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Research article

Investigating the adoption of voluntary sustainability initiatives when mining for battery minerals: An iterative systems thinking approach

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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 on 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.

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 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 et al., 2022).

Several elements play a role in the scale between demand for battery minerals and 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 et al., 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) involve 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 et al., 2017). They originated in response to growing pressures from investors, regulators, and civil society for companies to address the adverse

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impacts of their operations (Franken et al., 2022; Erdmann et al., 2022). 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 et al., 2022), 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, we adopted a group-model building (GMB) approach (Zagonel, 2002), 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.

2. Materials and methods

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-chains 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 conceptualize 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 et al., 2008). System 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. Fig. 1 contains the steps of a system dynamics model building exercise, compiled by Zagonel (2002), and inclusive of frameworks developed by leading authors in this space (Richardson et al., 1995). The focus of our research study will be on *Problem Identification and definition,* and *Model conceptualisation*, focusing on producing a qualitative reflection or analogue of the problem space.

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 Section 2.2. Moreover, Section 2.3. describes the process of going from that to causal loop diagrams and includes the expected outcomes of this research.

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 (Homer, 2019; Haji Gholam Saryazdi et al., 2021; 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 (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 1. As a starting point, we focused this on developing a systems-level understanding related to the "voluntary mitigation of environmental impacts by battery mineral producers".

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* presented at Table 1. In order to identify the system components, we adopted a '*variables elicitation*' script from Luna-Reyes et al. (2006), which incorporates elements from previous participatory model building approaches (Delbecq et al., 1976; Vennix et al., 1997; Stroebe et al., 2014). 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

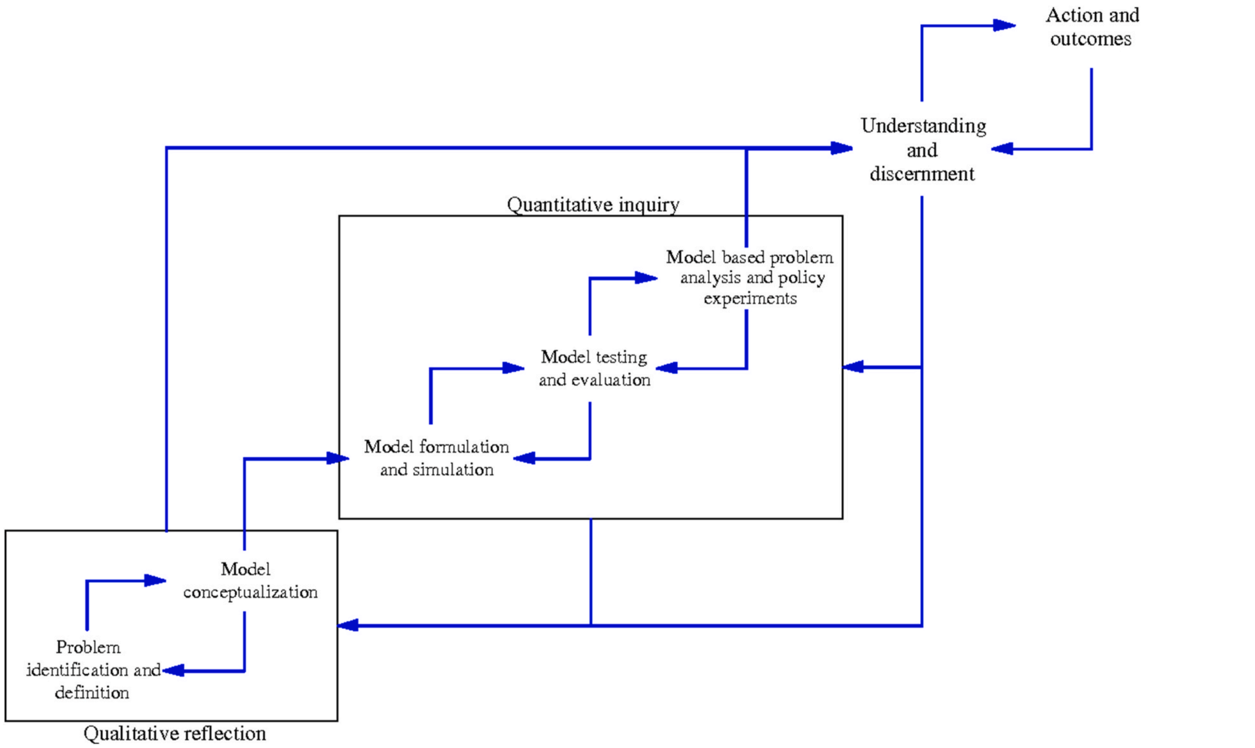

Fig. 1. Steps of system conceptualisation, from Aldo A. Zagonel (Erdmann et al., 2022).

Table 1
Stages included in the participatory systems thinking approach.

Stage	Process	Activities
1.Problem Identification and Definition	Stakeholder workshops	• reaching out to participants • Elicitation of variables • Connection circles • Consolidating variables • 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 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 validation workshop • Identification of causal relationships between key variables • Iterations of CLD until Final CLD
	Researcher Interpretation	• Identification of system boundaries • Definition of metrics for variables • Identification of system archetypes

Table 2
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

participants. This effort led to 12 workshops (individual or small group), engaging a total of 15 people (Table 2).

The scripts mentioned were applied to the participants described in Table 2. 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 Fig. 2. 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.

Given the extended geographical network that battery supply-chains entails, 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*

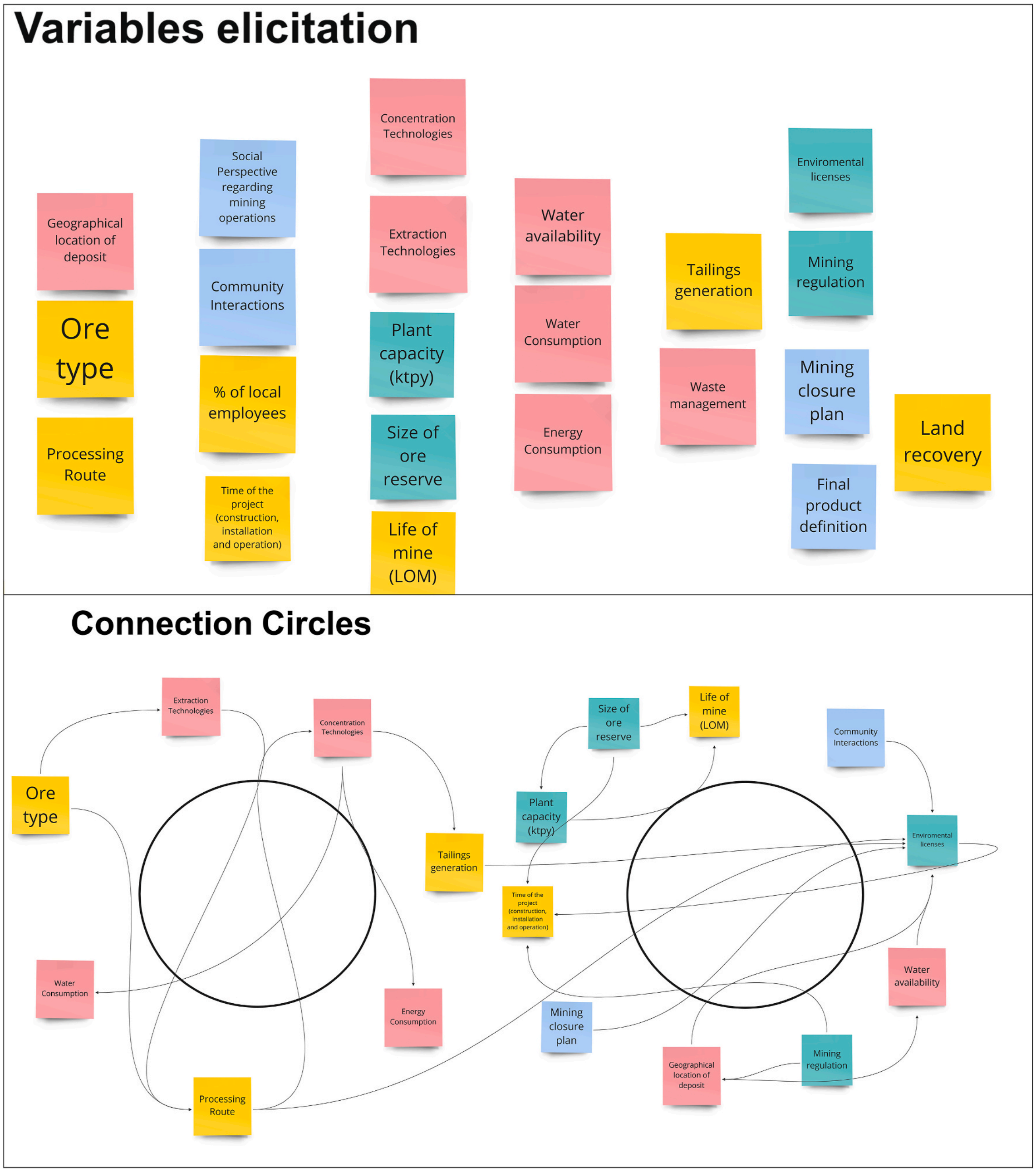

Fig. 2. Outcome of one of the workshops held with participants. On the top panel, a list of variables referred by the participant as the most influential to the system. On the bottom panel, two 'connected circles' in which the participants attempt to connect them through links of causality.

time and effort invested in bringing a system's mapping experience into an online environment was worth it" (Wilkerson et al., 2020).

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 integrations 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), were 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 that 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 for 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 1, 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 1, 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 Fig. 3.

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 Fig. 4.

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. In one hand, a country with higher levels of corruption can have an operation with *less 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 and showcasing the multiple links in between them.

3. Results and discussion

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 on Table 3. These variables are often central to analysis, intervention, or policy implementation. Based on our initial research focus, we have extracted and mapped two main variables 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 by Mace et al. (2012) and Oliver et al. (2015), and often cited in environmental frameworks 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 et al., 2018).

In addition to this iterative qualitative reflection, we have selected key variables based on their betweenness centrality, as presented on Table 4. 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 highest degree centrality, and closeness centrality, recognizing their roles as connectors/hubs and efficient spreaders of information, respectively (Perez et al., 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.

3.2. Supply chain activities and sub-system boundaries

In collaboration with the participants, as detailed in Table 2, 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 et al., 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 5.

3.3. Causal loop diagram

A static version of the final Causal Loop Diagram is presented in Fig. 5. The subsystems are color-coded for clarity: variables related to

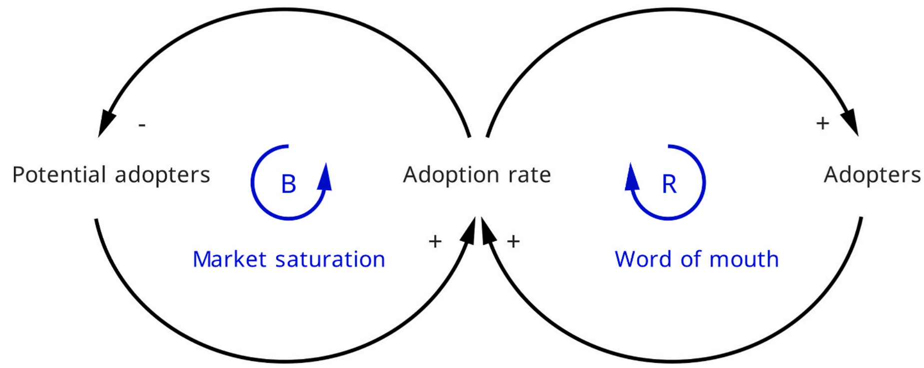

Fig. 3. Causal loop diagram of a new product adoption model by John Sterman (2001) Systems dynamics modelling: tools for learning in a complex world, California management review, Vol 43 no 1, Summer 2001.

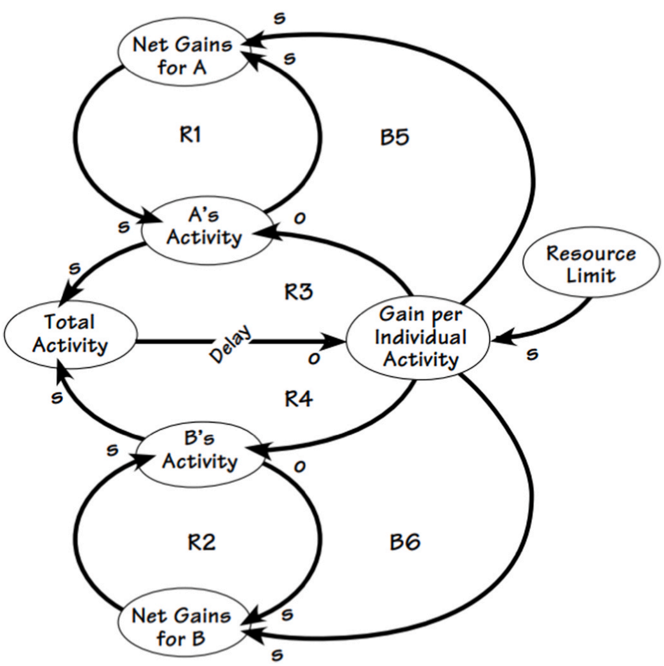

Fig. 4. Example of system archetype "Tragedy of the commons". From "The Fifth Discipline", adapted by Daniel, K. (Vennix et al., 1997).

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, interactive version can be found at https://kumu.io/bernardo-mendonca/cld-vsi-battery-minerals.

The data structure was prepared and organized for use in Kumu, a relationship-mapping software (Schoenenberger et al., 2021). 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 (Sverdrup, 2016; Olafsdottir et al., 2021), and methodological definitions of system boundary setting (Dhirasasna et al., 2020). The community detection analysis initially identified two subsystems, that 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.

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 its source, between primary extraction and recycling. A dynamic, interactive version can be found in the supplementary materials, and a static version is presented within Fig. 6 (top panel). One of the primary insights extracted from the CLD 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 Fig. 6 (**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 have 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 from 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

Table 3
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 the mining, mineral extraction and processing phase of the mineral and metal value chain. Expressed in kg of CO_2 equivalent.
	Biodiversity & Ecosystem Services	Biodiversity, which includes the variability among living organisms – including species, between species, and of ecosystem – underpins the benefits that humans can derive from the ecosystem (Mace et al., 2012). The ecosystem services are the outputs of ecosystem processes that proved 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 CO_2 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).

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 retainment of critical minerals onshore (Zhou et al., 2024).

From our workshops, one stakeholder argued that nickel being valued and traded as a commodity leads to limited preference amongst

Table 4
Variables with 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

Table 5
Supply-chain steps categorized 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.

purchasers to value non-price-based information when procuring nickel. An example of this is the closure of Australian nickel mines (ABC News, 2024a; ABC News, 2024b), at a time when Indonesian nickel operations are being opened or expanded[1] (GlobalData, 2024). Some stakeholders involved in our workshops argued that Australian nickel production has lower ESG impact or risk than Indonesian nickel production. In their opinion, mining in a place like Indonesia has higher risks to impacting the biodiversity, combined with higher rainfall volumes, which in our final CLD has a positive 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.

3.3.2. Subsystem 2: drivers to voluntary sustainability

The second subsystem emphasizes the variables influencing the

[1] 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.

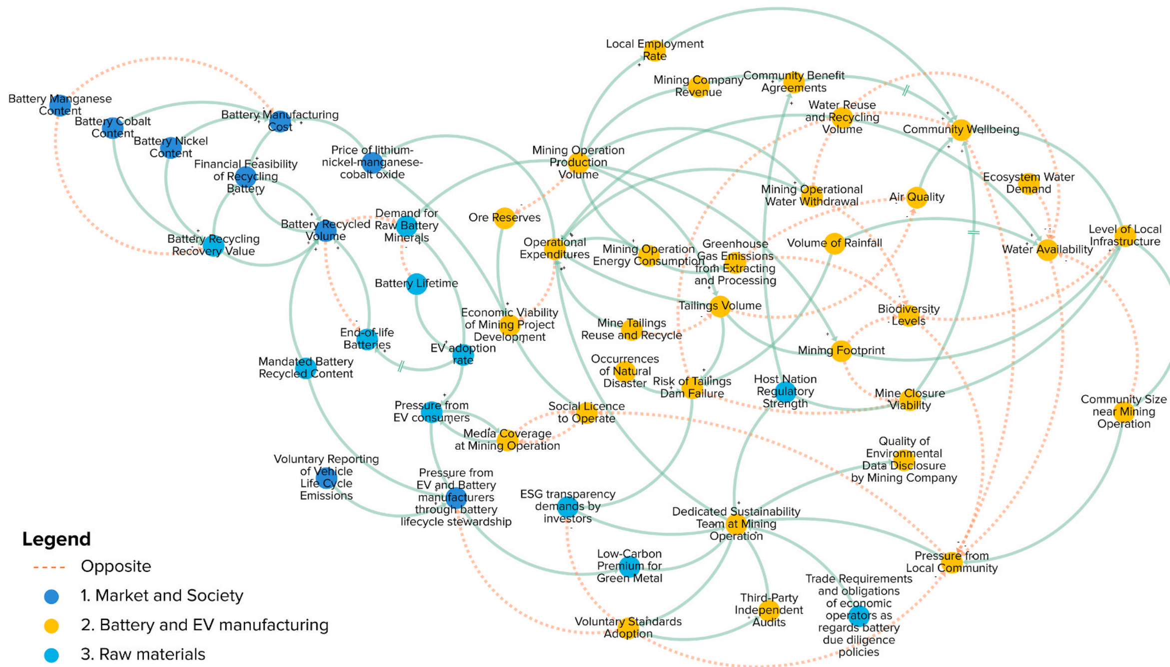

Fig. 5. Final Causal Loop Diagram. The green arrows denotes a positive relationship (+), red dotted arrows reflect an inverse relationship (−). Arrows with two stripes (||) denotes a delayed relationship (either positive or inverse).

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 (Fig. 7, 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 CO_2 equivalent per tonne of output across scopes 1–3 (London Metal Exchange, 2024a). 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, 2024b). 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" (Fig. 7, **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 over focus 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 co-horts 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.

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, 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 et al., 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 to 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."*

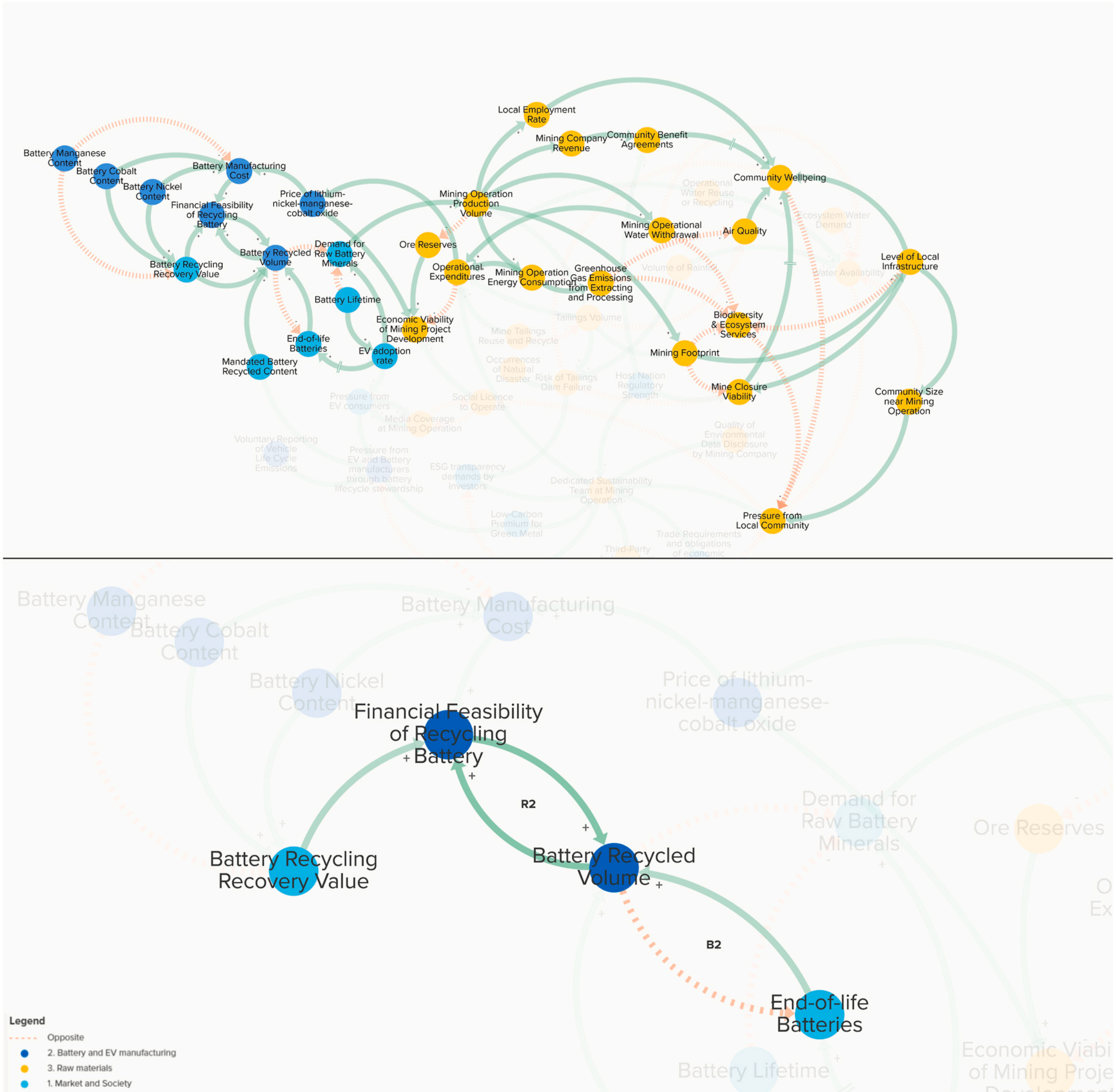

Fig. 6. Top – Static representation of Subsystem 1: Cost Dynamics of Recycling & Raw Materials Extraction; Bottom – Segment of Subsystem 1 with a focus on the 'limits to success' archetype.

(IRMA, 2018b). 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, 2018c). 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*.[2] 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.

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 et al., 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. To this matter, previous studies have associated a larger community with more extensive engagement efforts (Measham et al., 2019), and larger

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

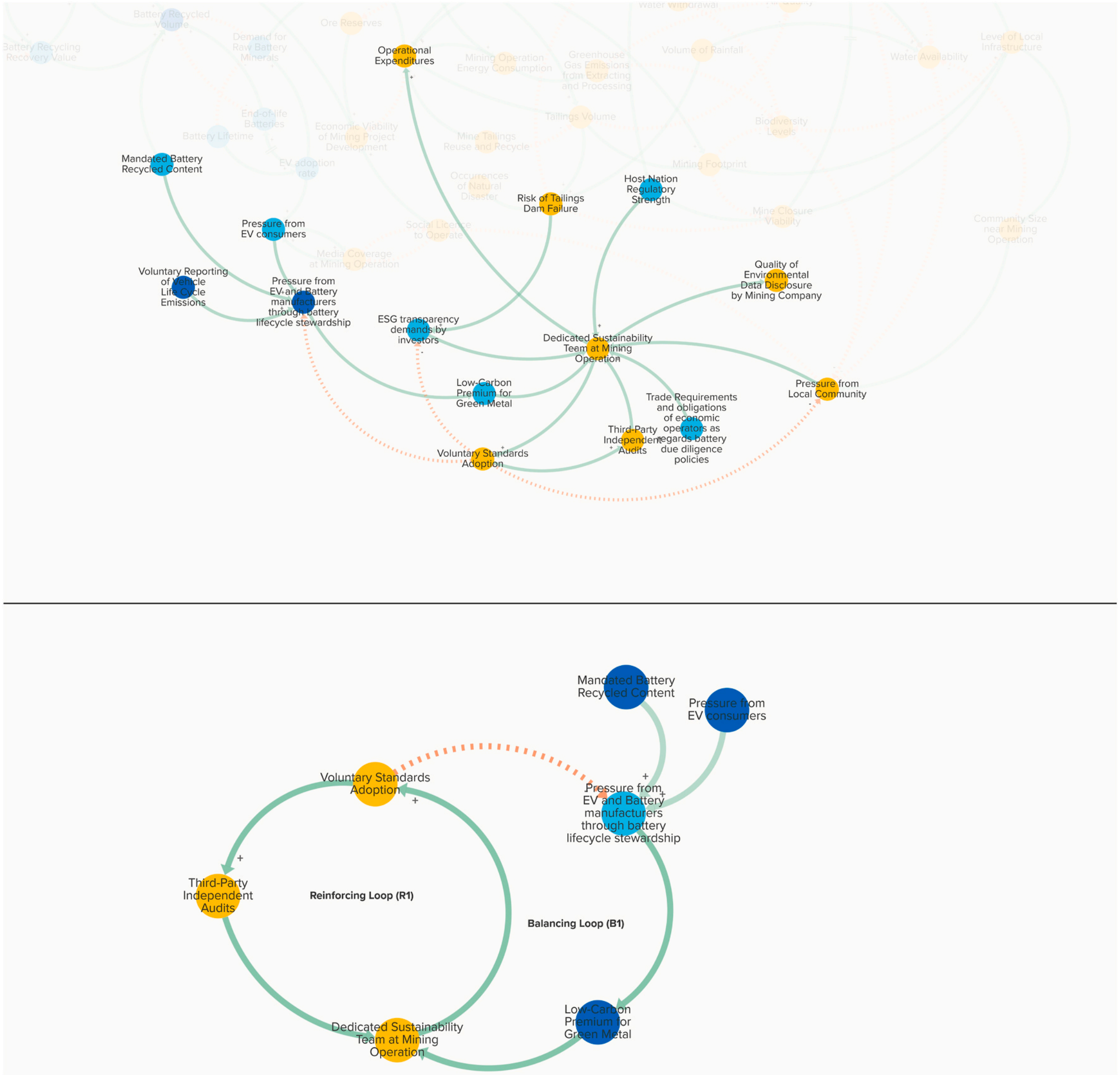

Fig. 7. Top - Subsystem 2 in focus; Bottom - Isolated "fixes that fail" archetype within subsystem 2.

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 et al., 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. (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 works have 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 et al., 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.

We can observe that *media coverage* is part of a reinforcing loop with *pressure from EV consumers*, as showcased in Fig. 8 (**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).

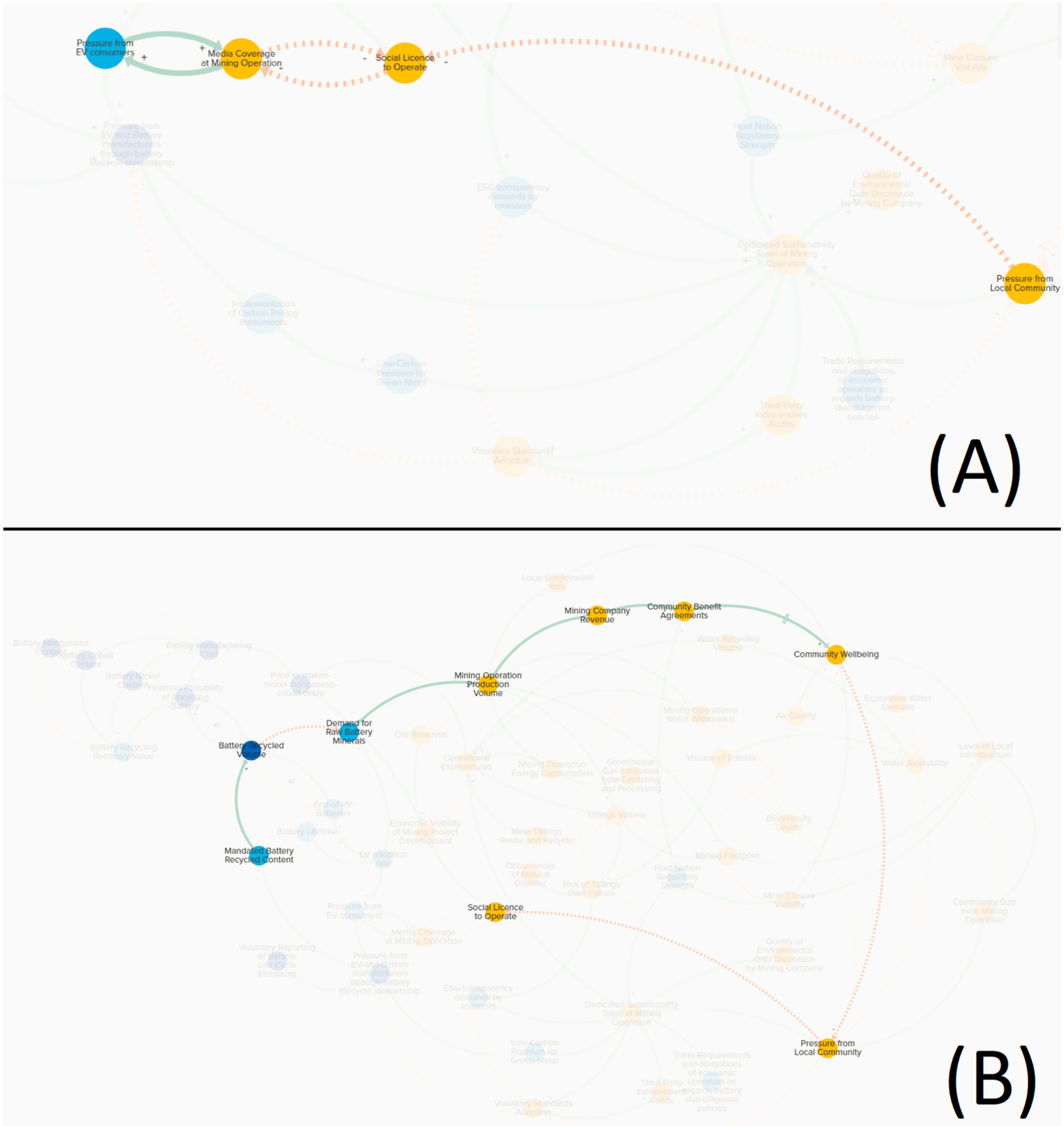

Fig. 8. Selected segments of the final CLD with a focus on: (A) The reinforcing and balancing feedback loops that characterize the 'limits to success' archetype within the system, and (B)The pathway from mandated battery recycled content and a social licence to operate.

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 phenomena 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 a 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 dusts from uncapped disposals 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 proved 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 mineral, 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 Fig. 8 (**bottom panel**), since CBAs are often based on a percentage of either the value of production, or a percent 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 note left in 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 of how such changes would affect the global market can be the focus of future quantitative system models.

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 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 a 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 suggestion for future studies, and the key findings and implications of the current analysis.

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 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 analyze the relationships between environmental impacts, their mitigation, and community trust and public opinion (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 et al., 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 synthesized 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.

4.2. 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 definition 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 their 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 commodified nature of battery minerals as 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 consideration, suggesting a review on 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 complimentary to the understanding we currently have about a companies' preconditions for successful implementation of sustainability standards (Ruokonen, 2020), such as the roles of mine management, line managers, and environmental experts, and also 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 from a transition to a quantitative inquiry.

CRediT authorship contribution statement

Bernardo Mendonca Severiano: Writing – original draft, Software, Methodology, Investigation, Data curation, Conceptualization. **Stephen A. Northey:** Writing – review & editing, Supervision, Conceptualization. **Jayden Hyman:** Writing – review & editing. **Damien Giurco:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Bernardo Mendonca Severiano reports financial support was provided by Future Battery Industries CRC. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2025.124941.

Data availability

Data will be made available on request.

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