edits) between two strings S_1 and S_2 can be calculated and converted into a similarity measure (between 0.0 and 1.0) by using the formula:

$$sim_{ld}(s_1, s_2) = 1.0 - \frac{dist_{ld}(s_1, s_2)}{\max\,(|s_1|, |s_2|}$$

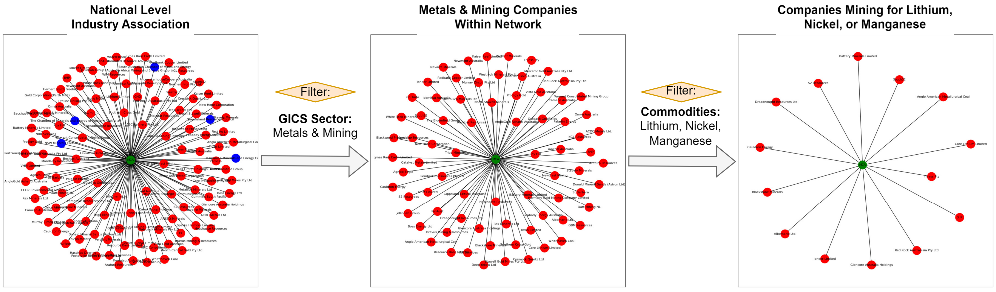
Each string from an association was compared against every string from every other association. This exhaustive comparison generated a unique dataset for each association, ensuring accurate matching. This process proved effective in identifying similarities such as JFE Mineral and JFE Mineral & Alloy (this pair yielded a 91.5% match). Moreover, it was supportive of findings typos on the original datasets extracted from public information, with an example being the 97.5% match between Sumitomo (correct spelling) and *Sumimoto* (wrong spelling).

5.3.3 Network Setup

We employed network theory to model the relationships between firms and industry associations within the mining sector. Our model consists of nodes and edges, where nodes represent entities such as organisations, individuals, or other units, and edges symbolise the connections between these nodes. This approach enables us to employ established network theory methodologies to examine the structural characteristics (Wiedmer & Griffis, 2021) and interfirm collaboration dynamics (Basole, 2016) within these networks. It is important to note that the network constructed is cross-sectional, based on publicly available association membership at a given point in time. Therefore, temporal dynamics such as changes in membership, firm exits or entries, and evolving relationships were not captured.

In our network-based framework, each national industry association is depicted as a core node with affiliated companies connected via edges, as visualized in **Figure 25**. We further categorised each company according to its corresponding Global Industry Classification Standard (GICS) code. This categorization facilitated an in-depth analysis of the entire network, with a specific focus on those entities within the *Metals & Mining* sector (GICS code 151040). For companies within the *Metals & Mining* sector, we added an additional attribute to their node representation, indicating the specific mineral commodities they have active mining operations or prospective projects. We further conducted extensive searches for each company in public databases to standardise their names and identify their parent companies. Companies sharing the same parent company were directly connected in our model.

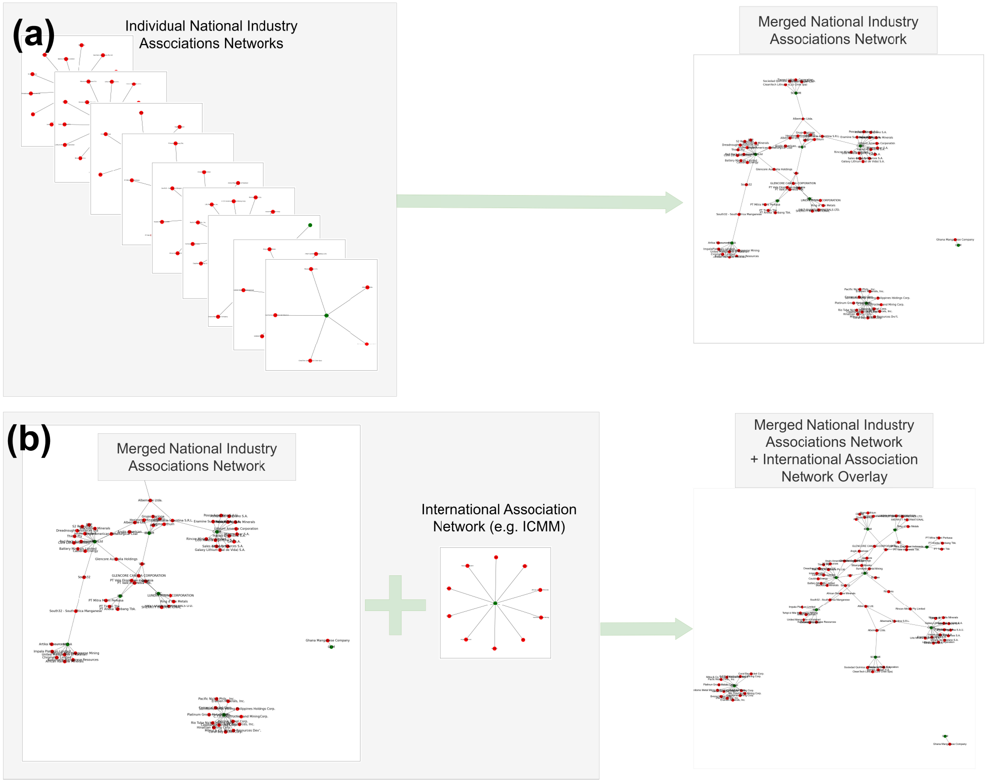
Figure 25. Initial network setup with industry associations at the centre and members connected to its central node. In red are overall members. In blue are other industry associations connected to the main industry association.



5.3.4 Network Innovation of Diffusion

After applying appropriate filters for industry sector and selected battery commodities, we conducted the diffusion analysis over the networks. Initially, all the national-level industry associations have been consolidated as one global network, as showcased in **Figure 26 panel (a)**. This global network represents the collective influence of industry associations on the innovation adoption process in battery minerals mining companies. We utilised this unified network as the basis for our initial diffusion analysis. Following this analysis, we overlaid the networks built using the data from ICMM, ILiA, IMnI, and Nickel Institute onto our global network, as showcased by **Figure 26 panel (b),** which depicts the overlay of ICMM over the national associations network. This additional step allowed us to assess how the inclusion of an influential international body modifies the potential diffusion dynamics.

Figure 26. Construction of networks using the national-level industry associations and ICMM. This construction has been done post-filtering the companies for their industry sector (Metals & Mining) and commodity specific (lithium, nickel, and manganese). The same process utilised to generate panel (b) has been applied to ILiA, IMnI, and Nickel Institute.



Post-constructing the networks, we employed a two-tiered diffusion model to analyse the spread of innovations across the global network. This model was built upon two core algorithms:

(i) **Diffusion Algorithm**: This algorithm initiates with each node in the network designated as *susceptible*. A selected *seed node*, representing an international industry association, is set to *'adopted'* status, signifying it is the initiator of the innovation. The diffusion process then unfolds iteratively, with each adopted node attempting to influence its susceptible neighbours based on a predetermined probability (*p-value*). Upon exerting its influence, the node transitions to an *immune* status, indicating its active phase in the diffusion process is complete. It neither adopts the innovation nor tries to influence adoption. The algorithm's output is the final count of nodes that have transitioned to the *immune* status, reflecting the total adoption spread. This can be observed in the following equation (1):

$$Output = \sum_{\{i=1\}}^{\{N\}} 1_{\{status(i)='immune'\}} \qquad (1)$$

Where:

N is the total number of nodes in the network.

$1_{\{.\}}$ is the indicator function, which is 1 if the condition inside the braces is true, and 0 otherwise.

$status(i)$ represents the status of node i after the execution of the diffusion process.

(i) **Network Diffusion Simulation**: Building upon the first algorithm, this simulation varies the *p-value* from 0.1 to 1.0, conducting 1000 iterations for each value. For each iteration and *p-value*, the total number of adopted nodes is tallied. The process is repeated for each industry association as the *seed node*, allowing us to assess how different starting points impact the diffusion's effectiveness. The results are then averaged for each *p-value*, creating a results dataset that compares the diffusion's efficiency across various industry organisations as the *seed node*. This process is detailed in the following equation (2).

$$R(p) = \frac{1}{1000 \times n} \sum_{\{i=1\}}^{1000} \sum_{\{j=1\}}^{n} A(p, j, i) \qquad (2)$$

Where:

p varies from 0.1 to 1.0.

n = 10, being the number of industry associations analysed

$A(p, j, i)$ is the number of adopted nodes for the i-th iteration, with the industry association j as the seed node, and at the p-value p.

By employing this approach, our study systematically explores how variations in starting conditions and probability thresholds affect the diffusion of innovations within the network. The integration of these algorithms, executed via the NetworkX (Hagberg et al., 2008) and Pandas (The Pandas Development Team, 2023) Python libraries, provided a robust framework for our analysis, enabling a detailed exploration of network dynamics and the influence of industry associations on the propagation of innovations.

It is imperative to note that this process assumes a *heterogeneous population*, which is not representative of our sample, but is effective in drawing a baseline. Recognising the absence of firm-level attributes such as company size, ownership structure, and innovation readiness, we adopted a probabilistic simulation strategy by systematically varying the probability of adoption (p-value) from 0.0 to 1.0 in steps of 0.1, with 1,000 iterations conducted at each value. Rather than aiming to predict absolute adoption rates, this approach enables the exploration of a range of diffusion behaviours under varying adoption scenarios. This approach allows us to compare the relative diffusion efficiencies between different network configurations, despite not explicitly modelling firm-level heterogeneity.

5.4 Results

5.4.1 National Level Industry Associations

The network built using the nodes and edges extracted from the national industry associations can be seen in **Figure 27**, with an overlay of the geographical position of the nodes in **Figure 28**. Similar figures for all the other networks can be found in the *supporting information.* The transnational nature of the network seems evident, with notable isolations happening in the Ghana Chamber of Mines and the Chamber of Mines of the Philippines.

Figure 27. Global network of industry associations involved with Metals & Mining companies mining for lithium, nickel, and manganese. Not inclusive of ICMM. Top-producing countries such as China, Gabon, New Caledonia, Russia, and India haven’t been covered due to a lack of publicly available data on industry association members.

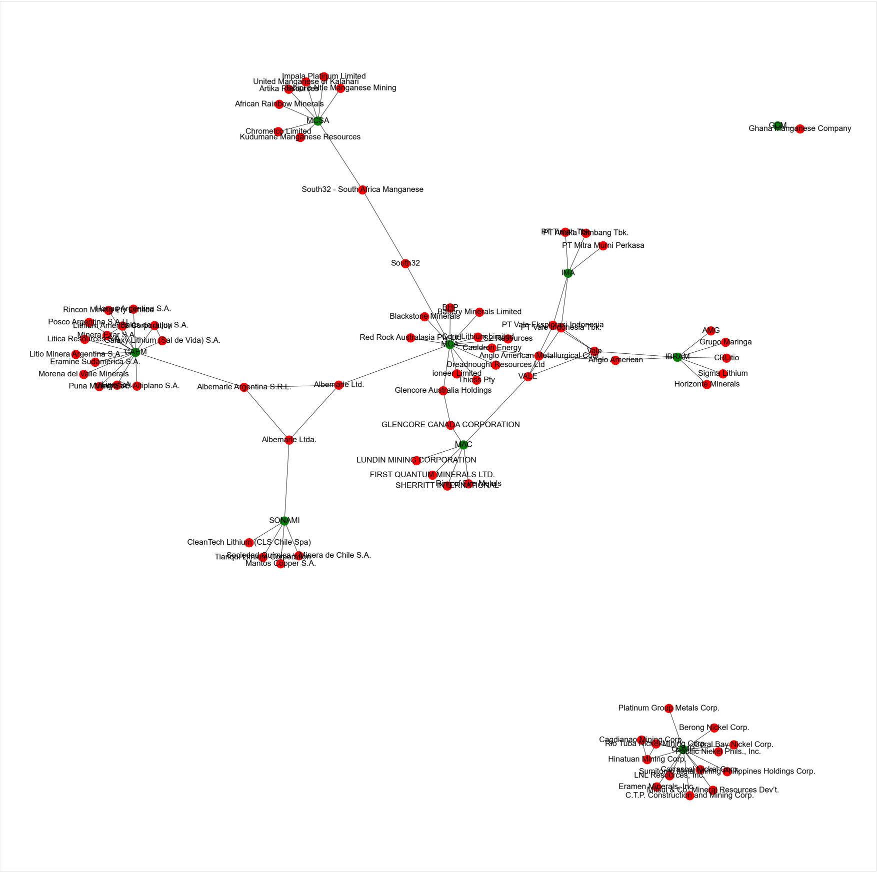
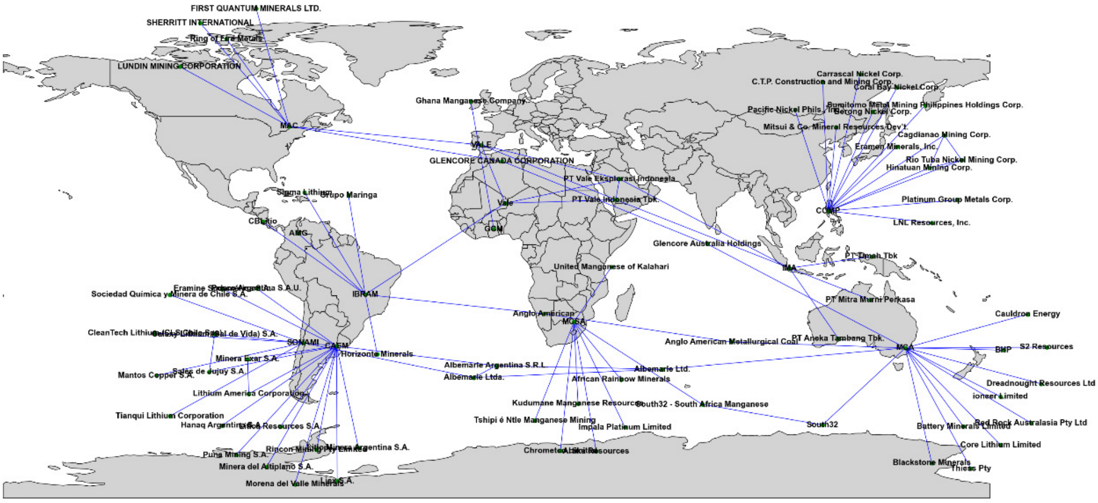


Figure 28. Global network of industry associations involved with Metals & Mining companies mining for lithium, nickel, and manganese, overlayed with a global map. Not inclusive of ICMM. Top-producing countries such as China, Gabon, New Caledonia, Russia, and India haven't been covered due to a lack of publicly available data on industry association members.



Our diffusion routine allowed an innovation to travel along the following pathways:

1. **Intra-association pathway** – once a seed node (industry association) adopts, the innovation reaches every other member of that same association through their shared hub connection.

2. **Cross-association bridging pathway** – Some companies in our dataset hold memberships in two or more associations. when any one of these firms adopts, it immediately exposes the secondary association's entire membership to the innovation, greatly shortening path length.

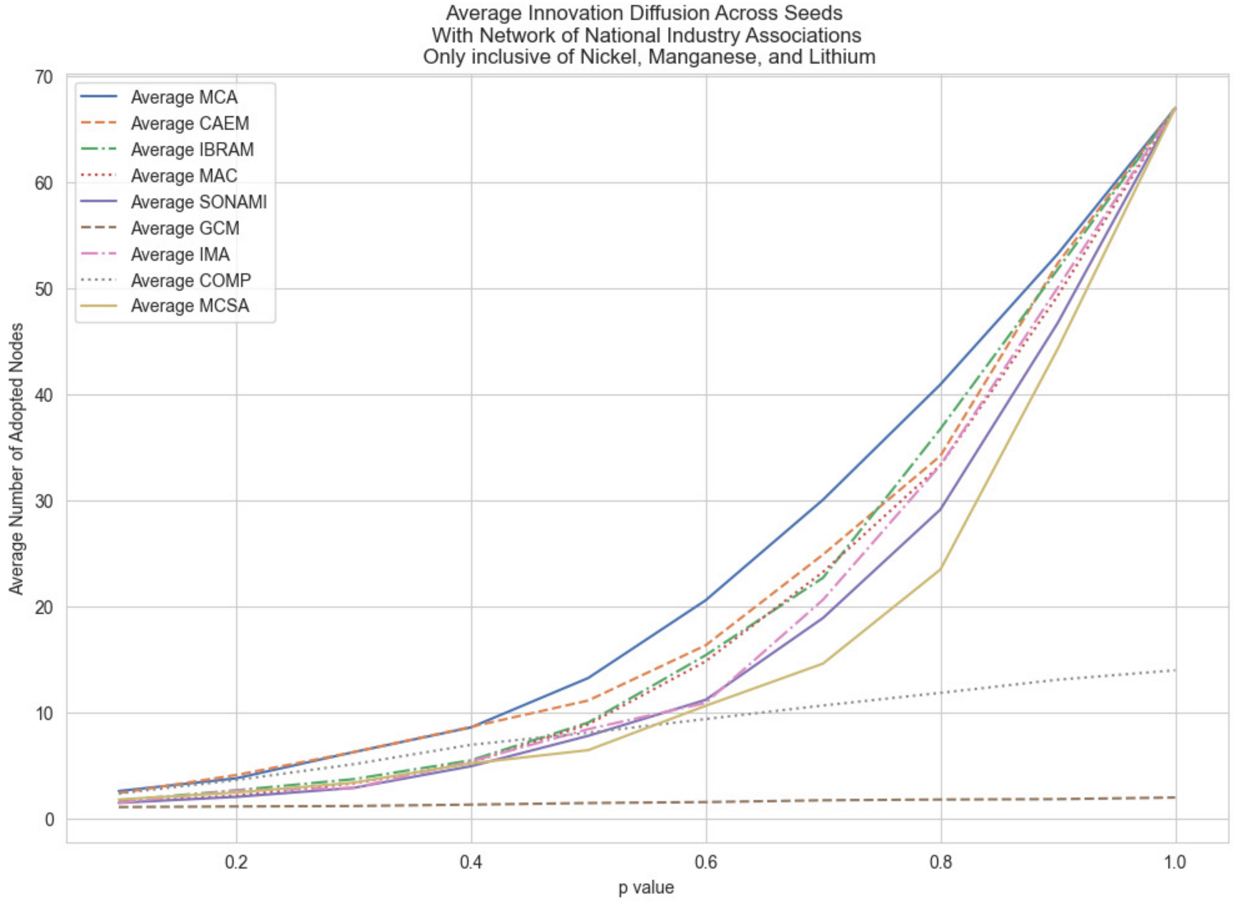
3. **Parent-subsidiary pathway** – Subsidiaries share a common parent company. Adoption by one subsidiary gives its sibling an independent chance (*p*) to adopt, after which that sibling can relay the innovation into every association to which it belongs.

Upon execution of the two-tiered diffusion model (detailed in **Section 5.3.4**), the results of the diffusion across the global network (only inclusive of national industry associations) can be seen in **Figure 29** and are presented in **Table 21**. For the *national associations only*, a total of 5 companies influenced the second pathway of adoption (cross-association bridging pathway), showcasing that the limited potential for this pathway is weak unless international associations are overlaid. Moreover, 17 parent-subsidiary pathways were present. Some initial perceptions showcase the isolation of the Ghana Chamber of Mines (GCM) and the Chamber of Mines of the Philippines (COMP), indicating potential barriers in transnational information exchange among these companies. The results also provide insights into how certain industry associations facilitate information diffusion among their member companies to varying degrees.

Table 21. Structural capacity of diffusion pathways across network variants

Network variant	Pathway 1 (Mean members)	Pathway 2 (Bridge companies)	Pathway 3 (Subsidiary pairs)
National associations only	8.2	5	17
ICMM Overlay	8.4	6	20
ILiA Overlay	10	13	29
NI Overlay	8.7	9	29
IMnI Overlay	11.5	8	24

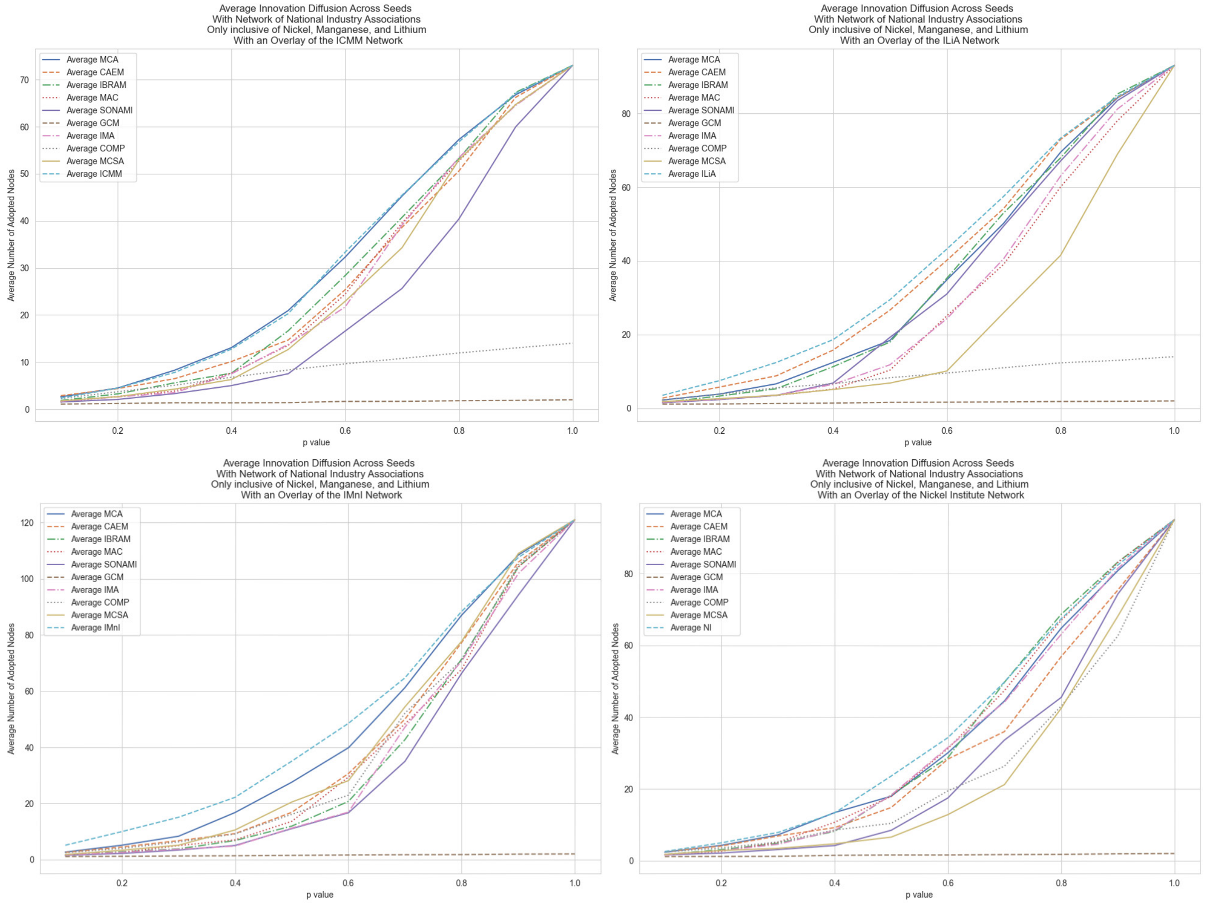
Figure 29. Tallied average results from the two-tiered diffusion model applied to the global industry association network. Limited to the Metals & Mining industry and commodity-specific to lithium, nickel, and manganese



5.4.2 Inclusion of International Industry Associations

Further, when we incorporated the international industry associations (ICMM, ILiA, IMnI, and NI) into the network, as shown in **Figure 30.** We can notice that there was a noticeable upward shift in the diffusion curve. This suggests that the involvement of influential organisations might positively impact the speed at which information travels among transnational companies within the network. These findings imply that the presence of prominent international bodies can enhance the dissemination of information across companies that operate globally.

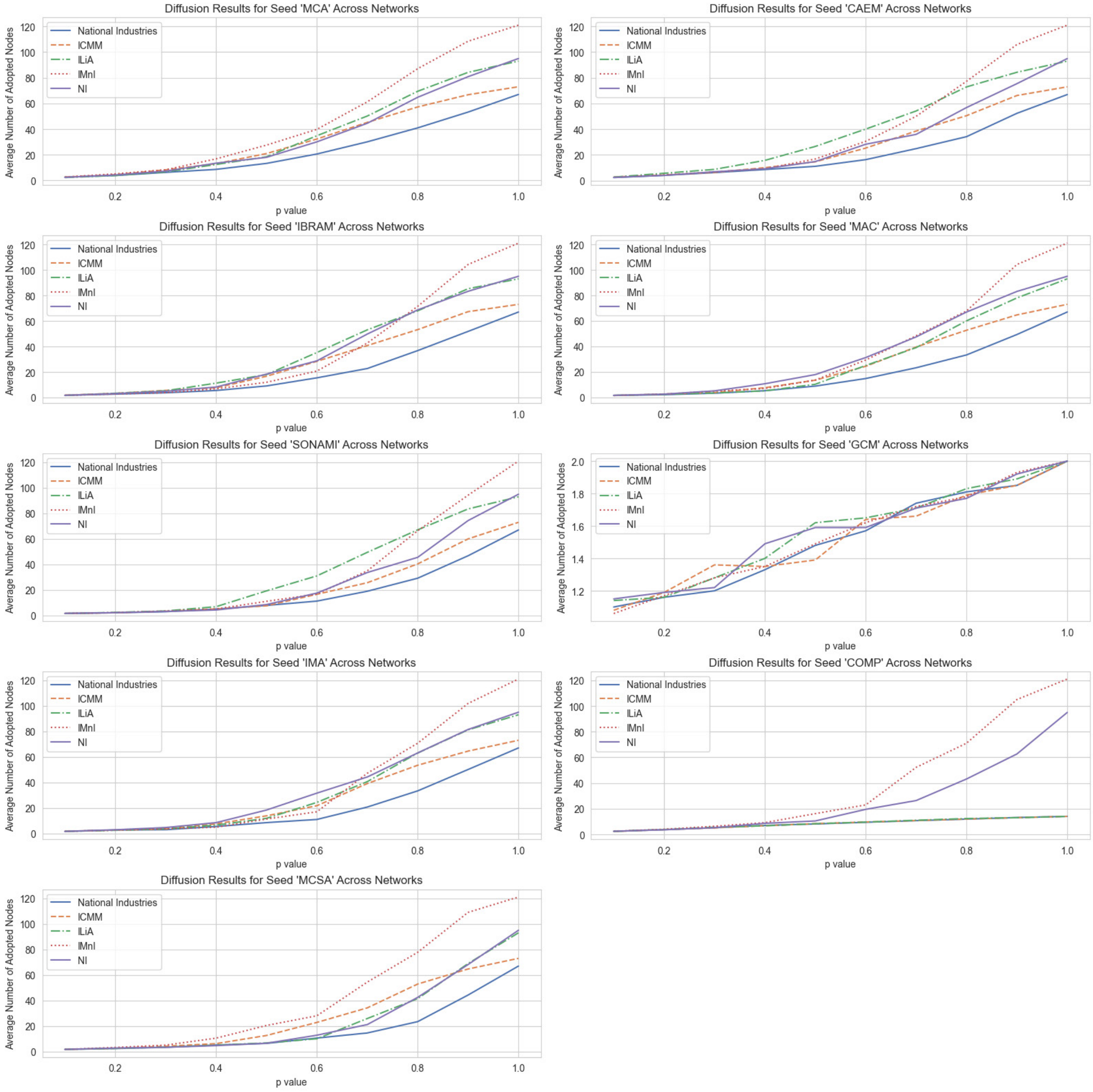
Figure 30. Tallied average results from the two-tiered diffusion model applied to the global industry association network, inclusive of the international collaboration networks. Limited to Metals & Mining industry and commodity-specific to lithium, nickel, and manganese



5.4.3 Impact of Seed Selection on Innovation Pathways Across Diverse Networks

Finally, to explore how various seeds of network-diffused innovation influence diverse innovation pathways, we applied the diffusion algorithm across different networks (either the combination of national industry associations or the overlaid networks with the international associations), keeping the same national industry association (e.g. from Australia or Canada). The results of this analysis are presented in **Figure 31**.

Figure 31. Tallied average results from the two-tiered diffusion model applied to distinct networks and keeping the seed of the diffusion process stable. Each graph depicts the same process for different starting national industry associations.


Diffusion Results for Seed 'MCA' Across Networks

Diffusion Results for Seed 'CAEM' Across Networks

Diffusion Results for Seed 'IBRAM' Across Networks

Diffusion Results for Seed 'MAC' Across Networks

Diffusion Results for Seed 'SONAMI' Across Networks

Diffusion Results for Seed 'GCM' Across Networks

Diffusion Results for Seed 'IMA' Across Networks

Diffusion Results for Seed 'COMP' Across Networks

Diffusion Results for Seed 'MCSA' Across Networks

5.5 *Conclusion*

5.5.1 Key Insights and Implications

Emphasizing network-based diffusion analysis, we selected lithium, nickel, and manganese as primary commodities due to their pivotal role in lithium-ion battery cathode production and analysed the information diffusion across companies operating transnationally and being members of national industry mining associations, leading to the unveiling of potentially influential actors. The findings resonate with van den Brink's identified research gap related to firm-oriented network analyses in mining supply chains (van den Brink et al., 2020). By focusing on the firm level, our study underscores the role of industry associations in mediating the diffusion of eco-innovations and highlights the impact of international bodies in enhancing global connectivity.

This study not only contributes to our understanding of network dynamics in mining but also provides a framework for future research to further explore firm-specific networks and their influence on sustainability practices in the sector. A fundamental aspect that must be further analysed is the association-to-association relationship and sphere of influence. The case of the Ghana Chamber of Mines (GCM), an association member of the ICMM, is particularly noteworthy. While GCM lacks transnational firm connections facilitating outbound and inbound information flows, it maintains a direct connection to ICMM (As of February 2024, GCM is a member of ICMM (ICMM, 2024)). Our results unveiled a distinct transnational nature of the network, with isolations like the Ghana Chamber of Mines and the Chamber of Mines of the Philippines highlighting potential information flow barriers. The inclusion of the ICMM in the network revealed an upward shift in the diffusion curve, suggesting that such influential bodies can significantly accelerate information exchange among transnational companies. Moreover, the inclusion of commodity-specific networks such as the *International Lithium Association* (ILiA), *the International Manganese Institute* (IMnI), and the *Nickel Institute* proved fundamental to help bridge the gap across national borders. The proactive stance of these associations towards fostering innovation and change could have a profound impact on the long-term sustainability outcomes in the sector.

In the national-association network alone, an innovation seeded in a single association can immediately reach, on average, eight member companies, which is the maximum reach of the intra-association (Pathway 1) mechanism. However, only five firms in that baseline graph hold multiple association memberships, and just seventeen unordered subsidiary pairs share pathways to information flow. Consequently, the cross-association (Pathway 2) and parent-subsidiary (Pathway 3) channels are weak, and cumulative adoption flattens quickly. By looking at Table 2 and Figure 8, we can see that overlaying international organisations alters the structure proactively. Adding ICMM, ILiA, IMnI, or the Nickel Institute raises the number of bridge firms to 6–13 and increases subsidiary connections to 20–29. These additional conduits shorten the average network path length and elevate international hubs' betweenness-centrality scores, producing the steeper diffusion curves observed in **Figure 30.** The results suggest that international associations may accelerate the propagation of environmental innovations by multiplying cross-cluster links and connecting otherwise distant parts of the network.

5.5.2 Limitations and Future Work

One important limitation of this work is that we assumed a *heterogeneous population* within our network (the *p-values* were varied but held the same across companies for a given diffusion round). To account for the unknown firm-level adoption behaviours, we implemented a systematic variation of the diffusion probability (p-value) across the full range from 0.0 to 1.0, with 1,000 iterations per step. This allowed us to generate a robust comparative baseline across different network structures, rather than rely on a single, potentially unrealistic assumption of adoption likelihood. While this approach cannot fully substitute for firm-specific diffusion modelling, it provides valuable insights into the relative capacities of industry association networks to facilitate innovation spread. Future studies could refine this approach by linking probability thresholds to firm characteristics such as size, ownership, or historical innovation behaviour. Finally, we acknowledge that, by restricting our quantitative analysis to eco-innovations, we do not capture the more heterogeneous diffusion dynamics of social-impact innovations. Future studies employing mixed-methods or longitudinal case-study designs will be required to address this complementary, and often overlooked, dimension of sustainability. Moreover, future studies could benefit from understanding and exploring the distinction between pathways of innovation adoption (e.g., employee inter-firm mobility). The relative importance of different pathways has not been assessed, and it may be possible that other pathways may be more influential than corporate memberships.

In future studies, a more intricate exploration of the network could be undertaken by incorporating an analysis of overlaid industry leadership organisations that are product-oriented, such as the Global Battery Alliance (Global Battery Alliance, 2023). This could be theoretically associated with the understanding of how such an organisation might help bridge the gap between commodities' expertise towards a product-oriented approach. The mechanisms by which previous eco-innovations have spread, such as Towards Sustainable Mining or comparable schemes, could also be assessed as case studies to understand how industry associations and their member companies communicate and coordinate to drive innovation in the sector. Moreover, future work could incorporate quantitative measures of innovation adoption to construct a more robust and intricate picture of the network's architecture and its capacity for innovation diffusion. This approach will not only refine our current understanding but also provide a scaffold for developing more effective strategies for managing and directing the flow of innovation within the industry.

6 A look ahead: How voluntary initiatives can shape the future impacts of battery production

This chapter explores the potential for environmental mitigation related to VSI adoption. As the electrification of the transport sector intensifies, ensuring that the extraction and processing of battery minerals occur with minimal environmental harm becomes a pressing concern. Traditional life cycle assessments (LCAs) have largely focused on carbon emissions and potential for climate change and are often limited by a static temporal range. This study broadens the perspective to include multiple environmental impact categories, informed by potential mitigation pathways aligned with VSIs, whilst incorporating a temporal element to its analysis.

This work employs a prospective life cycle assessment (pLCA) approach, which is a nascent field of research (Harpprecht et al., 2024), to model how future mining operations and raw material processing for Nickel-Manganese-Cobalt (NMC) oxides might evolve under various global scenarios. By integrating shared socioeconomic pathways (SSPs) and representative concentration pathways (RCPs) into the background datasets, changing energy mixes and process efficiencies through to 2040 were simulated and included in the lifecycle inventory. On the foreground side, VSI-inspired mitigation strategies, such as emissions controls or optimised chemical use, were directly incorporated into the lifecycle inventory, enabling a dynamic evaluation of environmental impacts over time.

Recognising the complexity of modelling future conditions, the *stepwise approach for Scenario-based Inventory Modelling for Prospective LCA a structured methodology* (SIMPL) (Langkau et al., 2023), was utilised to identify key parameters, refine inventory data, and apply mitigation coefficients, strengthening the robustness of the SIMPL approach within the field of pLCA. This work included parameterising emissions reductions at the process level and openly sharing the resultant datasets and source code, so future researchers can build on these scenarios, adjust assumptions, and replicate this approach to other compounds and processes.

Our results highlight how shifts in the background energy systems (related to the SSPs) can lower greenhouse gas emissions, while targeted operational improvements (potentially adopted through VSI adoption), like air pollution control devices, further reduce other environmental impacts, such as particulate matter and toxic emissions, which are a pathway to damage to human health (Huijbregts et al., 2017). Although not all impact categories are equally responsive to these measures, the findings underscore how coupling systemic energy transitions with operational best practices offers a pathway to sustainable battery mineral supply chains. By moving beyond carbon and considering a wider array of environmental factors, it strengthens the case for integrated strategies that promote both decarbonization and improved local environmental performance at the mining source.

Life cycle assessment of battery minerals to 2040: contribution of voluntary sustainability initiatives

Abstract

The expansion of electric mobility is intensifying demand for lithium, nickel, and manganese, increasing the environmental burdens of mineral extraction and processing. Voluntary sustainability initiatives (VSIs) have emerged to encourage improved environmental management, yet their long-term effectiveness remains uncertain. This study provides the first attempt to model the potential benefits of VSI adoption using a proof-of-concept prospective life cycle assessment (pLCA) of NMC111 oxide production from 2025 to 2040. By integrating Shared Socioeconomic Pathways (SSPs) with VSI-aligned process measures such as air-pollution control devices, we assess midpoint impacts including climate change, particulate matter formation, and human toxicity. Results show that systemic background decarbonization dominates reductions, while VSI-inspired interventions deliver complementary benefits, including up to ~75% reductions in particulate matter formation for nickel beneficiation and localized process-level reductions of up to ~90%. These findings highlight how coupling systemic and operational measures can improve resource efficiency and environmental performance in battery-mineral supply chains.

Keywords: Life Cycle Assessment (LCA), prospective LCA, NMC Batteries, environmental impacts, Shared Socioeconomic Pathways (SSP)

6.1 Introduction

6.1.1 NMC Batteries, oxides, their routes and impacts

The decarbonization of the transportation sector is a pivotal strategy in mitigating climate change, necessitating a transition to low-carbon technologies (Habib et al., 2020), driving unprecedented demand for lithium-ion batteries (LIBs) and the critical minerals they rely on, such as lithium, nickel, manganese, and cobalt (Dominish et al., 2019). Among these, nickel-manganese-cobalt (NMC) batteries dominate due to their optimal balance of energy density, safety, and longevity, making them indispensable in electric vehicles (EVs) (Nitta et al., 2015). Demand for NMC batteries is projected to grow exponentially, raising concern over the production of compounds such as nickel sulfate, manganese sulfate, lithium carbonate, and lithium hydroxide, which involve complex, impact-intensive processes (Sadhukhan & Christensen, 2021; Xu et al., 2022). These materials are often sourced from resource-rich regions in the global south, where concerns over environmental, social, and governance (ESG) risks further complicate supply chains and have become a critical consideration in the sustainability of battery materials (Lèbre et al., 2020).

6.1.2 VSIs and potential for impact mitigation

Voluntary Sustainability Initiatives (VSIs) have emerged as a response to growing pressure on the mining sector from investors, regulators, and civil society to adopt more sustainable practices (Franken & Schütte, 2022a). These initiatives encompass standards and certifications aimed at improving transparency and reducing the environmental and social impacts associated with mining supply chains. Their adoption has been connected with the rise in material demand by industries like EV manufacturers (Amnesty International, 2017b). Notable mentions include global schemes aimed towards large-scale mining operations, like the *International Council on Mining and Metals* (ICMM) Sustainable Development Framework (ICMM, 2023), the *Initiative for Responsible Mining Assurance* (IRMA) (IRMA, 2018a), and the *Global Reporting Initiative* (GRI) Reporting Principles and Standards (GRI, 2023).

Although a range of VSIs has been implemented, their effectiveness in driving long-term sustainability remains debated. While they can support early adoption, foster cooperative relations with regulators, and bring non-industry stakeholders to the discussion table, criticisms persist regarding their potential to facilitate greenwashing by focusing on short-term impacts. Moreover, the voluntary nature of these initiatives leaves them vulnerable to inconsistencies in enforcement and impact (Tröster & Hiete, 2018). Nevertheless, the growing demand for battery minerals and the expected uptake in VSIs underscore the importance of monitoring VSI adoption to mitigate future environmental risks. We view VSI adoption as part of an adaptive management strategy, where monitoring and transparency are key components. To our knowledge, this is the first study to explicitly integrate VSI-inspired technologies (e.g., Air Pollution Control Devices) into a prospective LCA of battery mineral extraction and processing, linking sustainability initiatives to process-level engineering interventions.

6.1.3 Structure and scope of research

We evaluate potential impact mitigation in the LIB supply chain from 2025 to 2040 through a prospective LCA (pLCA) of NMC oxides, focusing on nickel, manganese, and lithium. The analysis integrates Shared Socioeconomic Pathways (SSP1, SSP2, SSP5) to capture evolving energy systems alongside VSI-inspired interventions. This study builds on a growing body of research employing prospective life cycle assessment (pLCA) to evaluate the environmental impacts associated with material extraction and processing for energy transition technologies (Harpprecht et al., 2024). Previous studies have explored critical factors influencing life cycle impacts, including production location (Ambrose & Kendall, 2020), variations in ore grades (Harpprecht et al., 2021), energy efficiency (Watari et al., 2022), and the role of the background energy mix (van der Meide et al., 2022). However, much of the existing research concentrated on major metals, such as copper and iron, which, while economically significant, are not as central to emerging clean energy technologies (Harpprecht et al., 2024). Moreover, impacts beyond climate change from greenhouse gas (GHG) emissions are often overlooked (Watari, Nansai, & Nakajima, 2021), even though the potential for environmental impacts of mining activities has been extensively documented in literature, ranging from land-use change (Sonter et al., 2018), impacts on water quality and access (Kemp et al., 2010), decreased air quality (Franks et al., 2013), and biodiversity loss (Sonter et al., 2018), among others. Given the localized and often severe environmental burdens associated with mining operations at the point of extraction, it is critical to expand the scope of assessments to capture a wider range of environmental impacts. This expansion must also consider mitigation strategies beyond the current status quo to account for innovative and operationally feasible solutions.

The following sections outline the methods employed to model these processes and scenarios (section 6.2), the results obtained (section 6.3), and their implications for stakeholders and policymakers (section 6.4). Moreover, the supplementary material contains significant information to replicate this methodology with different compounds, processing routes, and background scenarios.

6.2 Materials and Methods

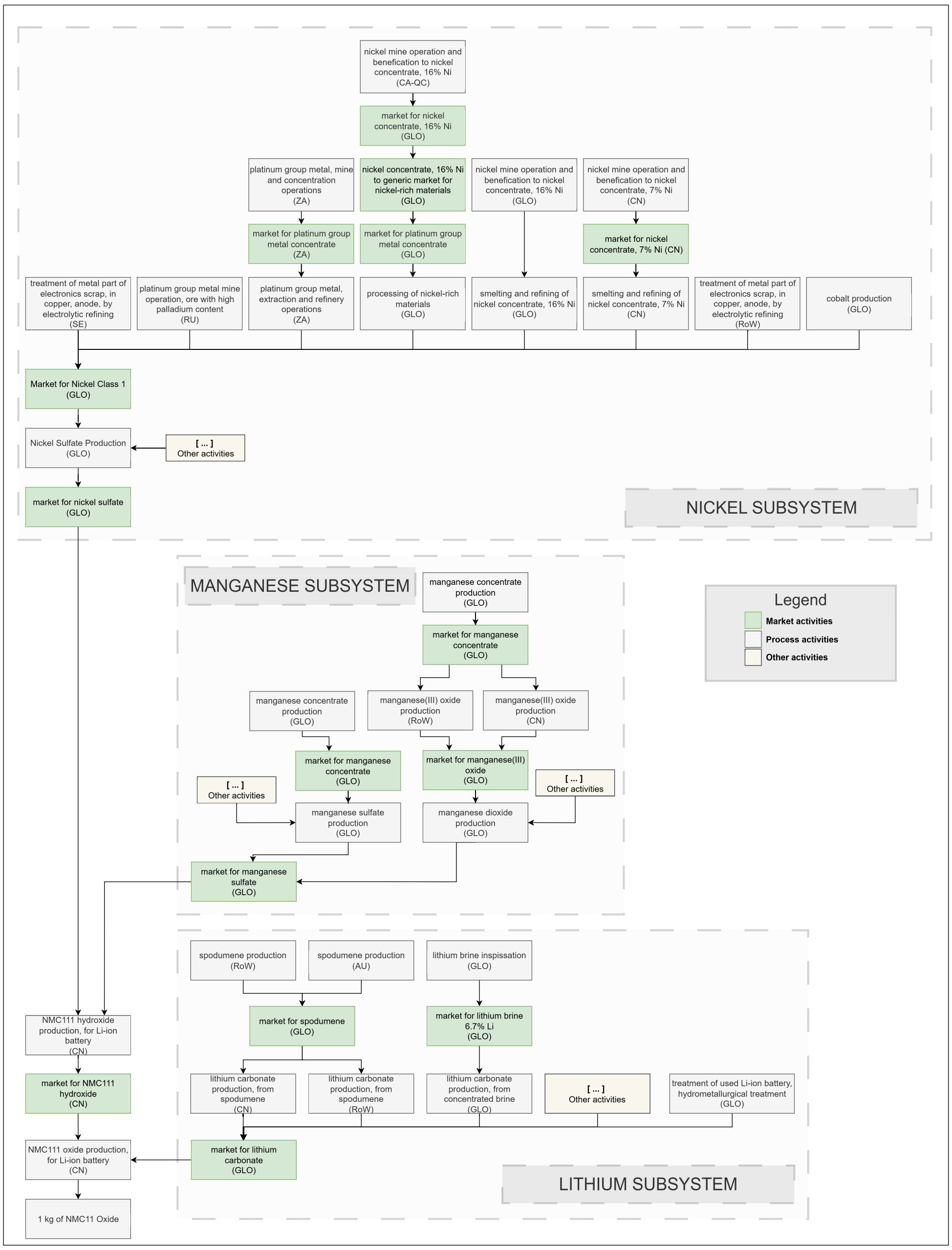
We modelled the extraction and processing of lithium, nickel, and manganese used in nickel-manganese-cobalt (NMC) oxides, key compounds in the production of lithium-ion battery cells. The selection of these three materials is particularly relevant due to their significant contributions to a wide range of environmental impacts of NMC oxide production and, consequently, battery cell manufacturing (Murdock et al., 2021).

We employed the stepwise approach of Scenario-based Inventory Modelling for Prospective Life Cycle Assessment (SIMPL) (Langkau et al., 2023) to systematically identify and model relevant factors. The SIMPL approach involves: (a) identifying key inventory parameters and critical factors, (b) establishing assumptions for each identified parameter, and (c) combining these assumptions to generate future scenarios. To identify key factors and parameters, we built on previous works that utilized a group-model building approach rooted in system dynamics, leading to the development of a causal loop diagram (CLD) with inputs from industry stakeholders (Mendonca Severiano et al., 2025). This collaborative process provided valuable insights into the parameters influencing voluntary impact mitigation in the context of battery mineral mining. Results from this exercise were subsequently refined to align with the SIMPL framework. The parameters and factors' definition and modelling involved the following key steps:

1. **Mapping the production route**:
    - The production route for NMC111 oxide used in lithium-ion batteries was mapped using the ecoinvent 3.8 cut-off database (Wernet et al., 2016) (**Figure 32**). Relevant upstream unit processes supplying compounds for NMC111 oxide production, such as lithium hydroxide, lithium carbonate, manganese sulfate, and nickel sulfate, were identified and further explored.
    - Processes involved in the supply of the products used in these compounds (e.g., nickel mine operation and beneficiation to nickel concentrate, and smelting and refining of nickel concentrate to produce nickel class 1) were further identified and selected for a detailed parameter exploration.
2. **Initial inventory modelling, preliminary impact assessment, and parameter selection:**
    - An initial life cycle inventory and impact assessment were conducted using data from ecoinvent 3.8 (details available in the supplementary material).
    - For each unit process (e.g., smelting and refining of nickel concentrate), impacts were disaggregated by impact category, and contributions were analysed at the level of elementary flows to specific compartments (e.g., ecotoxicity impacts of sulfur dioxide emissions to non-urban air).
    - A hotspot analysis was performed to identify which elementary flows contributed the most to each impact category, using a threshold of ≥ 1% of relative impact per category.
3. **Foreground inventory modelling:**
    - Potential strategies for impact mitigation were identified based on the hotspot analysis, with a focus on the highest-impact emissions categories.
    - These strategies were incorporated as coefficients of reduction, applied directly to the elementary flows of each unit process to reflect potential voluntary emissions reductions.
4. **Background inventory modelling:**
    - New inventories were incorporated from results extracted from REMIND for a range of socioeconomic pathways.
5. **Inventory modelling and impact assessments were performed:**
    - The background and foreground inventories were combined, and prospective impact assessments were performed to evaluate the cumulative effects across various scenarios.

The environmental impacts were quantified through a cradle-to-gate approach, with a functional unit of 1 kg of material (e.g., 1 kg of Nickel Class 1, or 1 kg of NMC111 oxide). Our timeframe includes 2025, 2030, 2035, and 2040. All inventory and impact assessment calculations have been performed using Brightway2.5, an open-source framework for life cycle assessment (Mutel, 2017). Further details about the Python code used in the different steps of the process can be found in the supplementary material. Additionally, we used *premise*, an open-source Python library (Sacchi et al., 2022), to incorporate climate mitigation scenarios from the Integrated Assessment Model (IAM) REgional Model of INvestments and Development (REMIND) into the background system (Baumstark et al., 2021). The following sections provide the scenario definitions and describe the steps taken for our systematic scenario modelling approach (sections **6.2.1** – **6.2.5**)

Figure 32. Cradle-to-gate production route of NMC111 Oxide, with a focus on lithium hydroxide, nickel sulfate, and manganese sulfate production based on processes from ecoinvent 3.8.



6.2.1 The production route: Battery cell production, NMC oxide, and upstream activities

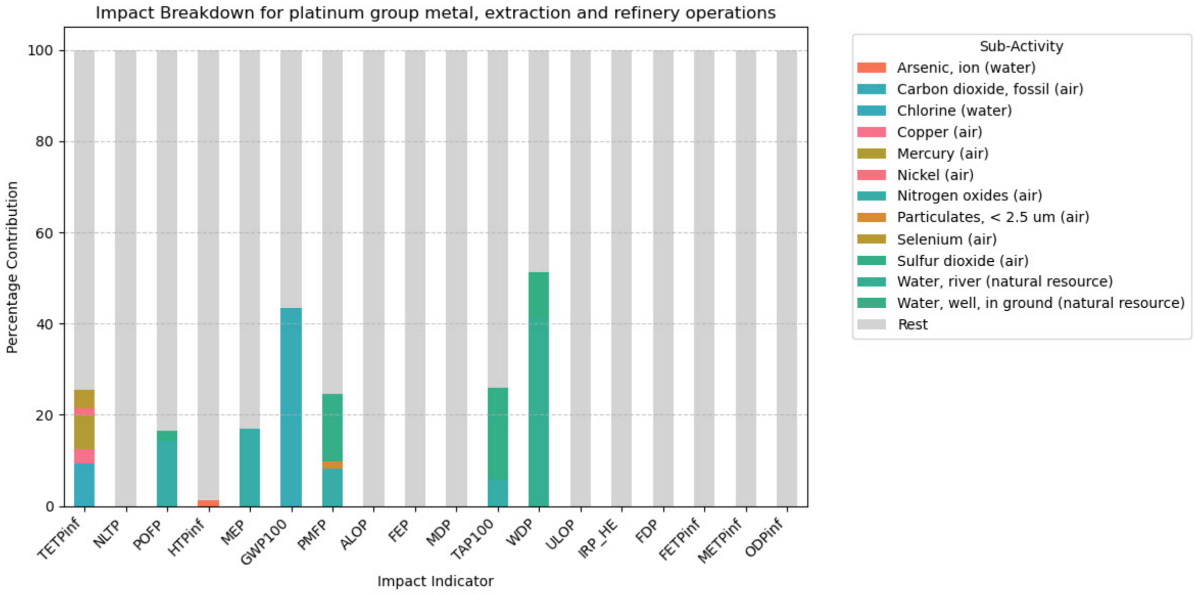
The initial focus of our process modelling was on the production of NMC111 oxide, for Li-ion battery (CN). From this processing route, the markets for NMC111 hydroxide and Lithium carbonate were disaggregated (**Figure 32**). For these two unit processes, the supporting unit processes involved in the production of lithium carbonate, nickel sulfate, and manganese sulfate were identified and listed. Similar to previous studies that explored the prospective life cycle assessment of lithium-ion batteries (Xu et al., 2022), we analysed the cradle-to-gate production of battery cell compounds based on the inventories available on ecoinvent 3.8. We included raw materials' extraction, materials' production, and materials' upgrading. When incorporating potential environmental impact, voluntary mitigation strategies associated with modifications to specific unit processes, exchanges within these processing routes were modified by applying mitigation coefficients over time.

6.2.2 Inventory modelling, preliminary impact assessment, and parameter selection

We employed a group model-building approach to integrate diverse perspectives into a cohesive causal loop diagram (CLD), previously introduced in Mendonca Severiano et al. (2025) and now expanded to include key parameters relevant to our modelling framework. To quantify environmental impacts, we conducted a lifecycle inventory and impact assessment for each identified processing route utilizing the inventories available in ecoinvent 3.8, with detailed results for all impact categories provided in *Supplementary Material 1, Section 2*. The assessment utilized the ReciPe 1.6 Midpoint (H) (Huijbregts et al., 2017), and the Python code used for the analysis, along with the impact results, is available in the Supplementary Material.

To identify the most significant emissions, we performed a contribution analysis across all impact categories, examining the percentage contribution of individual emissions from each processing step. These emissions were categorized by compartment (e.g., air, water, soil) and sub-compartment (e.g., low population density, long-term), as detailed in *Supplementary Material, Section 3*. For example, when evaluating the particulate matter formation (PMFP) impact category to produce 1kg of Nickel, Class 1 through *platinum group metal, mine and concentration operations (ZA)*, the analysis revealed that sulfur dioxide (SO_2), nitrogen oxides (NO_x), and particulate matter (<2.5 μm) emissions to air were the primary contributors, as exemplified in **Figure 33**. These findings informed our selection of mitigation strategies, ensuring that efficiency gains, technological advancements, and process optimizations (**Figure 34**) directly targeted the most impactful emissions, thereby reducing the overall environmental impact.

Figure 33. Contribution analysis for platinum group metal, mine and concentration operations (ZA), producing 1 kg of Nickel, Class 1. The stacked bars represent the percentage contribution of individual emissions, with biosphere exchanges color-coded according to their respective compartments (e.g., air, water, soil). These insights were used to guide the selection of mitigation strategies aimed at reducing key emissions, particularly sulfur dioxide (SO_2), nitrogen oxides (NO_x), and particulate matter (<2.5 µm) emissions to air. TETPinf = terrestrial ecotoxicity; NLTP = Natural land transformation; POFP = photochemical oxidant formation; HTPinf = human toxicity; MEP = Marine eutrophication; GWP100 = Climate change; PMFP = particulate matter formation; ALOP = Agricultural land occupation; FEP = freshwater eutrophication; MDP = Metal depletion; TAP100 = terrestrial acidification; WDP = Water depletion; ULOP = Urban land occupation; IRP_HE = Ionising radiation; FDP = Fossil depletion; FETPinf = freshwater ecotoxicity; METPinf = marine ecotoxicity; ODPinf = Ozone depletion;



6.2.3 Background Modelling

The background system of our analysis is built based on the ecoinvent 3.8 database (Frischknecht et al., 2005). We consider future changes in energy scenarios affecting the supply of battery materials previously described as being part of our foreground scenario. We used the open-source library *premise* to generate future-scenario versions of ecoinvent 3.8 cut-off, expanding the background inventory to reflect changes related to Shared Socioeconomic Pathway (SSP) scenarios, using scenarios from the integrated assessment model REMIND (Sacchi et al., 2022). By using *premise v2.0.1*, the original database (ecoinvent) is systematically transformed and expanded by emerging and future technologies not originally available in the database. REMIND models the energy system by integrating a variety of energy conversion technologies and energy services (such as the ones used by industry sectors) (Baumstark et al., 2021). When using *premise*, the created background inventories are modified according to the selected SSP and henceforth referred to as '*SSP-Base'*. SSPs are scenarios used in climate modelling to explore different pathways for global socioeconomic development. A key driver of changes in environmental impacts is the transformation of the electricity mix, particularly the increasing share of renewables, which influences the background emissions of industrial processes. These can be perceived as "directions" of development, taking into consideration climate change impacts, adaptation, and mitigation (O'Neill et al., 2014). SSPs are used across research and feed into the

Intergovernmental Panel on Climate Change (IPCC) reports (IPCC, 2023). SSPs reflect future worlds based on their mitigation and adaptation challenges, giving us long-term projections over a range of socioeconomic conditions (Hausfather, 2018). For our analysis, we considered the following background scenarios, informed by (Hausfather, 2018), and the premise documentation (premise, 2025), listed in **Table 22.** It's important to iterate that we used ecoinvent 3.8 to ensure compatibility with the current codebase and libraries used. Later versions (3.9, 3.11) and newer lithium inventories (e.g., (Schenker et al., 2022) and (Khakmardan et al., 2025)) provide improvements, but incorporation was beyond the scope of this first implementation. The modular design of our framework allows updates as these datasets mature.

Table 22. Background scenarios utilised. Narratives were informed by the works of Riahi et al., the descriptions on CarbonBrief (Hausfather, 2018), and the default IAM scenarios description from the premise documentation (premise, 2025).

Background Scenario	**Adaptation and Mitigation**	**Description**
None	-	Business as usual.
SSP1- Base	Low challenges to mitigation and adaptation	"Taking the green road" scenario: Gradual and pervasive shift to a more sustainable path. Emphasis on inclusive development and respect for environmental boundaries.
SSP2-Base	Moderate challenges to mitigation and adaptation	"Middle of the road" scenario: Socioeconomic and technological trends do not shift significantly from historical patterns.
SSP5-Base	High challenges to mitigation, low challenges to adaptation	"Taking the highway" scenario: The push for economic and social development is coupled with the exploitation of abundant fossil fuel resources and the adoption of resource and energy-intensive lifestyles around the world.

6.2.4 Foreground Modelling

To better understand how specific mitigation technologies can translate into mitigated impacts, we modelled their impact mitigation potential through limiting the emissions of a certain pollutant to certain compartments (e.g. emissions of particulate matter to air, which can lead to an increase in respiratory diseases (Huijbregts et al., 2017)). These mitigation technologies include: (i) Air pollution control devices (APCD) (Wu et al., 2019; Zhang et al., 2022), (ii) Nitrous Oxides (NOx) suppression (Rebrov & Gorlov, 2011), (iii) green reagents and efficiency gains (International Finance Corporation, 2023), (iv) fixed-bed biofilm reactors (FBBR) (Zaitsev et al., 2008), (v) membrane bioreactors (MBR) (Dobson & Burgess, 2007; Melin et al., 2006), (vi) ion exchange in solid carbonate (Cueto & Hansen, 2019), and (vii) mist generators with added surfactants (Lee et al., 2022). We assessed the emission reduction potential for each technology by elementary flow. For example, the adoption of Flue Gas Scrubbers (FGS) (a type of APCD) during a mineral processing activity can reduce the emissions of Copper (Cu) to air by almost 99.9% (Zhang et al., 2022). Similarly, a combination of FGS and Electrostatic demister (ESD) can reduce PM10 (particles with a diameter of 10 micrometers or less) by 94%, and PM2.5 by 99% (Wu et al., 2019). We then applied these technologies to individual processes in each sub-system (e.g. *platinum group metal, mine and concentration operations (ZA)* producing *1kg of Nickel, class 1*).

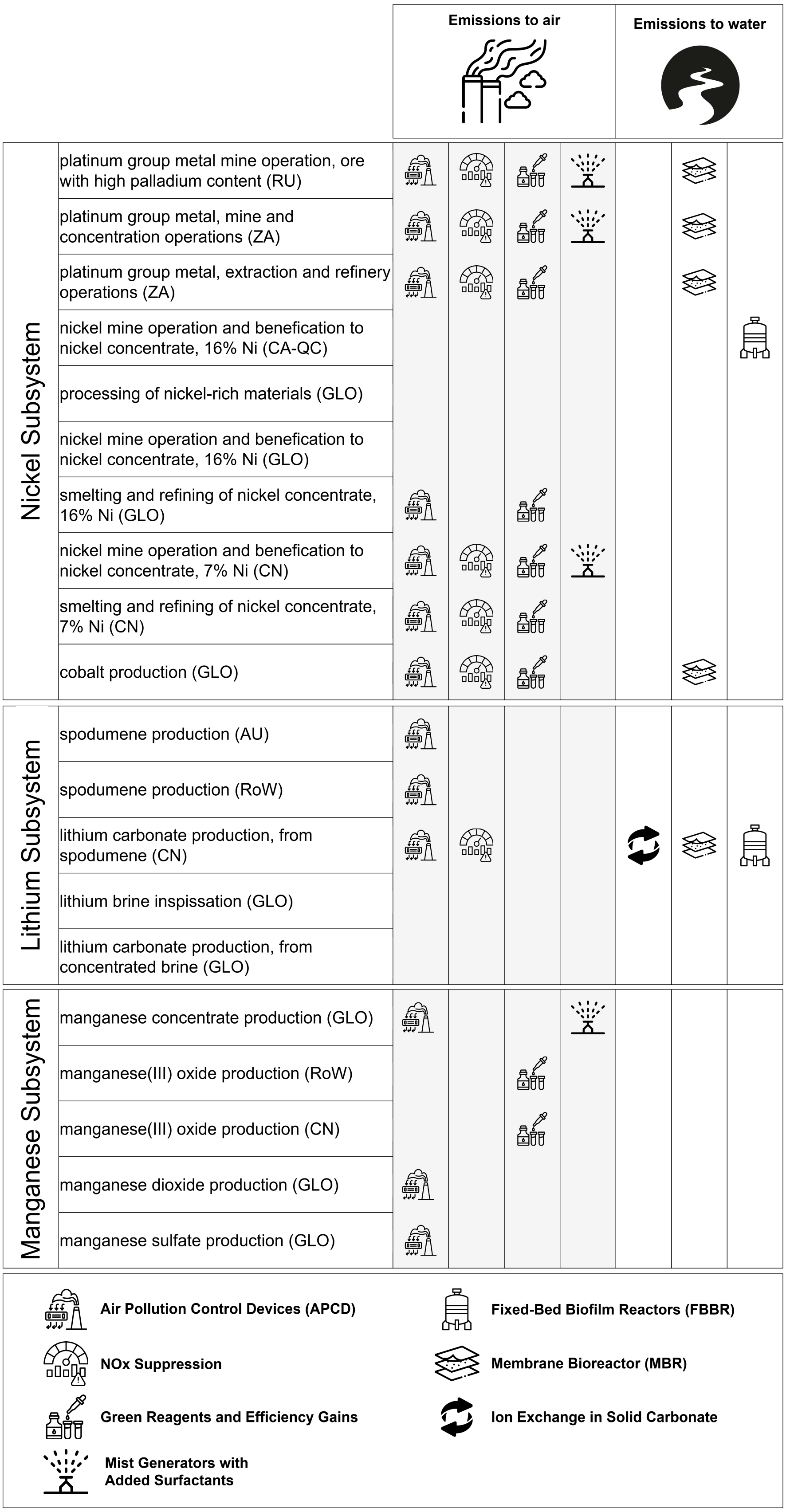
The individual mitigation factors (i.e., emission reduction coefficients) assigned to each technology and their specific application to elementary flows and compartments are systematically detailed in the supplementary material (**Appendix D**). This supplementary material provides the full list of targeted processes, the quantitative coefficients used for each pollutant and compartment, and the assumptions behind their temporal evolution within each scenario. Additionally, we structured our approach using a time-explicit mitigation strategy, in which we assumed an adaptive management approach that mitigates *emissions-to-compartments* over time. To reflect this, we assumed that impacts are not mitigated in the starting year (e.g. 2025), achieve the full potential for mitigation in the final year (e.g. 2040), and follow a logistic growth between the starting and final year, represented by the equation:

$$y = \frac{L}{1+e^{-k(x-x_0)}} \text{ , where:}$$

- x is the independent variable (e.g., the year for which the interpolated value is required);
- L represents the upper asymptote (set to the coefficient value of the second known point, y_2);
- k is the growth rate, calculated as $k = \frac{1}{x_2 - x_1}$;
- x_0 is the midpoint between the two known values, calculated as $x_0 = \frac{x_1+x_2}{2}$

Our approach represents VSI-inspired mitigation as reductions in elementary flows. This constrains possible outcomes to reductions but indicates directional potential. A full process-based inventory of these technologies would capture trade-offs more comprehensively and is a recommended step for future work. **Figure 34** presents mitigation technologies modelled against respective processes. The individual mitigation factors of each mitigation technology against their respective elementary flow and compartment are provided in the supplementary material (**Appendix D**).

Figure 34. Mitigation strategies adopted and their mitigation within production subsystems. Activities with no mitigation strategies applied to them had only the background inventories modified according to the SSP.



		Emissions to air				Emissions to water		
Nickel Subsystem	platinum group metal mine operation, ore with high palladium content (RU)	✓	✓	✓	✓		✓	✓
	platinum group metal, mine and concentration operations (ZA)	✓	✓	✓	✓		✓	
	platinum group metal, extraction and refinery operations (ZA)	✓	✓	✓			✓	
	nickel mine operation and benefication to nickel concentrate, 16% Ni (CA-QC)							
	processing of nickel-rich materials (GLO)							
	nickel mine operation and benefication to nickel concentrate, 16% Ni (GLO)							
	smelting and refining of nickel concentrate, 16% Ni (GLO)	✓		✓				
	nickel mine operation and benefication to nickel concentrate, 7% Ni (CN)	✓	✓	✓	✓			
	smelting and refining of nickel concentrate, 7% Ni (CN)	✓	✓	✓				
	cobalt production (GLO)	✓	✓	✓			✓	
Lithium Subsystem	spodumene production (AU)	✓				✓	✓	✓
	spodumene production (RoW)	✓						
	lithium carbonate production, from spodumene (CN)	✓	✓					
	lithium brine inspissation (GLO)							
	lithium carbonate production, from concentrated brine (GLO)							
Manganese Subsystem	manganese concentrate production (GLO)	✓			✓			
	manganese(III) oxide production (RoW)			✓				
	manganese(III) oxide production (CN)			✓				
	manganese dioxide production (GLO)	✓						
	manganese sulfate production (GLO)	✓						

Air Pollution Control Devices (APCD)

NOx Suppression

Green Reagents and Efficiency Gains

Mist Generators with Added Surfactants

Fixed-Bed Biofilm Reactors (FBBR)

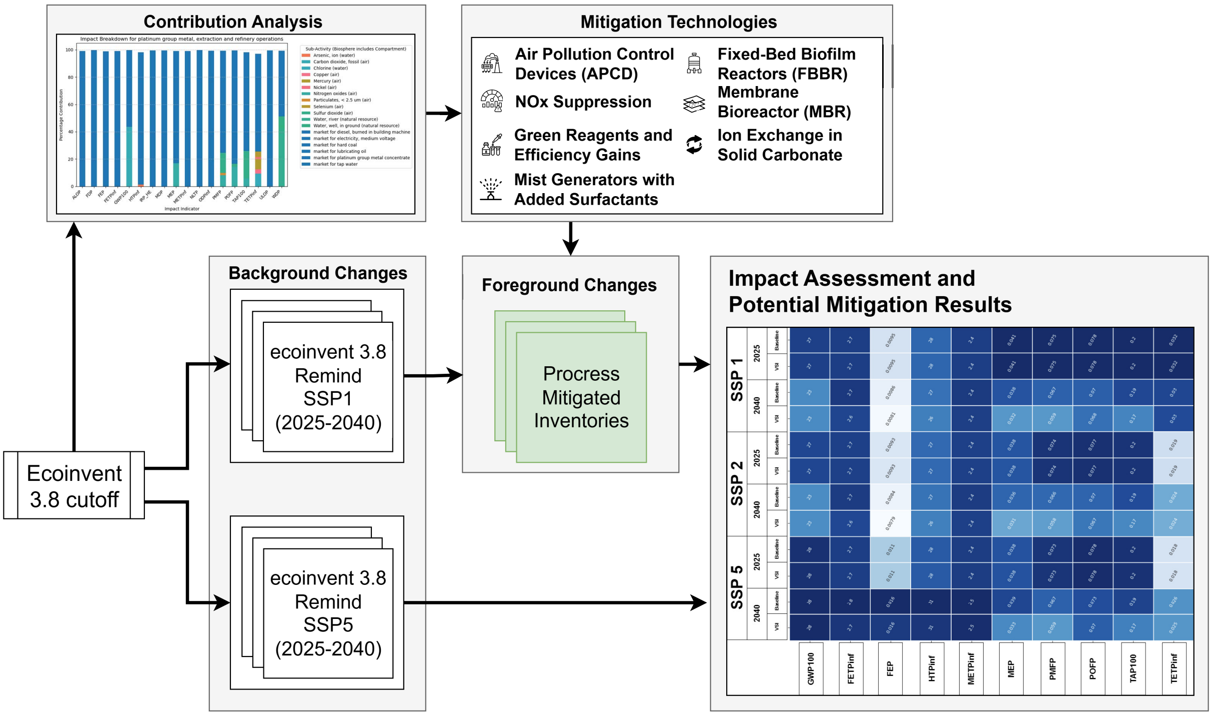
Membrane Bioreactor (MBR)

Ion Exchange in Solid Carbonate

6.2.5 Scenario Combination

Following the SIMPL approach, we combined our background scenarios with foreground scenarios. To generate the background datasets, we employed the *premise* tool (Sacchi et al., 2022). Specifically, we utilised the existing implementation of REMIND's projections for different socio-economic pathways (Baumstark et al., 2021). Subsequently, we created additional scenario-specific datasets (combining both background and foreground inventories) to explore the potential impact of voluntary sustainability initiatives (VSIs). These datasets were structured into two distinct categories: (i) Background Changes: SSP scenarios only, (ii) Foreground Changes: Process Mitigated Inventories, and (iii) Background + Foreground changes. A graphical representation of this workflow is provided in **Figure 35**. This structured methodology allowed for a comparative analysis of the relative contributions of SSP scenarios and VSIs to impact mitigation.

Figure 35. Diagram of data generation, transformation, expansion, processing, and expected outputs. SSP = Shared Socioeconomic Pathway.

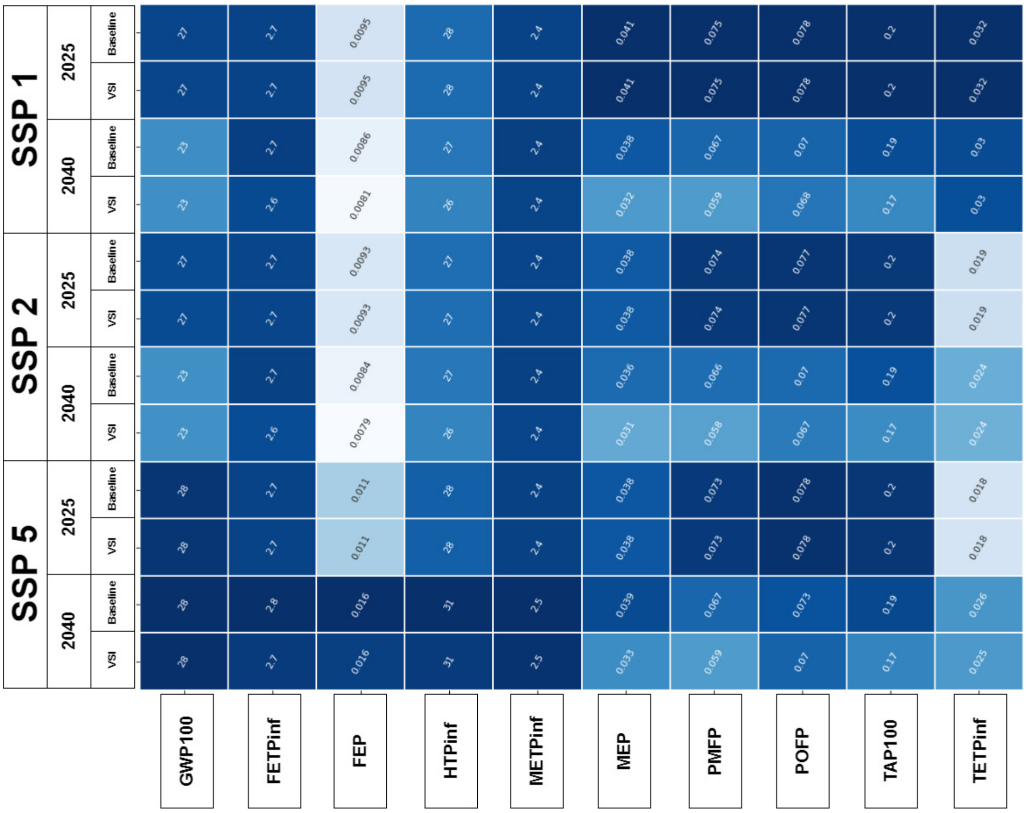


6.3 *Results*

6.3.1 Future impacts and mitigation of NMC111 oxide production

Figure 36 presents the prospective LCA results for NMC111 oxide production under different SSPs, comparing base and mitigation scenarios informed by the strategies outlined in **Figure 34**. In general, most impact categories exhibit a downward trend over time, primarily driven by changes in background systems. This trend can be solely attributed to background modifications whenever no variations between the *base* and *VSI* scenarios are present. When differences do arise – such as for marine eutrophication (MEP) in SSP1 for 2040 – they are attributed to foreground modifications applied to the activities listed in **Figure 34**. These results should be interpreted in the context of the chosen modeling assumptions, especially the reliance on the ecoinvent 3.8 inventories, which reflect certain data gaps and baseline process assumptions. The figures illustrate how prospective LCA can incorporate time-varying changes in both the background system (e.g. energy grids) and the foreground system (e.g. mitigation measures). This section focuses on the methodological approach of scenario-based prospective LCA, rather than on the accuracy of the absolute values of future impacts.

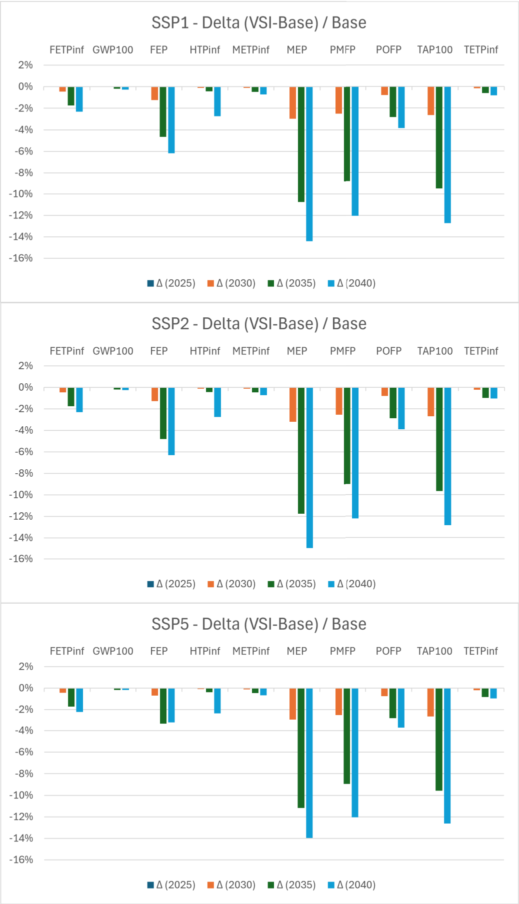
Figure 36. Prospective LCA results to produce 1 kg of NMC111 oxide. Results presented in absolute values per impact category from ReCiPE (H) midpoint. Results are disaggregated by SSP, initial year (2025), final year (2040), and whether the results represent the base SSP scenario or the modified inventory with VSI coefficients applied. Results were filtered to include only impact categories that presented potential impact mitigation from foreground inventory changes. GWP100 = Climate change; FETPinf = freshwater ecotoxicity; FEP = freshwater eutrophication; HTPinf = human toxicity; METPinf = marine ecotoxicity; MEP = marine eutrophication; PMFP = particulate matter formation; POFP = photochemical oxidant formation; TAP100 = terrestrial acidification; TETPinf = terrestrial ecotoxicity.



			GWP100	FETPinf	FEP	HTPinf	METPinf	MEP	PMFP	POFP	TAP100	TETPinf
SSP 1	2025	Baseline	27	2.7	0.0095	28	2.4	0.041	0.075	0.078	0.2	0.032
		VSI	27	2.7	0.0095	28	2.4	0.041	0.075	0.078	0.2	0.032
	2040	Baseline	23	2.7	0.0086	27	2.4	0.038	0.067	0.07	0.19	0.03
		VSI	23	2.6	0.0081	26	2.4	0.032	0.059	0.068	0.17	0.03
SSP 2	2025	Baseline	27	2.7	0.0093	27	2.4	0.038	0.074	0.077	0.2	0.019
		VSI	27	2.7	0.0093	27	2.4	0.038	0.074	0.077	0.2	0.019
	2040	Baseline	23	2.7	0.0084	27	2.4	0.036	0.066	0.07	0.19	0.024
		VSI	23	2.6	0.0079	26	2.4	0.031	0.058	0.067	0.17	0.024
SSP 5	2025	Baseline	28	2.7	0.011	28	2.4	0.038	0.073	0.078	0.2	0.018
		VSI	28	2.7	0.011	28	2.4	0.038	0.073	0.078	0.2	0.018
	2040	Baseline	28	2.8	0.016	31	2.5	0.039	0.067	0.073	0.19	0.026
		VSI	28	2.7	0.016	31	2.5	0.033	0.059	0.07	0.17	0.025

To highlight the extent of the foreground influence, **Figure 37** illustrates the relative impact variations from the VSI scenario compared to the corresponding SSP scenario. The figure indicates that the introduction of the technologies and processes described can lead to varied and meaningful mitigation across a range of impact categories, namely marine eutrophication (MEP), particulate matter formation (PMFP), terrestrial acidification (TAP100), freshwater ecotoxicity (FETPinf), freshwater eutrophication (FEP), photochemical oxidant formation (POFP), and human toxicity (HTPinf). While these improvements may appear modest when viewed through the lenses of producing NMC111 oxide, compound-disaggregated results will provide a more granular perspective in the following sub-section **6.3.2**. Across all categories, the relative mitigation potential presents little variation across SSP scenarios, with freshwater eutrophication (FEP) as the sole exception, displaying a slightly lower mitigation potential in the combined scenario compared to SSP1 and SSP2. Impact categories that are not affected by the VSIs, i.e. have a change rate of 0%, are not displayed.

Figure 37. Relative changes in environmental impacts from VSI-aligned foreground changes, expressed as percentage change compared to the corresponding SSP-Base scenario, for the production of 1 kg of NMC111 oxide from 2025 to 2040. Relative changes in environmental impacts from VSI-aligned foreground changes, expressed as percentage change compared to the corresponding SSP-Base scenario, for the production of 1 kg of NMC111 oxide. Results are shown for each year from 2025 to 2040 and calculated as: Δ% = (VSI – SSP-Base) / SSP-Base × 100. Impact categories with no change (Δ% = 0%) are omitted. FETPinf = freshwater ecotoxicity; FEP = freshwater eutrophication; HTPinf = human toxicity; METPinf = marine ecotoxicity; MEP = marine eutrophication; PMFP = particulate matter formation; POFP = photochemical oxidant formation; TAP100 = terrestrial acidification; TETPinf = terrestrial ecotoxicity;



6.3.2 Mitigation potential for individual activities

As with the aggregated results in Section **6.3.1**, these process-disaggregated findings serve primarily to illustrate the potential influence of targeted mitigation strategies when combined with time-varying background scenarios. The absolute values should be interpreted cautiously, given the inherent limitations of the ecoinvent 3.8 data. Among the activities analysed, 12 exhibited significant changes in impact scores due to foreground modifications. **Figure 38** presents the mitigation potential for selected mineral extraction and processing activities contributing to NMC111 oxide production. This figure compares impact changes under the SSP1, SSP2, and SSP5 background scenarios, both with and without the implementation of previously outlined foreground mitigation strategies. Of the 18 impact categories assessed, 8 remained unaffected by foreground changes: NLTP, ALOP, MDP, WDP, ULOP, IRP_HE, FDP, and ODPinf. Consequently, only the impact categories influenced by foreground interventions are shown in **Figure 38**.

Within the nickel subsystem, most processes exhibit a relatively consistent mitigation potential for 10 categories across all scenarios (SSP1, SSP2, SSP5). In some cases, significant mitigation can be observed. For example, “nickel mine operation and beneficiation to nickel concentrate, 7% Ni (CN)” can achieve substantial PMFP reductions, up to an additional 75% reduction, through the implementation of air pollution control devices (APCDs). Terrestrial ecotoxicity (TETPinf) is the category exhibiting a higher variability, as exemplified by platinum group metal mine operation, ore with high palladium content (RU), which shows distinct rates of change under different SSP scenarios, i.e. up to 2% under the SSP1 scenario, 6% in the SSP3 scenario, and 9% in the SSP5 scenario. Overall, nickel-related processes consistently demonstrate mitigation potential in PMFP, POFP, TETPinf, and TAP100 through air pollution control devices, and in some cases, reduced climate change through the adoption of green reagents and process optimizations.

For lithium-related processes, most mitigation potential arises from background system improvements rather than foreground interventions. Nonetheless, both spodumene production activities examined could further reduce PMFP through air pollution control devices, while phosphorus capture technologies like ion exchange in solid carbonate can mitigate MEP and FEP in lithium carbonate production. Lastly, within the manganese subsystem, the most notable mitigation potential lies in reducing HTPinf via air pollution control devices that capture heavy metals’ emissions. These control measures also confer benefits in freshwater and marine ecotoxicity categories. Additionally, the production of manganese (III) oxide can achieve further climate change mitigation using green reagents and enhanced process efficiencies.

Figure 38. LCIA results for the selected processes involved in NMC111 oxide production (see Figure 32), considering SSPs (Table 22), and operational voluntary initiatives for mitigating hotspots (Figure 34). Results are shown for 2040 as relative percentage changes compared to the corresponding LCIA scores in 2025. Results only show impact categories in which foreground changes influence impact categories. Nickel-related activities are in blue, lithium-related activities in green, and manganese-related activities in orange. Δ represents the relative mitigation attributed to VSI-aligned foreground changes and is calculated as the difference between the impact result under the combined SSP + VSI scenario and the corresponding SSP Base scenario (i.e., Δ = [SSP + VSI] − [SSP base]). Due to rounding, displayed percentage differences may vary by up to ±1%. FETPinf = freshwater ecotoxicity; FEP = freshwater eutrophication; HTPinf = human toxicity; METPinf = marine ecotoxicity; MEP = marine eutrophication; PMFP = particulate matter formation; POFP = photochemical oxidant formation; TAP100 = terrestrial acidification; TETPinf = terrestrial ecotoxicity; GWP100 = climate change. Categories not included are NLTP = natural land transformation; ALOP = agricultural land occupation; MDP = metal depletion; WDP = water depletion; ULOP = urban land occupation; IRP_HE = ionising radiation; FDP = fossil depletion; ODPinf = ozone depletion.

		Scenario								
Activity	Impact Category	SSP1	SSP1 + VSI	Δ	SSP2	SSP2 + VSI	Δ	SSP5	SSP5 + VSI	Δ
platinum group metal mine operation, ore with high palladium content (RU)	TETPinf	-9	-32	-24	33	-12	-45	53	6	-48
	POFP	0	-94	-93	0	-94	-93	0	-93	-93
	HTPinf	-6	-18	-12	-6	-18	-12	-6	-17	-11
	MEP	-15	-19	-4	-11	-15	-4	-7	-11	-4
	GWP100	-8	-10	-1	-7	-8	-1	5	4	-1
	PMFP	0	-96	-96	0	-96	-96	0	-96	-95
	FEP	-24	-24	0	-24	-24	0	-15	-15	0
	TAP100	0	-97	-96	0	-97	-96	0	-96	-96
	FETPinf	-1	-1	0	-1	-1	0	-1	-1	0
	METPinf	-1	-3	-2	-1	-3	-2	-1	-3	-2
platinum group metal, mine and concentration operations (ZA)	TETPinf	-11	-13	-2	73	66	-8	142	133	-9
	POFP	-2	-5	-2	-2	-4	-2	-1	-3	-2
	HTPinf	-1	-1	0	-1	-1	0	-1	-1	0
	MEP	-3	-3	0	-2	-2	0	-2	-2	0
	GWP100	-33	-33	0	-31	-31	0	-16	-16	0
	PMFP	-6	-22	-16	-6	-22	-16	-5	-21	-16
	FEP	-8	-8	0	-7	-7	0	-6	-6	0
	TAP100	-7	-29	-22	-6	-28	-22	-6	-28	-22
	FETPinf	0	0	0	0	0	0	0	0	0
	METPinf	0	0	0	0	0	0	0	0	0
nickel mine operation and benefication to nickel concentrate, 7% Ni (CN)	TETPinf	0	-88	-88	0	-89	-89	1	-89	-89
	POFP	0	-71	-71	0	-71	-71	0	-71	-71
	HTPinf	0	-2	-2	0	-2	-2	0	-1	-2
	MEP	0	-78	-78	0	-78	-78	0	-78	-78
	GWP100	-1	-36	-35	0	-35	-35	0	-35	-35
	PMFP	-2	-76	-74	-2	-76	-74	-2	-76	-74
	FEP	0	0	0	0	0	0	0	0	0
	TAP100	0	-81	-81	0	-81	-81	0	-81	-81
	FETPinf	0	0	0	0	0	0	0	0	0
	METPinf	0	-14	-14	0	-14	-14	0	-14	-14
smelting and refining of nickel concentrate, 16% Ni (GLO)	TETPinf	-6	-15	-9	33	17	-16	54	36	-17
	POFP	0	-71	-71	0	-71	-71	0	-70	-71
	HTPinf	-1	-6	-5	1	-4	-5	1	-4	-5
	MEP	-1	-1	0	3	3	0	6	6	0
	GWP100	-12	-16	-4	-9	-13	-4	-1	-5	-4
	PMFP	-1	-91	-90	-1	-91	-90	-1	-91	-90
	FEP	-3	-3	0	2	2	0	5	5	0
	TAP100	0	-94	-94	0	-94	-94	0	-94	-94
	FETPinf	0	0	0	0	0	0	0	0	0
	METPinf	0	0	0	0	0	0	0	0	0
smelting and refining of nickel concentrate, 7% Ni (CN)	TETPinf	-2	-3	-1	7	7	-1	11	10	-1
	POFP	-1	-45	-44	-1	-45	-44	0	-44	-44
	HTPinf	0	-2	-2	0	-2	-2	1	-1	-2
	MEP	-1	-43	-42	1	-43	-44	2	-42	-44
	GWP100	-2	-26	-24	-2	-25	-24	-1	-24	-24
	PMFP	-4	-49	-45	-3	-48	-45	-3	-48	-45
	FEP	0	0	0	0	0	0	2	2	0
	TAP100	-1	-52	-50	0	-51	-51	0	-51	-51
	FETPinf	0	0	0	0	0	0	0	0	0
	METPinf	0	0	0	0	0	0	0	0	0
cobalt production (GLO)	TETPinf	-3	-45	-42	21	-44	-65	33	-35	-68
	POFP	-6	-17	-11	-6	-17	-11	-4	-15	-11
	HTPinf	-1	-20	-19	0	-19	-19	1	-18	-19
	MEP	-6	-12	-7	1	-7	-8	3	-5	-8
	GWP100	-7	-9	-3	-5	-7	-3	-1	-4	-3
	PMFP	-6	-45	-39	-5	-45	-40	-5	-45	-40
	FEP	-5	-4	0	0	0	0	8	8	0
	TAP100	-3	-48	-45	-2	-47	-46	-1	-47	-46
	FETPinf	0	0	0	1	1	0	1	1	0
	METPinf	0	-5	-6	1	-5	-6	1	-5	-6

		Scenario								
Activity	Impact Category	SSP1	SSP1 + VSI	Δ	SSP2	SSP2 + VSI	Δ%	SSP5	SSP5 + VSI	Δ
spodumene production (AU)	TETPinf	13	13	0	99	99	0	172	172	0
	POFP	-3	-3	0	-3	-3	0	2	2	0
	HTPinf	-39	-39	0	-33	-33	0	-30	-30	0
	MEP	-5	-5	0	-4	-4	0	1	1	0
	GWP100	-22	-22	0	-19	-19	0	7	7	0
	PMFP	0	-90	-90	0	-90	-90	0	-90	-90
	FEP	-54	-54	0	-44	-44	0	-45	-45	0
	TAP100	-8	-8	0	-8	-8	0	-1	-1	0
	FETPinf	-23	-23	0	-18	-18	0	-20	-20	0
	METPinf	-24	-24	0	-19	-19	0	-21	-21	0
spodumene production (RoW)	TETPinf	13	13	0	149	149	0	298	298	0
	POFP	-7	-7	0	-7	-7	0	-3	-3	0
	HTPinf	-26	-26	0	-26	-26	0	31	31	0
	MEP	-8	-8	0	-6	-6	0	-1	-1	0
	GWP100	-29	-29	0	-27	-27	0	2	2	0
	PMFP	-1	-90	-89	-1	-91	-89	-1	-91	-89
	FEP	-35	-35	0	-36	-36	0	54	54	0
	TAP100	-12	-12	0	-11	-11	0	-8	-8	0
	FETPinf	-1	-1	0	0	0	0	21	21	0
	METPinf	-2	-2	0	-1	-1	0	20	20	0
lithium carbonate production, from spodumene (CN)	TETPinf	-15	-15	0	44	44	0	75	75	0
	POFP	-8	-11	-3	-8	-11	-3	-5	-8	-3
	HTPinf	-6	-6	0	-6	-6	0	23	23	0
	MEP	-3	-68	-65	-2	-68	-67	1	-66	-66
	GWP100	-19	-19	0	-20	-20	0	3	3	0
	PMFP	-9	-44	-36	-9	-44	-36	-7	-43	-36
	FEP	-7	-56	-49	-9	-58	-50	41	-3	-44
	TAP100	-7	-8	-1	-6	-7	-1	-4	-5	-1
	FETPinf	1	-33	-33	1	-33	-33	5	-28	-33
	METPinf	1	-3	-3	1	-3	-3	7	4	-3
manganese(III) oxide production (RoW	TETPinf	-16	-16	0	89	89	0	165	165	0
	POFP	-24	-24	0	-25	-25	0	-4	-4	0
	HTPinf	-30	-30	0	-32	-32	0	-22	-22	0
	MEP	-26	-26	0	-21	-21	0	-9	-9	0
	GWP100	-24	-39	-15	-24	-39	-15	4	-10	-14
	PMFP	-26	-26	0	-27	-27	0	-22	-22	0
	FEP	-49	-49	0	-52	-52	0	-32	-32	0
	TAP100	-29	-29	0	-29	-29	0	-25	-25	0
	FETPinf	0	0	0	0	0	0	-2	-2	0
	METPinf	-1	-1	0	-1	-1	0	-3	-3	0
manganese dioxide production (GLO)	TETPinf	-17	-17	0	72	72	0	129	129	0
	POFP	-21	-21	0	-21	-21	0	-5	-5	0
	HTPinf	-4	-72	-68	-5	-72	-67	-2	-69	-67
	MEP	-24	-24	0	-17	-17	0	-5	-5	0
	GWP100	-25	-25	-1	-25	-25	-1	3	2	-1
	PMFP	-20	-20	0	-20	-20	0	-17	-17	0
	FEP	-38	-38	0	-40	-40	0	-13	-13	0
	TAP100	-16	-16	0	-15	-15	0	-13	-13	0
	FETPinf	0	-5	-5	1	-5	-5	1	-4	-5
	METPinf	0	-8	-8	0	-8	-8	0	-7	-8
manganese sulfate production (GLO)	TETPinf	-14	-14	0	72	72	0	126	126	0
	POFP	-10	-11	-2	-9	-11	-2	-5	-7	-2
	HTPinf	-3	-76	-72	-3	-76	-73	2	-70	-72
	MEP	-20	-20	0	-14	-14	0	-2	-2	0
	GWP100	-28	-28	0	-28	-28	0	0	0	0
	PMFP	-8	-11	-3	-8	-11	-3	-7	-10	-3
	FEP	-33	-33	0	-35	-35	0	29	29	0
	TAP100	-3	-6	-4	-2	-6	-4	-2	-5	-4
	FETPinf	0	-15	-15	0	-15	-15	4	-10	-15
	METPinf	0	-16	-16	0	-16	-16	4	-12	-16

6.4 Discussion

This study aimed to evaluate the prospective lifecycle impacts of NMC111 oxide production and to assess the potential of VSIs in mitigating these impacts across varying SSPs. By integrating VSI-aligned environmental mitigation technologies, such as APCDs, with SSPs (drawing from works from Mendoza Beltran et al. (2020)), our study expands on prior lifecycle assessments implemented with premise (Sacchi et al., 2022) applied to ecoinvent 3.8 (cutoff version) by incorporating dynamic changes in both background and foreground-level systems. Crucially, the numerical results we present are meant as an illustration of how prospective LCA can capture future-oriented changes, rather than as definitive, fixed predictions. Additionally, we explored the individual mining and mineral processing unit processes involved in the production of NMC111 oxide, providing a granular perspective on their environmental impacts and mitigation potential. Given that the inventories extracted from ecoinvent 3.8 rely on processes that may not reflect the most recent industrial changes, our results likely underestimate (or overestimate) the potential of certain emergent technologies. Nonetheless, the strength of the prospective LCA framework is its modular design, allowing future updates as more robust data sources become available.

Our findings demonstrate that while background system improvements, such as decarbonized electricity grids, are critical drivers of impact reductions, the adoption of VSI-aligned mitigation technologies offers complementary benefits. The former results are consistent with previous works that have shown global warming potential reduction for battery cell production (inclusive of anode material such as NMC oxides) (Xu et al., 2022), and battery-grade nickel (Harpprecht et al., 2021). The latter results, pertaining to voluntary adoption of mitigation technologies, are novel to the best of our knowledge (Harpprecht et al., 2024). They extend prior work by explicitly modelling VSI-aligned environmental mitigation technologies and quantifying their contributions to environmental performance. These technologies were evaluated for their potential to mitigate emissions to air and soil at mining operations, focusing on the most impactful elementary flows identified in our hotspot analysis. For instance, APCDs showed significant potential to reduce particulate matter formation (PMFP) and terrestrial acidification (TAP100), while green reagents contributed to reductions in global warming potential (GWP100) in certain unit processes. These findings emphasize the importance of coupling systemic changes in energy supply with targeted operational interventions.

The results reveal that nickel production consistently exhibits the highest mitigation potential among the three subsystems examined, with technologies such as APCDs achieving up to 75% reductions in PMFP and TAP100. In contrast, lithium production demonstrated more limited mitigation opportunities at the operational level, with most impact reductions stemming from background system changes, such as a greener electricity supply. Manganese-related processes showed notable potential for reductions in human toxicity impacts through the use of advanced heavy metal capture technologies. These process-specific findings, however, may be caused by data scarcity, exacerbated in prospective LCA. The data constraints of ecoinvent 3.8 were particularly exacerbated for lithium, with very few limited generic operations. Moreover, inventories for nickel mining were often generalised and not project-specific. This, combined with an inherently uncertain future, means that the exact percentages or absolute figures should be interpreted with caution. This is a significant limitation of this study, and was already flagged in several other prospective LCA studies (Arvidsson et al., 2018). It is important to note that these results show the direction and possible magnitude of impact reductions rather than a final quantitative benchmark.

These limitations suggest directions for future research. First, efforts should be made to fill foreground data gaps, an effort that is being addressed by generating high-quality inventories (Khakmardan et al., 2023; Schenker et al., 2022), which could be incorporated into LCA databases that can be used in conjunction with *premise* to generate futurized inventories. Second, prospective LCAs should aim to incorporate the life cycle inventories of the mitigation technologies themselves, as these may introduce new impacts (e.g., energy and material requirements for APCDs or MBRs). Third, while this study focuses on NMC111 oxide production, many of the mitigation strategies explored (e.g., particulate and SO_2 capture, process water treatment) could be adapted to other material supply chains, such as copper. Likewise, reductions in the impacts of nickel, lithium, and manganese production could provide benefits across various sectors, including stainless steel, fuel cells, and alternative battery chemistries.

6.5 Conclusion

The decarbonization of the transportation sector is driving unprecedented demand for lithium-ion batteries, necessitating the NMC oxides. This, in turn, requires increased mining and processing of battery-grade lithium, nickel, and manganese, often in resource-rich regions of the global south. These operations, while critical for enabling the energy transition, present localized environmental challenges that must be mitigated to ensure sustainable supply chains. In response, this study modelled the future lifecycle impacts of NMC111 oxide production and its constituent mineral activities, integrating voluntary sustainability initiatives (VSIs) taking the form of emission mitigation technologies. By integrating VSI-aligned environmental mitigation technologies, such as Air Pollution Control Devices (APCDs), with expected decarbonization from Shared Socioeconomic Pathways (SSPs), the analysis demonstrates the importance of coupling systemic energy transitions with targeted interventions at mining and mineral processing operations.

Our findings reveal that while improvements at the NMC111 oxide production level can be modest (below 15%) as per **Figures 36** and **37**, significant mitigation potential exists at the level of individual mineral extraction and processing activities (sometimes as high as 90%) as per **Figure 38**. This is achieved through direct reductions in emissions to air and soil, enabled by VSI-aligned technologies such as APCDs and bioreactors. Our results corroborate that systemic changes in background systems, such as decarbonized electricity grids, provide substantial reductions in categories like global warming potential (Harpprecht et al., 2024; Harpprecht et al., 2021; Xu et al., 2022), while VSI-aligned technologies effectively address emissions to air and soil, delivering measurable benefits in particulate matter formation and terrestrial acidification. These findings underscore the relevance of integrating mitigation technologies into broader sustainability frameworks. However, it is critical to view these figures as illustrations of what is technologically plausible given certain assumptions about background decarbonization and operational interventions, rather than fixed forecasts.

Despite our contribution, the study has a range of limitations. First and foremost, by using data from ecoinvent 3.8, our study is constrained by the scarcity of high-quality, first-hand data for the foreground inventory. Also, the mitigation coefficients used are based on available data and assume logistic growth in adoption, which may not fully capture site-specific conditions. Moreover, by assuming full mitigation achieved, we modelled a techno-optimistic future, an often common pitfall of prospective LCAs (Prospective LCA network, 2024). Lastly, our background scenarios rely exclusively on the “Base” variants of SSP1, SSP2, and SSP5. More ambitious trajectories, such as RCP 2.6 (<2 °C) or RCP 1.9 (<1.5 °C), would further decarbonise the electricity supply and could shift the relative importance of VSI-driven improvements. Exploring those low-carbon pathways is a logical next step for future prospective LCA studies. To address these challenges and support the refinement of this work, please contact the authors if you wish to receive the LCI data. The full LCI data could not be shared openly here due to the End User Licence Agreement of ecoinvent. If you have an ecoinvent license, the authors can share the entire dataset with you.

Looking ahead, addressing data quality limitations is crucial, both at a background and foreground level. Further research is also needed to explore the socioeconomic dynamics of VSI adoption and its financial scalability across diverse geographic-, commodity-, and operational contexts. By bridging operational improvements with systemic energy transitions, the battery sector can support the sector-wide decarbonization of the transportation sector, whilst preserving the quality of life of local communities around mining operations. Equally important is advancing the discussion on publicly available inventory data itself. A future in which site-specific data are widely accessible would dramatically enhance transparency and accountability, empowering researchers, policy analysts, and industry stakeholders to apply prospective LCA more rigorously to local contexts.

These findings emphasize the importance of coupling systemic changes in energy supply with targeted operational interventions. This highlights a key advantage of prospective LCA, allowing analysts, policymakers, and industry stakeholders to see how different technological or policy pathways might unfold over time and where targeted interventions could yield significant environmental benefits. Policymakers should consider regulatory frameworks that support the adoption of VSI-aligned technologies to complement global-level decarbonisation policies. Stricter and broader emission reporting standards should be advocated for, and financial mechanisms such as green premiums for low-impact materials implemented (beyond *green premiums* that solely benchmark CO_2-eq. emissions (London Metal Exchange, 2024a)). For mining companies, investments in emissions control technologies and process optimization represent critical pathways to achieving measurable reductions in environmental impacts, albeit these are only likely to be implemented with clear market signals. Ultimately, the prospective LCA approach we adopt and build upon offers a roadmap for refining these strategies when site-specific data becomes available.

7 DISCUSSION

This thesis focuses on deepening our understanding of Voluntary Sustainability Initiatives within the battery minerals sector, an area of critical importance as the transportation industry undergoes rapid electrification to mitigate climate change. It adopted a multi-method, integrative approach and the research results advance knowledge across four key dimensions: (1) identifying drivers and barriers to VSI adoption within operations mining for battery minerals; (2) eliciting stakeholder perspectives and complex system interactions through group-model systems modelling; (3) examining the transnational diffusion of sustainability-oriented innovations in mining industry networks; and (4) assessing the potential environmental benefits of VSI-aligned interventions using prospective life cycle assessment. Taken together, these distinct pieces of work build on top of each other to expand our collective knowledge on how multiple factors affect VSI adoption within this sector, how far they can go, and how much environmental impact they could mitigate.

7.1 *Answering the research questions*

7.1.1 RQ1: What is driving the adoption of voluntary sustainability initiatives in lithium-ion battery minerals' supply chains?

From the first study (**Chapter 3**), a thematic analysis of the literature revealed a series of drivers that reinforce findings by scholars who emphasise market forces and stakeholder pressure as central to VSI uptake. These include increased need for frameworks that improve company–community communication, supply-chain disruption risk mitigation, and investment attraction.

Regarding the need for frameworks that improve company–community communication, our review confirms that local conflicts, including opposition during pre-operational mine stages, remain ubiquitously cited in the literature, often translate to financial impact, and impact a company's social licence to operate (Franks et al., 2014a; Moffat & Zhang, 2014). Therefore, companies may pursue voluntary sustainability initiatives as a means to signal engagement with local stakeholders and pre-empt reputational damage or outright project closures. This finding reinforces prior analysis, which sees CSR and related programs primarily as risk management tools (Agusdinata et al., 2023).

However, our results also complicate this narrative by underscoring that adopting a VSI does not guarantee genuine community acceptance. Cases such as the Jadar Lithium mine project in Serbia illustrate how public opposition can persist despite membership in globally recognised frameworks (Rio Tinto, 2022; Undisciplined environments, 2023). This supports the discussion from previous authors, in which CSR practices have been criticised as ways to circumnavigate popular discontent. An example of corporate dissonance is the Weda Bay Nickel (WBN) Mine Project on Halmahera Island, Indonesia. Palpacuer and Roussey (2023) described the repression and defeat of several countermovements, also corroborated by the Environmental Justice Atlas (EJ Atlas, 2023), whilst Eramet describes it as a *'success story'* (Eramet, 2023). Hudayana et al. (2020) conclude that communal conflicts can be resolved through cooperation between companies and communities through an established mechanism for compensation. Such financial compensation might be sufficient to eliminate public opposition, but no studies have shown a direct correlation with long-lasting sustainability goals.

Beyond local conflicts, supply-chain disruption risk ranks among the most prominent drivers. Lithium, nickel, cobalt, and manganese face high geopolitical or resource concentration risk (Helbig et al., 2018), compelling downstream manufacturers, such as EV manufacturers, to demand verifiable responsible sourcing. Our analysis builds on previous findings that emphasise the importance of long-term supply strategies to address supply risk through cross-sector collaboration (Petavratzi & Gunn, 2023), with VSIs potentially playing a role in signalling risk management and mitigation through transparent adaptive management. Additionally, new and upcoming regulatory frameworks, such as the EU Battery Regulation (Parliament, 2023), are strengthening accountability measures. While these regulations are mandatory, the transnational nature of battery minerals means that voluntary management practices at mine sites can serve as a bridge to meet or exceed these evolving legal baselines. This corroborates earlier observations that consumer-facing companies play a role in pressuring upstream suppliers to conform to voluntary initiatives (Amnesty International, 2017b; Young & Fonseca, 2010). Lastly, institutional investors also emerge as key drivers, aligning with previous works that showed shareholder proposals and impact investing can spur corporate adoption of sustainability standards (Dyck et al., 2019).

Besides the drivers mentioned, our review also highlights barriers like short-term greenwashing and traceability challenges. Greenwashing can undermine the sincerity of company–community engagement, while provenance tracking difficulties, especially at smelters (Young et al., 2019), limit the effectiveness of mine-level standards. Consequently, the presence of robust drivers does not automatically translate to broad or genuine VSI adoption.

All in all, companies may be motivated to reduce supply-chain risk, improve market access, meet investor pressure, and incur reputational advantages. Downstream buyers, particularly EV manufacturers and battery producers, increasingly demand transparent, responsibly sourced materials. Barriers, such as complexity, costs, greenwashing concerns, and interoperability challenges, remain prominent and seem to need external incentives to be overcome (e.g., the case of the Chilean government supporting ISO14001 adoption (Newbold, 2006)). These challenges are even more prominent for junior companies. This foundational insight adds nuance to the existing body of VSI literature by narrowing down the analysis to focus on battery mineral producers relevant to a growth-intensive sector.

This research contributes to the expanding body of studies on voluntary sustainability initiatives for battery minerals by identifying the drivers and barriers most relevant to VSI adoption. This alignment is particularly salient as nations seek to avert supply crises and meet energy transition deadlines (Lèbre et al., 2020). The legitimacy of such initiatives remains a contested subject in the literature, evidenced by conflicting drivers around global alliances (e.g., the Global Battery Alliance, Nickel Mark) versus short-term greenwashing. Notably, few studies have holistically assessed the cost–benefit trade-offs involved in certification adoption, and none have systematically explored whether premium pricing might accrue to firms that implement VSIs. Addressing these gaps would reveal how financial and competitive factors shape the adoption landscape. Moreover, global and national industry peak bodies, along with business advisers, increasingly promote voluntary practices as key to retaining a social license to operate (Mayes, 2015). This observation sets the stage for another study of this thesis (**Chapter 5**), examining how industry associations further shape VSI adoption.

7.1.2 RQ2: What systemic factors, informed by stakeholder perspectives, influence the adoption of voluntary sustainability initiatives in battery mineral mining?

To better understand the motivations that shape the adoption of VSIs, industry representatives, NGOs, and academics were included in a group-model-building process (Zagonel, 2002) (**Chapter 4**). This collaboration supported the development of a Causal Loop Diagram (CLD) illustrating feedback loops, systemic archetypes, and key variables influencing VSI uptake within the battery minerals sector. The resulting model highlights how regulatory pressures, downstream consumer expectations, social license considerations, and recycling incentives interconnect. By moving beyond purely conceptual frameworks and constructing a stakeholder-informed systems model, this study provides a segmented perspective on the factors that shape sustainability outcomes for the selected cohort of stakeholders. Prior research on VSI adoption in mining has often focused on single-issue drivers (e.g., reputational risk, community conflict, and investor demand, as presented in **Chapter 3**). Our group-model-building approach bridges this gap by showing how these drivers interact dynamically and supporting an understanding that spans across different clusters of battery minerals' supply chains.

Part of our analysis highlights a "limits to growth" archetype, in which higher recycling rates can alleviate environmental burdens from mining but simultaneously reduce the economic viability of certain operations or undermine local communities' benefit structures from Community Benefit Agreements (CBAs). Our findings extend on recently legislated global recycling mandates (e.g. Parliament (2023)) and how they must be carefully integrated with local socio-economic considerations. This outcome builds on previous discussions on financial returns, such as Gunton et al. (2021), and extends it to suggest a potential disaggregation from operational production and profit.

Another insight from our causal loop diagram (CLD) emphasises how regulatory pressures, OEM requirements, and investor demands converge to drive VSI adoption. As outlined in **Chapter 3**, these were key factors identified in previous literature, and our analysis thus supports those earlier findings. However, I also caution that applying a low-carbon premium to mineral markets may yield unintended consequences. One of the archetypes uncovered in our CLD is the "fixes that fail" archetype: while such a premium can spur the formation of sustainability teams at mine sites, effectively mitigating sources of climate change in the short term, it can also incentivise a narrow focus on compliance rather than holistic environmental stewardship. These insights call into question whether carbon-intensity metrics alone can adequately capture a mining operation's overall ESG performance. This observation is particularly timely given the recent discussions on pre-determined price premiums for green nickel (London Metal Exchange, 2024a, 2024b)

Thirdly, our CLD highlights community well-being as central to maintaining a social license, reinforcing prior claims that community acceptance is non-negotiable for operational stability (Jenkins, 2004; Owen & Kemp, 2013), must be achieved through constant quality engagement (Moffat & Zhang, 2014), and has significant impacts on operational finances (Franks et al., 2014a). However, our co-constructed CLD remains based on the notion of corporate reliance on compensation. Transactional CSR can mask deeper social and environmental grievances (similar to what was seen in RQ1's findings). This supports that social license may be periodically "achieved" but not genuinely secured over a project's lifespan.

To objectively identify key variables and relationships, structural analysis methods within the CLD were employed (Schoenenberger et al., 2021; Xie et al., 2011). To our knowledge, these methodologies have not been previously applied to this context, providing novel insights into the architecture and dynamics underlying VSI uptake. This approach, drawing from social network metrics (Perez & Germon, 2016; Schoenenberger et al., 2021), shines a spotlight on high-leverage points, for instance, the role of a *dedicated sustainability team at a mining operation*, which emerged as one of the most central variables. Such an insight supports the argument in existing literature that well-resourced environmental or sustainability teams are a precondition for the successful implementation of sustainability standards (Ruokonen, 2020). These findings set the stage for quantitative system dynamics modelling, which could further investigate how changes in recycling policies, low-carbon premiums, or community compensation structures quantitatively shape VSI adoption and environmental outcomes over time. Such expansion would refine or revalidate the causal relationships discovered in the CLD.

7.1.3 RQ3: How can the dynamics of industry adoption be characterised for voluntary initiatives aimed at reducing environmental impacts?

Within **Chapter 5,** network theory and diffusion algorithms were employed to explore the transnational character of mining industry affiliations and the role they can play in supporting VSI adoption. Building on the notion that market-driven innovation travels through complex, multi-tiered corporate networks, a dataset of national and international industry associations was compiled, along with their member companies, focusing on the battery minerals sector. A range of studies have been conducted around the innovation dynamics of networks, including eco-innovation through inter-firm networks (Ramkumar et al., 2022), and the role of networks and relationships in driving eco-innovation has been successfully demonstrated (Pellegrini et al., 2019). However, the application of such network analyses has been extremely limited when applied to the mineral sector. Nuss et al. (2016) made a noteworthy contribution in bringing network theory to the analysis of mineral supply chains (Nuss et al., 2016), and more recently, van den Brink et al. (2020) have done work in incorporating network theory into the analysis of cobalt supply chain disruption risk (van den Brink et al., 2020).

Our results showed that international industry associations, such as the International Council on Mining and Metals (ICMM), and commodity-focused groups like the International Lithium Association (ILiA), can accelerate the dissemination of sustainability innovations. Differences in network topology, including isolated clusters and globally connected hubs, shape how rapidly new standards or practices spread. This research builds on previous works in minerals governance and sustainability standards by providing empirical insights into how non-state market-driven initiatives travel through complex, multi-layered corporate networks. This finding extends previous works highlighting the importance of multi-stakeholder or industry-driven frameworks (Franken et al., 2020), going further by quantitatively showing how these bodies affect network diffusion. Specifically, it's observed that companies nested within globally connected hubs are more likely to receive new information or adopt voluntary initiatives than those in isolated clusters, being particularly limiting to national industry associations from Ghana (Ghana Chamber of Mines) and the Philippines (The Chamber of Mines of the Philippines). These findings refine our understanding of the strategic role industry associations play in legitimising and normalising voluntary standards, and the level of power they hold, which they should be accountable for.

Lastly, beyond these findings, our project brings a methodological contribution by employing *Levenshtein* distance for robust name harmonisation across datasets. This approach ensures comparability and accuracy in building large-scale membership networks, addressing a common data-quality issue in analysing the global supply chain.

7.1.4 RQ4: To what extent can environmental impact, when mining for battery minerals, be mitigated through VSI adoption?

Chapter 6 utilised a forward-looking perspective, integrating VSI-inspired mitigation strategies, such as air pollution control devices (APCD) and process efficiency improvements**,** into a prospective lifecycle assessment (pLCA) framework. Focusing on three key production subsystems (manganese sulfate, nickel sulfate, and lithium carbonate, all vital for NMC111 lithium-ion batteries), foreground interventions were superimposed, aligned with potential VSI requirements, on future decarbonization pathways defined by Shared Socioeconomic Pathways (SSPs) and Representative Concentration Pathways (RCPs). We've reinforced previous findings showing the importance of systemic energy transitions in reducing climate impacts (Harpprecht et al., 2024; Harpprecht et al., 2021) and confirmed earlier observations that per-unit global warming potential (GWP) continues to decline over time (Xu et al., 2022). Moreover, I extended this scholarship by revealing that targeted process-level changes from voluntary initiatives (e.g., air emission control devices, wastewater treatment upgrades) can further mitigate local environmental burdens.

Our findings show that nickel-related processes consistently exhibit the highest mitigation potential among the three subsystems examined, with technologies such as APCDs achieving up to 75% reductions in particulate matter formation (PMFP) and terrestrial acidification TAP100. In contrast, lithium-related processes demonstrated more limited mitigation opportunities at the operational level, with most impact reductions stemming from background system changes. Manganese-related processes showed notable potential for reductions in up to 70% human toxicity (HTPinf) impacts using advanced heavy metal capture technologies. We’ve suggested caution when interpreting our findings, which potentially reflect data scarcity, and discussed how these are exacerbated in pLCA, an issue already noted within the pLCA community (Arvidsson et al., 2018).

Lastly, the granularity challenge in pLCA reporting was highlighted. While the overall mitigation effect at the NMC111 oxide level often stayed below 15% by 2040, disaggregated analyses at individual extraction and processing stages sometimes revealed substantially higher gains. For instance, as mentioned, improvements in nickel sulfate production led to significantly reduced PMFP and TAP100. This outcome not only underscores the value of multi-criteria sustainability assessment but also illustrates how VSIs can act as catalysts for environmental improvements under plausible future scenarios, filling gaps that top-down decarbonization initiatives alone may overlook.

7.2 Limitations

While this thesis makes significant contributions to understanding VSIs in the battery minerals sector, each study encountered inherent limitations that suggest avenues for further inquiry and methodological refinement. The range of limitations and suggestions is as follows:

For the paper presented in **Chapter 3**, the thematic analysis relied solely on the existing corpus of academic literature. This being a field that’s moving fast, this presents a slice-in-time other than the state-of-the-art. Also, although this approach helped identify key drivers and barriers to VSI adoption, it may have overlooked practical, real-time insights found in industry publications, grey literature, and corporate sustainability reports. The lack of extensive direct stakeholder perspectives also limits our understanding of how theoretical drivers and barriers manifest within mining operations. However, this has been covered to some extent in the work presented in **Chapter 4**. Long-term studies and impact assessments are needed to determine the enduring effectiveness of VSIs, corroborated by effectiveness frameworks such as the ones presented by Mori Junior et al. (2016). Moreover, impacts of adaptive management strategies such as VSIs can be analysed through the lens of managing cumulative impacts (Franks et al., 2013).

In the second paper (**Chapter 4**), the emphasis on qualitative systems thinking produced a useful conceptual model, presented as a Causal Loop Diagram, but it did not fully capture the system’s quantitative dynamism. Without a quantitative system dynamics model (such as a stock-and-flow diagram), feedback loops cannot be fully explored, threshold effects, or scenario testing with the necessary rigour. The analysis would also benefit from engaging additional stakeholders, such as those from manganese extractive operations (absent from the workshops conducted), to ensure more comprehensive coverage of the sector. Future research should support analytical methods, like structural analysis (Schoenenberger et al., 2021), to identify key leverage points and variables with the greatest potential to drive system change. Furthermore, regionalising and making the models commodity-specific would increase the precision and policy relevance of these models.

For the third paper (**Chapter 5**), the network analysis assumed a uniform innovation adoption across diverse firms, which allowed for the diffusion algorithm to be implemented, but reduced complex entities (firms) to unitary agents. This reduction is not realistic since companies differ widely in their financial capacity, technological readiness, and strategic priorities. Nonetheless, it was necessary for an initial model. Future work could calibrate firm-level parameters, integrating more granular data to reflect heterogeneity in adoption behaviour. Moreover, the selection of industry associations was limited to national associations (e.g., The Mining Association of Canada), one international association (ICMM), and three commodity associations (ILiA, IMnI, Nickel Institute). Incorporating product-oriented leadership organisations, like the Global Battery Alliance, could illuminate how commodity-level expertise aligns with product-specific initiatives.

The fourth and last work (**Chapter 6**) presented data and methodological constraints. Dependence on generic background inventories (ecoinvent 3.8) simplified complex processes. Mitigation coefficients assumed full, logistic adoption curves (starting slow and ramping up), potentially overstating realised improvements at the end of the time period selected. This techno-optimistic approach to prospective lifecycle assessment has been described as an often common pitfall of this method (Prospective LCA network, 2024). In this case, the techno-optimistic approach was applied to understand the limits of future possible improvement. More realistic future modelling could incorporate partial adoption rates, probabilistic approaches, and conditional parameters to better reflect actual operational contexts. However, fully addressing these aspects would require remodelling entire process inventories based on the specific implementation of technologies, rather than simply applying external factors to adjust target inventory items. Higher-quality site-level data would also reduce uncertainty. These limitations highlight the need for improved data quality and transparency within the prospective lifecycle assessment field.

8 CONCLUSION AND RECOMMENDATIONS

As the global effort to electrify transportation and stationary energy storage accelerates, the imperative to secure ethically sourced and environmentally sustainable battery minerals intensifies. This thesis, through its integrative and methodologically diverse approach, explores why and how voluntary sustainability initiatives can be a tool to steer the sector toward more responsible practices. It shows that while VSIs hold promise as tools for risk mitigation, reputational enhancement, and incremental environmental improvements, their effectiveness is conditional and by no means guaranteed. Complex supply chains, data scarcity, divergent stakeholder interests, and the sheer pace of mineral demand growth complicate the translation of voluntary standards into meaningful long-term sustainability outcomes. These findings are encapsulated into four interconnected chapters, presented as follows.

Through a thematic literature analysis, drivers were exposed, such as reputational concerns, investor pressures, market incentives, and community conflict avoidance, that motivate companies to adopt VSIs. Whilst also revealing barriers like potential greenwashing, high certification costs, and provenance tracking issues, complicating how such initiatives truly translate to operational improvements or social license maintenance. In doing so, **Chapter 3** broadly supported scholarship on risk management as a primary function of CSR, but highlights that neither community acceptance nor long-term impact is guaranteed simply by membership in recognised frameworks. Moving from the literature review and integrating stakeholders' perspectives, these insights were extended by constructing a Causal Loop Diagram (CLD) through a group-model-building exercise. Therefore, moving the field beyond theoretical considerations to stakeholder-informed mental models. Through this process, feedback loops were identified. For instance, how recycling incentives can alleviate resource pressure but potentially undermine economic returns or community benefit agreements. The CLD's focus on community well-being as a basis for social license also echoes themes from **Chapter 3**, stressing that stakeholder engagement is more than a box-ticking exercise, it is central to avoiding unintended consequences, here exemplified by archetypes such as the "fixes that fail."

Moving to a systematic, quantitative approach, **Chapter 5** applied network theory and diffusion algorithms to reflect how international associations (e.g., ICMM), commodity-specific groups (e.g., Nickel Institute, ILiA), and national industry associations (e.g., Minerals Council of Australia) shape the pace and reach of VSI-related innovations. These results reinforce that a well-connected "hub" in the global mining network can expedite the flow of best practices, whereas isolated associations are less likely to benefit from or contribute to collective learning. We've discussed how membership structures, ties, and bridging organisations form pathways for knowledge diffusion, particularly relevant to EV battery minerals. Lastly, **Chapter 6** introduced a future-oriented lens and drew from findings from **Chapter 5**, using pLCA to model how VSI-inspired operational changes (e.g., air pollution controls, heavy-metal capture systems) intersect with plausible decarbonization scenarios (SSPs and RCPs). Even though background system changes drive large climate benefits, the foreground interventions often achieved up to 75–90% mitigation in localised categories (e.g., particulate matter formation or human toxicity) for selected nickel or manganese processes. This chapter thus underscores the value of coupling systemic energy transitions with site-specific innovations to address environmental concerns not captured by a sole focus on carbon emissions' reduction.

The findings presented here highlight the power of informed, evidence-based decision-making. By making underlying factors such as drivers, barriers, networks, and environmental outcomes more visible and intelligible, this research aims to empower researchers and stakeholders alike. By openly sharing datasets and source code, this thesis encourages replication, verification, and further innovation, laying the groundwork for more detailed assessments of battery minerals' environmental metrics. Future research can build upon these methods to incorporate more granular, site-specific data, expand the range of environmental and social impact categories considered, and deepen understanding of how evolving geopolitical and market conditions influence VSI uptake and effectiveness. Some suggested future research includes:

i. **Longitudinal studies**: Chapters 3 and 4 are limited by a temporal dimension. Most studies reviewed in **Chapter 3**, and the workshops conducted and presented in **Chapter 4** capture a section in time. Future work could track real-time adoption patterns and long-term outcomes, discerning whether early gains persist or dilute. This will support a better understanding of the effectiveness of VSI as opposed to solely its adoption.

ii. **Advanced system dynamics**: The CLD in Chapter 4 could evolve into a stock-and-flow model, enabling scenario analyses that weigh community compensation structures against recycling mandates, and limits to loss of *biodiversity & ecosystem services* affecting *community well-being*, and by proxy, *social licence to operate*.

iii. **Heterogeneous firm data**: **Chapter 5**'s diffusion model may be enriched by firm-level parameters reflecting different financial capabilities, company size, and number of international operations. This heterogeneity would yield a more realistic view of how eco-innovations spread in unevenly resourced sectors. Publicly available datasets, such as the ones provided by the Responsible Mining Foundation (Responsible Mining Foundation, 2022) can be supportive of such implementation.

iv. **Site-specific LCA data for pLCA**: As revealed in **Chapter 6**, data constraints limit the precision of pLCA results, and local environmental metrics remain underreported. More granular site-level data for nickel, manganese, and lithium production routes, coupled with clearer documentation of technology assumptions embedded in existing life cycle inventories, could ground pLCA scenarios in realistic adoption rates.

Beyond these future research directions, this thesis contributes to a more coherent understanding of how voluntary sustainability initiatives interact with a rapidly changing battery minerals sector. The findings from the literature review performed indicate that reputational concerns, investor pressures, market incentives, and community conflict avoidance are key reasons why companies might adopt VSIs. The causal loop diagrams built through a group-model approach further highlight that air, water, and biodiversity impacts heavily shape community acceptance of mining operations, placing genuine environmental stewardship as part of maintaining a social licence. Meanwhile, industry associations wield substantial power in both creating and promoting VSIs, as their network structures can accelerate the diffusion of these standards, with commodity-specific associations (e.g., Nickel Institute) and international organisations (e.g., ICMM) being able to greatly accelerate or halt the range and pace of innovation adoption. However, the extent to which VSIs actually mitigate environmental impacts remains unverified, requiring transparency and longitudinal independent studies that translate these frameworks into demonstrable on-the-ground outcomes. In addition, the prospective life cycle assessment (pLCA) shows that VSI-inspired mitigation strategies, such as air pollution control devices and filtering membranes, can reduce localised environmental impacts (e.g., particulate matter formation, terrestrial ecotoxicity) by up to 90%, in addition to projected future decarbonization measures. When aggregating results for NMC111 oxide production, the overall impact mitigation in these categories can reach about 15% by 2040. In conclusion, robust accountability, transparent reporting, and site-specific interventions are essential if battery mineral extraction is to align with the sustainability goals proposed by VSIs, especially under the pressures of the current clean energy transition.

Taken together, the four studies presented here bridge analytical scales that are rarely connected in research on mining governance. At the *micro* level, the thesis examines how individual firms respond to reputational, financial, and operational pressures when deciding whether and how to adopt voluntary sustainability initiatives. At the *meso* level, it reveals how networks of associations create diffusion pathways that accelerate (or constrain) the spread of best practices. At the *macro* level, the work situates these organisational and network dynamics within the wider architectures of global governance that link downstream market expectations, international reporting frameworks, and national regulatory settings. By combining these perspectives, the thesis exposes feedbacks and dependencies that would remain invisible if these scales were analysed separately. For example, how corporate adoption decisions are conditioned by association-level legitimacy contests, or how international traceability requirements cascade down to influence community relations at mine sites.

Methodologically, this thesis demonstrates the value of multi-method, system-based inquiry in the social-environmental governance of mineral extraction. The combination of thematic synthesis, participatory causal-loop mapping, network diffusion modelling, and prospective life-cycle assessment moves the analysis from static insights to dynamic understandings of flows of influence, adoption, and impact. Each method addresses the questions raised by the previous: qualitative synthesis identifies motivations and barriers, whereas participatory modelling captures feedbacks and stakeholder reasoning, whilst network analysis quantifies structural constraints and leverage points, and lastly, pLCA translates behavioural and governance shifts into measurable environmental outcomes. This integrated design therefore makes a stronger case for transdisciplinary research that connects literature, practitioner perspectives, and quantitative modelling, an approach that I hope can advance both theory and practice in sustainability transitions research.

Finally, this thesis delivers actionable insights for multiple end users. For the industry, it clarifies which barriers are most binding, how network position shapes diffusion, and which interventions, such as association-led knowledge sharing or commodity-targeted capacity building, can accelerate uptake of responsible practices. For policymakers and NGOs, it identifies leverage points where incentives or reporting requirements can trigger wider systemic change, aligning local practices with global traceability demands. For LCA practitioners and sustainability managers, it connects organisational adoption dynamics to quantifiable impact reductions, demonstrating how firm-level innovation contributes to system-level sustainability outcomes.

Collectively, these findings position the thesis as a whole-of-system account of battery-minerals governance, demonstrating that systemic, multi-method analysis is not only feasible but also uniquely capable of revealing how social, organisational, and technical processes co-evolve in this rapidly transforming sector. By integrating diverse analytical lenses, the thesis moves beyond treating governance, diffusion, and environmental performance as separate domains, instead presenting a unified framework that captures the interdependencies driving change. Therefore, it shows the added value of such integrative approaches for steering the sector toward a genuinely sustainable future.

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A. APPENDIX A: SUPPLEMENTARY MATERIAL TO CHAPTER 3

The supplementary material for **Chapter 3** can be found in the **following** repository:

Mendonca Severiano, B. (2025). Appendix A: Supplementary material to chapter 3 [Zenodo]. https://doi.org/10.5281/zenodo.14788069

B. APPENDIX B: SUPPLEMENTARY MATERIAL TO CHAPTER 4

B.1 WEB-BASED CAUSAL LOOP DIAGRAM

To visualize and analyse the causal relationships and feedback loops identified during the workshops, Kumu was utilised. Kumu is a web-based platform for creating interactive causal loop diagrams. Kumu's capabilities allowed for an intuitive and dynamic representation of the complex interactions within the system (Kumu, 2024). The resulting diagrams are accessible via the following link:

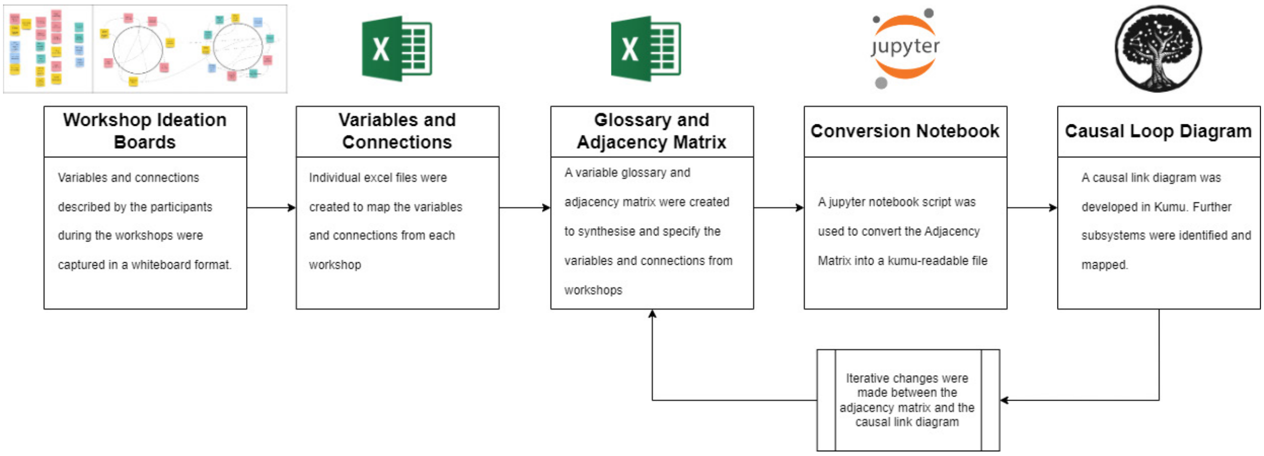
https://kumu.io/bernardo-mendonca/cld-vsi-battery-minerals

B.2 DATA WORKFLOW

The data collection, classification, and processing workflow are depicted in **Figure 39**. Detailed descriptions of the workshops are provided in **Chapter 4.2**, with the outcomes of each individual workshop presented at **Appendix B.4**. Moreover, **Chapter 4.2** of the main manuscript contains further information on the workshop participants. The Excel files used in this study are described in **Appendix B.5**. Further explanations on the causal loop diagrams can be found in **Chapter 4.2**. The code utilized for converting the adjacency matrix to a Kumu-readable file is contained in the supplementary repository:

Mendonca Severiano, B. (2025). Appendix B: Supplementary material to chapter 4 [Zenodo]. https://doi.org/10.5281/zenodo.14788079

Figure 39. Data workflow and storage for the development of the causal loop diagram



B.3 STAKEHOLDERS' WORKSHOPS

B.3.1 WORKSHOP AGENDA

Table 23. Standard workshop agenda

Time	Activity	Description	Methodological Reference
0:00 ~ 0:10	**Welcome / Introductions / Context**	• Thank everyone for making time to attend the session. • Review purpose and agenda of the session.	N/A
0:10 ~ 0:30	**Variables Elicitation**	• Explain system, describe system goal, and how to name variables • Collect variables after prioritizing • Places variables on a board (physical or using software) according to general themes, building clusters.	(Luna-Reyes et al., 2006)
0:30 ~ 0:50	**Connection Circles**	• Introduce the concept of connection circles. • Highlight the idea of causal links with positive and negative polarity. • Encourages groups to start with the prioritized variables. • Consider if new variables should be added. • Participants work on their connection circles • Facilitators to provide support.	(Cohen, 2018)
0:50 ~ 1:00	**Next steps and closing**	• Thank group for their contributions and participation. • Discuss next steps	(Chalise et al., 2010)

B.3.2 DESCRIPTION OF WORKSHOP GOALS AND HOW TO NAME VARIABLES

During the Variables Elicitation part of the workshop, participants agree on a goal and focus and are queried to participants were variables that "influence the system the most", the following goal and variable influence was presented:

(i) **Workshop Goal**: Devise a list of variables that influence the system

(ii) **The influence such variables have on the system:** Increased voluntary mitigation of environmental & social impacts at a mining operation by companies mining for battery minerals

Moreover, a standardized formula to name variables was used, based on (Luna-Reyes et al., 2006), and the following guidelines were presented to the participants on "How to name variables":

(i) **Use nouns:**
Avoid verbs, action phrases, or terms that suggest a direction of change.
For example, "Decreasing Sales" will cause confusion when you read through the diagram and ask what happens when "Decreasing Sales" increases or decreases. "Sales" is a better choice.

(ii) **Variables should be quantities that can vary over time:**
Things that can rise or fall, grow or decline.

(iii) **Is time used in any of the variables?**
Time itself should generally not be included as a causal agent. When something changes over time, it generally does not change because of the passage of time.

B.3.3 PROMPTS TO GUIDE VARIABLES ELICITATION

Q1: What factors most significantly influence the environmental footprint of the lithium-ion battery supply chain?

Q2: Which variables are critical in assessing the potential for environmental impacts of lithium-ion battery mineral mining?

Q3: Are there variables that are affected by government regulations and policies?

Q4: Which market-driven variables are most influential in motivating or hindering the adoption of VSIs?

Q5: What economic variables play a pivotal role in determining the feasibility and willingness to adopt VSIs?

Q6: How do technological advancements and limitations act as variables affecting the adoption of VSIs?

Q7: Which variables related to supply chain transparency and traceability are essential for the adoption of VSIs?

If the prompt wasn't so effective, and extra question was asked afterwards to complement the question: *"How do these influence the decision to adopt voluntary sustainability initiatives?"*

B.4 VARIABLES AND CONNECTED CIRCLES FROM WORKSHOPS

The following images are a direct export of the workshop results with the participants described in **Chapter 4.2**. Note that for workshop #1 there is not export since the workshop was face-to-face. Pictures of the whiteboard were taken and can be made available on request.

Figure 40. Outcomes of workshop #2. On the left panel, a list of variables referred by the participant(s) as the most influential to the system. On the right panel, three 'connected circles' in which the participant(s) attempt to connect such variables through links of causation.

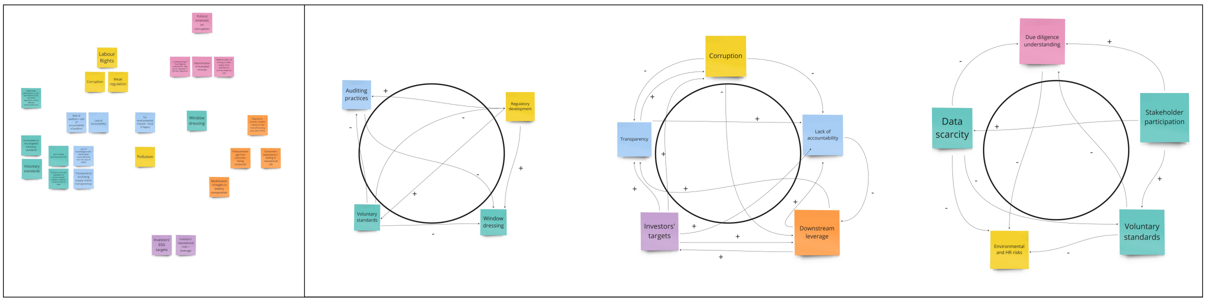


Figure 41. Outcomes of workshop #3. On the left panel, a list of variables referred by the participant(s) as the most influential to the system. On the right panel, two 'connected circles' in which the participant(s) attempt to connect such variables through links of causation.

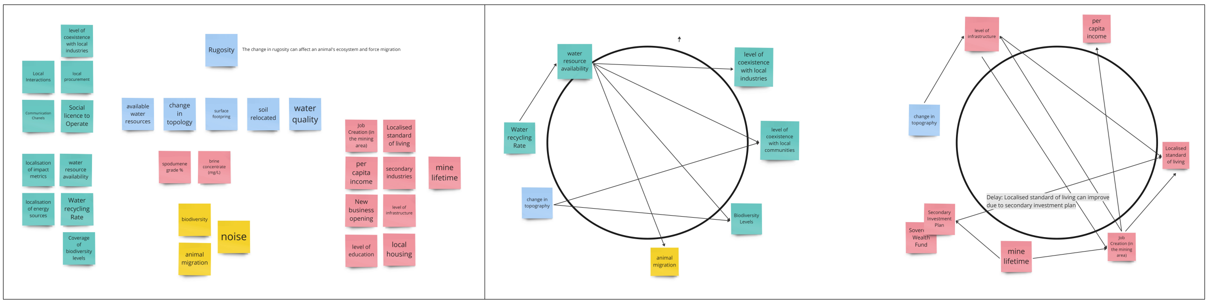


Figure 42. Outcomes of workshop #4. On the left panel, a list of variables referred by the participant(s) as the most influential to the system. On the right panel, two 'connected circles' in which the participant(s) attempt to connect such variables through links of causation.

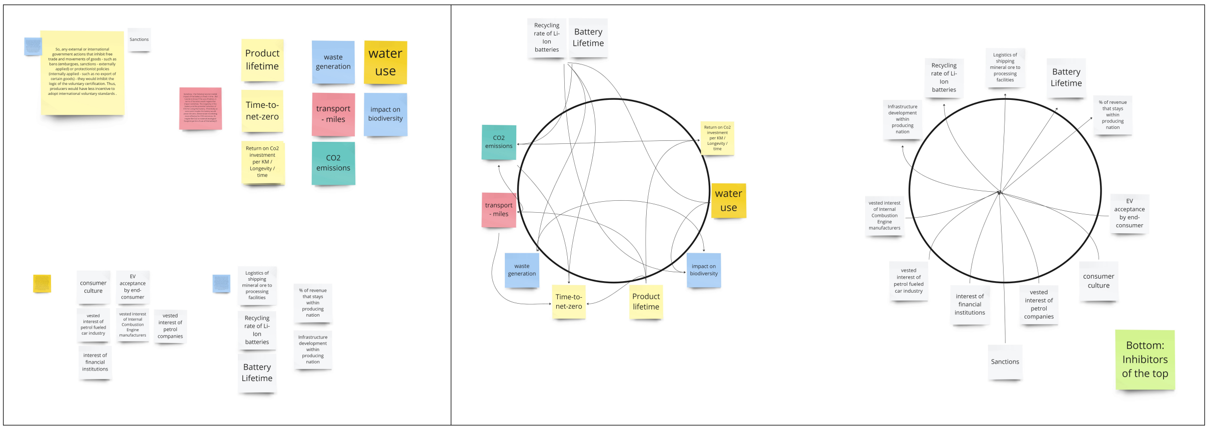


Figure 43. Outcomes of workshop #5. On the left panel, a list of variables referred by the participant(s) as the most influential to the system. On the right panel, two 'connected circles' in which the participant(s) attempt to connect such variables through links of causation.

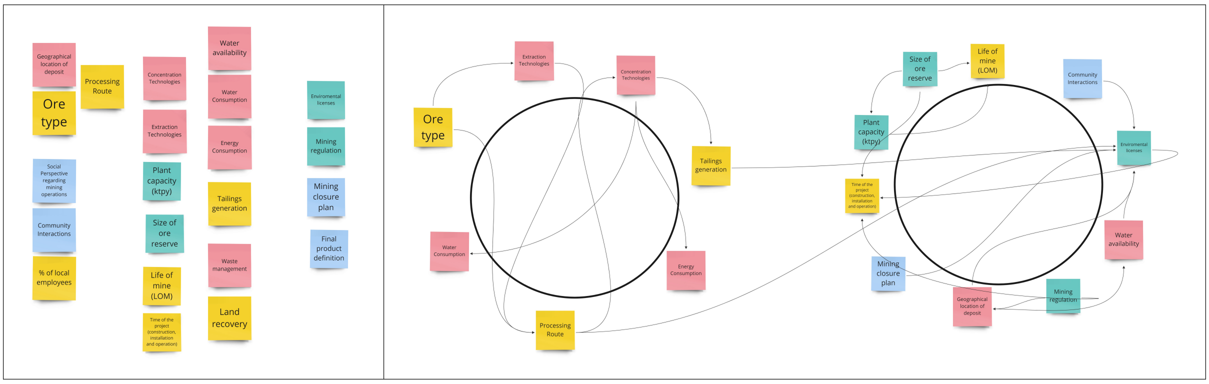


Figure 44. Outcomes of workshop #6. On the left panel, a list of variables referred by the participant(s) as the most influential to the system. On the right panel, two 'connected circles' in which the participant(s) attempt to connect such variables through links of causation.

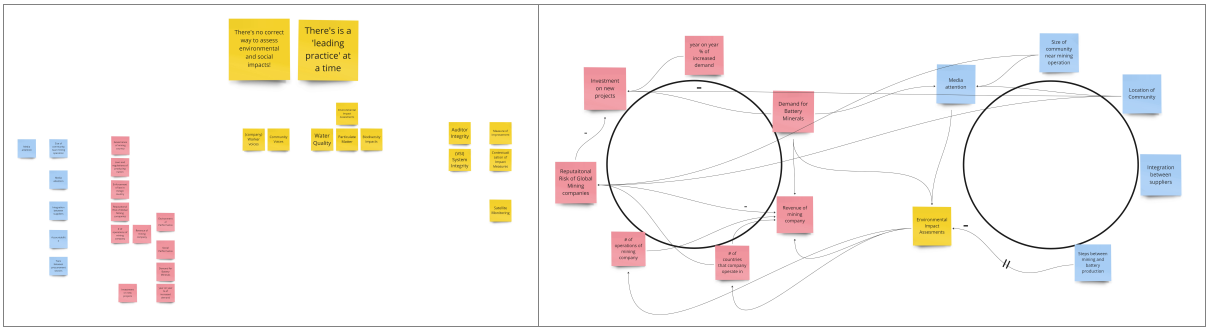


Figure 45. Outcomes of workshop #7. On the left panel, a list of variables referred by the participant(s) as the most influential to the system. On the right panel, two 'connected circles' in which the participant(s) attempt to connect such variables through links of causation.

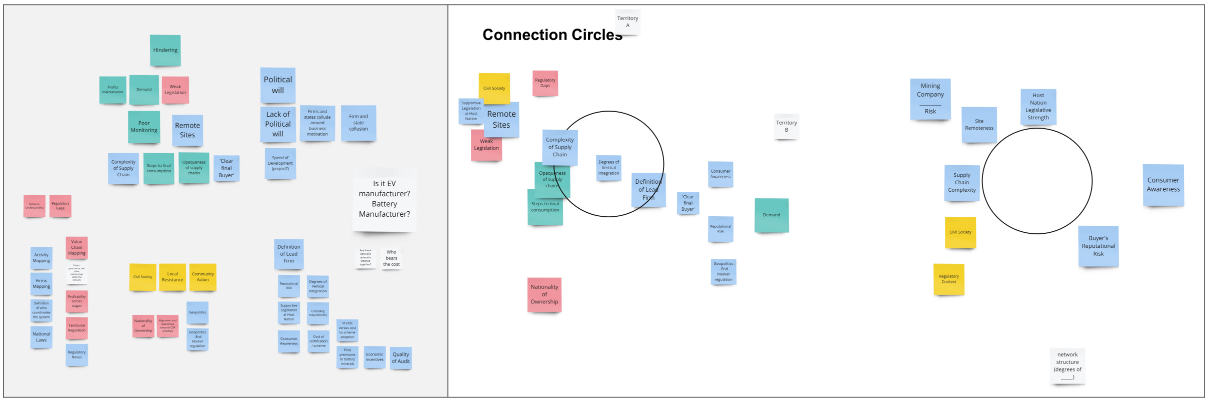


Figure 46. Outcomes of workshop 8. On the left panel, a list of variables referred by the participant(s) as the most influential to the system. On the right panel, two 'connected circles' in which the participant(s) attempt to connect such variables through links

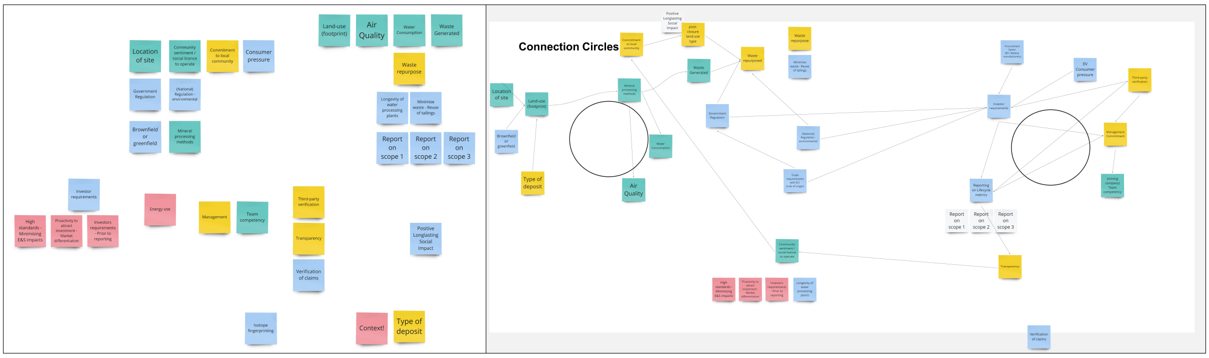


Figure 47. Outcomes of workshop #9. On the left panel, a list of variables referred by the participant(s) as the most influential to the system. On the right panel, one 'connected circle' in which the participant(s) attempt to connect such variables through links of causation. No substantial links have been made in this workshop.

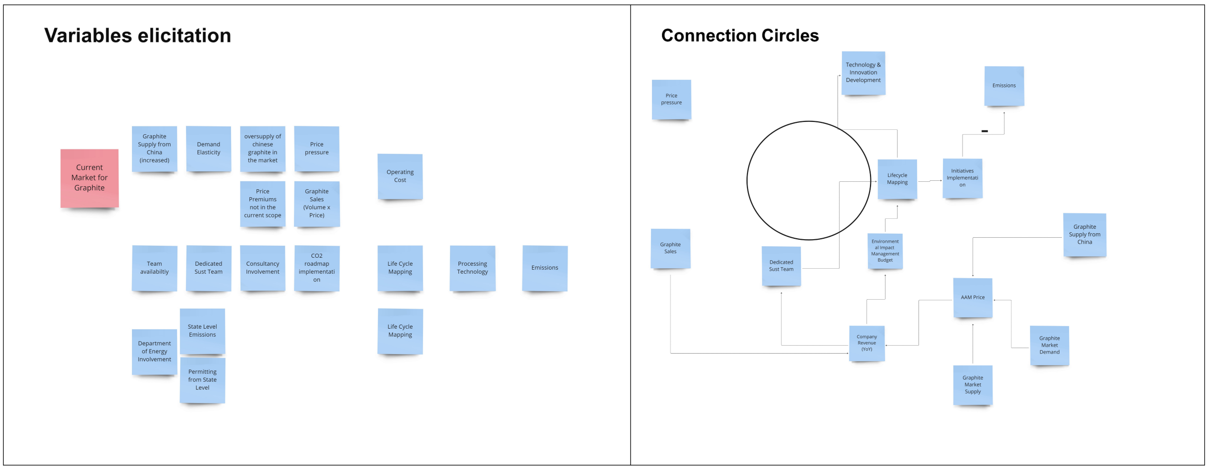


Figure 48. Outcomes of workshop #10. On the left panel, a list of variables referred by the participant(s) as the most influential to the system. On the right panel, two 'connected circles' in which the participant(s) attempt to connect such variables through links of causation.

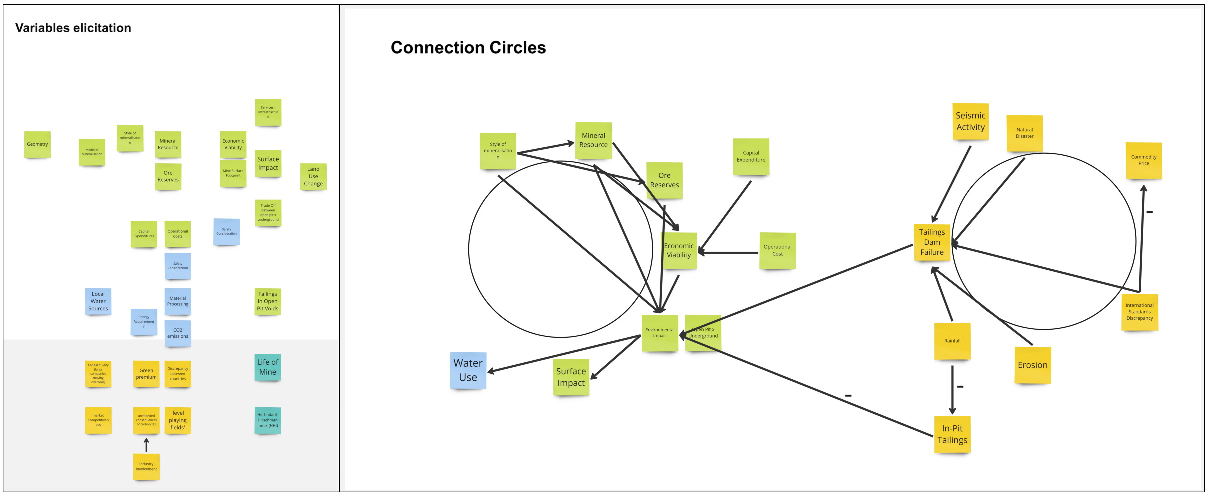


Figure 49. Outcomes of workshop #11. On the left panel, a list of variables referred by the participant(s) as the most influential to the system. On the right panel, two 'connected circles' in which the participant(s) attempt to connect such variables through links of causation.

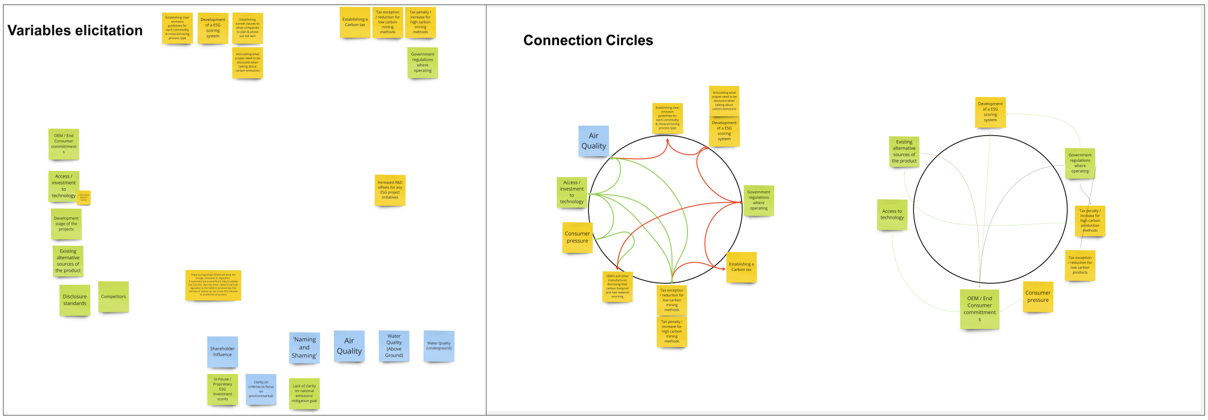
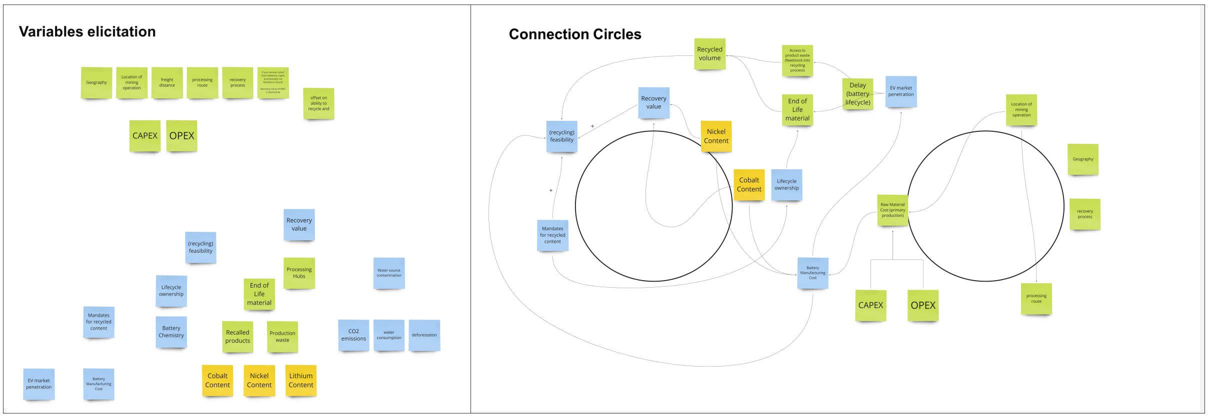


Figure 50. Outcomes of workshop #12. On the left panel, a list of variables referred by the participant(s) as the most influential to the system. On the right panel, two 'connected circles' in which the participant(s) attempt to connect such variables through links of causation.



B.5 EXCEL FILES

B.5.1 VARIABLES GLOSSARY AND ADJACENCY MATRIX

To ensure clarity and consistency in our analysis, a comprehensive variables glossary was developed. This glossary is crucial as it standardizes the terminology used, ensuring that all stakeholders have a common understanding of each variable's definition and role within the system (Dhirasasna et al., 2020).

Building on this glossary, an adjacency matrix was created, a tool used to systematically represent the relationships between variables. An adjacency matrix is a square matrix used to describe the directed relationships between variables, where each cell indicates the presence or absence of a connection. This matrix is instrumental in constructing causal loop diagrams as it facilitates the visualization of direct interactions and feedback loops within the system (Shen & Ma, 2007; Visualisation Design Lab).

The detailed variables glossary and the adjacency matrix can be found in the following repository:

Mendonca Severiano, B. (2025). Appendix B: Supplementary material to chapter 4 [Zenodo]. https://doi.org/10.5281/zenodo.14788079

B.6 ALGORITHMS AND METRICS

B.6.1 SLPA

The Speaker-listener Label Propagation Algorithm (SLPA) is a method used for detecting communities within networks (Xie et al., 2011). SLPA works in three main steps, as showcased with the pseudocode in **Algorithm 1**, also from(Xie et al., 2011):

(i) Initialization: Each node in the network is initialized with a unique label.

(ii) Iterative Propagation:

   a. Speaking Phase: Each node (speaker) selects a label from its memory based on a probability distribution.

   b. Listening Phase: Each node (listener) updates its memory by adding the most frequently heard label from its neighbours

(iii) Post-processing: After a predefined number of iterations, the final labels in the nodes' memories are used to determine the community structure. Nodes can belong to multiple communities based on the labels they possess.

Algorithm 1: SLPA(T,r) from (Xie et al., 2011)

```
[n,Nodes]=loadnetwork();
Stage 1: initialization
for i= 1 : n do
      Nodes(i).Mem=i;
Stage 2: evolution
for t= 1 : T do
      Nodes.ShuffleOrder();
      for i= 1 : n do
            Listener=Nodes(i);
            Speakers=Nodes(i).getNbs();
            for j= 1 : Speakers.len do
                  LabelList(j)=
                  Speakers(j).speakerRule();
            w=Listener.listenerRule(LabelList);
            Listener.Mem.add(w);
Stage 3: post-processing
for i= 1 : n do
      remove Nodes(i) labels seen with probability < r;
```

B.6.2 NETWORK METRICS

B.6.2.1 BETWEENNESS CENTRALITY

Betweenness centrality is a measure of the extent to which a node lies on the shortest paths between other nodes in the network. It quantifies the importance of a node in facilitating communication or the flow of information between pairs of nodes (Freeman, 1977). The betweenness centrality of v is represented by:

$$BV(v) = \sum_{s \neq v \neq t} \frac{\sigma_{st}(v)}{\sigma_{st}}$$

where:

(i) σ_{st} is the number of shortest paths from node s to node t
(ii) $\sigma_{st}(v)$ is the number of such paths that go through v

B.6.2.2 DEGREE CENTRALITY

Degree centrality is a measure of the number of connections a node has in the network. It indicates the immediate influence of a node by counting its direct connections. The degree of a node v is simply the count of the edges connected to v, represented by:

$$DC(v) = \deg(v)$$

B.6.2.3 CLOSENESS CENTRALITY

Closeness centrality measures how close a node is to all other nodes in the network. It is the reciprocal of the sum of the shortest path distances from a node to all other nodes. In general, elements with high closeness can influence other nodes most easily and usually have high “visibility” into what is happening across the network (Perez & Germon, 2016).

$$CC(v) = \frac{1}{\sum_{t \in V} d(v,t)}$$

Where:

(i) $d(v,t)$ is the shortest path distance between nodes v and t

(ii) V is the set of all nodes

C. APPENDIX C: SUPPLEMENTARY MATERIAL TO CHAPTER 5

C.1 DATASET OF INDUSTRY ASSOCIATION

The datasets generated and analysed within Chapter 5 are publicly available in the following repository:

https://zenodo.org/records/15393296

Moreover, all the remaining source code can be found in:

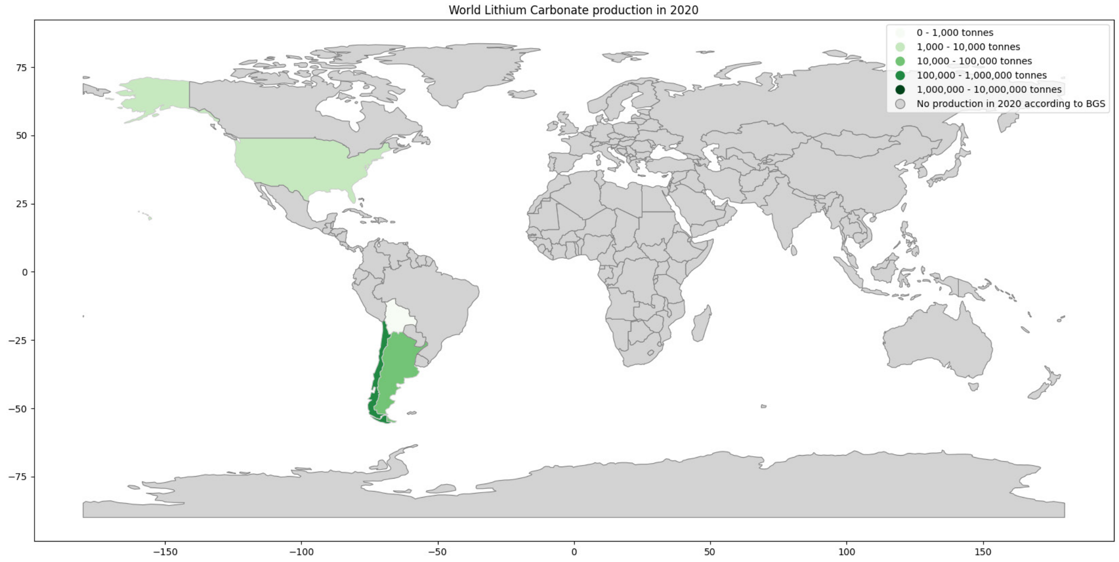
Mendonca Severiano, B. (2025). Appendix C: Supplementary material to chapter 5 [Zenodo]. https://doi.org/10.5281/zenodo.14788095

C.2 SUPPORTING INFORMATION ON COUNTRY SELECTION

C.2.1 TOP LITHIUM PRODUCING COUNTRIES

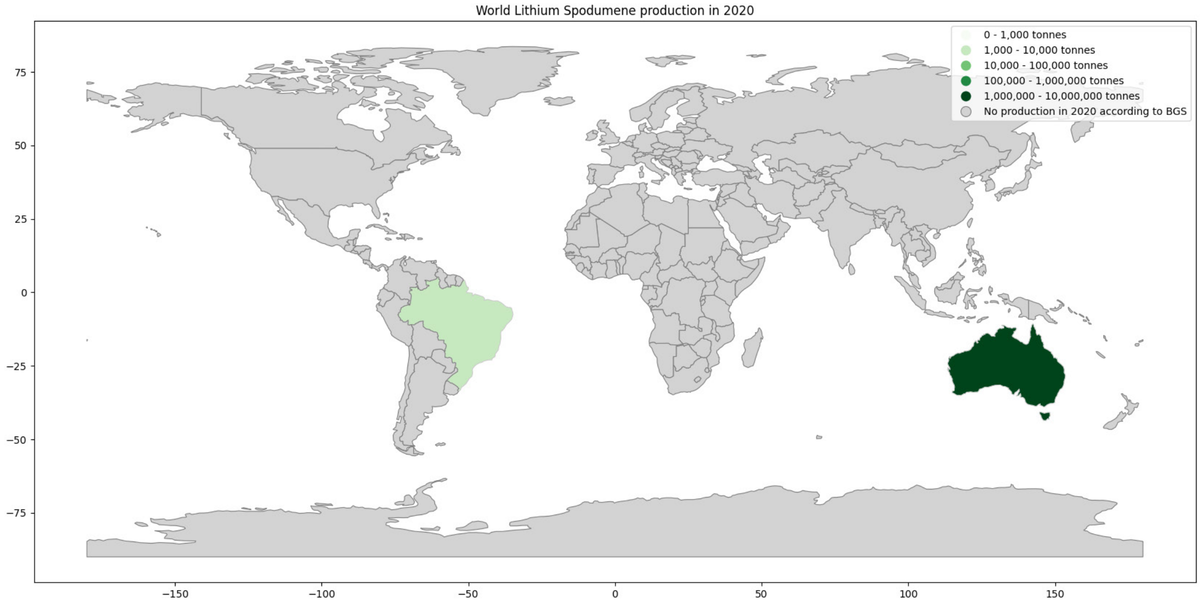
C.2.1.1 LITHIUM CARBONATE

Figure 51. World lithium carbonate production in 2020 and top producing countries.



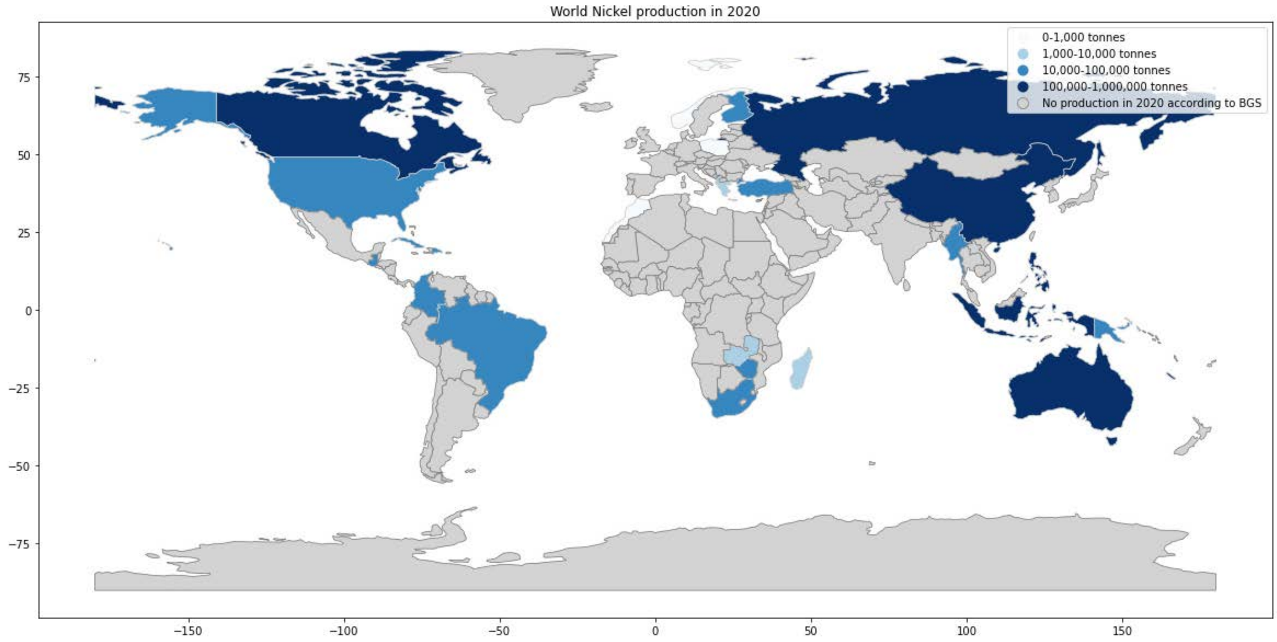
C.2.1.2 LITHIUM SPODUMENE

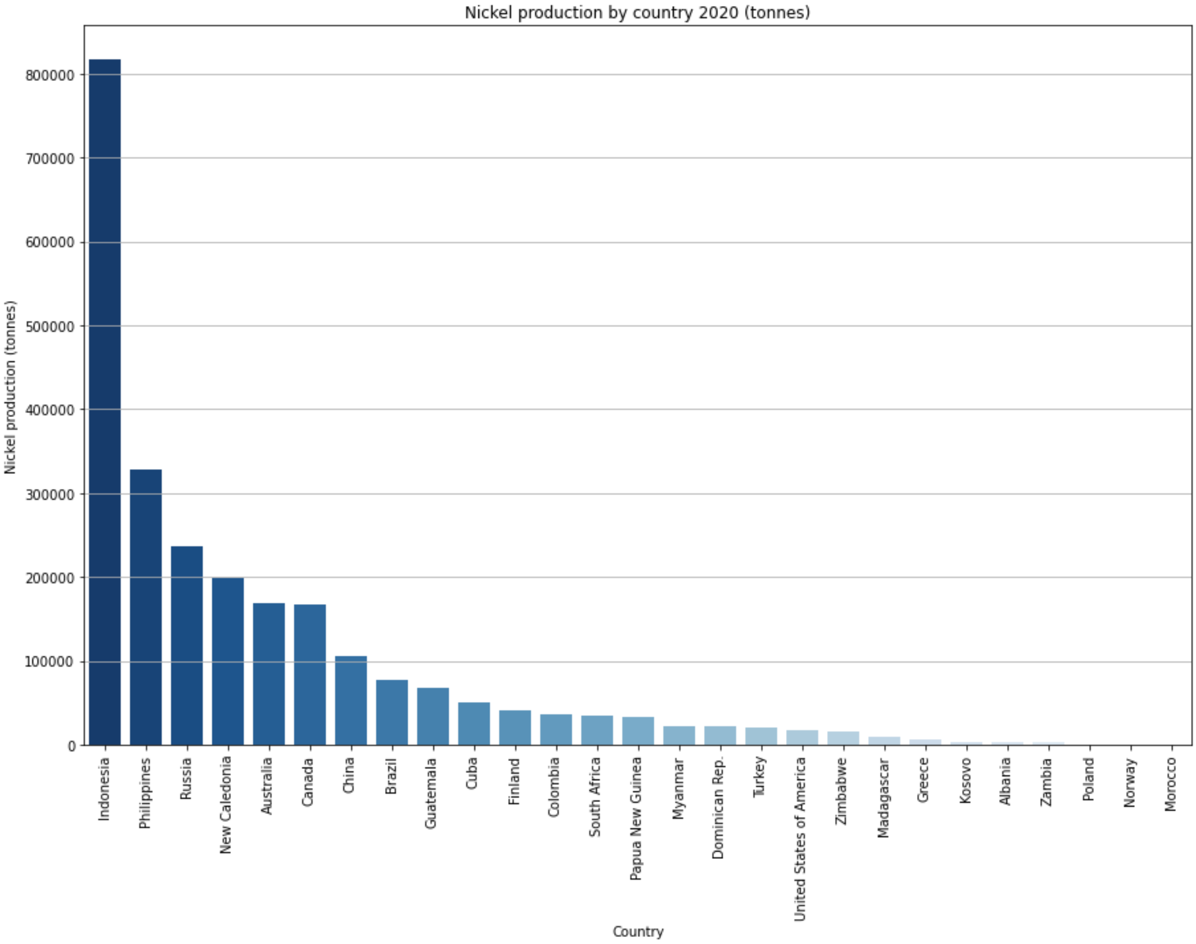
Figure 52. World lithium spodumene production in 2020 and top producing countries.



C.2.2 TOP NICKEL PRODUCING COUNTRIES

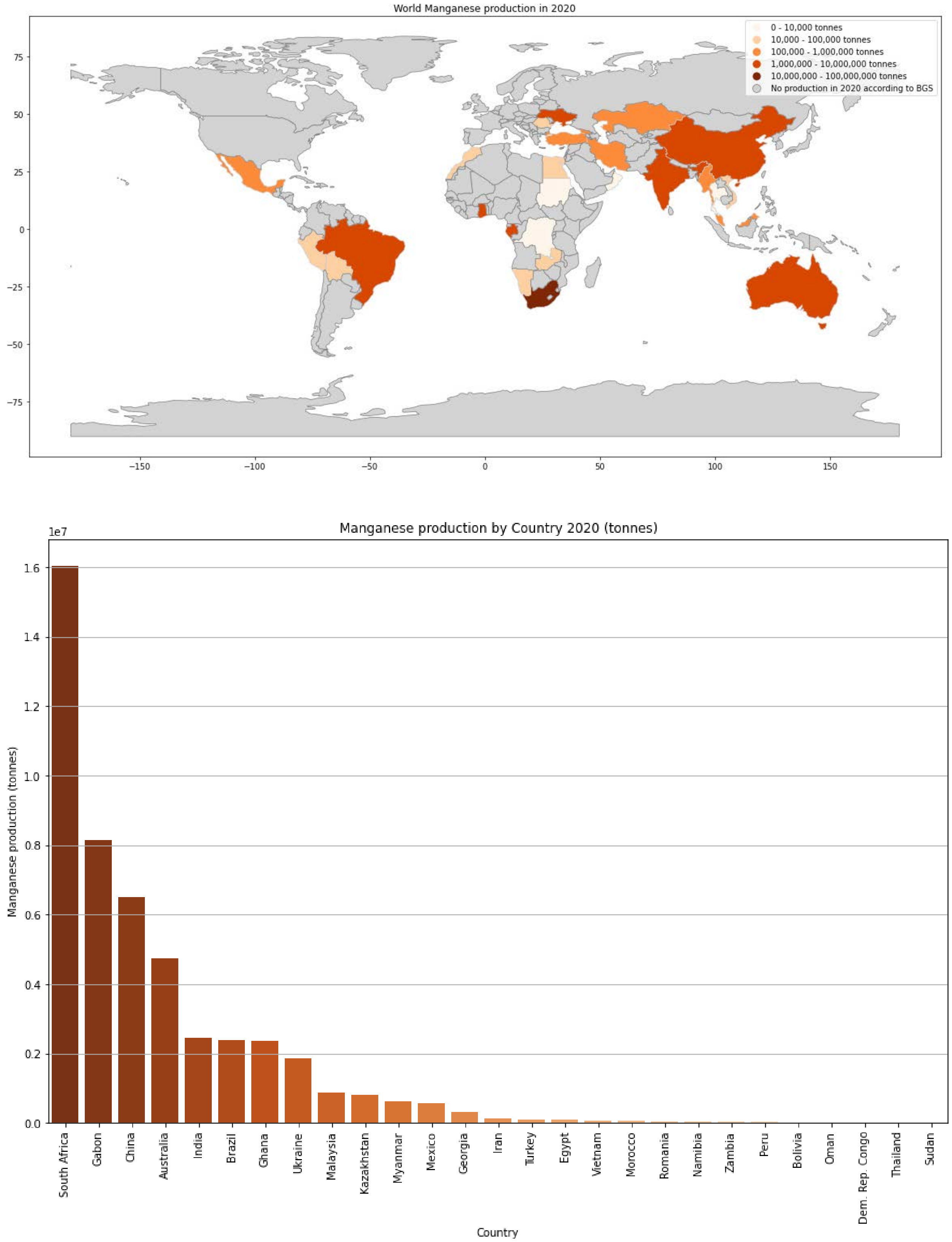
Figure 53. World nickel production in 2020 and top producing countries.





C.2.3 TOP MANGANESE PRODUCING COUNTRIES

Figure 54. World manganese production in 2020 and top producing countries.



C.3 STANDARDISATION OF COMPANY NAMES

C.3.1 LIST OF SUFFIXES REMOVED

Table 24. Suffixes removed from industry associations' dataset during standardisation step.

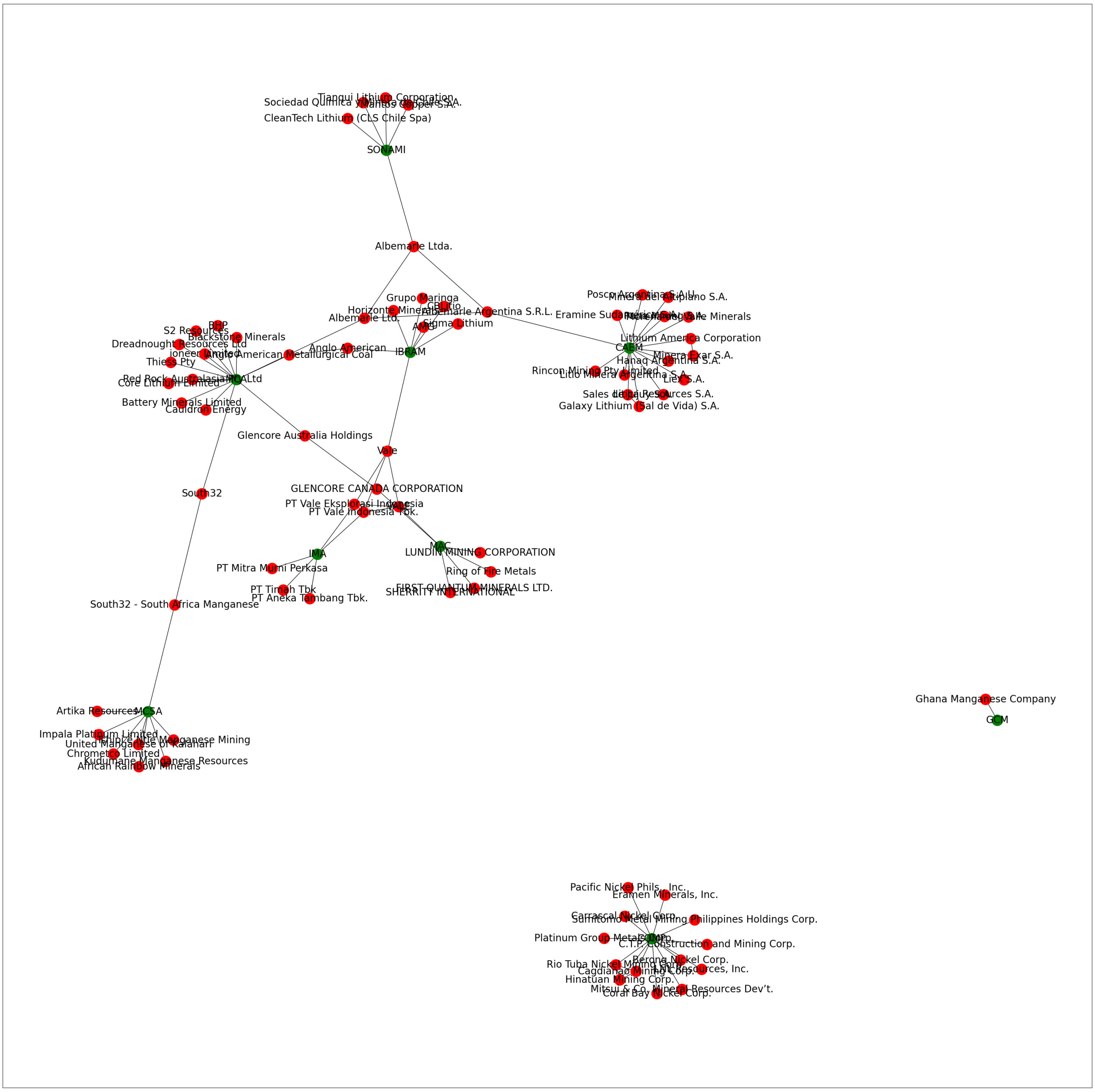
Business Structure	**Abbreviations and Terms**
Corporation	company, incorporated, corporation, corp., corp, inc, & co., & co, inc., s.p.a., n.v., a.g., ag, nuf, s.a., s.f., oao, co., co
General Partnership	soc.col., stg, d.n.o., ltda., v.o.s., a spol., veř. obch. spol., kgaa, o.e., s.f., s.n.c., s.a.p.a., j.t.d., v.o.f., sp.j., og, sd, i/s, ay, snc, oe, bt., s.s., mb, ans, da, o.d., hb, pt
Joint Stock / Unlimited	unltd, ultd, sal, unlimited, saog, saoc, aj, yoaj, oaj, akc. spol., a.s.
Joint Venture	esv, gie, kv., qk
Limited	pty. ltd., pty ltd, ltd, l.t.d., bvba, d.o.o., ltda, gmbh, g.m.b.h, kft., kht., zrt., ehf., s.a.r.l., d.o.o.e.l., s. de r.l., b.v., tapui, sp. z.o.o., sp. z o.o., spółka z o.o., s.r.l., s.l., s.l.n.e., ood, oy, rt., teo, uab, scs, sprl, limited, bhd., sdn. bhd., sdn bhd, as, lda., tov, pp
Limited Liability Company	pllc, llc, l.l.c., plc., plc, hf., oyj, a.e., nyrt., p.l.c., sh.a., s.a., s.r.l., srl., srl, aat, 3at, d.d., s.r.o., spol. s r.o., s.m.b.a., smba, sarl, nv, sa, aps, a/s, p/s, sae, sasu, eurl, ae, cpt, as, ab, asa, ooo, dat, vat, zat, mchj, a.d.
Limited Liability Limited Partnership	lllp, l.l.l.p.
Limited Liability Partnership	llp, l.l.p., sp.p., s.c.a., s.c.s.
Limited Partnership	gmbh & co. kg, lp, l.p., s.c.s., s.c.p.a, comm.v, k.d., k.d.a., s. en c., e.e., s.a.s., s. en c., c.v., s.k.a., sp.k., s.cra., ky, scs, kg, kd, k/s, ee, secs, kda, ks, kb, kt

Mutual Fund	sicav
No Liability	nl
Non-Profit	vzw, ses., gte.
Private Company	private, pte, xk
Professional Corporation	p.c., vof, snc
Professional Limited Liability Company	pllc, p.l.l.c.
Sole Proprietorship	e.u., s.p., t:mi, tmi, e.v., e.c., et, obrt, fie, ij, fop, xt

C.4 NETWORKS

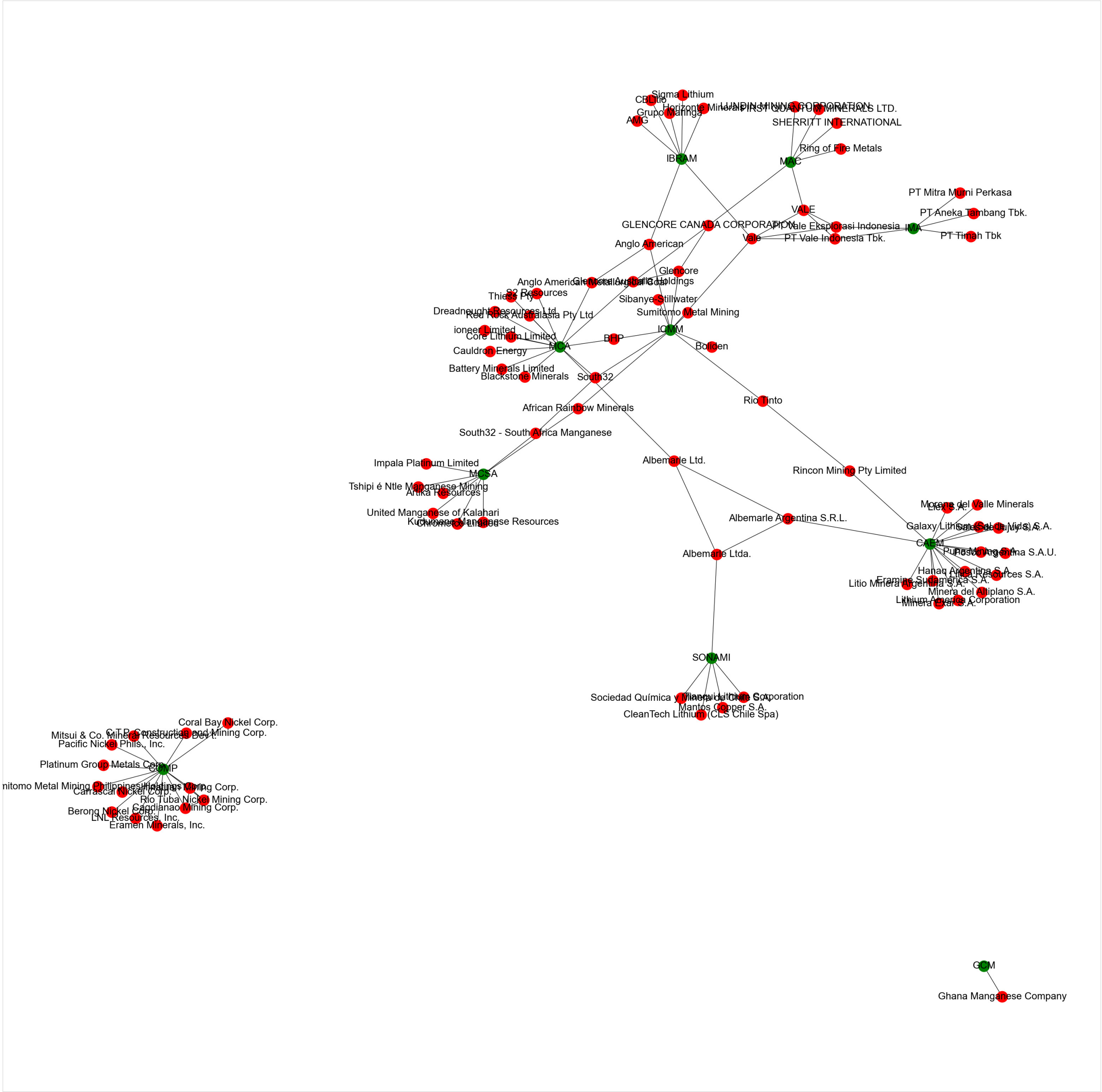
C.4.1 NETWORK BUILT WITH NATIONAL INDUSTRY ASSOCIATIONS

Figure 55. Network constructed with integration of national industry associations.



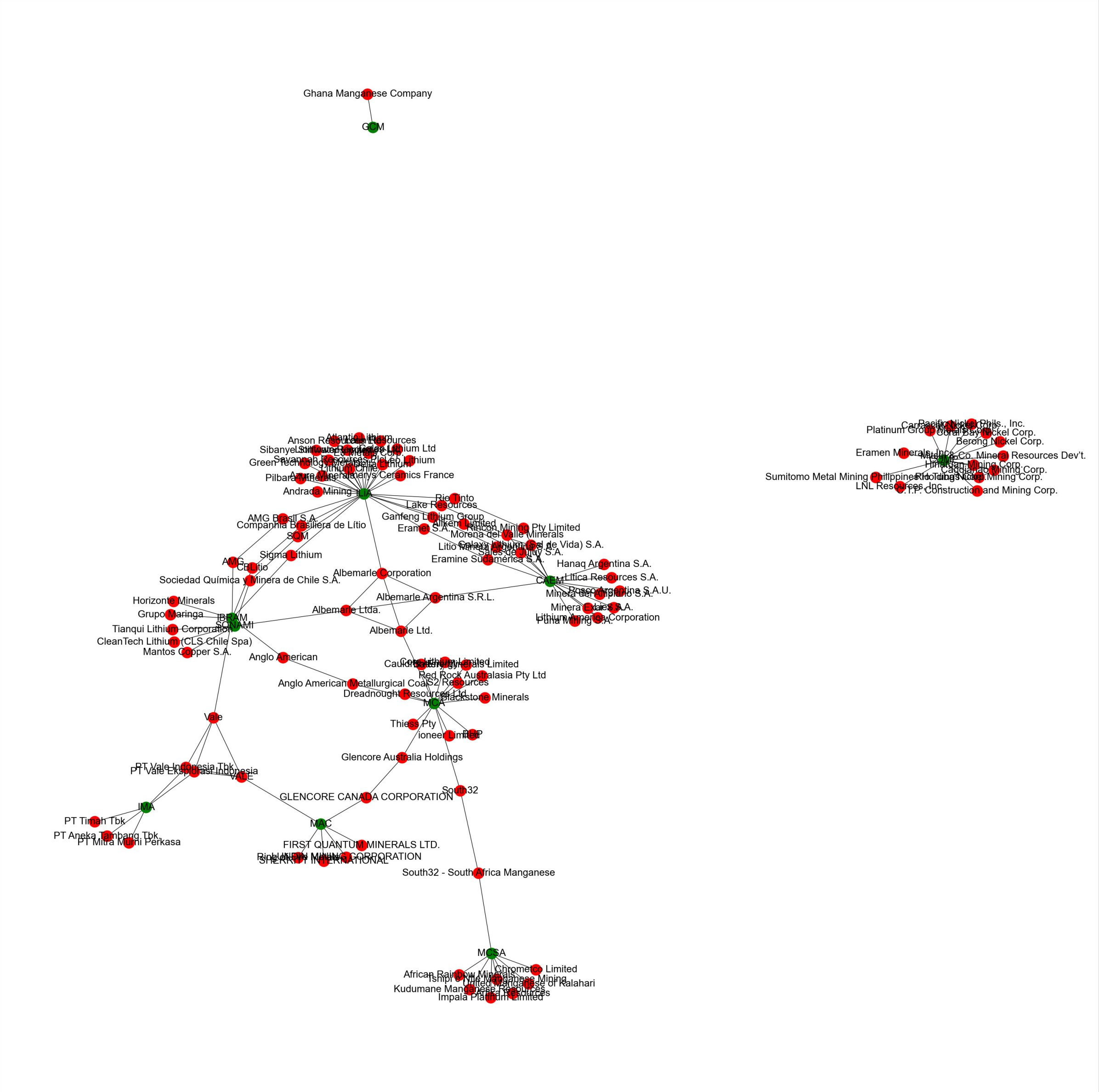
C.4.2 NETWORK BUILT WITH NATIONAL INDUSTRY ASSOCIATIONS AND OVERLAY OF INTERNATIONAL COUNCIL ON MINING AND METALS

Figure 56. Network constructed with integration of national industry associations and overlay of ICMM.



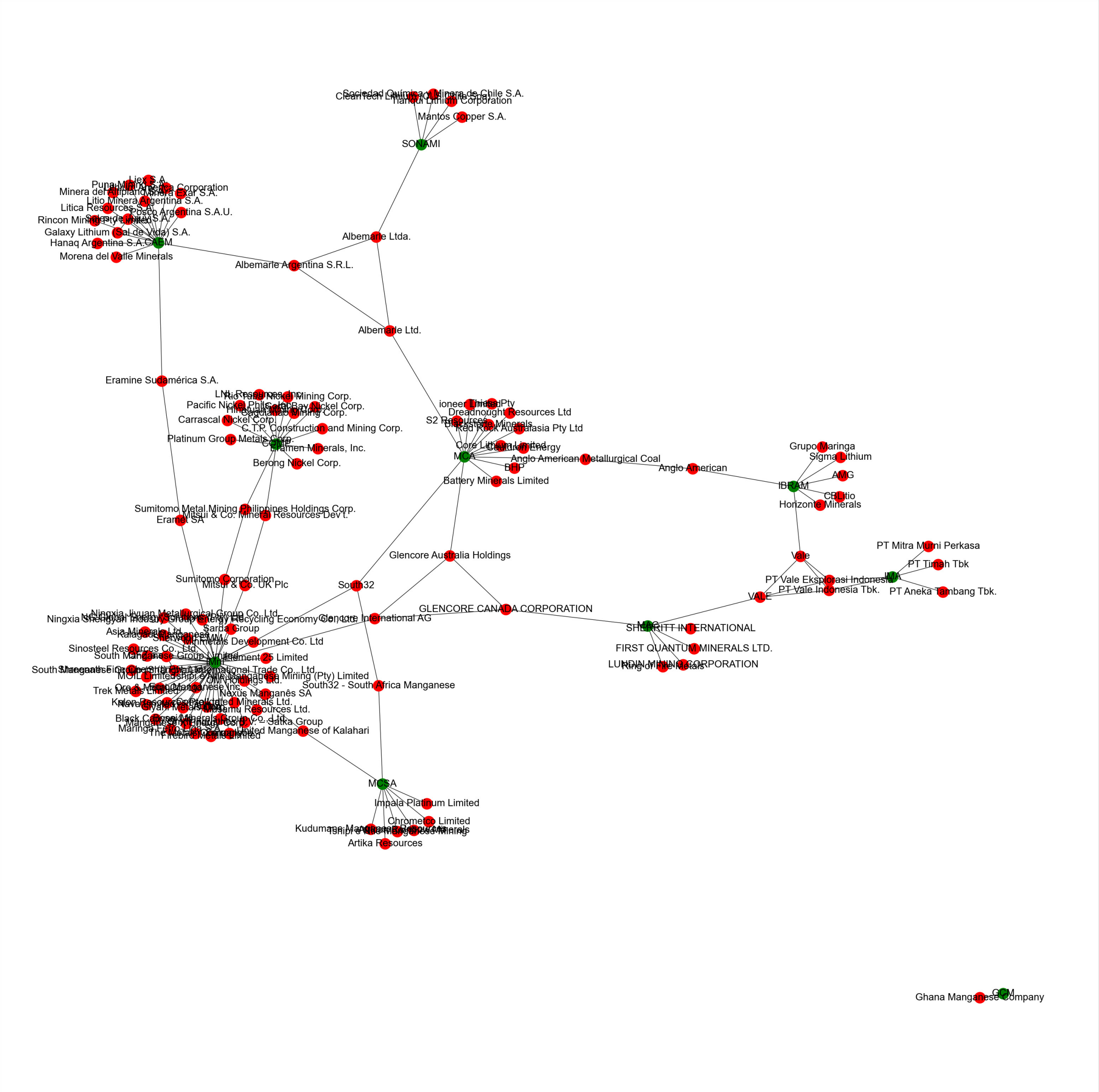
C.4.3 NETWORK BUILT WITH NATIONAL INDUSTRY ASSOCIATIONS AND OVERLAY OF INTERNATIONAL LITHIUM ASSOCIATION

Figure 57. Network constructed with integration of national industry associations and overlay of ILiA



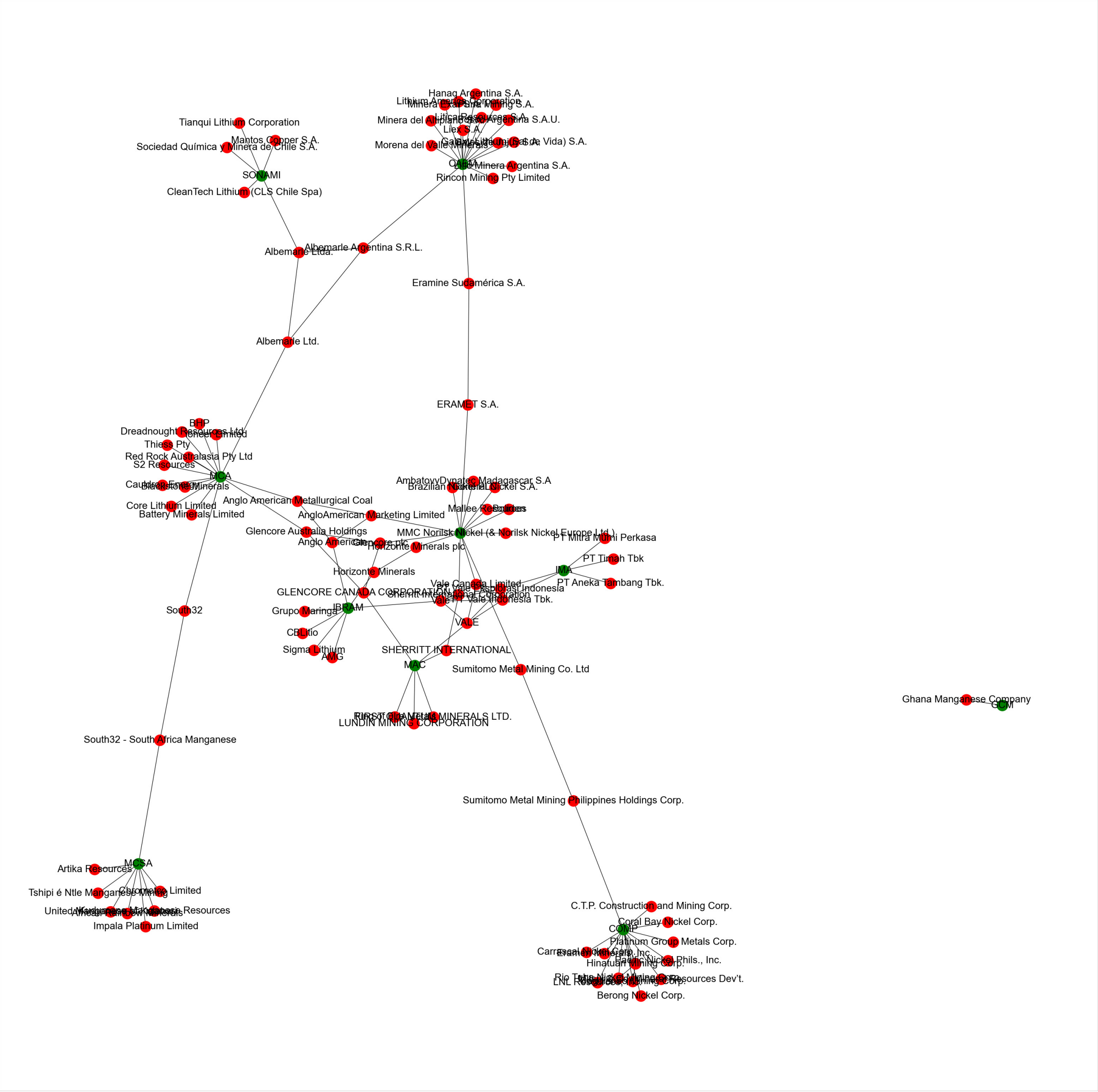
C.4.4 NETWORK BUILT WITH NATIONAL INDUSTRY ASSOCIATIONS AND OVERLAY OF INTERNATIONAL MANGANESE INSTITUTE

Figure 58. Network constructed with integration of national industry associations and overlay of International Manganese Institute



C.4.5 NETWORK BUILT WITH NATIONAL INDUSTRY ASSOCIATIONS AND OVERLAY OF NICKEL INSTITUTE

Figure 59. Network constructed with integration of national industry associations and overlay of Nickel Institute.

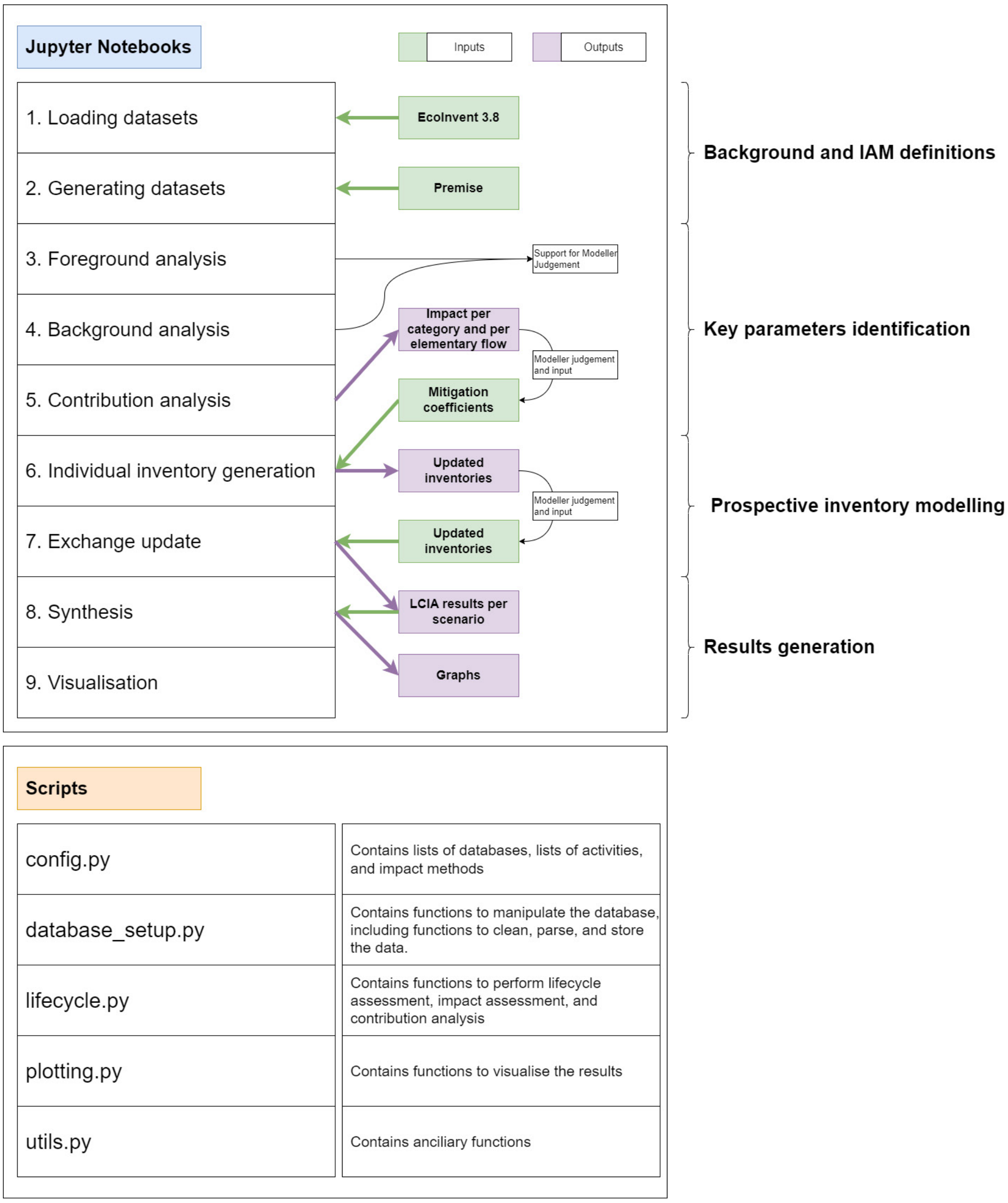


D. APPENDIX D: SUPPLEMENTARY MATERIAL TO CHAPTER 6

D.1 WORKFLOW STRUCTURE WITH JUPYTER NOTEBOOKS AND PYTHON SCRIPTS

Our workflow is structured such as **Figure 60**. Each individual jupyter notebook draws from a series of functions (existent within the scripts). Each individual jupyter notebook performs a transformation and generates a set of outputs that are either used or transformed by the modeller. A specific description of each notebook is detailed under **Table 24**. Moreover, to preserve replicability, each python environment used has also been provided, with detailed descriptions in **Table 25**.

Figure 60. Workflow used in the research. Each individual Jupyter notebook draws from functions found in the Python scripts.



config.py	Contains lists of databases, lists of activities, and impact methods
database_setup.py	Contains functions to manipulate the database, including functions to clean, parse, and store the data.
lifecycle.py	Contains functions to perform lifecycle assessment, impact assessment, and contribution analysis
plotting.py	Contains functions to visualise the results
utils.py	Contains anciliary functions

D.1.1 JUPYTER NOTEBOOKS

Table 25. Detailed Jupyter notebooks

Notebook	Description
1_loading_datasets	Used to read ecoinvent 3.8 and generate the biosphere3 database. Uses the bw2-toloadei38 environment.
2_generating_datasets	Used to generate the datasets. Uses the bw2premise-ei38compat-ok environment. New inventories are imported and updated, to better reconcile with the IAM scenario outputs. These datasets cover a temporal range (e.g. 2025 to 2040).
3_foreground_analysis	This notebook is used to perform an initial comprehensive exploration of the activities of interest involved in the production of NMC oxides. This step is crucial to properly understand the key parameter and key factors that will be modelled under each scenario.
4_background_analysis	This notebook is used to perform an initial comprehensive exploration of the activities of interest involved in the production of NMC-811 oxide.
5_contribution_analysis	Based on our list of activities, this notebook calculates the contribution analysis across all the impact categories for each flow within each activity within that list. This step is crucial to properly understand the key parameter and key factors that will be modelled under each scenario. The results are then saved as CSV files, and the modeler apply the coefficients of mitigation based on the mitigation technologies.
6_individual_inventory_generation	After the coefficients of mitigation are associated with the activities and their respective elementary flows, this notebook is used to properly organize these into input files that can be read by notebook 7_exchange_update
7_exchange_update	This notebook reads from a list of transformation coefficients (based on mitigation technologies) and transform the respective inventories within selected databases.
8_synthesis	Contains functions to synthesise the results and generate datasets for visualisation
9_visualisation	Contains functions that read from the result files and provide visualizations.
10_useful_db_functions	Useful database access and transformation functions. Includes functions to delete databases, if necessary.

D.1.2 ENVIRONMENTS

Table 26. Python environments

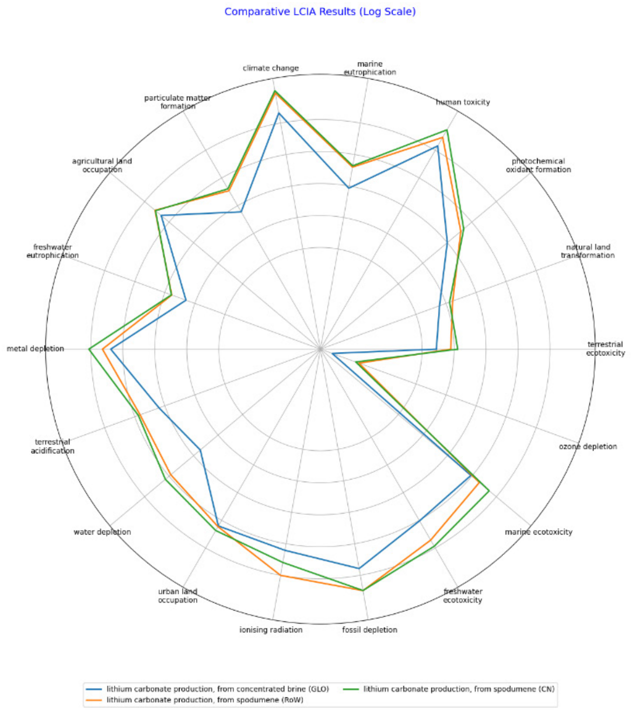
Environment Name	Description
bw2-toloadei38 (Python 3.11.9)	Environment used to load the EcoInvent 3.8 dataset. Only used with notebook 1_loading_ei38 due to inconsistencies with ecoinvent 3.8 import, brightway2.5, and premise.
bw2-ei38compat-ok (Python 3.11.9)	Environment used to perform premise extractions and transformations. Also used for results analysis.
bw2-visualisation (Python 3.11.9)	Environment used to generate the graphs based on the outputs.

D.2 INDIVIDUALISED LCIA

As described under **section 6.2** of the main manuscript, an initial lifecycle inventory and impact assessment was performed for each processing route identified as relating to mineral extraction and processing leading to the production of NMC111 oxide (see **Figure 61**). Individualized results covering all impact categories have been presented, based on the ReciPe 1.6 Midpoint (H) impact method. Results have been presented in a logarithmic scale.

D.2.1 PRODUCTION OF 1KG OF LITHIUM CARBONATE

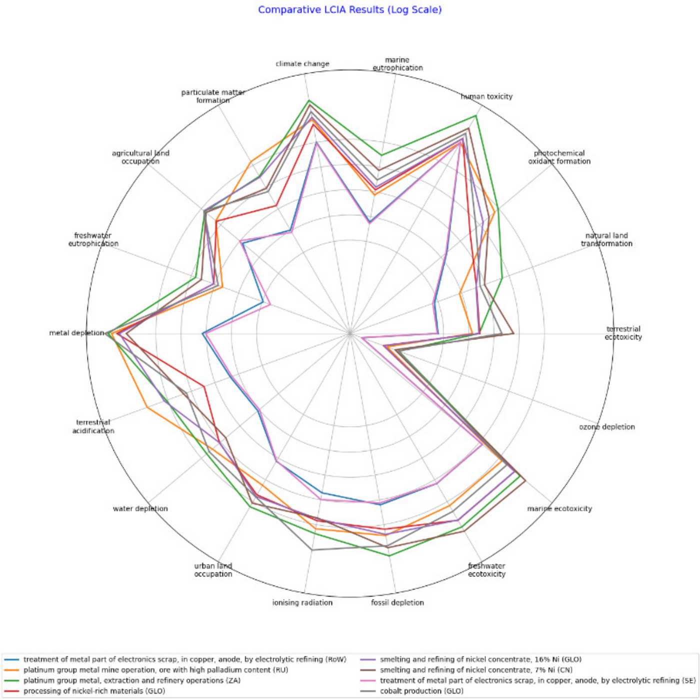
Figure 61. Comparative lifecycle impact assessment across all ReCiPe 1.6 (H) midpoint categories, covering a range of lithium carbonate producing routes. Reference product is 1Kg of lithium carbonate.

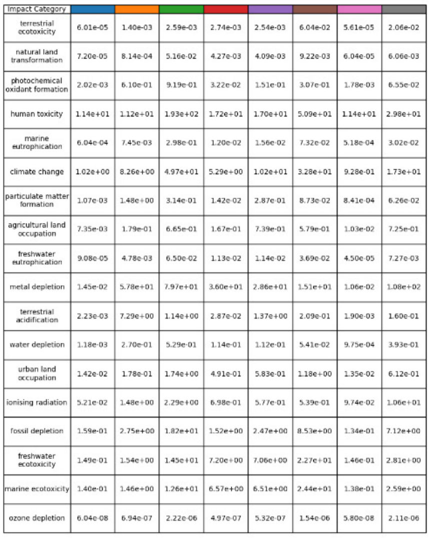


Impact Category	🟦	🟧	🟩
terrestrial ecotoxicity	2.80e-04	7.86e-04	1.30e-03
natural land transformation	6.10e-04	1.67e-03	1.32e-03
photochemical oxidant formation	9.98e-03	3.55e-02	4.67e-02
human toxicity	1.44e+00	2.93e+00	5.48e+00
marine eutrophication	8.52e-03	3.98e-02	4.37e-02
climate change	2.08e+00	8.87e+00	1.06e+01
particulate matter formation	6.00e-03	3.47e-02	4.05e-02
agricultural land occupation	2.10e-01	3.74e-01	3.58e-01
freshwater eutrophication	1.98e-03	5.87e-03	6.03e-03
metal depletion	2.39e-01	4.34e-01	1.16e+00
terrestrial acidification	1.55e-02	6.65e-02	7.58e-02
water depletion	5.32e-03	8.52e-02	1.42e-01
urban land occupation	1.60e-01	1.69e-01	2.34e-01
ionising radiation	1.61e-01	1.00e+00	3.92e-01
fossil depletion	6.12e-01	3.06e+00	3.04e+00
freshwater ecotoxicity	1.05e-01	5.19e-01	8.65e-01
marine ecotoxicity	9.20e-02	2.03e-01	5.14e-01
ozone depletion	1.63e-07	1.27e-06	9.95e-07

D.2.2 PRODUCTION OF 1KG OF NICKEL, CLASS 1

Figure 62. Comparative lifecycle impact assessment across all ReCiPe 1.6 (H) midpoint categories, covering a range of nickel, Class 1 producing routes. Reference product is 1Kg of nickel, class 1.

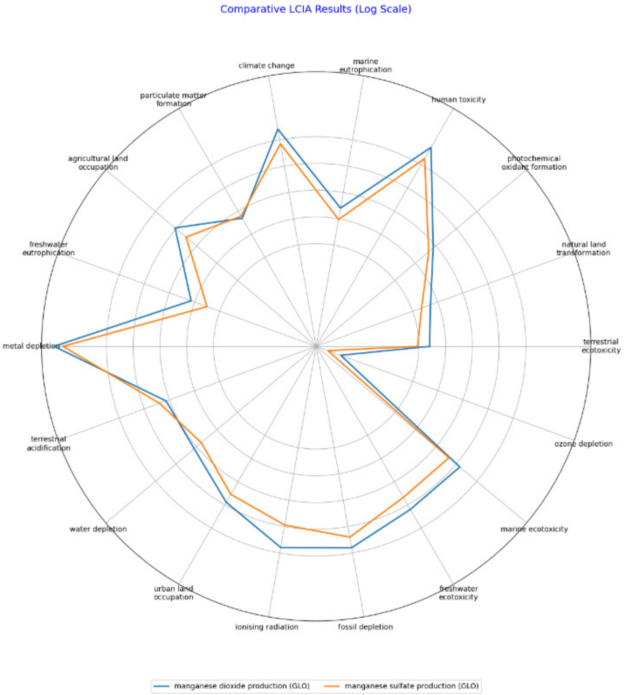


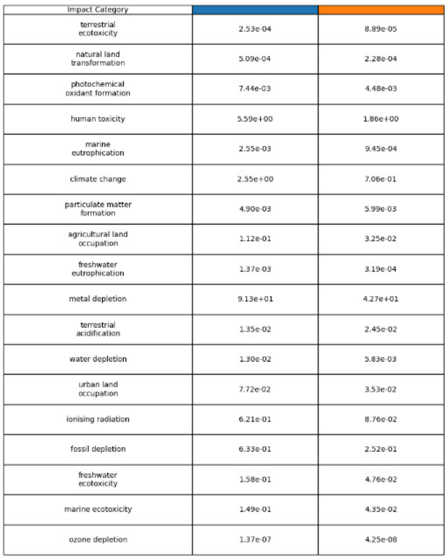


Impact Category	🟦	🟧	🟩	🟥	🟪	🟫	■	■
terrestrial ecotoxicity	6.01e-05	1.40e-03	2.59e-03	2.74e-03	2.54e-03	6.04e-02	5.61e-05	2.06e-02
natural land transformation	7.20e-05	8.14e-04	5.16e-02	4.27e-03	4.09e-03	9.22e-03	6.04e-05	6.06e-03
photochemical oxidant formation	2.02e-03	6.10e-01	9.19e-01	3.22e-02	1.51e-01	3.07e-01	1.78e-03	6.55e-02
human toxicity	1.14e+01	1.12e+01	1.93e+02	1.72e+01	1.70e+01	5.09e+01	1.14e+01	2.98e+01
marine eutrophication	6.04e-04	7.45e-03	2.98e-01	1.20e-02	1.56e-02	7.32e-02	5.18e-04	3.02e-02
climate change	1.02e+00	8.26e+00	4.97e+01	5.29e+00	1.02e+01	3.28e+01	9.28e-01	1.73e+01
particulate matter formation	1.07e-03	1.48e+00	3.14e-01	1.42e-02	2.87e-01	8.73e-02	8.41e-04	6.26e-02
agricultural land occupation	7.35e-03	1.79e-01	6.65e-01	1.67e-01	7.39e-01	5.79e-01	1.03e-02	7.25e-01
freshwater eutrophication	9.08e-05	4.78e-03	6.50e-02	1.13e-02	1.14e-02	3.69e-02	4.50e-05	7.27e-03
metal depletion	1.45e-02	5.78e+01	7.97e+01	3.60e+01	2.86e+01	1.51e+01	1.06e-02	1.08e+02
terrestrial acidification	2.23e-03	7.29e+00	1.14e+00	2.87e-02	1.37e+00	2.09e-01	1.90e-03	1.60e-01
water depletion	1.18e-03	2.70e-01	5.29e-01	1.14e-01	1.12e-01	5.41e-02	9.75e-04	3.93e-01
urban land occupation	1.42e-02	1.78e-01	1.74e+00	4.91e-01	5.83e-01	1.18e+00	1.35e-02	6.12e-01
ionising radiation	5.21e-02	1.48e+00	2.29e+00	6.98e-01	5.77e-01	5.39e-01	9.74e-02	1.06e+01
fossil depletion	1.59e-01	2.75e+00	1.82e+01	1.52e+00	2.47e+00	8.53e+00	1.34e-01	7.12e+00
freshwater ecotoxicity	1.49e-01	1.54e+00	1.45e+01	7.20e+00	7.06e+00	2.27e+01	1.46e-01	2.81e+00
marine ecotoxicity	1.40e-01	1.46e+00	1.26e+01	6.57e+00	6.51e+00	2.44e+01	1.38e-01	2.59e+00
ozone depletion	6.04e-08	6.94e-07	2.22e-06	4.97e-07	5.32e-07	1.54e-06	5.80e-08	2.11e-06

D.2.3 PRODUCTION OF 1KG OF MANGANESE DIOXIDE.

Figure 63. Comparative lifecycle impact assessment across all ReCiPe 1.6 (H) midpoint categories, covering a range of manganese sulfate producing routes. Reference product is 1Kg of manganese sulfate.





Impact Category	🟦	🟧
terrestrial ecotoxicity	2.53e-04	8.89e-05
natural land transformation	5.09e-04	2.28e-04
photochemical oxidant formation	7.44e-03	4.48e-03
human toxicity	5.59e+00	1.86e+00
marine eutrophication	2.55e-03	9.45e-04
climate change	2.55e+00	7.06e-01
particulate matter formation	4.90e-03	5.99e-03
agricultural land occupation	1.12e-01	3.25e-02
freshwater eutrophication	1.37e-03	3.19e-04
metal depletion	9.13e+01	4.27e+01
terrestrial acidification	1.35e-02	2.45e-02
water depletion	1.30e-02	5.83e-03
urban land occupation	7.72e-02	3.53e-02
ionising radiation	6.21e-01	8.76e-02
fossil depletion	6.33e-01	2.52e-01
freshwater ecotoxicity	1.58e-01	4.76e-02
marine ecotoxicity	1.49e-01	4.35e-02
ozone depletion	1.37e-07	4.25e-08

D.3 CONTRIBUTION ANALYSIS

As outlined in **Section 6.2.2** of the main manuscript, a contribution analysis was conducted to identify the *biosphere* exchanges associated with each sub-activity that contributed most to each impact category. Additionally, this analysis highlights the respective emissions to their compartments (e.g., air, water, soil). The findings from this analysis provide a basis for selecting targeted mitigation strategies aimed at reducing these emissions effectively. A visualisation of the contribution breakdown can be found in the following subsections. All the *biosphere* exchanges (the focus of our analysis) are presented individually.

D.3.1 LITHIUM SUBSYSTEM

The following figures showcase the contribution analysis for producing 1kg of Lithium Carbonate from a range of processing routes. It shows the breakdown of biosphere exchanges across impact categories. The stacked bars represent the percentage contribution of each sub-activity to different impact indicators. Biosphere exchanges are color-coded according to their associated compartment (e.g., air, water, soil). This visualization aids in identifying key emissions and guiding targeted mitigation strategies.

Figure 64. Contribution analysis and impact breakdown for producing 1kg of lithium carbonate through 'lithium carbonate production, from spodumene (CN)'.

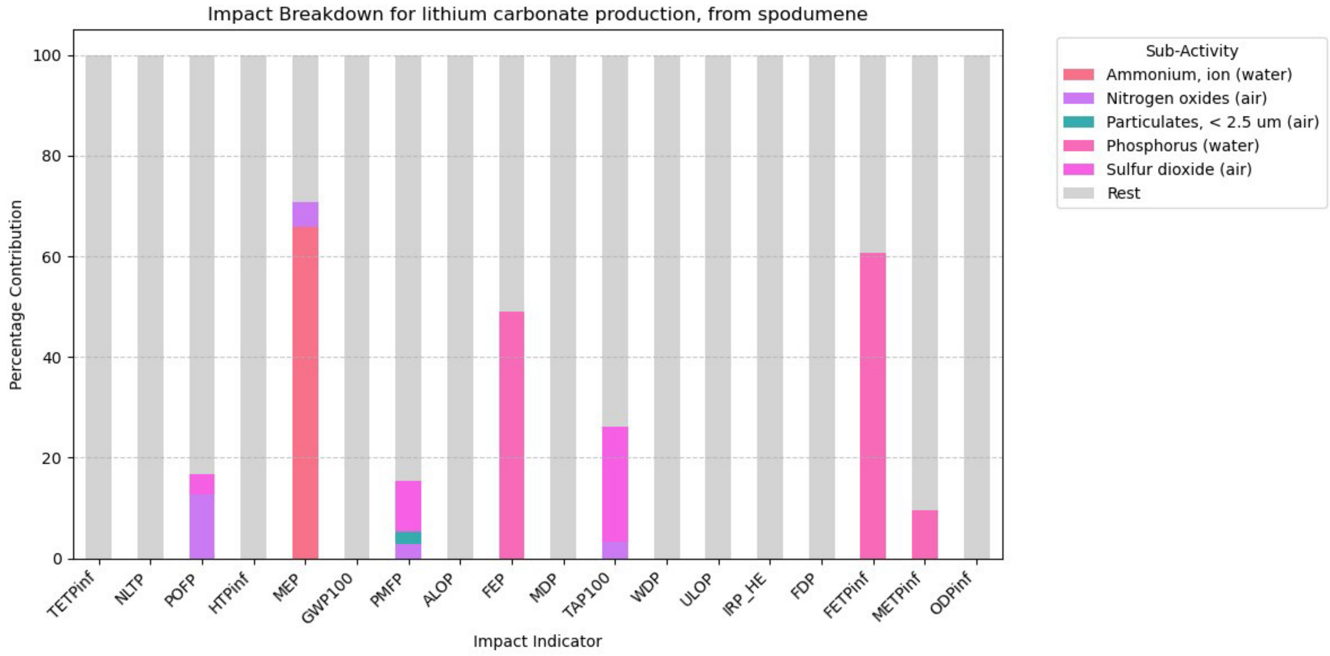
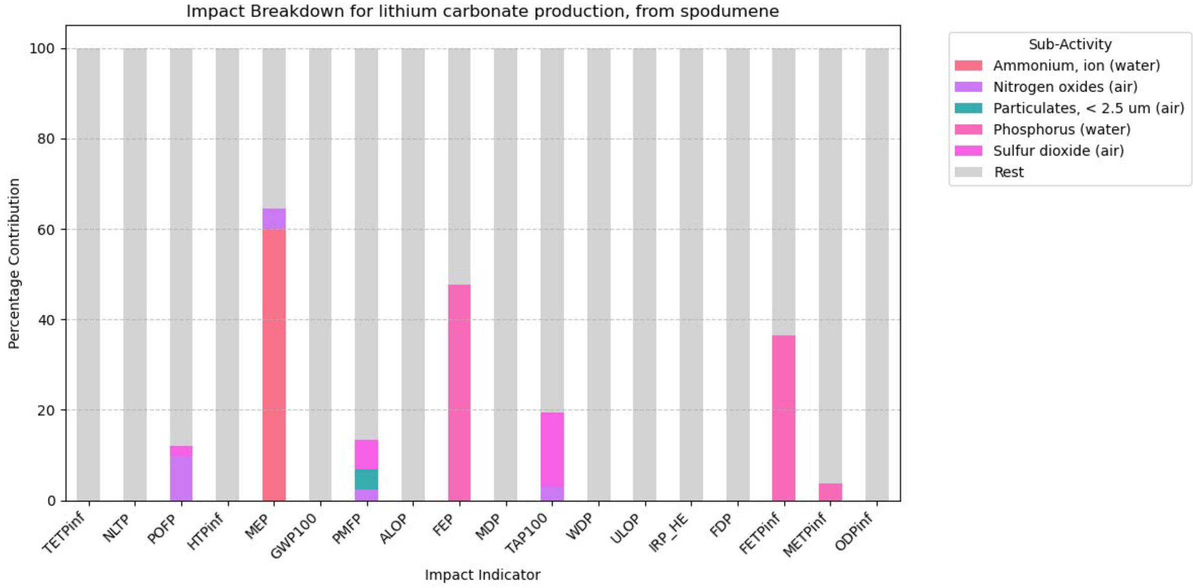


Figure 65. Contribution analysis and impact breakdown for producing 1kg of lithium carbonate through 'lithium carbonate production, from spodumene (GLO)'.



D.3.2 NICKEL SUBSYSTEM

The following figures showcase the contribution analysis for producing 1kg of Nickel, Class 1 from a range of processing routes. It shows the breakdown of *biosphere* exchanges across impact categories. The stacked bars represent the percentage contribution of each sub-activity to different impact indicators. *Biosphere* exchanges are color-coded according to their associated compartment (e.g., air, water, soil). This visualization aids in identifying key emissions and guiding targeted mitigation strategies.

Figure 66. Contribution analysis and impact breakdown for producing 1kg of nickel, class1 through 'treatment of metal part of electronics scrap, in copper, anode, by electrolytic refining (GLO)'.

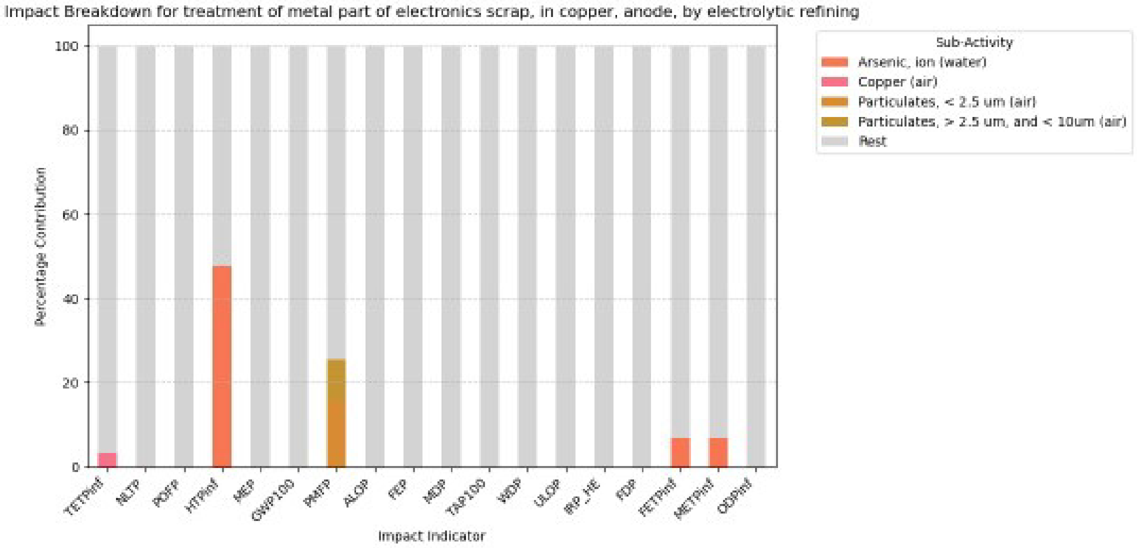


Figure 67. Contribution analysis and impact breakdown for producing 1kg of nickel, class1 through 'platinum group metal mine operation, ore with high palladium content (RU).

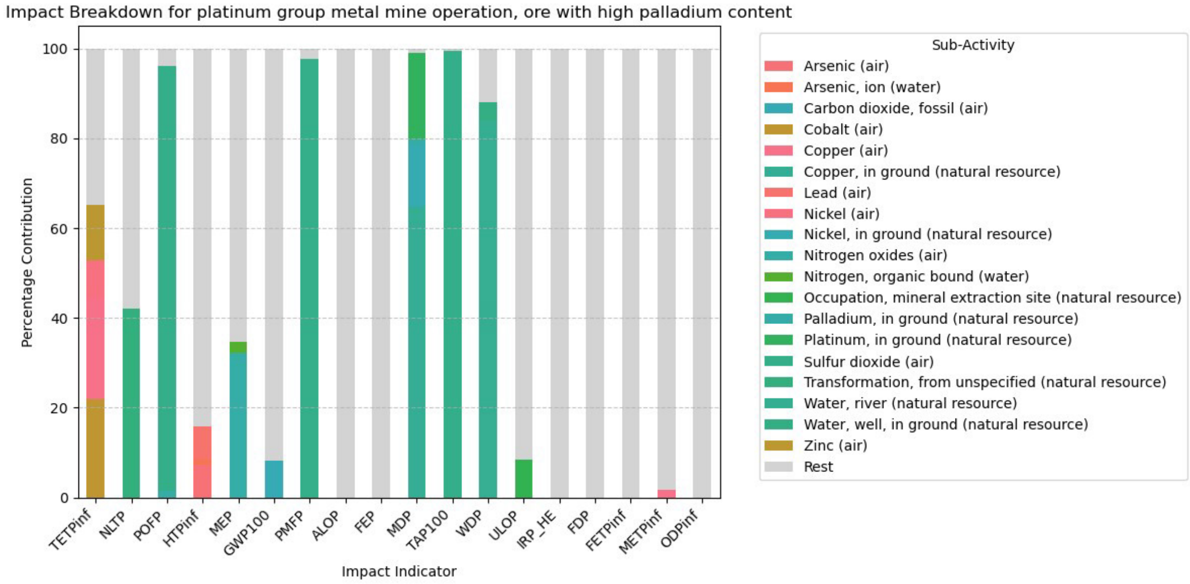


Figure 68. Contribution analysis and impact breakdown for producing 1kg of nickel, class1 through ‘platinum group metal, mine and concentration operations (ZA)’.

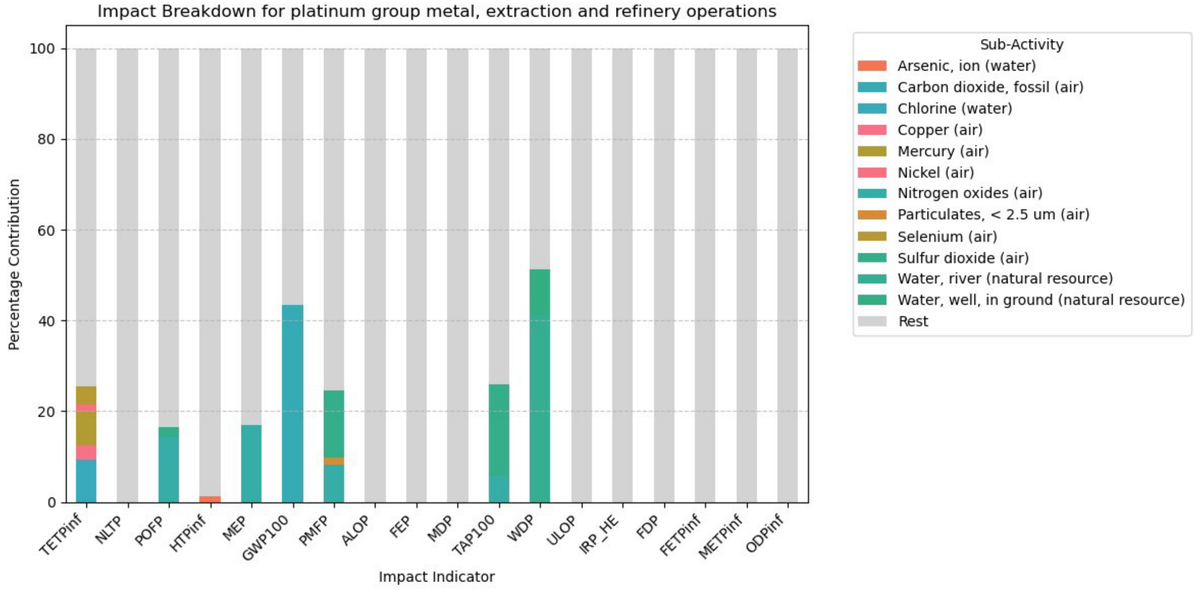


Figure 69. Contribution analysis and impact breakdown for producing 1kg of nickel, class1 through ‘processing of nickel-rich materials (GLO)’.

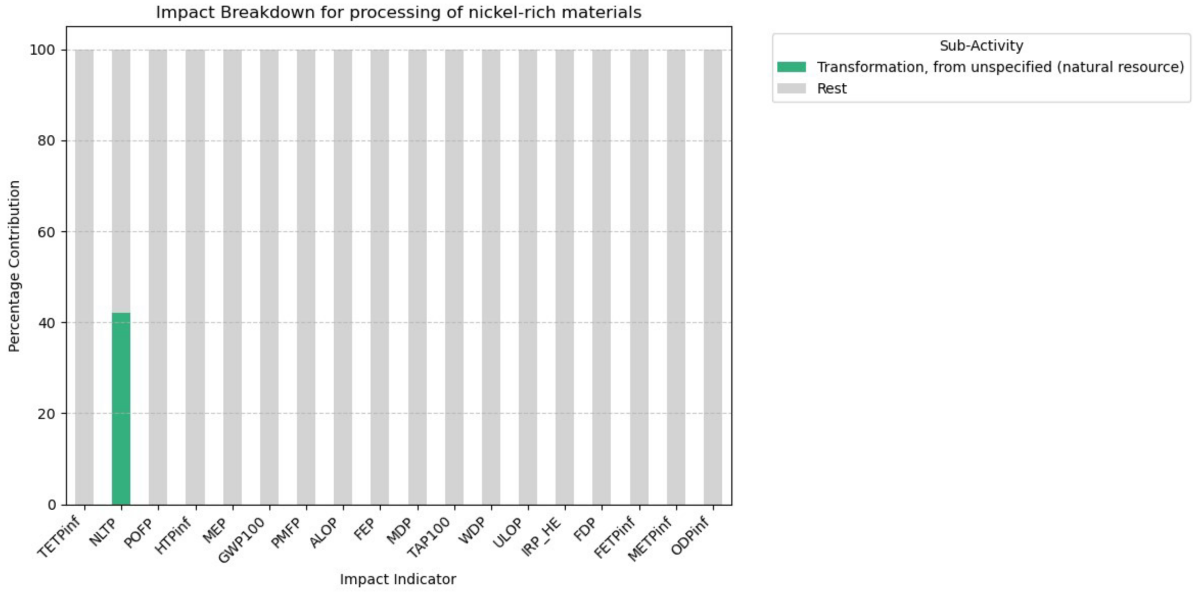


Figure 70. Contribution analysis and impact breakdown for producing 1kg of nickel, class1 through ‘smelting and refining of nickel concentrate, 16% Ni (GLO)’.

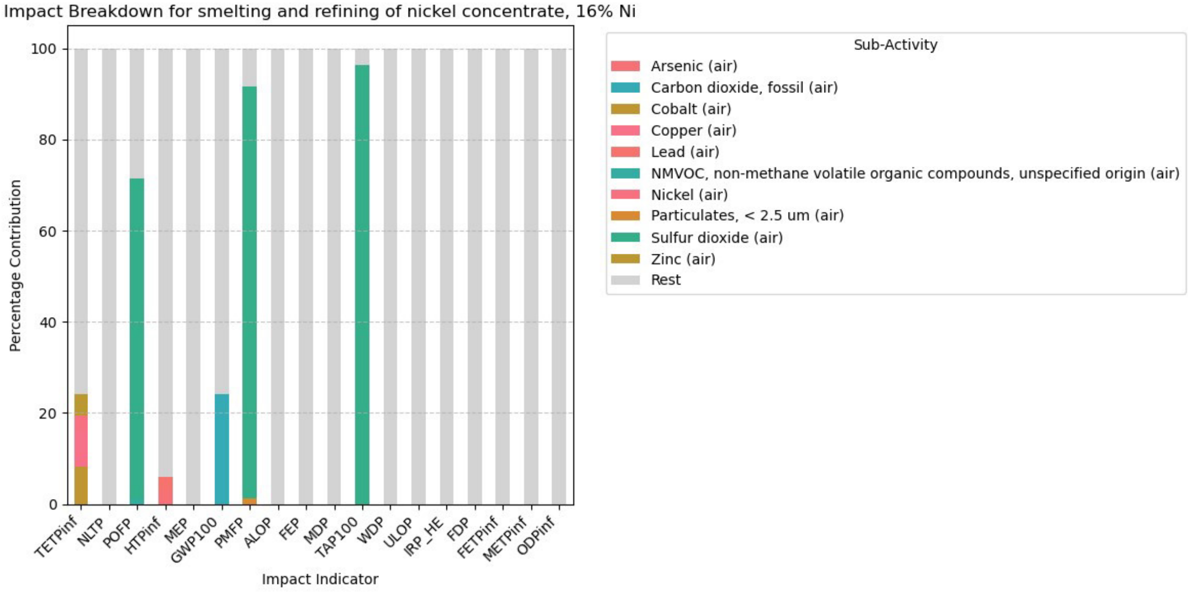


Figure 71. Contribution analysis and impact breakdown for producing 1kg of nickel, class1 through ‘smelting and refining of nickel concentrate, 7% Ni (CN)’.

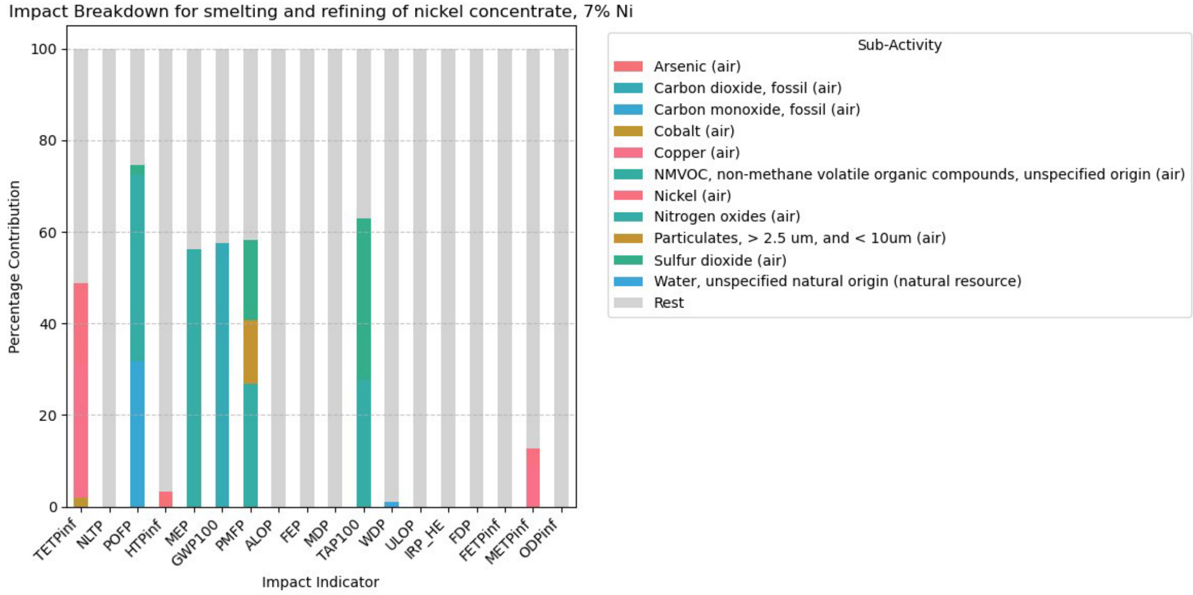


Figure 72. Contribution analysis and impact breakdown for producing 1kg of nickel, class1 through 'treatment of metal part of electronics scrap, in copper, anode, by electrolytic refining (SE)'.

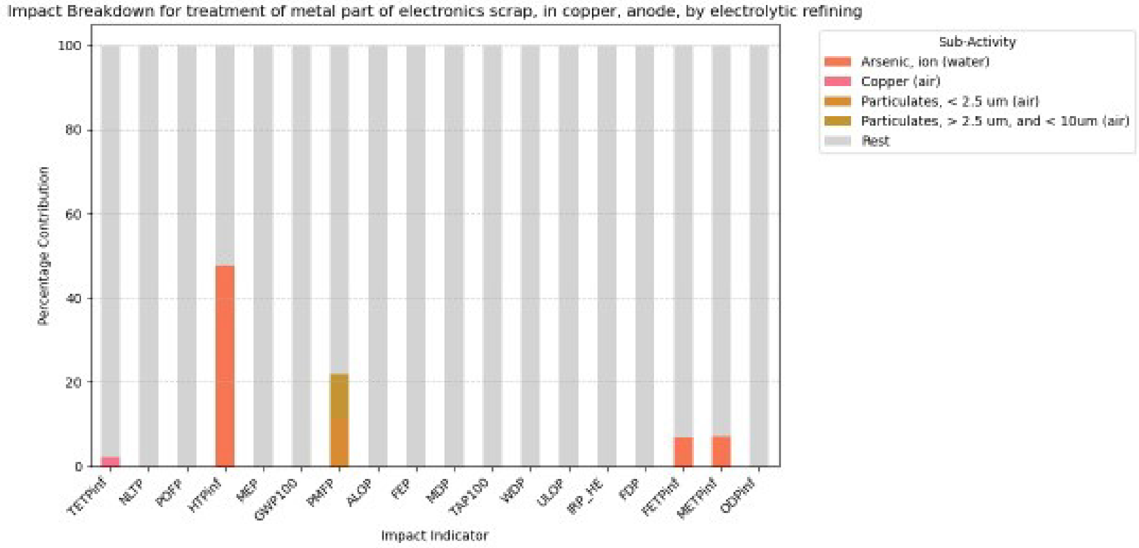
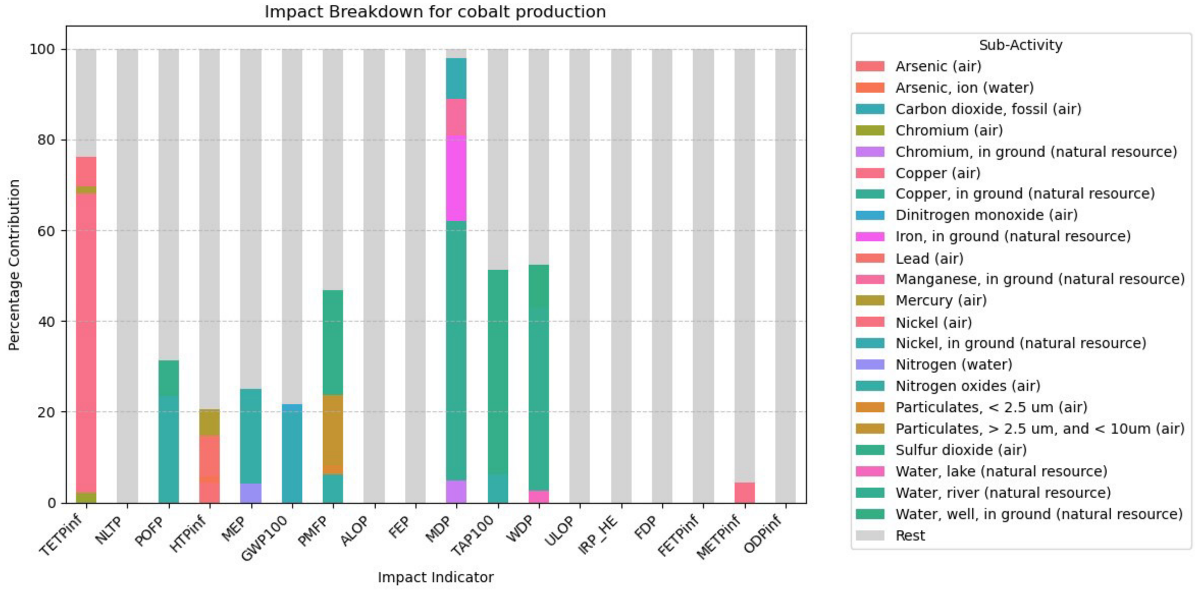


Figure 73. Contribution analysis and impact breakdown for producing 1kg of nickel, class1 through 'cobalt production (GLO)'.



D.3.4 MANGANESE SUBSYSTEM

The following figures showcase the contribution analysis for producing 1kg of Manganese Sulfate from a range of processing routes. It shows the breakdown of *biosphere* exchanges across impact categories. The stacked bars represent the percentage contribution of each sub-activity to different impact indicators. *Biosphere* exchanges are color-coded according to their associated compartment (e.g., air, water, soil), while *technosphere* exchanges are aggregated and displayed in blue. This visualization aids in identifying key emissions and guiding targeted mitigation strategies.

Figure 74. Contribution analysis and impact breakdown for producing 1kg of manganese sulfate through 'manganese dioxide production (GLO)'.

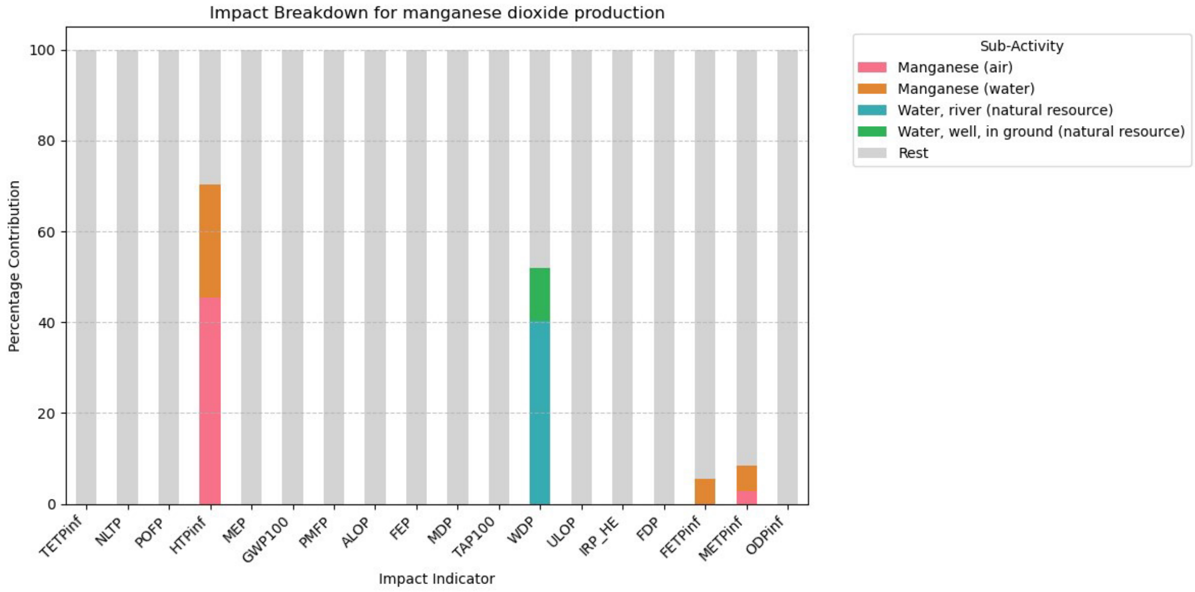
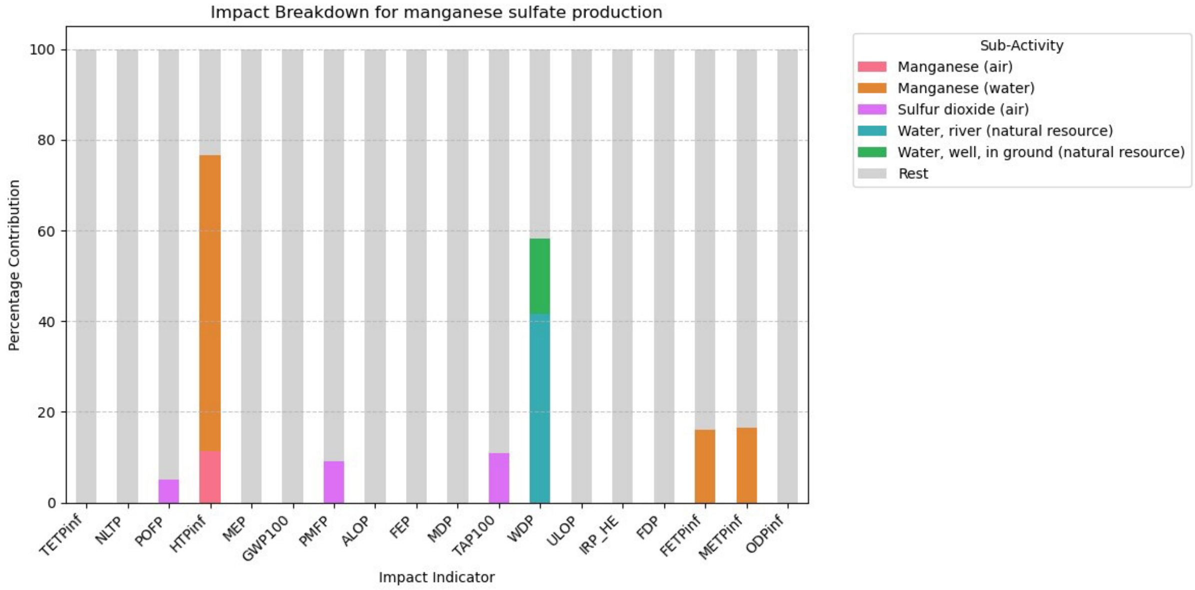


Figure 75. Contribution analysis and impact breakdown for producing 1kg of manganese sulfate through 'manganese sulfate production (GLO)'.



D.4 SUPPLEMENTARY EXCEL FILES

The individual mitigation factors (i.e., emission reduction coefficients) assigned to each technology and specific application to elementary flows and compartments mentioned in **Section 6.2** can be found in:

https://zenodo.org/records/15833468

D.5 SOURCE CODE

The source code used can be found in:

https://github.com/bernardomendonca/plca-NMC-oxide-BM-PhD