FUTURE BATTERY INDUSTRIES CRC

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Development of a trusted supply chain for Australian battery minerals and products

SCENE SETTING REPORT PREPARED FOR
FUTURE BATTERY INDUSTRIES CRC

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Curtin University

Research Team

John de Laeter Centre, Curtin University
Prokopiy Vasilyev
Kai Rankenburg
Brent McInnes
Noreen Evans

Curtin Institute for Computation, Curtin University
Kathryn Barker
Rebecca Lange
Dan Marrable

Murdoch University
Hans C. Oskierski

Source Certain
Cameron Scadding

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Disclaimer

List of acronyms used in this report

AFP	BGR's analytical fingerprinting system
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe (German Federal Institute for Geosciences and Natural Resources)
CEMAC	Clean Energy Manufacturing Analysis Centre
CoC	Chain of custody
CTC	Certified trading chains
DRC	The Democratic Republic of Congo
DTC	Diamond Trading Company
ESG	Environmental, social and governance
EVSE	Electric vehicle supply equipment
EU	European Union
FBICRC	Future Battery Industries Cooperative Research Centre
GBA	Global Battery Alliance
GFP	Geochemical fingerprinting
GIA	Gemological Institute of America
GTK	Geologian Tutkimuskeskus (Geological Survey of Finland)
GWh	Gigawatt hours
ITRI	International Tin Research Institute
iTSCi	ITRI Tin Supply Chain Initiative
JdLC	John de Laeter Centre, Curtin University
JORC	Joint Reserves Ore Committee
kt	Kilo tonne
LA-ICPMS	Laser ablation inductively coupled plasma mass spectrometry
LFP	Lithium ferrophosphate (lithium iron phosphate)
LMO	Lithium manganese oxide
NCA	Lithium nickel cobalt aluminium oxide
Mt	Mega tonne
MU	Murdoch University
NCM	Nickel cobalt manganese cathode battery
OECD	Organisation for Economic Co-operation and Development
PWC	Price Waterhouse Coopers
SEM	Scanning electron microscope
SCI	Source Certain International
SQM	Sociedad Química y Minera de Chile S.A.
SAESSCAM	Service d'assistance et d'encadrement du small scale mining
US	United States of America
WA	Western Australia
WEF	World Economic Forum
3TG	Tantalum, tin, tungsten and gold

EXECUTIVE SUMMARY

This scene-setting report focuses on project feasibility, market need, and the potential value add to Australian Lithium (Li) producers. The study report has been prepared by specialists from the John de Laeter Centre at Curtin University (JdLC), Murdoch University (MU), Everledger and Source Certain International (SCI) for the Future Battery Industries Cooperative Research Centre (FBI CRC) in support of a proposed 3-year research project to develop a trusted supply chain for Australian battery minerals and products.

In addition to providing some definition around the current market drivers for responsible sourcing, this report evaluates existing solutions on provenance verification, supply chain transparency and traceability. The report includes a literature review to explore the gaps within the current supply chain infrastructure and to identify the value a project like this could bring to stakeholders in the Australian battery sector.

In addition to the literature review, the following conclusions and recommendations are based on the review and solutions proposed by the research:

- Lithium-ion batteries will play a critical role in bringing the transportation and energy sectors to carbon emission neutrality by transforming 'renewable energy' from a perceived 'alternate' source to a genuinely accepted 'primary' source. This need for fundamental change in perception and its associated societal benefits will drive the development of new battery technologies.
- Raw mineral exports in Australia identify Li as the key element in the Australian battery material supply market today. A framework of source verification for Australian Li products will provide the technological guidelines for expanding protocols into other raw battery materials (e.g. Ni, Co, Mn) and to international sources for broader comparison and verification.

- Existing responsible sourcing initiatives focus predominantly on Tungsten, Tantalum, Tin and Gold (3TG) from the Central Africa region regarding human rights abuses and financing conflicts concerns. To achieve responsible sourcing through the mineral supply chain, effective solutions are essential to provide trust in the sourcing claim and to transfer critical information through the supply chain to end-users for improved collaborative performance along the supply chain.
- Countries and regions with existing high standards of mining and processing of battery minerals and metals, such as Australia, could derive market advantage and potentially value through highlighting responsible production practices. This will require demonstration of responsible sourcing data with globally recognised certification schemes, such as Initiative for Responsible Mining Assurance (IRMA) or Certification of Raw Materials (CERA). The effective demonstration will be achieved using a transparent traceability solution with an integrated trust-providing provenance verification mechanism and expanding market access for responsible producers.
- Traditional supply chain traceability methods (e.g. paper-based labels) and some novel technological solutions offer compliance and varying degrees of transparency with payoffs around accessibility, privacy, and efficiency. However, industries are addressing increasing supply chain requirements by digital transformation using emerging technologies, such as blockchain technologies, to create improvements in consumer satisfaction, auditability, logistical and economic efficiencies. Currently, a public, open-source and scalable blockchain technology provides transparency with regards to data transactions and storage through the Chain of Custody.
- A traceability solution based on blockchain technology with a mass- balance model approach increases trust and consensus along the Chain of Custody and minimises fraud risk with tamperproof verification methods to provide secure data sharing. Mineral supply chain challenges such as scalability, confidentiality and accessibility should be addressed in the platform development proposal, prepared in close interaction with service sector industry partners.
- The concept of provenance verification is at the core of a trust-building strategy for a responsible supply chain and offers a highly auditable process to minimize perceived financial, social, performance and physical risks. Provenance verification technology is based upon chemical information and is independent of conventional shipping documentation and tagging procedures, thus allowing for more robust verification of product provenance. The existing provenance verification methods focus predominantly on the mining side of a mineral supply chain and are employed in case of disputes through a highly auditable and often costly process. The suggested provenance verification method of battery materials and elements aims for the systematic and secure integration of the method in the Chain-of-Custody traceability solution. This must provide timely and cost-effective audit capabilities for supply chain actors, which is necessary for successful acceptance by end users.
- Geological processes impart a chemical 'fingerprint' on minerals that can be used to develop a geochemical fingerprinting (GFP) database for material identification. Unknown product samples accompanied by a provenance claim can be chemically compared against this database for source verification. Fingerprints may be isotopic or elemental, or a combination of both. An effective facilitated verification solution will connect upstream and downstream products using chemical signatures that retain their voracity throughout the supply and production chain.
- The material identification and trusted supply chain, in general, will support the emerging requirement of efficient recycling uptake as part of the rapidly emerging global market mandates for recycling and reuse in supply and manufacturing. The significance for the Australian resources industry is the potential differentiation opportunity brought through an effective traceability solution optimised to the circularity and Life-Cycle Assessment (LCA) equation of important sustainability metrics. This can be provided through a partnership with the "Certification and LCA" project and engagement with major responsible sourcing certification schemes, such as IRMA and CERA.

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1. BATTERY VALUE CHAIN

Battery technology will play a crucial role in transitioning the transport and energy sectors to carbon emissions neutrality by transforming renewables from an intermittent source to a reliable source of dispatchable energy, along with other storage technologies. Recently the World Economic Forum (WEF, 2020) reported that by 2030, batteries could provide electricity to 600 million people who are currently without electrification, create 10 million safe and sustainable jobs while contributing 30% of the required reductions in carbon emissions required by the Paris Agreement on Climate Change (UNFCC, 2015).

These societal benefits will require the adoption of a range of battery types (e.g. Nickel-Metal Hydride (NiMH), Vanadium Redox Flow (VRFB)); however, Li-ion batteries are by far the most widely used across a broad range of technologies, including consumer electronic devices, electric vehicles, and energy storage.

LITHIUM-ION BATTERY COMPONENTS

Following the introduction of the first commercial lithium-ion battery by Sony and Asahi Kasei in 1991, battery demand has grown at an annual rate of 25% and is expected to reach 2600 GWh in 2030 (Figure 1). Despite the name, Li-ion batteries are comprised of more than just Li. A commonly used cathode is NCM — lithium nickel cobalt manganese oxide powder — while graphite is a widely used anode. The ratio of metals in the cathode varies depending on the type of battery, stability limitations and its intended use. Once the most popular battery used in electric vehicles, the NCM 622 battery (nickel:cobalt:manganese in a 6:2:2 ratio) is rapidly being replaced by less costly and higher energy density batteries with different cathode metal ratios, such as NCM 811 (Figure 2). In September 2019, 18% of passenger EVs sold in China had NCM 811 battery cells, up from just 1% in January 2019 (Adamas Intelligence, 2019).

The International Energy Agency (IEA) Global EV Outlook 2020 Report (IEA, 2020) indicates that electric vehicle (EV) battery packs for transport and mobility purposes made up 89% of the total global battery market in 2019. In that year, 2.1 million electric vehicles were sold worth an estimated $USD 162.3 billion. Based on demand trends, the value of the EV market is expected to exceed $USD 800 billion by 2027. As battery demand increases, so will the demand for cobalt, lithium, manganese and nickel. In 2019, the IEA estimated material demand levels of about 19kt for Co, 17kt for Li, 22kt for Mn and 65kt for Ni. By 2030, the IEA projects global demand for these materials will expand to at least 180 kt/year for Co, 185 kt/year for Li, 177 kt/year for Mn and 925 kt/year for Ni.

The rapid pace of battery technology advancement and projected growth in EV demand will force the Li-ion battery manufacturing industry to secure supplies of battery-related minerals containing lithium, cobalt, nickel, and manganese. These elements, along with vanadium and the rare earth elements (REE), contribute to a major international supply-chain industry worth $6.5 billion in 2017 (Wilson and Martinus, 2020).

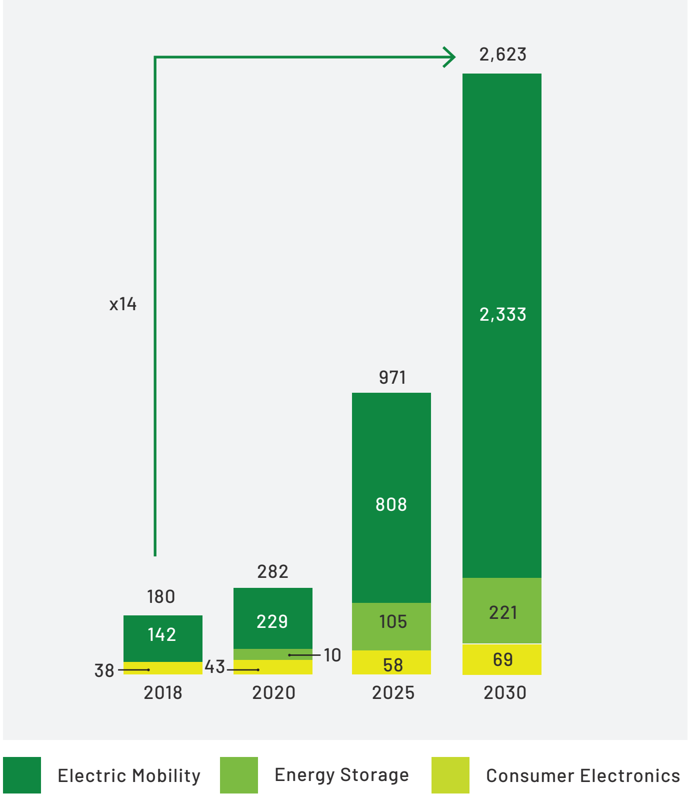


Figure 1: (from WEF, 2020). Global battery industry growth by application by 2030 in GWh. World Economic Forum, Global Battery Alliance, McKinsey analysis.

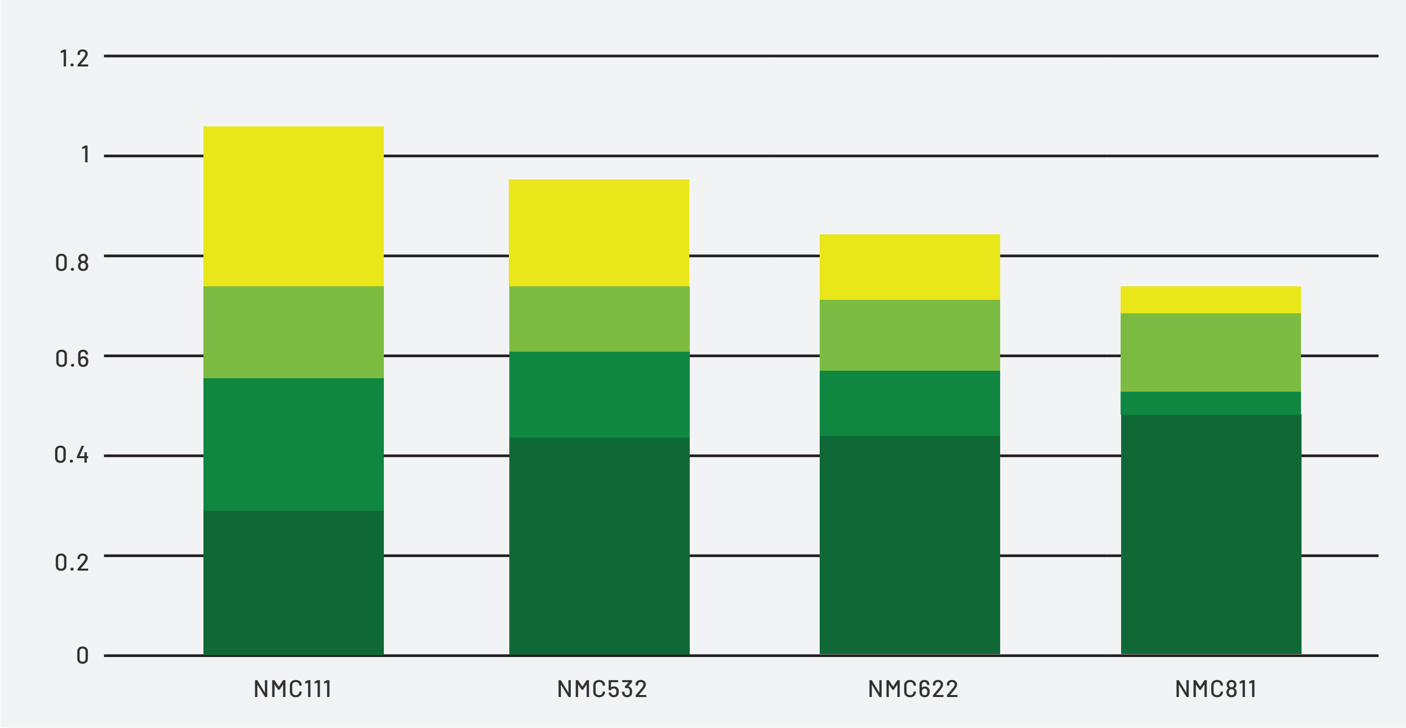


Figure 2: NMC Cathode materials – the weight of cathode in 1 kWh of battery (kg) (from Electric Vehicles Update report by Equita, 2018).

In 2015, the global raw material supply for the battery-intensive elements (Li, Ni, Co and Mn) was sourced from 32 countries (CEMAC, 2016); however, the supply and distribution of these materials is relatively concentrated, with 50% of products originating in only one or two countries:

- **Cobalt** production is primarily driven by the needs of the battery manufacturing industry, which accounts for 57% of global demand, and is estimated between ~124-140 kt per annum (90% mined; 10% recycled). Around 70% of cobalt is mined in the Democratic Republic of Congo (DRC), with the other major players (Russia and Cuba) comprising less than 13% of the global supply (McKinsey, 2018). As of December 2019, there was no commercial-scale production of battery-grade cobalt in Australia, although cobalt is produced as a by-product of nickel mining (Best and Vernon, 2020)
- **Nickel** (Class 1, High Grade) is predominantly produced from mining nickel sulphide ores, where Australian mining operations contribute 9% of the global supply. However, it is the conversion of nickel sulphide ore to a nickel sulphate chemical product that is the key constraint for the battery supply chain. According to SMM (2020), the global refining capacity for nickel sulphate was 1.39 Mt in 2019 (43% of supply fromChina), with capacity growth expanding to 2.5 Mt per annum by 2022. Australia is expected to contribute to the global market growth as a result of BHP Nickel West commissioning a 100 kt/a nickel sulphate plant by the second half of 2020 (Best and Vernon, 2020).
- **Manganese** sulphate and oxide demand for battery applications was 41.1kt in 2018, comprising only 0.2% of global Mn production (Talbot and Watts, 2020). Similar to Ni, the battery supply chain requires Mn ores to be refined and converted to a high-purity chemical - manganese sulphate monohydrate (HPMSM). Global production of HPMSM was estimated at 28 kt in 2017, with over 87% produced by Chinese suppliers. Australian supply of battery- grade Mn is projected to become available in 2021 with the completion of Mn Energy Ltd's plant in Western Australia (Best and Vernon, 2020).
- **Lithium** is mainly sourced from the mineral spodumene ($LiAlSi_2O_6$), which occurs widely throughout Western Australia, and from Li-enriched brines in hyperarid regions of South America such as Bolivia Argentina and Chile. Australia is responsible for more than 58% of the global supply of Li and expected to increase its output of the refined high-purity lithium hydroxide in coming years from new conversion plants built in Western Australia (i.e. Covalent Lithium).

LITHIUM SUPPLY: THE WORLD AND AUSTRALIA

Global lithium reserves are estimated at 17 million metric tons by the US Geological Survey, with continental brines and pegmatites (or hard rock ore) the main sources for commercial production. Li-bearing pegmatites (hard-rock) making up 51% of the supply, and South American Li brines sourced mainly from salar lake deposits making up 43% of the global supply (mainly from Latin America in Figure 4) (Austrade, 2018). Generally, lithium extraction from brine sources for Li_2CO_3 has proven more economical than production from hard rock ore. There are three types of lithium brine deposits: continental, geothermal and oil field. The most common are continental saline desert basins (also known as salt lakes,salt flats or salars) (Vikstrom et al., 2013). They are located in areas with geothermal activity and are made up of sand, minerals with brine and saline water with a high concentration of dissolved salts. Lithium brine deposits represent about 66 percent of global lithium resources and are found mainly in the salt flats of what is known as the "Lithium Triangle" — a region of the Andes Mountains that includes parts of Argentina, Chile and Bolivia (Houston et al., 2011).

The best example is the 3,000 square kilometre Salar de Atacama in Chile, which has an average lithium concentration of about 0.14 percent — the highest known — and estimated lithium resources of 6.3 million Mt (Flexer et al., 2018). Bolivia has the world's largest deposit of lithium, the Salar de Uyuni, which reportedly contains up to 50 to 70 percent of known world reserves. However, the deposit has magnesium-to-lithium ratios that are three times higher than those at the Atacama, making it more difficult and costly to refine salt into lithium carbonate. Additionally, the evaporation rate at Uyuni is only 40 percent of that at the Atacama, which means refining would be more time consuming (Flexer et al., 2018).

South American brine extraction follows two production routes: (1) solar evaporation and (2) direct lithium extraction (DLE). Both methods require the concentration of a lithium salt from a lithium brine. The solar evaporative route uses vast shallow ponds to concentrate the brine salt, and then a reagent-intensive hydrometallurgical

TABLE 1: LITHIUM PROJECTS AND JORC ESTIMATED RESOURCES IN WA

DEPOSIT	ORE (MT)	GRADE (%)	LI_2O (MT)	MINING COMPANY
Greenbushes	157.8	2.25	3.56	Talison Lithium/ Tianqi
Mt Cattlin	16.42	1.08	0.18	Galaxy Resources
Mt Marion	77.80	1.37	1.07	Mineral Resources
Wodgina	195.8	1.18	2.32	Mineral Resources
Mt Holland	128.0	1.44	1.84	Covalent Lithium
Bald Hill	18.90	1.18	0.22	Tawana Resources (closed)
Pilgangoora (1)	47.50	0.99	0.47	Altura Mining Limited
Pilgangoora (2)	150.6	1.24	1.86	Pilbara Minerals
Lynas Find	5.60	1.57	0.09	Pilbara Minerals
Total	**798.4**		**11.61**	

process is used to remove impurities and convert the lithium chloride into lithium carbonate (Swain, 2017). The DLE process reduces the need for large scale evaporation ponds and can process lithium brines containing higher concentrations of impurities (Roskill, 2020).

The manufacture of NCM 811 battery cells favours LiOH over Li_2CO_3 (New Age Metals Inc. 2019), and therefore further processing of South American brine products is required to satisfy that market. Hard rock lithium deposits associated with felsic granites are present on nearly every continent and have a higher and more consistent Li grade than brine deposits (Kesler et al., 2012).

Western Australia is currently the largest producer of hard-rock Li and has the third-largest estimated reserves of Li (11.61 Mt Li_2O; Geoscience Australia, 2018) in the world. The mineral spodumene, found in pegmatite deposits, is the primary Li mineral being produced, or targeted for production, at six key resource operations in Western Australia (Figure 3, Table 1).

Processing of hard-rock Li ores requires physical methods such as crushing, grinding and flotation to liberate and concentrate spodumene. Typically, spodumene concentrates undergo chemical processing at high temperatures to make the required cathode product, primarily Li carbonate (Li_2CO_3) or Li hydroxide (LiOH) (Talbot and Watts, 2020).

Australian Li producers currently export Li as spodumene concentrate grading 2.6%-2.8% Li (94% of export) compared with 6% of export Li as LiOH (Austrade, 2018). Chemical processing of Australian Li ores is carried out overseas (China produces 89% of the world's LiOH); however, three Li chemical processing projects are being commissioned in Western Australia: (1) Tianqi / IGO in Kwinana; (2) Covalent (Wesfarmers/ SQM) in Kwinana; and (3) Albemarle in Kemerton. Each plant aims to produce 50,000 to 100,000 tonnes per annum of high purity, battery-grade LiOH (Austrade, 2018) for export to battery manufacturers overseas.

IMPROVING AUSTRALIA'S POSITION IN THE LITHIUM-ION BATTERY VALUE CHAIN: OVERVIEW AND CHALLENGES

Austrade (2018) delivered a report concluding that very little of the value incorporated into Li-ion batteries is retained in Australia. Australia achieves value in this area almost exclusively by exporting Li mineral concentrate and has negligible input in downstream stages of the supply/value chain (Figure 4). The significant battery value is realised in the later stages of the supply chain: cathode production, battery assembly and some cell manufacturing.

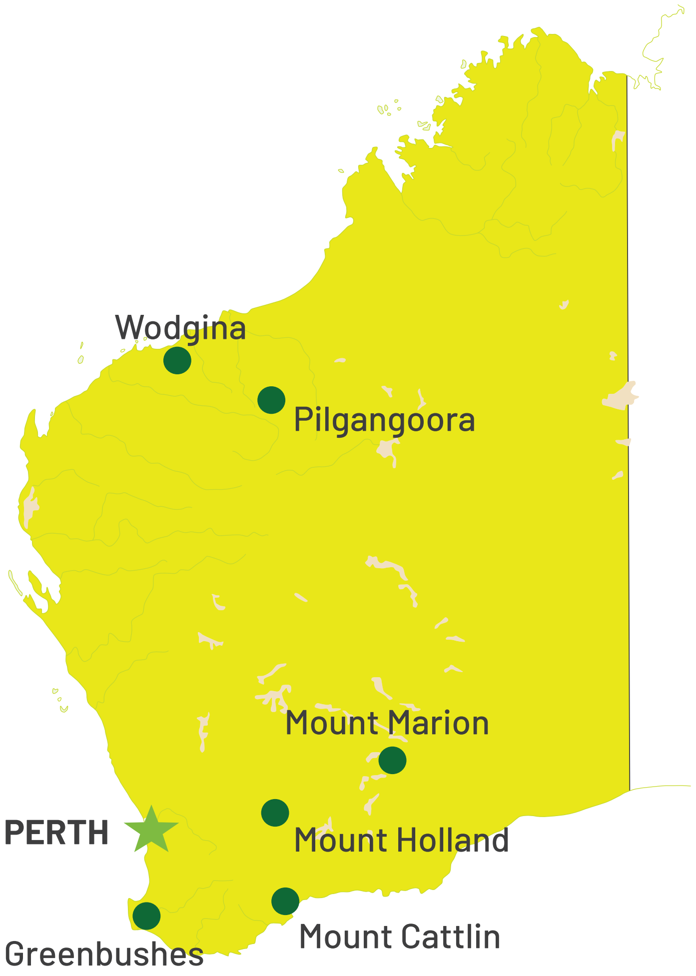
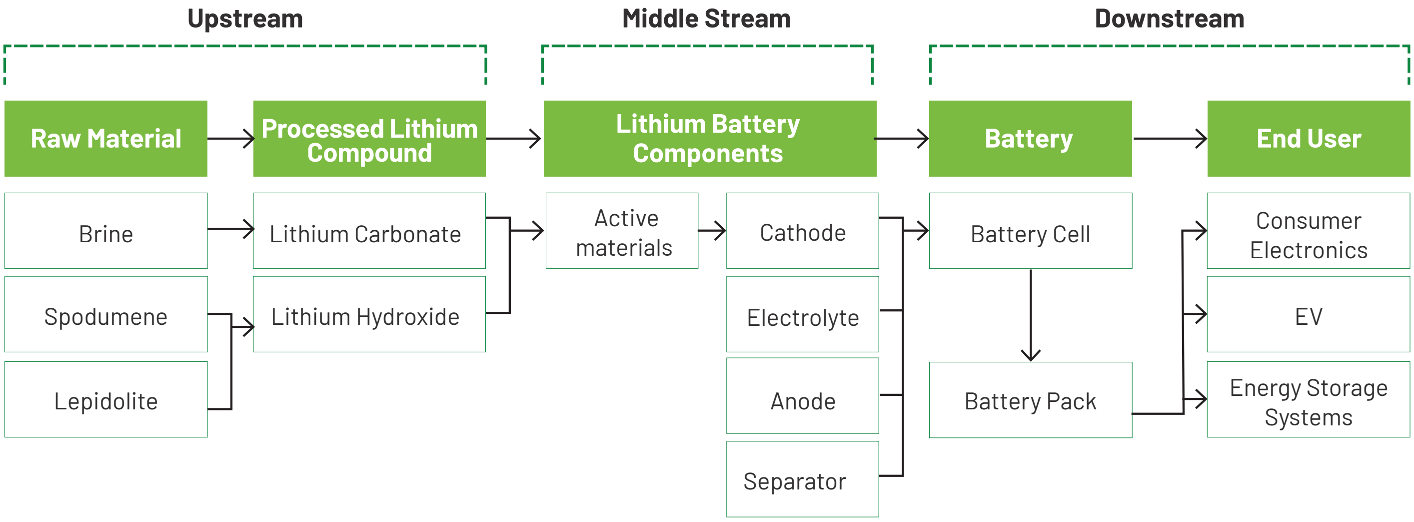


Figure 3: Main Li deposits in WA (map sourced from Geological Survey of Western Australia)



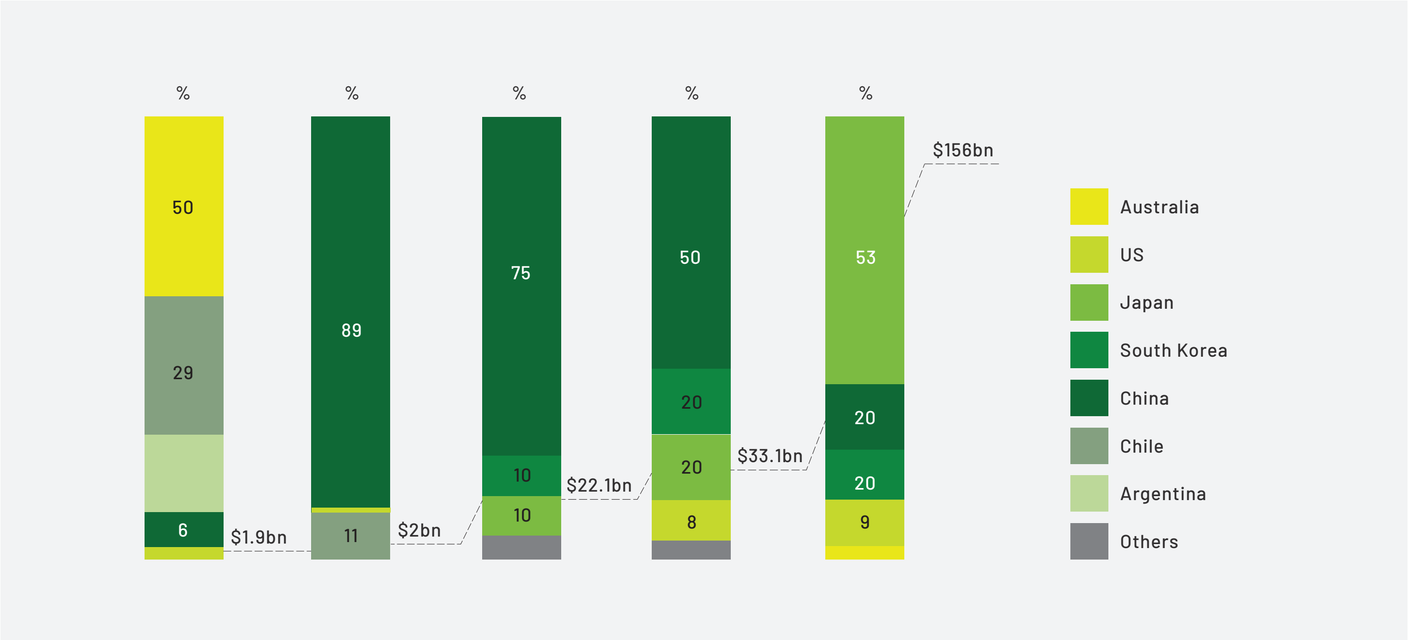


Figure 4: Simplified Li supply chain and stage value estimate for Australia and the rest of the world (Association of Mining and Exploration Companies, 2017).

The key players in the middle stream chemical processing of the supply chain are mainly represented by Chinese companies, with South Korea and Japan completing the list of the top three countries involved in downstream battery production (Figure 4). Consequently, it is these countries that gain maximum economic activity and value from battery products being used in the end-user battery consumer markets (e.g. EU, US).

Highly concentrated stages of the supply chain mean that the battery minerals market is subject to very high levels of supply risk (Wilson and Martinus, 2020). With a small number of countries accounting for the bulk of world raw mineral refining, adverse events can easily lead to interruptions in international trade. Additionally, consumers of battery products want to know they are making environmental, social and governance (ESG) responsible choices and are not served by this structure, choices that are limited by existing non-transparent trade practices at the manufacturing stage of the battery supply chain (Wilson and Martinus, 2020).

If upstream producers can directly connect to the end-users and demonstrate that battery minerals and materials sourced from Australia are produced in socially acceptable, environmentally and governance responsible operations with the promise of a secure supply of quality raw materials, and if Australian minerals can be verifiably differentiated from competitors with negative ESG impacts, there will be an opportunity for the Australian industry to capture market access and potentially attract a premium price for their products. Innovative solutions are required so that Australian producers fully benefit from this advantage by delivering this value-add information to end consumers without disrupting the supply chain.

Australia can benefit from a trusted supply chain

Despite being a significant global supplier of critical battery minerals, without supply chain traceability, Australia has limited ability to market the benefits or leverage further value from the high-yield end of the battery consumer market. The complex battery supply network, with concentrated middle stream stages, is sensitive to supply disruptions (security risks) and non-responsible sourcing and manufacturing practices (ethical and sustainability risks). Australia has a unique opportunity to benefit from demonstrating responsible sourcing and high product quality.

2. ETHICAL MINERAL SOURCING AND RESPONSIBLE BATTERY SUPPLY CHAIN

End consumers of high-technology products are becoming increasingly aware of the impact that their purchasing decisions have on society and the environment. A significant share of global reserves of battery minerals are located in countries rife with corruption and political instability (Ali et al., 2017), and where under-resourced government agencies struggle to ethically and sustainably regulate the production industry. The responsible consumption also includes the environmental impact of the product supply chain, such as the carbon emission of mineral mining needed to produce Electric Vehicles (Tesla Impact Report, 2019).

EXISTING ETHICAL AND ENVIRONMENTAL SUPPLY CHAIN RISKS FOR BATTERY MINERALS

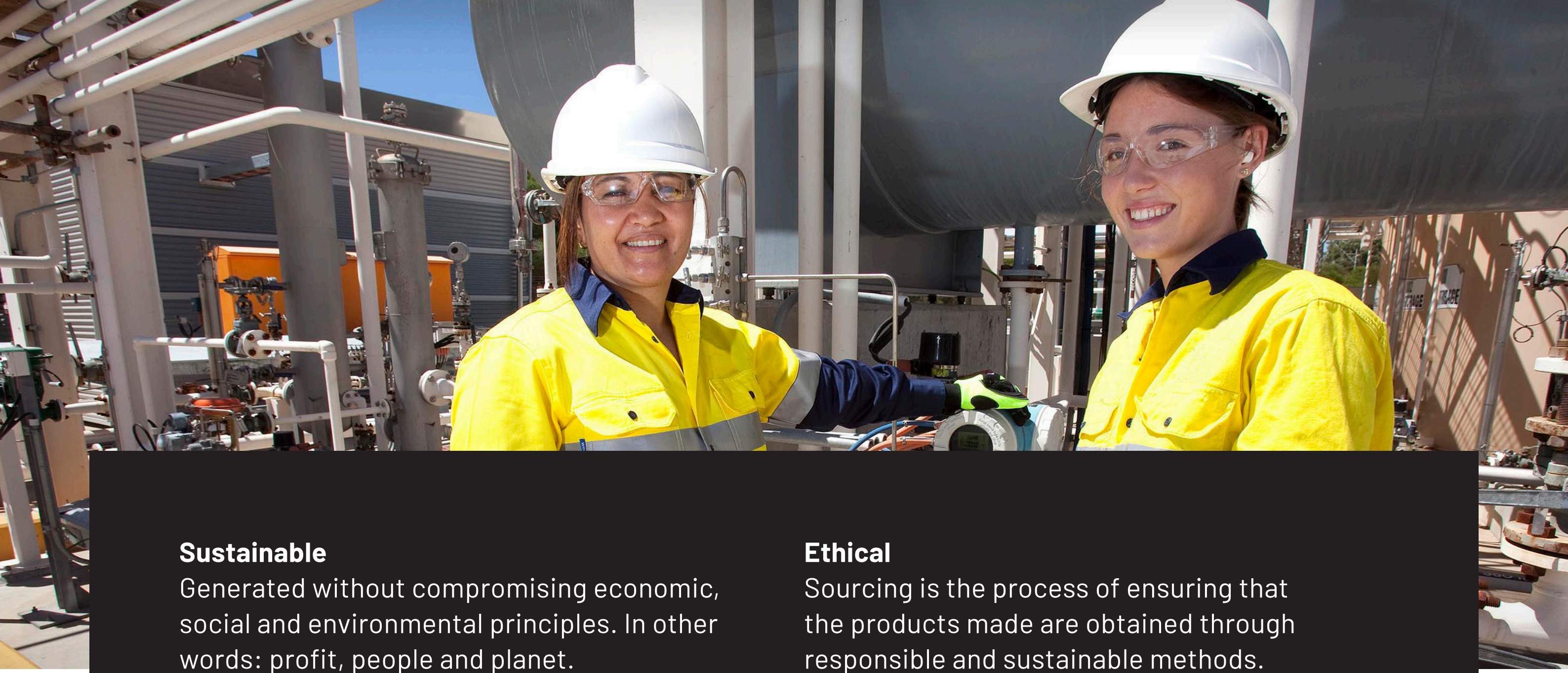
Some countries acknowledge these risks and have started to react and address the issues of non-responsible mineral sourcing practices by putting regulations and policies in place.

In July 2010, the US Congress passed the Dodd-Frank Wall Street Reform and Consumer Protection Act. Section 1502 of the Act requires US stock exchange-listed companies involved in a mineral supply chain to disclose whether any of the minerals originated in the DRC or an adjacent country (US Securities and Exchange Commission, 2012).

In May 2017, the EU adopted Regulation EU 2017/821 to address the same due diligence obligations for EU importers of 3TG (EU Parliament and Council, 2017). The regulation requires EU companies to follow the OECD Due Diligence Guidance for Responsible Supply Chain of Minerals from Conflict-Affected and High-Risk Areas (OECD, 2020). It enforces five steps of risk management around mineral sourcing from conflict-affected and high-risk areas.

The Risk Management Protocol of the OECD identifies seven risk categories:

- **Human Rights** – Child and Forced Labour, Discrimination and Inhumane Treatment
- **Security** – International Humanitarian Law, Non-State Armed Groups
- **Legality** – Corruption, Legal Tax Paying, Operational Legality and Reporting
- **Community** – Business Conflict, Community Development and Indigenous/Heritage
- **Working Conditions** – Occupational Health and Safety and Workers Rights
- **Environment** – Emissions/Waste, Water, Mine Closure, Environment Protection
- **Chain of Custody** – Traceability



Sustainable
Generated without compromising economic, social and environmental principles. In other words: profit, people and planet.

Responsible
Generated with social and environmental considerations.

Ethical
Sourcing is the process of ensuring that the products made are obtained through responsible and sustainable methods.

Trusted
The claim (ethical or any other) is verifiable by independent scientific methods.

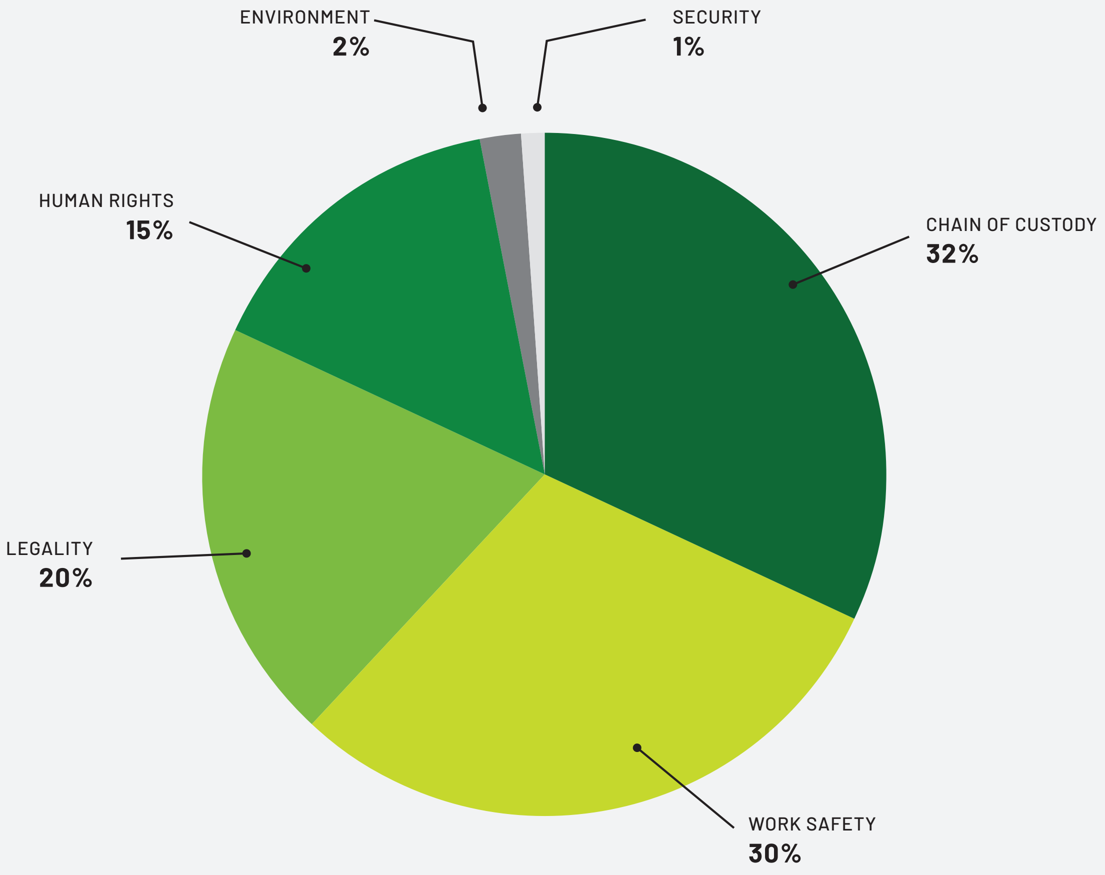


Figure 5: The proportion of incidents registered in the DRC by RCS Global.

The first two risks were the primary drivers for implementing regulations; however, studies show that the remaining items pose a disproportionately higher risk when minerals are sourced from high-risk areas, especially the DRC (e.g. cobalt mining; RCS Global Group, 2019) (Figure 5).

It's not just the sourcing of minerals from high-risk countries that creates risks. Inability to trace a commodity through a complex battery supply chain is a significant risk for the industry, an issue specifically identified by Apple in their 2018 report (Apple Inc., 2019):

"Apple has not, to date, been able to determine whether the reported incidents [in the DRC] were connected to specific 3TG included in Apple's products. The challenges with tracking specific mineral quantities through the supply chain continue to prevent the traceability of any specific mineral shipment through the entire manufacturing process".

The electronics market (including the Li-ion battery market) has been a focus of significant social scrutiny, predominantly due to the presence of Co in various components, such as cathodes and the reported ethical issues regarding mining and trade in the DRC (The Guardian, 2019). The FBI CRC report "The governance of battery value chains: Security, sustainability and Australian policy options" identified two key risks associated with the battery mineral supply chain – security and sustainability (Wilson and Martinus, 2020). If the security risk is related to the complexity of the battery supply chain (international and multistage chain of custody) and highly concentrated mid-stream companies described in the previous chapter, the sustainability risk is predominantly linked to mineral sourcing.

Along with the previously mentioned Congolese conflict Co sourcing issues, the Li supply chain is also susceptible to sustainability issues, such as environmental and community risks.

Latin America's Li triangle (Bolivia, Chile and Argentina) holds 2/3 of known world lithium resources. It faces significant problems with sustainability of the Li production process: water usage and waste generation/disposal. In close relation to these issues, Flexer et al., 2018 raises the question of flora and fauna conservation. Lithium-bearing brine production techniques require a large amount of water to deliver brine from the underground to the surface and form large brine lakes. Data provided by Provincial and National Mining Offices in Argentina suggest that no less than 5 and up to 50 m^3 of freshwater are needed per tonne of final battery-grade Li_2CO_3 that is produced. This might not seem a huge volume, except it is being pumped out from very arid land (Flexer et al., 2018).

Additionally, there is also concern about the possible interaction of the different aquifers, i.e. brine water and freshwater, and in particular, what is going to happen if brine starts to get depleted by lithium mining (Houston et al., 2011).

However, there is minimal government oversight and regulation surrounding the ecological impacts of lithium mining in Latin America's Li triangle. As a result, protests and conflicts surround this issue, and companies come under fire for allegedly encroaching on indigenous land and restricting water access (National Geographic, 2019).

Some battery supply chain companies created a trade solution with reputable suppliers to avoid security and sustainability risks associated with mineral sourcing. The BMW group identified critical elements in the supply chain and adopted a short-term strategy to source only from approved sources (e.g., an agreement worth €540M for five years with Ganfeng Lithium for Australian hard-rock Li; Benchmark Minerals, 2019). It should be noted that this solution is a short term fix, limited to supply chain consortiums with long-standing partnerships and addresses only limited battery elements and associated risks.

Financial, legal and reputational risks associated with unethical sourcing of raw materials in non-transparent supply chains are potentially high for downstream technology industries and especially for battery manufacturers. Widely accepted initiatives can minimise those risks by imposing due diligence, thereby increasing battery consumer confidence and enhancing market share for countries with highly regulated production standards.

EXISTING INITIATIVES FOR RESPONSIBLE MINERAL SOURCING

A number of initiatives have been aimed at responsible mineral sourcing, with most aiming to capture and measure mining sector standards for ethical and sustainable production (Potts et al., 2018). Currently, at least 40 different certification schemes exist for mining activity alone, a value that increases exponentially if the entire value chain is considered. Some certification schemes are specific to a single geographic location, process or risk category, while others focus on a single mineral or element. Existing certification processes are complex and inconsistent, resulting in a porous and diffuse approach to defining sustainability and ethics from country to country, mineral to mineral, and company to company (DMT group, 2020).

The FBI CRC "Certification and LCA of Australian Battery Materials – Drivers and Options" scene-setting report conducted a detailed review of the literature and documentation and concluded that most of the existing certification schemes do not apply to lithium (Rutovitz et al., 2020). Of the forty included in the World Economic Forum review (WEF, 2015), the majority were only guidelines with a focus on only the ethical aspects of responsible mineral sourcing. Seven schemes were identified that offered additional sustainability certification for mineral extraction, with five of those for specific commodities, leaving just two schemes that are available for certification of lithium, the IRMA and the CERA schemes. Both offer comprehensive responsible mineral sourcing certification schemes, with the main difference being that IRMA applies to the mine site, while CERA will eventually apply to the full supply chain. The FBI CRC report highlights the unresolved issue about CERA governance and transparency and concludes that the IRMA scheme seems to offer a no-regrets approach for certification of Australian mines (Rutovitz et al., 2020).

A comprehensive certification scheme designed to capture and demonstrate responsible sourcing information should require mechanisms to apply a traceability solution that provides trust in the integrity of the supply chain and demonstrates ethical and sustainability claims with provenance verification.

Knowing the provenance of a product with confidence underpins any "essential source claim", including those that may be delivered as part of a supply chain due diligence process. Supply chain management and reporting systems, including traceability, are also developed from a foundation of trust in and assumption of the accuracy of the data relating to source or origin. The importance of provenance is amplified for high-risk products such as diamonds. Initiated by the 2003 Kimberley Process to stop "blood diamond" traffic, certified diamonds on the market currently have a provenance claim in the form of a "provenance certificate" (Diamond Trading Company, 2013) documenting geographical origin, type of rock source and mining practices. However, the governance issues and paper-based data collection (audit reports and contracts) make this system susceptible to tampering and do not entirely deliver on its objective (Williams, 2017).

Clearly, more reliable provenance verification mechanisms are needed, especially for complex multielement mineral supply chains, such as battery or electronics ones. Since any physical attributes are lost due to material transformations through processing stages, verification methods should preferably be based on inherent commodity attributes such as chemical profiles. The only existing method that utilises geochemical mineral information is the Geochemical Fingerprinting tool (GFP) developed by The German Federal Institute for Geosciences and Natural Resources (BGR) (BGR, 2018) for 3TG commodities sourced from the Central Africa region (DRC and neighbouring countries). Currently, the tool does not include other minerals, but future plans will include Co in the portfolio. It should be noted that GFP is designed as an optional proof of origin within a certification framework and does not represent an alternative to everyday mineral traceability techniques (e.g., tagging). Instead, GFP is used on a spot check basis (i.e., reserved for special investigations) to verify the integrity, and thus credibility, of the applied traceability solution. The method is described in Chapter 4 with other emerging approaches, such as BATTRACE.

The majority of supply chain traceability solutions focus on 3TG sourced from the DRC and utilise specialised certification schemes developed by a consortium of countries and organisations (EurAC, 2017), such as the Certified Trading Chains (CTC) initiative traceability protocol launched by the BGR (BGR, 2018) (Table 2). The CTC initiative provides assurance through the supply chain with traceability methods containing a mass balance approach, a system for administratively monitoring the inputs and outputs of certified material/product throughout the supply chain.

Traceability methods and existing technological solutions for mineral supply chains are described in Chapter 3. It should be noted that traceability solutions often utilize existing responsible sourcing certification schemes to translate critical information through the supply chain, such as the Responsible Sourcing Blockchain Network (IBM, Ford, Volkswagen, Volvo). The solution is based on a blockchain trial looking at Co mining in DRC, with the initial stage trying to verify responsible sourcing standards (developed by the OECD) for large scale mines through a simulated supply chain. The existing solutions and almost all blockchain examples are at a case stage and cannot directly be used in the lithium supply chain due to differences in mining practices and variations of CoC structure. As such, these examples face the same issues, i.e., the establishment of a certification process for Li and uncertainty around whether the final product has a verifiable amount of the certified mineral or can only provide assumptions around the supposed mass-balance.

OPPORTUNITY FOR AUSTRALIA IN RESPONSIBLE MINERAL SUPPLY CHAIN

Existing responsible sourcing and traceability solutions with demonstrable case studies are mostly commercial (driven by business) and focus almost exclusively on minerals and metals sourced from the DRC (Table 2). Their objective is to avoid the possible negative impacts associated with materials that are NOT responsibly sourced. However, there is a potential to shift the focus of the market from the negative-impact scenario to include a positive-impact paradigm where responsible producers of raw materials can be identified and traced through the supply chain, adding value to their product.

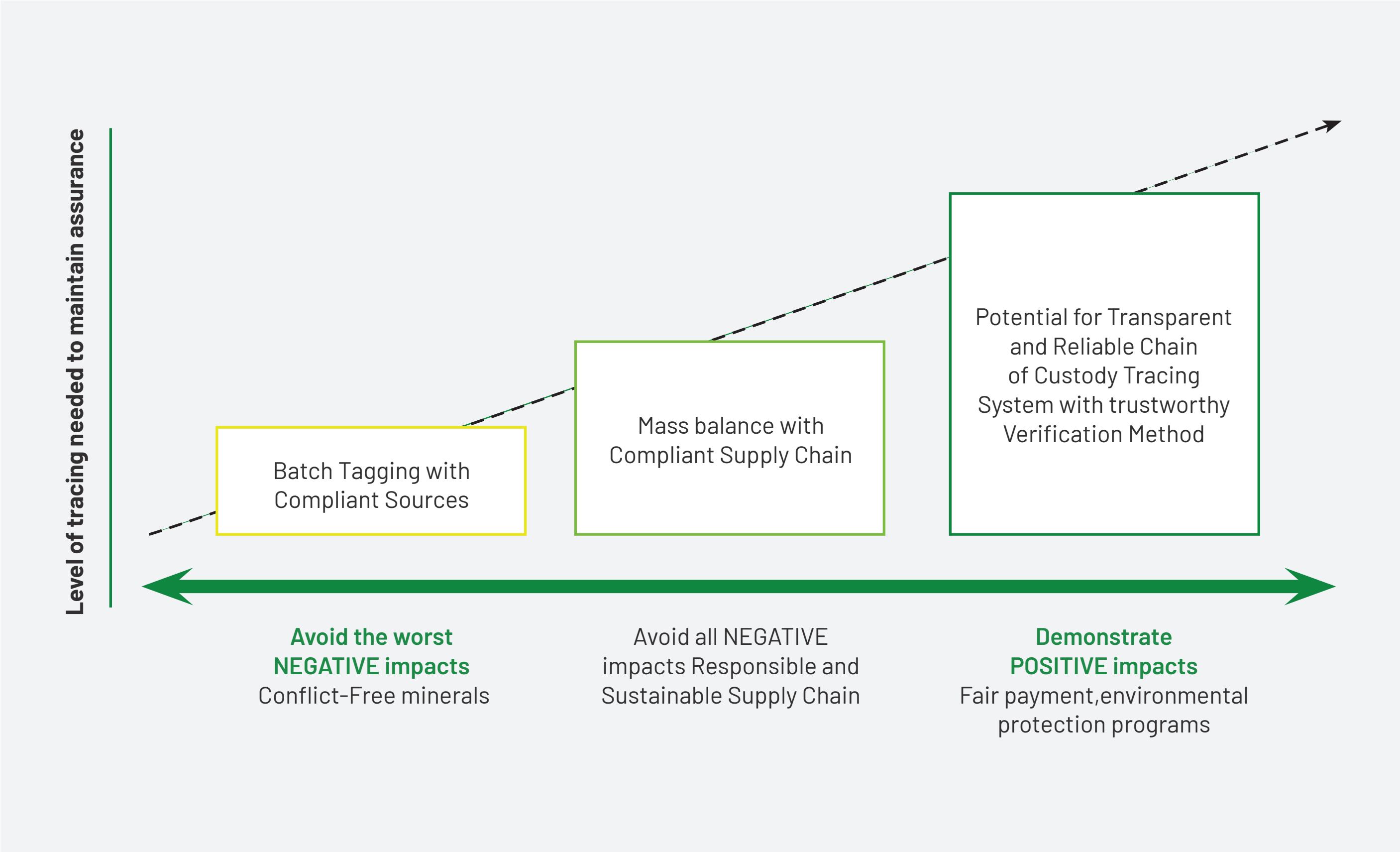


Figure 6: Supply chain due diligence approaches to maintain assurance depending on the product sourcing sustainability impact.

Figure 6 proposes the supply chain due diligence approaches adopted to address different levels of sustainable (social, economic and environmental) mineral sourcing requirements. These "premium" products, sourced under existing high standards, should have an economic advantage in the market. To maintain the level of assurance in "premium" products, traceability solutions need to be reliable, transparent and verifiable with an integrated tamperproof and trustworthy provenance verification system.

Trusted supply chains can capture more value

Existing initiatives focus predominantly on responsible sourcing of 3TG from the Central Africa region and are designed to minimise risk by avoiding the negative impact of conflict minerals. For the far-reaching impact of responsible sourcing through the mineral supply chain, provenance verification and traceability solutions are essential to provide trust in the sourcing claim and to transfer critical information through the supply chain to end-users, respectively.

Countries and regions with existing high standards of mining and processing of battery minerals and metals, such as Australia, would benefit by highlighting the positive benefits of responsible production practices as a market advantage. Demonstration of responsible sourcing data with globally recognised certification schemes, such as IRMA or CERA, through transparent traceability solution with integrated trust-providing provenance verification mechanism, would expand market access for responsible producers.

TABLE 2: THE TABLE OF NOTABLE RESPONSIBLE SOURCING INITIATIVES WITH REPORTED SUPPLY CHAIN TRACEABILITY OR PROVENANCE VERIFICATION CAPABILITIES (STRADE, 2018; EURAC, 2017; ESTELLE LEVIN LTD, 2015)

NAME, YEAR AND ORGANISATION	DATA CAPTURE MECHANISM/ INFORMATION CERTIFICATION	TRACEABILITY/PROVENANCE VERIFICATION
ITRI Tin Supply Chain Initiative (iTSCi) 2010 ITRI	• Relies on information provided by provincial and national audit and supervision organisation of DRC (SAESSCAM and the Division des Mines). The audit maps mines as low, medium and high risk (green, yellow and red) by carrying CTC certification missions.	• The physical traceability solution "bag and tag": each bag weighed and barcoded with a mine of origin information. • GFP, chemical profile provenance verification method based on reference materials from licensed mines and conducted by auditors.
GeoTraceability 2014 Optel, before PWC	• Based on communications, supply chain transparency, building broader factors into supply chain due diligence, management systems advice, flexibility in traceability system choice, releasing data to buyers before export.	• The traceability solution includes GPS tracking, barcoding and mobile tagging. • No provenance verification capability reported.
Better Sourcing Program, 2014	• BSP relies on the implementation of due diligence management systems across the supply chain.	• Data is collected by trained BSP field agents and local partners via a smartphone app, while traceability is provided through the use of a third-party system. • No provenance verification capability reported.
SourceMap, 2019	• Local partner provided information build into the mapping tool.	• Traceability solution based on a blockchain platform. • No provenance verification reported.
RCS Global, 2008	• Consortium provided audit information.	• Uses mass balance concept and smart trade contracting to provide tracing utilising a blockchain platform. No provenance verification capability reported.

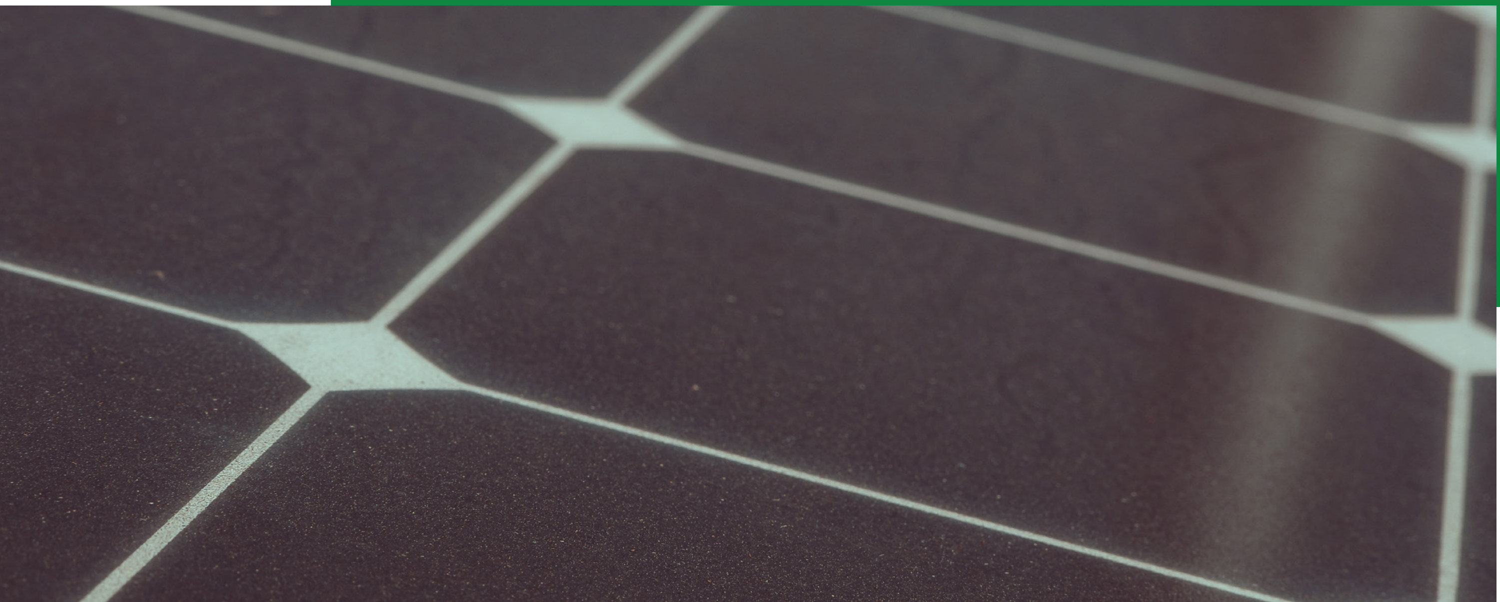
BUSINESS MODEL	CHALLENGES AND ISSUES
• Primarily funded by upstream actors (80%), including Congolese artisanal miner (20%). Only 2% is financed by downstream companies (World Bank, 2015).	• Evidence of contamination of certified "green" products with "red" products. • Cross border smuggling and loss of export profits. • Evidence of manipulation of the "bag and tag" system.
• It is a downstream business- oriented product. Serves downstream stakeholders, and certificate standards are business-oriented.	• The use of software as a service (SaaS) creates a closed environment, barriers of entry for artisanal miners and a lack of transparency.
• A market-based system, paid by user and consumer of information.	• Overreliance on demand for responsible sourcing information from downstream actors. • Conflict of interest with affiliated RCS Global harmed the business model.
• A market-based system, paid by user and consumer of infomation.	• No information on existing work cases.
• A market-based system, paid by user and consumer of information.	• No information on existing work cases. • Consensual certificate standards, quality of data input and audits, accessibility and cost of digital technologies (blockchain).

3. TRACEABILITY OF AUSTRALIAN BATTERY SUPPLY CHAIN

An ethical and sustainable mineral supply chain starts with responsible sourcing, which aims to mitigate the impacts caused by minerals and metals extraction, refining and production. Academic studies suggest a definition for responsible sourcing for the mineral supply chain as the management of social, environmental and/or economic sustainability in the supply chain through the information on the production location and production process of the material, which may be provided either by the suppliers or through a sustainability scheme (van den Brink et al., 2019). The term 'responsible sourcing' can thus relate to a range of sustainability objectives and can address sustainability concerns at various links in the supply chain; however, credentials always have to be clearly communicated through the supply chain to the product end-user. This requires a due diligence framework, sustainability certification initiative and traceability solution so that accountability and quality control at all levels of the supply chain can be assured.

The core principles of the implementation of responsible sourcing of minerals with a due diligence framework and supply chain mapping were discussed in the previous chapter. The FBI CRC "Certification and Life Cycle Analysis" scene-setting report reviewed in detail requirements for sustainable sourcing (ethical, environmental and governance) and the list of sustainable due diligence certification initiatives applicable to a mineral supply chain with only two (IRMA and CERA) being identified as potentially suitable frameworks to demonstrate responsible Australian battery mineral and material sourcing.

This chapter reviews supply chain traceability models, existing solutions, and "fit for purpose" in the development of a transparent, accountable, and effective material sourcing framework.



CONCEPT OF TRACEABILITY

Traceability is the ability to trace the history, application, use and location of an item or its characteristics through recorded identification data according to the International Organization for Standardization (ISO 9001) quality management system. In the context of a responsible mineral supply chain, the need for traceability is accomplished through supply chain due diligence and compliance management with specific sustainability schemes (Airbus, 2017). The ISO 9001 system specifies the following requirements for supply chain traceability in order for a framework to meet quality tracing standards:

- Appropriate means to identify inputs when it is necessary to ensure the future conformity of products and services
- Clearly identified status of outputs with respect to monitoring and measuring requirements throughout production and service provision
- Control the unique identification of the outputs when traceability is a requirement, and retain documented information to enable traceability

Identification is an especially important concept for supply chain traceability. In this context, identification means a common recognition shared among the entire production processes or the entire supply chain. For that purpose, a traceability system assigns identifiers using a representation format such as serial numbers or lot numbers, as well as using transfer medium such as labels and RF tags.

In the mineral resources sector, supply chain traceability models often employ identity preservation ("bag and tag") applications due to the mixing of materials from different sources and segregation models to enable certain claims for source and exclusion/inclusion goals. These models are the backbone of the closed pipe supply chain and rely on the physical isolation of sustainably certified minerals from conventional materials to guarantee the full traceability of the actual physical mineral back to the mine or region.

However, the dependence of a model on a limited number of processing/ transforming units in a supply chain and heavily regulated data management generate substantial risks of systematic failure and expensive initial investments (Strade, 2018). Additionally, a supply network with highly concentrated processing stream stages and material transformation (such as a battery supply chain) make it almost impossible to preserve the individual mineral source identity by employing conventional representation format (e.g. RF tags) and requires a model with an alternative approach. This is why mass-balance or "book and claim" approaches are used more broadly in the metals market to accept the realities of fluid/blended materials and refining/smelting processes.

Given the emerging demands and scrutiny of supply chain stakeholders on responsible mineral sourcing means that Governments and consumers alike dictate transparency and accountability, which is underpinned by a robust and reliable traceability solution. The industry is quickly meeting those requirements by adopting emerging digital technologies, such as blockchain (RCS, 2017). Though blockchain technology is generally associated with cryptocurrencies like bitcoin, researchers see its potential in resource governance, too (Chapron, 2017), as it would enable secure traceability of certifications and other information in the supply chain. Blockchain traceability solutions can potentially minimise the reputational risks associated with non-responsible mineral sourcing by directly connecting responsible upstream miners with downstream manufacturers.

In summary, supply chain traceability is the process of tracking the provenance and journey of products and their inputs, from the very start of the supply chain through to end-use by ensuring and demonstrating responsible sourcing and handling according to the specific demands of standards and initiatives.

TRACEABILITY MODELS AND EXISTING SOLUTIONS FOR SUPPLY CHAINS

In general, product tracking through a supply chain provides opportunities to find logistical efficiencies, meet regulatory requirements, connect with the actors in the upstream supply chain, and story-tell to consumers about the provenance and journey of products.

To ensure traced products reach the end-user without being mixed inthe supply chain with products from unknown sources, industry and service providers have developed a chain of custody model to support traceability. In a legal context a chain of custody refers to the chronological documentation, or 'paper trail', recording the sequence, custody, control, transfer, analysis and disposition of physical or electronic evidence (EDRM, 017).

There are four chain of custody or traceability models currently in use for a supply chain product and process tracking (Figure 7). Any existing supply chain traceability solution employs the following models:

IDENTITY PRESERVATION

The identity preservation model ensures that the certified sustainable product delivered to the end-user is uniquely identifiable and can be related to the identity of the producer (Figure 7). To be able to preserve the identity of the certified resource, all intermediate materials have to be kept physically isolated and separated from non-certified equivalents at each stage of the value chain, as well as from certified counterparts from another resource base. The logistics, monitoring, reporting and verification required for identity-preserved systems result in high costs along the value chain, and this approach is often used only for products with short supply chain and low transformational potential (Mol and Oosterveer, 2015).

Example: The Canadian Identity Preserved Recognition System (CIPRS) utilises the model for the certified seed market traceability to monitor the production, handling and transportation of specialty grains, oilseeds or pulses.

SEGREGATION

In this model, only products or materials from equivalent sources are mixed and separated from non-certified counterparts at every step of the supply chain (Figure 7). Also, in a segregated system of sustainability certification, it is assured to the end-user that a certified product consists of natural resources and production processes (storage, transportation, processing, trading, packaging, selling) that fulfil all the requirements of the certification scheme (Mol and Oosterveer, 2015). The model is often referred to as a responsible procurement rather than traceability since it ensures direct suppliers meet sustainability criteria (e.g. through a supplier code of conduct) (van den Brink et al., 2019). While more costly and complex to implement than other models, this model allows for better supply chain control and transparency, which is particularly relevant for high value/low volume minerals that present high fraud infiltration potential, such as gold or diamonds (Strade, 2018)

Example: The model is mostly utilised in "closed pipe" supply chains, characterised by a limited number of actors in the supply chain and/or direct trade agreements between members of chain of custody (e.g. Consortium of BMW Group with Ganfeng Lithium Co. to source Australian lithium.)

MASS BALANCE

The mass balance model is used when identity preservation and specific material segregation are not required, but the overall compliance of the company, practices or materials should be maintained. This will likely mean that product claims for material from this process will be based on the processing timespan and overall material inputs, as there will be physical mixing of sustainable claimed material as well as material that may not have sustainability claims. In the mass balance model, the traded volume of verified sustainable production is administratively monitored throughout the entire value chain to ensure that the volume of certified products downstream equals the volume of certified resource base upstream of that very same value chain (Manning and Soon, 2014) (Figure 7). Mass balance does not require any segregation or physical separation of materials or any special infrastructure throughout the supply chain but can result in a mixture of certified and non-certified source materials in the final product. However, through effective administration, it can allow the identification of certified sustainable materials in the final product with a simple, inexpensive accounting measure.

Example: The Responsible Minerals Initiative (RMI), which audits most of the largest cobalt refiners in the world, includes a mass balance component to assess the reasonableness of the inputs, outputs, and losses. This also includes verifying the source of the upstream inputs that are typically classified and segregated as acceptable or unacceptable, but it is mostly based on the presence or absence of any unacceptable sources of materials.

Cobalt recyclers have been audited based on mass balance to also report their recycled content. Apple has reported these activities since 2017.

BOOK AND CLAIM

The book and claim model, also referred to as certificate trading, is an approach where the sustainability claims are entirely decoupled fromthe material. Instead, the sustainability claims are traded as certificates or credits and traced on a separate market. Book and claim systems are seldom considered - if ever implemented - for mineral supply chains due to the detached nature of a traceability model from the product qualities and increased vulnerability to fraud (Strade, 2018). A well-functioning farm-gate and end-user monitoring and registration system, a market of certificates, and a central registry are crucial preconditions for this model to function.

Example: Roundtable on Sustainable Palm Oil sells responsibly produced palm oil certificates on a separate market (rspo.org)

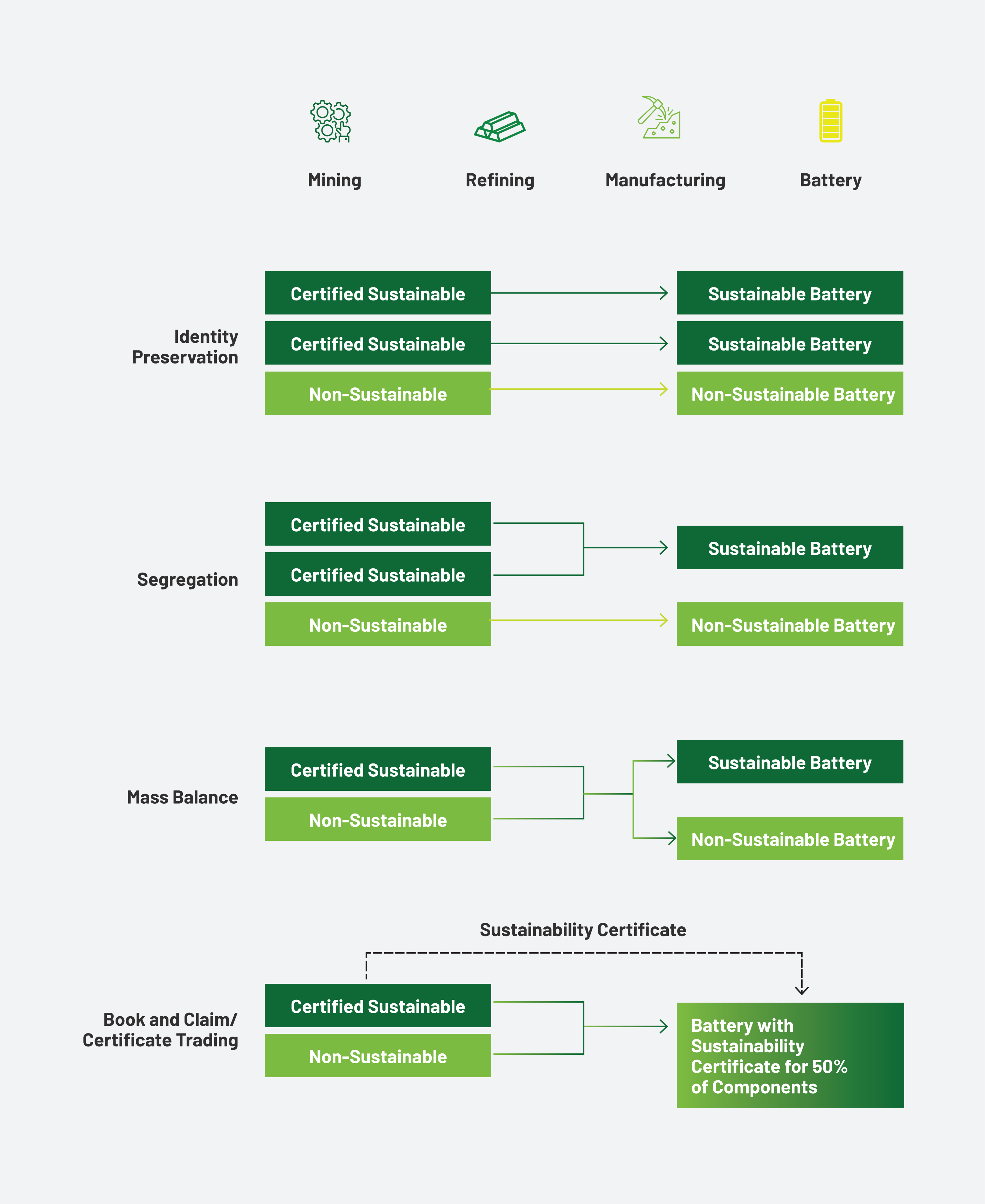
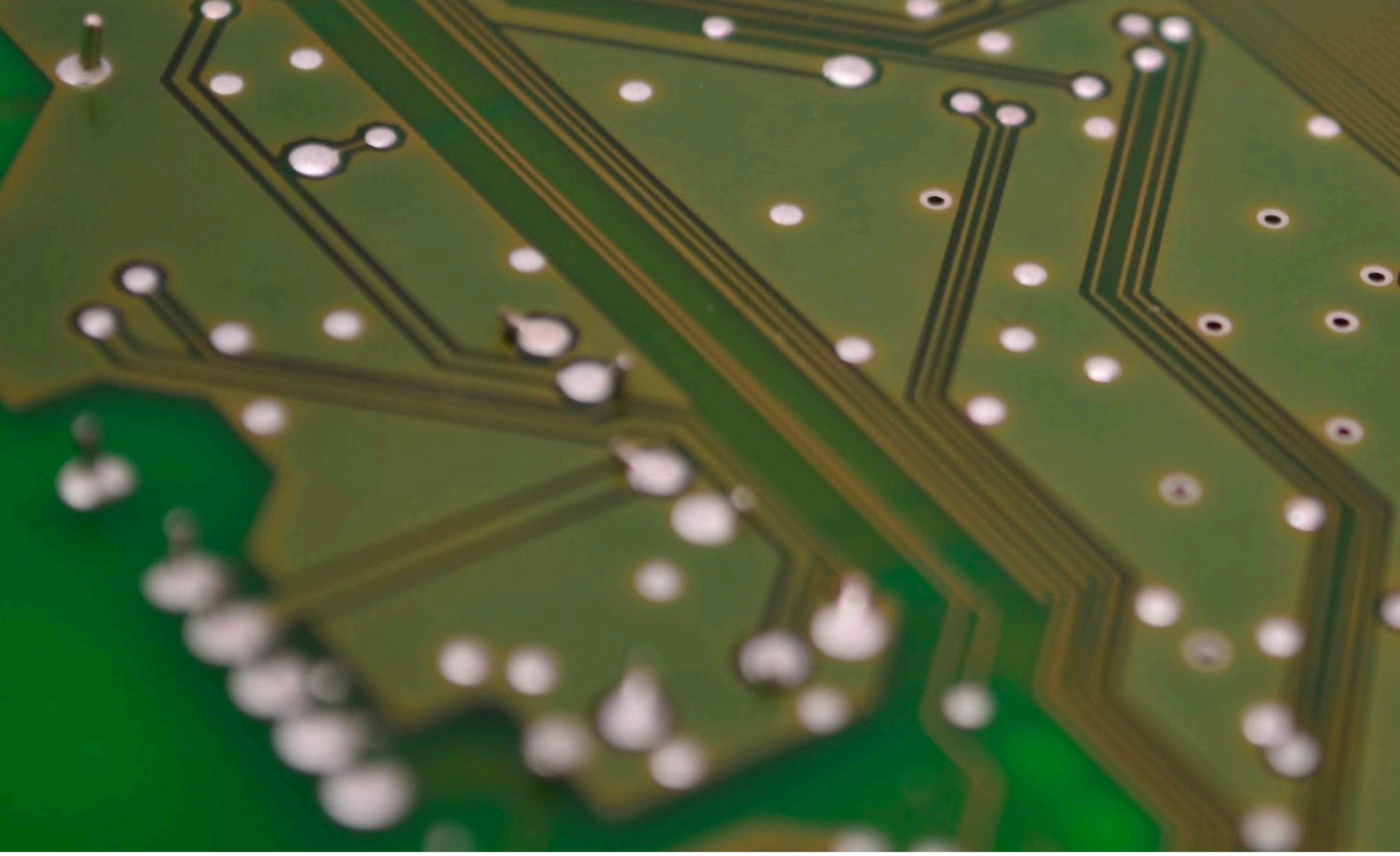


Figure 7: Four traceability models for a supply chain (adapted from Staaji et al., 2012; Mol and Oosterveer, 2015)

Initial responsible mineral supply chain traceability frameworks were mostly focused around the Central Africa region and followed the segregation model (Strade, 2018).

More recently, it should be recognised that due to expanding complexity of mineral supply chains and the highly concentrated midstream stage (See Chapter 1.

Battery Supply Chain), the segregation model is perceived as a costly and ineffective approach. Instead, the mass-balance approach is emerging as preferable for global mineral supply chains (e.g. RMI). The model, coupled with a transparent and trustworthy administrative solution, could be a viable option to trace Australian sourced battery minerals through the supply chain to the final product.



CHALLENGES OF A MINERAL SUPPLY CHAIN TRACEABILITY

The first and the most obvious challenge for effective traceability is mineral supply chain due diligence. For instance, mid-stream actors, the smelters, have been a focus of due diligence intervention as they represent natural choke points in mineral supply chains (see Chapter 2). When a company identifies a supplier not meeting responsible sourcing criteria, it may be difficult for them to exert pressure on that supplier or find a new one, particularly if the company is small or medium-sized, implying that the leverage is upstream in the supply chain (Hofmann et al., 2015).

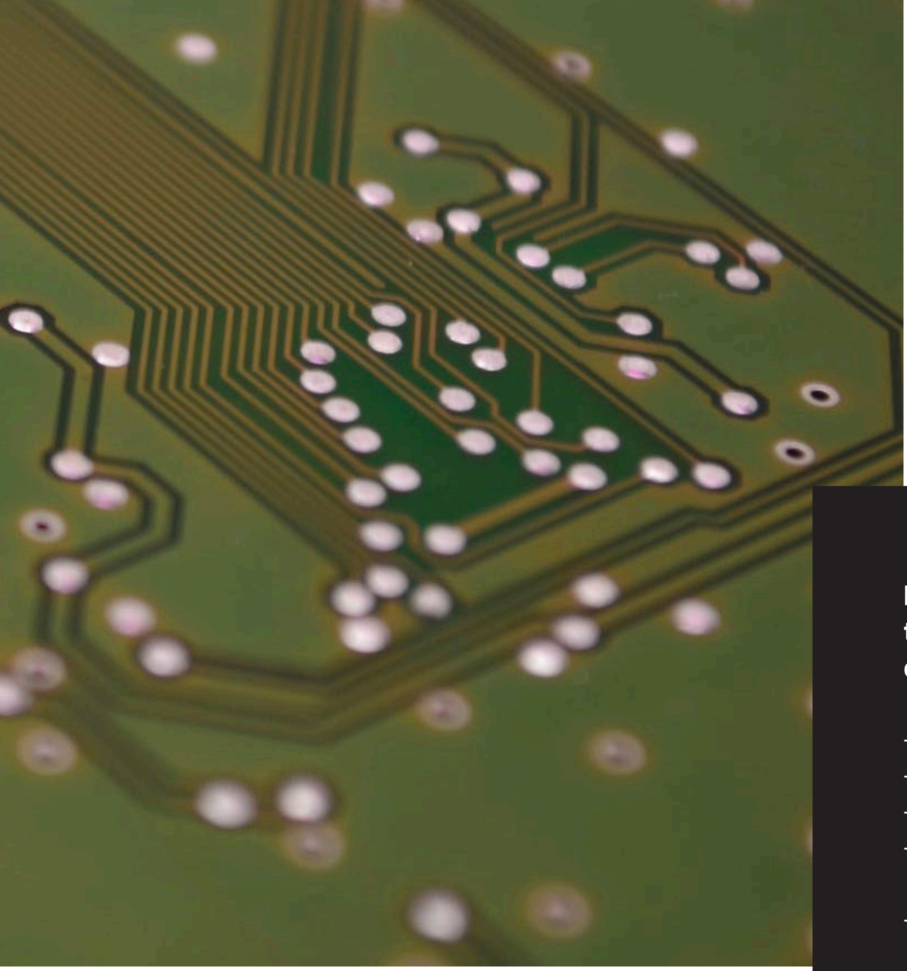
The second challenge is the appropriate traceability model adopted by all supply chain actors. The challenge is most likely to be delivered by mid- stream actors and supply chain logistics which might follow one of three different scenarios at the smelter level (Strade, 2018):

- Smelters will make mass-balance statements, clarifying the amount of their production, which is from responsible origins.
- Individual smelters will maintain physical separation of responsibly mined minerals to comply with downstream demands.
- Individual smelters will solely source and process responsible minerals.

While the two last scenarios might, under certain circumstances and with the correct systems in place, allow for batch traceability to the mine site, they are more costly scenarios due to physical material separation and exclusive contracting. The first scenario would result in a much more manageable, cheaper and faster adoption, provided that downstream users can obtain correct provenance information.

The third challenge is the scalability of the process. Historically, the first traceability systems in the 1990s for the timber and agricultural markets (FSC, Fairtrade) utilised the identity preservation or segregation models to trace a product back to a specific sawmill or farm, respectively (Esty, 2003). With the increasing globalisation of supply chains, both models are simply too expensive to utilise on a larger scale and for complex supply chains. Therefore, mass balance or book and claim models, which don't require physical separation of certified products, could be employed for battery supply chain traceability.

Fourth, the employment of a recognised certification initiative with merit- based requirements to preserve and demonstrate responsible sourcing qualities of a battery product to the end-users. Currently, there is no universally accepted certification scheme for the responsible battery material supply chain. Therefore, a traceability model should prioritise interoperability while incorporating adaptability and scalability potential to demonstrate competitive



expectations from various stakeholders of the battery supply chain (Rutovitz et al., 2020).

The fifth challenge for responsible mineral supply chain traceability is integrity and independent validation. Human and institutional factors will remain determinant and should be addressed with comprehensive data management systems and transparent administrative tools to prevent fraud.

Finally, the last challenge is the implementation of a responsibly sourced mineral traceability initiative by the supply chain. Industry reports (Estelle Levin Ltd, 2015; Strade, 2018) state that supply chain traceability initiatives can be blocked by a single uncooperative actor and downstream manufacturers often lack the leverage necessary to enforce compliance or obtain the needed information. As a result, responsible sourcing compliance is seen as a cost with minimal benefits from the downstream perspective and leads to treating compliance as a required box-ticking exercise.

In summary, a responsible mineral supply chain traceability should meet specific requirements dictated by challenges:

- Due diligence
- Acceptance by the supply chain actors
- Cost-effective scalability
- Adaptable to emerging certification requirements and initiatives
- Transparency and independent validation capability
- Compliance

Traditional supply chain traceability methods (e.g., paper-based labels) and some novel technological solutions offer compliance and varying degrees of transparency with pay offs around accessibility, privacy, and efficiency (e.g. The internet-of-things concept, Astill et al., 2019). However, industries address these requirements by undergoing digital transformation through the use of emerging technologies, such as blockchain technologies, to create improvements in consumer satisfaction, logistical and economic efficiencies (RCS, 2017). Currently, a public, open-source and scalable blockchain technology could provide complete transparency with regards to data transactions and storage through the chain of custody.

BLOCKCHAIN TECHNOLOGY AS A SOLUTION FOR SUPPLY CHAIN TRACEABILITY

Blockchain is an emergent technology that addresses this challenge through both cryptography and decentralisation of a network of computers in a system that is incentivised to maintain integrity and authenticity of all data written to a shared public ledger. The exact mechanisms of how blockchain addresses the challenge of data integrity vary in implementation, valuing and balancing aspects of privacy, speed, efficiency and security differently.

The basic principle around how blockchain increases transparency is the same for all implementations; networks of computers invest energy (Proof of Work) or currency (Proof of Stake) to partake in the network and are incentivised through a consensus algorithm to faithfully reproduce and share a copy of a ledger on behalf of users of that ledger - a so-called 'distributed ledger'. Any copies that have been altered or tampered with by 'bad actors' in the network are immediately identified and 'punished' by rejecting their tampered records from the ledger. This network consensus, or agreement, by all network nodes, forms the basis of a decentralised network. Rather than having a single central authority, all participants in the network have to agree on all transactions. In a suitably decentralised blockchain network, the energy, or 'stake', required (through its consensus algorithm) to write a record to the ledger should be orders of magnitude greater than the reward they stand to gain by attempting to make fraudulent transactions. This disincentivises network nodes (computers) to attempt to alter records and make fraudulent transactions resulting in an immutable ledger.

The value that a decentralised network has over traditional databases and transaction chains is that they are effectively immutable without the need for third party verification. No single actor can alter or generate fraudulent transactions; the entire network has to reach consensus, and the larger the network and the more geopolitically diverse nodes there are that have to reach consensus, the greater the security. Another potential solution is to remove the leverage from uncooperative (or non-trustworthy) supply chains actors by the decentralisation of the supply chain information ownership. The section below explains the value that decentralisation would bring to supply chains. All transactions and agreements are handled by computer code and this 'network effect'. This profound, unique property of the blockchain has given rise to the 'smart contract', immutable pieces of software code that can execute completely autonomously, and through a network of computers, a faithful and unchanging record (the blockchain)of all transactions and computations is forever recorded on the blockchain ledger. Smart contracts are used to increase efficiency by increasing transparency and security through the immutable record-keeping the blockchain offers.

Users of blockchain technology, such as a traceability project, do so by writing their own smart contracts and having their execution handled by the blockchain. The network of computers that execute them and maintain the ledger do so independently from the writers or users of the smart- contracts. The users (e.g. mine site operators) of the traceability solution simply interact with pieces of software wherein the concept of blockchain is completely abstracted from them, much in the same way users interact with their email without dealing with the underlying software that handles email transactions or the internet providers that handle internet communication between computer servers. In this example, the end-user would be the person sending the email, the smart contract would be an email service, and the blockchain would be the internet service providers. This is why blockchain is often called the "internet of value".

Blockchain plays only one of many roles in a full end-to-end traceability solution. Digitising real world data such that it can be recorded on the blockchain remains a significant challenge, as once on the blockchain, it cannot be removed. Any errors or corruption of data before it is written to the blockchain are permanent - only after data is written to the blockchain can it be validated and verified using blockchain consensus mechanisms, and 'junk in ' will result in 'junk out'. Therefore, a full end-to-end traceability solution needs to account for and address the fifth challenge of data integrity, and this will be a focus of the traceability subproject in the context of a chemical fingerprinting solution.

In general, blockchain technology can be characterised as:

Immutable - once recorded, the data in any given block and subsequent blocks cannot be retroactively altered without the consensus of the network majority.

Trustworthy - every node in a decentralised system has a copy of the blockchain, and data quality is maintained by database replication and computational trust.

Transparent - Blockchain offers a "trust-less" solution, whereby no one centralised network or database is entrusted with all the data, and participants (nodes) involved do not need to know or trust others or a third part of the system to function.

Self-governing - decentralisation means no single actor controls the network and is entirely different from the centralised databases used by many sectors, including banks and supply chains.

Cost-effective - the open distribution of the system allows the participants to verify and audit transactions independently and relatively inexpensively, compared to hardware solutions, such as physical tagging and verification equipment.

Secure - Operating a centralised system has a security problem; if a centralised database is compromised, e.g. by hacking, everything that is stored on it is vulnerable. Authentication by mass collaboration powered by collective self-interest marginalises any uncertainty over data security in blockchain.

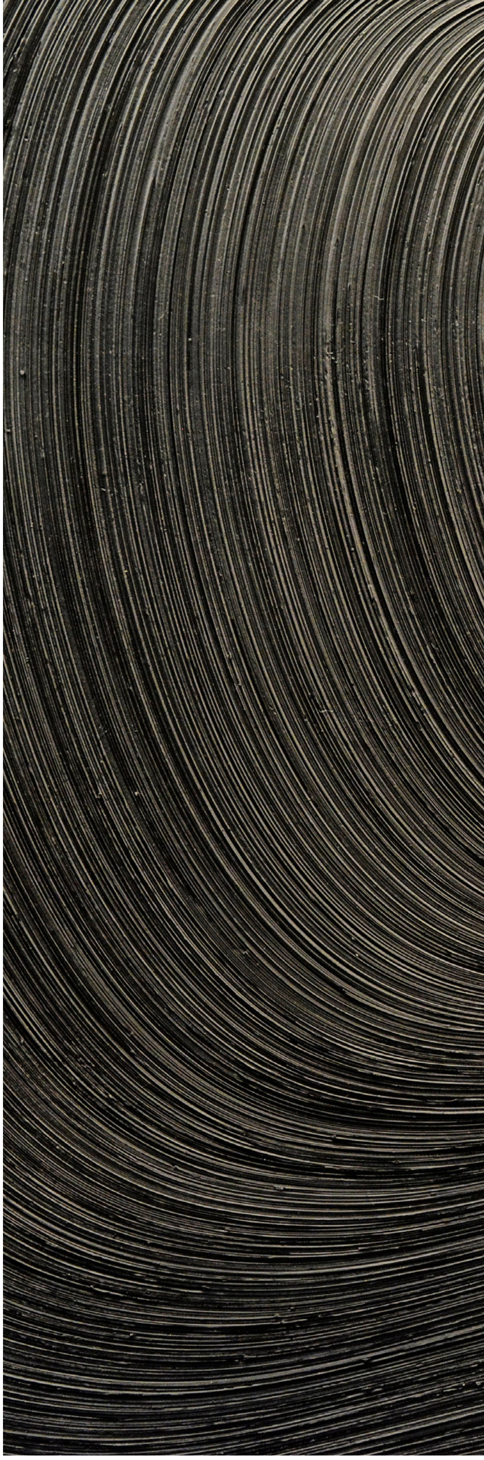
Smart contracts - Automation of the execution of transactions, documentation or control of digital assets. This is the mechanism of how people interact with the blockchain.

BLOCKCHAIN AND ITS ROLE IN A SUPPLY CHAIN TRACEABILITY

A supply chain encompasses the sequence of suppliers and processes in the production of a commodity. It is inherently difficult for companies to fully trace a supply chain of a product or parts thereof, as there are typically several points of aggregation, e.g., several smaller manufacturers delivering to the same assembly company. This, in turn, makes it hard to verify the authenticity and sustainability of components that went into the final product.

Record keeping in the supply chain is often done on paper, and a chain of custody (CoC) might only be established ad hoc when needed (e.g. for auditing purposes). Besides, downstream companies might have different reporting requirements from the same upstream supplier, which creates extra work for the supplier.

A digital system (such as a database) makes it easier to identify ledgers in the CoC, like barcodes and QR codes in use to track physical items virtually (see an example of the identity preservation traceability model). Moreover, a traceability solution for CoC based on digital systems records who has taken possession of a product along the supply chain. It should support claims as to the stewardship of the material and its responsible production by providing the records of custody (RCS Global, 2017).



However, there are several challenges for a digital system to work over an entire supply chain of an industry from source to end consumer:

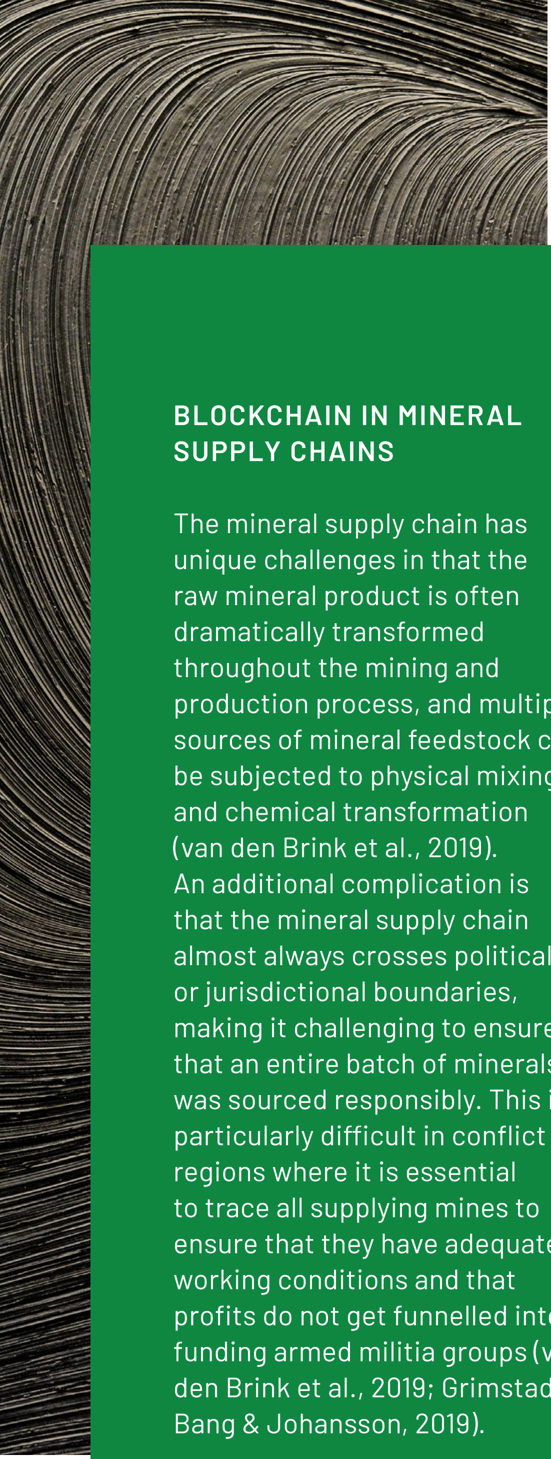
- A standard for data representation would have to be agreed upon, or the design would need to be flexible with the standard of data reporting. Otherwise, if each downstream company sets up their digital system, the reporting requirements on the upstream suppliers remain onerous.
- The tagging of product unit can be impossible, i.e. if solutions like QR code scanning cannot be implemented. For example, early on in the supply chain, when a product is manufactured from raw materials.
- The security of the digital system; data needs to be encrypted so that only authorised parties can access it, and it needs to be tamperproof.
- Around traceability and many other supply chain problems, there is a data validation issue: garbage in, garbage out. If the data ingested is not accurate, the results are not useful.
- The data validation and transaction verification system are required to ensure the authenticity of the CoC.

Adapting the supply chain for blockchain can overcome many of these challenges, as it offers transparency, immutability, encryption and decentralisation of the information. The industry is responding with emerging blockchain applications for the supply chain traceability; many of these concentrate on the food supply chain to help track down potential sources of contamination, for example, the IBM food trust (IBM, 2019) or Curtin University's proposed provenance for oranges (Curtin University, 2019).

Other examples concentrate on tracing the ownership and guaranteeing the authenticity of the product, for example, the BMW PartChain (BMW, 2020) and various examples in the pharmaceutical industry (Ledger Insights, 2019; SAP, 2020). Most of these blockchains trace a final product and may not be directly relevant to the battery supply chain with the added challenge of tracking an ever-changing product.

It should be noted that the blockchain technology for supply chain traceability comes with several shortcomings, which the technology industry is currently addressing:

- Blockchain can improve data integrity and security, but mathematical verification (consensus) can slow the process down and increase the cost.
- Blockchain can provide an immutable record that is unchangeable unless an onerous reconciliation process is initiated. Immutable records can have value in situations where the truth needs to be permanently recorded, such as product origin.
- There are interoperability challenges. For example, blockchain ledgers operating on different technology companies' ledgers cannot be shared interchangeably. The industry continuously addresses the issue, and new universal standards are emerging regularly.



BLOCKCHAIN IN MINERAL SUPPLY CHAINS

The mineral supply chain has unique challenges in that the raw mineral product is often dramatically transformed throughout the mining and production process, and multiple sources of mineral feedstock can be subjected to physical mixing and chemical transformation (van den Brink et al., 2019). An additional complication is that the mineral supply chain almost always crosses political or jurisdictional boundaries, making it challenging to ensure that an entire batch of minerals was sourced responsibly. This is particularly difficult in conflict regions where it is essential to trace all supplying mines to ensure that they have adequate working conditions and that profits do not get funnelled into funding armed militia groups (van den Brink et al., 2019; Grimstad Bang & Johansson, 2019).

An RCS Global (2017) report found that blockchain can be used as a potential solution to tracing in the mineral supply chain as it offers:

- Trust and consensus
- Minimised fraud risk due to its immutable and decentralised nature
- Data is encrypted but can be shared with other parties
- Confidentiality by sharing proof of fact as opposed to open data
- Scalability

However, the RCS Global report also identified the key challenges to implementing a blockchain solution as:

- What production method and associated data constitutes responsible sourcing?
- How is data brought onto the blockchain and verified?
- How to trace a mineral during a complex refining process which includes aggregation and mixing of different sources?
- Is the cost of computing offset by savings from going paperless?
- Is the technology easily accessible for all actors in the supply chain?

An additional challenge of the battery supply chain is that it involves many actors who will almost certainly be spread across different continents with different legal and regulatory systems. When you add that these different actors manage many different inputs and potential transformation stages of the input materials, you have a picture of the complexity of this supply chain. While the concept of traceability can be simplified to a simple sharing of information and being able to report this information to demonstrate a trace of product from one point to another, it is far from simple.

There is a substantial challenge of the inability to align stakeholders around the information that is required to be shared and how this information may and may not be shared or communicated. A non-competitive data traceability standard can be a way of assigning data to items and how this is shared. This non-competitive standard approach has been successful in other supply chains such as food.

Most examples of blockchain in the mineral supply chain concentrate only on conflict (social) aspects, such as cobalt or tungsten from the DRC. Many of these blockchain examples are at a proof-of-concept stage and cannot directly be used in the lithium supply chain. As such, these examples face the same issues as the platforms reviewed above, i.e., the establishment of a certification process for lithium and uncertainty around whether the final product has a verified amount of the certified mineral or can only provide assumptions around the supposed mass-balance.

Below are short overviews of several blockchain platforms found in the mineral supply chain space:

- **MineSpider** (Williams, 2018) is built on the Ethereum blockchain and uses encrypted certificates issued by trusted certifiers on the blockchain. These certificates identify how much mineral can be responsibly sourced at a mine and subsequently bought by an upstream manufacturer. To trace the mineral through the blockchain and its chain of custody mass-balance is used; however, this means that an end-user can only say that they paid for X% responsibly sourced materials but have no way of confirming the final percentage delivered to them from the upstream source. An agnostic certificate proofing system layer can be added, with the content and quality of data negotiated between seller and buyer. The Minespider infrastructure also offers smart contracts which manage commercial interactions between certifiers, sellers and buyers. The certificate and blockchain layers are linked with the blockchain recording the amount of minerals sourced, bought and sold. To access the information associated with the certificates, a key is required to decrypt the data layer. These keys are provided as part of the certificate purchase. This means that the blockchain layer is public and can be audited to see how much mineral has been traded; however, supply chain critical and sensitive data is only accessible on the certificate layer, ensuring that a company's trading information remains private and encrypted

- **Responsible Sourcing** Blockchain Network (IBM, Ford, Volkswagen, Volvo) is a blockchain trial looking at the cobalt mining industry in the Democratic Republic of Congo, with the initial stage trying to verify responsible sourcing standards (developed by the OECD) for large scale mines through a simulated supply chain. The consortium is utilising IBM's blockchain platform built on hyperledger blockchain technology.

- **SustainBlock** focuses on tracing minerals from artisanal and small-scale mines, particularly from conflict-prone areas. The goals of a 2019 pilot study were to track tungsten sourced from the Great Lakes region in Africa and establish the required data acceptance criteria necessary to implement a proof-of-concept blockchain for a fully verified supply chain (SustainBlock, 2020).

- **Minexx** via its MineSmart platform utilises blockchain, IoT and digital payments to provide transparency of the supply of minerals sourced from small artisanal miners. MineSmart deploys Finboot's MARCO technology to integrate blockchain into their platform. As this platform is aimed at small artisanal miners to ensure they get a fair payment, it is less appropriate for our purpose of tracking minerals across the supply chain.

- **Everledger:** The Everledger platform is a permissioned, private, shared (i.e. distributed) ledger that uses blockchain, Artificial Intelligence (AI), Internet of Things (IoT) and nanotechnology to identify, track, and trade commodities. For example, for the diamond supply chain, a digital twin of the diamond (including its GIA grading report) is created and stored in the ledger, and the information is made available to customers purchasing the diamond and other members of the blockchain. Additionally, its origin and trades (e.g. who) are also tracked on the blockchain. The data is divided into different access tiers to give control to stakeholders on which level data is shared with others on the blockchain platform. Everledger is also working on "technology that enables full lithium ion battery life cycle traceability across the supply chain, supporting responsible and efficient reuse and recycling of electric vehicle and portable electronics batteries" (Everledger, 2020).

- **Current** work includes a battery passport which creates a digital identity of the battery, which can be tracked on the blockchain and information on the battery can be shared between authorised stakeholders.

We recommend a blockchain traceability solution

A proposed solution of a blockchain traceability solution is presented, based on a mass-balance traceability model and includes technological concepts to increase trust and consensus along the chain of custody, to minimise fraud risk with tamperproof verification methods and to provide secure data sharing with an asymmetric encryption solution. However, significant challenges such as scalability, confidentiality and accessibility should be addressed in the platform development proposal, prepared in close interaction with technological industry partners.

4. PROVENANCE VERIFICATION OF AUSTRALIAN BATTERY MATERIALS

In the previous chapter, we recognised that a traceability solution is required to follow the material through multiple tiers of chain of custody, but supply chain actors face multiple challenges and require a separate instrument to verify the chain of custody information, especially the product provenance (Young, 2018). In the context of a responsible mineral supply chain, provenance verification supports the initial links of a material to the upstream supply chain, or "the supply chain from the mine to refiners" (OECD, 2016). However, a lack of transparency in mineral supply chains (especially in 3TG commodities) and further chain of custody management issues make verification of responsible sourcing difficult and physical material analysis is often required to verify the upstream source (van den Brink et al., 2019). Provenance verification based on the undisputable attributes (e.g., chemical profile) of a material can provide the necessary trust for downstream product manufacturers and minimise the customer perceived risks for their products.

WHY DO WE NEED PROVENANCE VERIFICATION?

For customers, the interpretation of a product label relies on visual cues that provide accessible indicators of the perceived risk or benefit associated with the purchase (Grewal et al., 1994; Berthon et al., 2009). Typical labels state the country-of-origin (e.g., "made in Australia"), certification of claims (e.g., fair trade, organic, non-GMO) and/or intangible qualities (e.g. "luxury brands") aimed at reassuring customers and/or reducing perceived risks (Mitchell and Greatorex, 1988). Unfortunately, the reliability of these conventional label frameworks has been thrown into question due to widespread falsification of, and tampering with, product labels (Falkheimer and Heide, 2015).

In the case of the mineral supply chain, the validity of labels and documentation for a product is challenged by two main factors mentioned previously: the complexity of chain-of-custody and the transformational nature of mineral product through the chain. If a comprehensive traceability solution (Chapter 3) focuses on connecting the supply chain actors to solve the first issue with a transparent and secure peer-to-peer platform; the second factor needs to be resolved with a method based on a product and its physical attributes since traceability only operates with the product's chain of custody and does not differentiate products based on their physical or chemical attributes.

Provenance verification is an independent scientific method that can be used to check the documented origin of product labels or evaluate whether the origin given in the documents of a product in question is plausible or not. The method often utilizes a single attribute of a product (e.g. pollen in honey or paint in the artwork) to check with a reference sample of the documented origin stored in a database. More comprehensive methods can combine multiple identifications of characteristic physical and chemical features preserved in a product and verify the provenance by applying statistical analysis on multiple parameters (e.g. 4C and chemistry of diamonds). The provenance verification has a significant fraud prevention potential if implemented as an additional proof of origin within the framework of product certification (Young, 2018).

While supply chain due diligence and provenance verification in principle can be applied to support sustainable, socially and environmentally responsible sourcing, analysis of industry reports shows that the current focus is mainly on the sourcing of 'conflict-free' minerals (van den Brink et al., 2019). A primary case of the 'conflict-free' mineral industry and involving provenance verification technology is the diamond market. The market concern is driven by a weakness of the Kimberley Process, based on a paper certificate of origin, which is a non-verifiable, non-transparent medium and is susceptible to fraud.

Analytical technologies have been widely used to test claims of diamond origin independent of the supplier certificate by measuring the elements incorporated within diamonds during their formation. Source Certain International, provides services in the verification of diamond provenance claims with TSW Trace® technology (Figure 8). The figure shows that based upon supporting documentation, all of the investigated diamonds should have originated from one location. However, the analytical results demonstrate that the diamonds originated from multiple sources.

Diamonds - Id of conflict (smuggled) diamonds

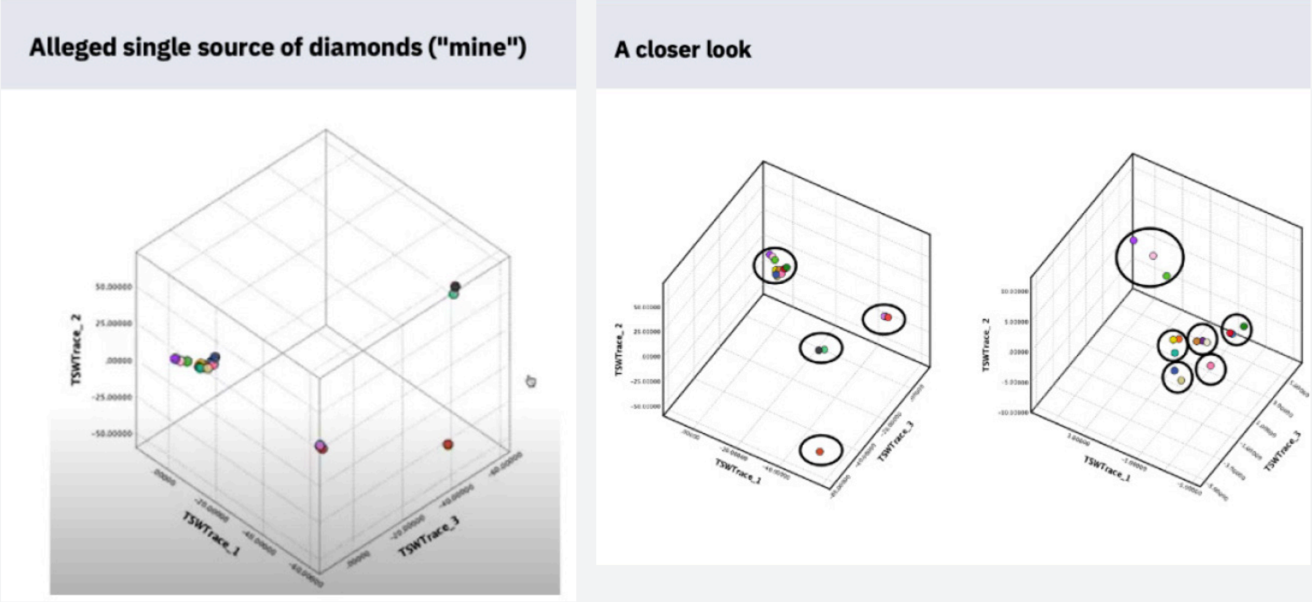


Figure 8: Source Certain - Illustration of a consignment of diamonds, assayed to verify a single source or provenance.

The processing of battery minerals through the battery value chain manufacturing processes provides additional challenges for initial mineral ore provenance verification in the finished products. The critical mineral groups for battery production are characterised by significant supply chain security (e.g., rare earth elements minerals, and ethical risks (e.g. Li brine water management conflict). From the Australian battery market perspective, raw mineral export clearly identifies Li as the most significant element to verify through the battery value chain. It suggested that a provenance verification framework for raw battery materials should initially focus on Li in order to resolve consumer perceived risks, to positively impact purchasing decisions of ethically sourced battery materials (Wilson and Martinus. 2020).

EXISTING PROVENANCE VERIFICATION METHODS

The topic of responsible sourcing of minerals is relatively new and does not have a large research library or documented analytical methods (van den Brink et al., 2019). Existing research literature and industry reports mainly focus on responsible sourcing of the conflict minerals tin, tantalum, tungsten and gold from the Central African region. For example, a research paper to determine the chemical composition of niobium and tantalum ore as one of the means of ascertaining its provenance contributed to minimise the illicit export of coltan ore from the Democratic Republic of the Congo (Harmon et al., 2011). The method included laser induced breakdown spectroscopy (LIBS) to distinguish different geographic sources with partial least squares discriminant analysis, allowing correct sample-level geographic discrimination at a success rate exceeding 90%.

Analytical Fingerprint method by the Federal Institute for Geosciences and Natural Resources of Germany

Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) has been developing an analytical fingerprinting (AFP) method since 2006 as part of technical cooperation efforts within the National support program (BGR, 2008). The AFP system verifies the provenance based on the mineral chemical profiles in the supply chain segment stretching from mine sites to local exporters, prior to mixing materials from different sources in a container load for export (BGR, 2013b). BGR offers AFP as an optional tool for interested parties (e.g., companies or auditors) to substantiate 3TG mineral origin risk. The AFP system combines randomly targeted fingerprinting of a small percentage of samples before export and relies on a collected dataset of reference materials.

The Federal Institute for Geosciences and Natural Resources of Germany supported the growth of AFP capacity in the Central African region, and it has since been adopted by the region's national geological (or equivalent) services. The expansion was prompted by potential sanctions on artisanal miners and traders to strengthen the system implementation, to deter fraud attempts and to positively support the credibility of the upstream supply chain. Mine operators in DRC and nearby countries seeking certification under the Certified Trading Chains (CTC) schemes are required to allow AFP reference sampling on their concession area or else risk being labelled as non-trustworthy.

The AFP analytical method was developed by a multi-disciplinary research team on a wide range of ore concentrate samples and utilized the following key parameters which can be used to verify the documented origin of an ore concentrate sample in question (BGR, 2013b):

- Geochemical composition (major and trace elements) of ore minerals
- Geological age of ore minerals
- Mineralogical composition and variability of ore concentrates.

The method follows a streamlined analytical protocol:

- Preparation of polished sections from mineral concentrates
- Quantification of mineral proportions in ore concentrates using scanning electron microscopy (SEM) combined with automated mineral identification capabilities.
- Determination of the chemical composition and of uranium-lead isotopes of about 50 individual ore mineral grains representative for a given concentrate sample using laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS).

Analytical data obtained from "reference samples" of known origin (mine) are stored in a database. The claimed origin of a "sample of interest" taken along a supply chain (from mine to exporter) may be verified by cross-referencing its compositional data with the information stored in the reference database using statistical methods.

The AFP results are designed to be integrated into audit, or risk assessment findings, not intended to be applied as a stand-alone method for mineral sourcing decisions and not an alternative to everyday mineral traceability techniques (e.g. tagging), but AFP serves to verify the integrity, and thus credibility, of the latter.

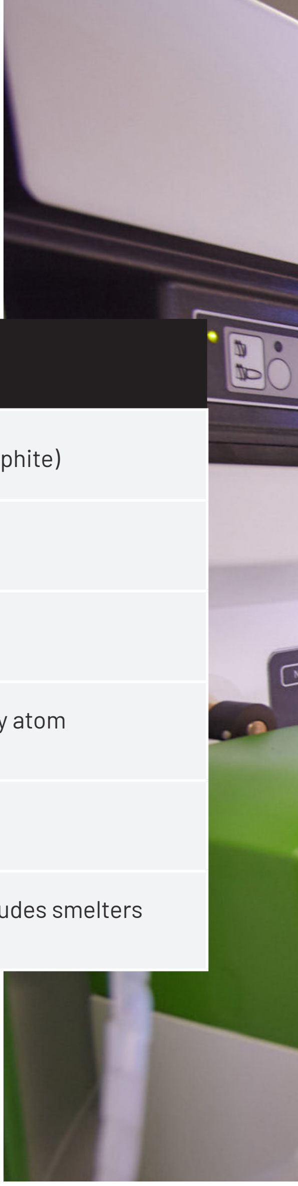


TABLE 3: COMPARISON OF THE KEY FEATURES OF PROVENANCE VERIFICATION INITIATIVES.

	AFP BY BGR	BATTRACE BY GTK
Focus Mineral and Material	3TG	Battery raw minerals (Li, Co, Graphite)
Focus Region	DRC and Central Africa Region	Finland
Objective	Avoid conflict raw minerals	Enhance Sustainability
Fingerprinting method	Reference sample authentication by SEM, LA-ICP-MS	Chemical forensic verification by atom level absorption
Governance	GFP (survey)	GTK (survey)
Supply Chain Traceability	Upstream focused (miners)	Upstream focused (miners), includes smelters and LCA for recycled materials

BATTRACE by the Geological Survey of Finland GTK

Another notable provenance verification project for the mineral supply chain was announced in mid-2020. Finland launched a material traceability project, the BATTRACE project, aimed at enhancing sustainability in the mining industry. The project includes research aspects of provenance verification and a fingerprinting solution for battery minerals and materials conducted by VTT Technical Research Centre of Finland and the Geological Survey of Finland GTK. The research will be based on atom-level observations made on the composition of materials to reveal the material origin, and also will be used to indicate the share of recycled metals, to optimise the metal production processes for the needs of the battery industry and to ensure their sustainability by such means as life-cycle assessments. It is reported that the total project's budget is about €5.8m, €2.7m, of which is allocated for research. The funding model is similar to FBI CRC and comes from Business Finland, research and industry partners.

Table 3 provided above summarizes key features of both provenance verification initiatives, AFP and BATTRACE. They both focus on the upstream parts of the mineral supply chain and are developed by a national survey organisation. Similarly, the BRGM (French Geological Survey) has initiated a program to analytically verify and chemically fingerprint battery minerals with an initial focus on Li ores source (personal connections).

European organisations are highly interested and acting quickly to develop a provenance verification method for battery (and critical) minerals, however without a comprehensive chemical fingerprinting method capable of verifying mineral source for processed battery materials through the supply chain; initiatives might risk not delivering critical origin information to the battery consumers due to challenges of processed material transformations.

THE PROPOSED SOLUTION - GEOCHEMICAL FINGERPRINTING (GFP) FOR LI SUPPLY CHAIN

The term 'Geochemical Fingerprint' refers to a combination of scientific techniques, which can be used as a verification method to check whether the alleged origin of ore concentrates or minerals can be verified as declared in accompanying documents. GFP

compares the unknown sample with documentation indicating a certain origin to a control sample from that same origin whose chemical characteristics are stored in a database (reference samples). This is done by analysing characteristic geochemical features preserved in mineral concentrates, which reflect the source specific mineralogical and geochemical features related to the unique geological context of each deposit. The final comparison of these features between the control and reference sample is achieved by applying statistical analysis to evaluate whether or not the declared origin of the unknown sample is plausible (BGR, 2018).

Ten key elements have been identified for the production of Li-ion batteries, Li, graphite, Co, Ni, Al, Cu, Mn, Fe, P, and Ti. More recent research has shown that the addition of Nb and W might have positive effects on anode materials. Whereas Li from brines is extracted via evaporation, filtration, ion exchange, and precipitation processes, Li extracted from hard rock sources follows more convoluted mining and processing practices, including physical (excavation, crushing, flotation, magnetic separation, roasting) and chemical (leaching and conversion) treatments. Nonetheless, the geologic setting from which the Li raw material is derived will impart a characteristic geochemical composition, or geochemical fingerprint, on those raw materials. For example, the Li-bearing mineral spodumene ($LiAlSi_2O_6$) is commonly found in pegmatites, a rock type associated with the late stages of granite emplacement. Pegmatites also show characteristic geochemical features such as enrichment in certain elements (Li, Cs, Be, Nb, Ta, Sn, etc.) that are incompatible in the predominant rock-forming minerals of granites. Hence, Li derived from pegmatitic sources should also be characterized by elevated concentrations of those incompatible elements. Especially useful for the classification of rock types or minerals are ratios of geochemically similar (trace) elements such as Nb/Ta or Rb/Cs. We will apply this technique to the characterisation of key Li raw materials and evaluate the robustness of trace element ratios through the mineral processing chain.

LITHIUM ISOTOPES FOR GEOCHEMICAL FINGERPRINTING METHOD

Lithium has two stable isotopes, ^{6}Li and ^{7}Li, which have abundances of ~7.5% and 92.5% in nature, respectively. The two isotopes have large mass differences (approximately 16.7%), which leads to large isotope fractionation during various geological processes (Tang et al., 2007). Therefore, lithium isotopes are a sensitive geochemical tracer that covers the interactions between fluids and minerals from the surface to the mantle (Misra and Froelich, 2012). Lithium isotopes can not only help solve the problem of the evolution of the ore-forming environment in space and time but also indicate the sources of ore-forming materials and the physical and chemical conditions of mineralization. For example, lithium isotopes were successfully used to ascertain the origin of lithium-rich playas by Araoka et al. (2014).

Here, we propose to use lithium isotopic compositions (expressed as δ^7Li, i.e., permil deviation from the international Li standard LSVEC := 0) to characterize Australian spodumene sources, and compare them to other Li sources worldwide, including Li derived from brines.

The ratio of lithium isotopes is expressed using the standard delta notation:

$$\delta^7\text{Li}(\text{‰}) = \left[\frac{\left(^7\text{Li}/^6\text{Li}\right)_{\text{unknown}} - \left(^7\text{Li}/^6\text{Li}\right)_{\text{standard}}}{\left(^7\text{Li}/^6\text{Li}\right)_{\text{standard}}} \times 10^3\right]$$

Experimentally determined fractionation factors for fluid-spodumene predict that fractionation of Li isotopes between rock and released aqueous fluid should be limited to <3‰ (Wunder et al. 2006, |Marschall et al. 2007).

This is consistent with preliminary literature data (Figure 9) of spodumene analyses from Archean LCT pegmatite locations, in that for any given location, there seems to be a narrow spread in δ^7Li measured for spodumene separates. There are, however, exceptions: 'green' spodumene from Tanco (Canada) shows markedly lower δ^7Li compared to fresh spodumene. Only two values reported for spodumene from the Bikita pegmatite in Zimbabwe show a 5‰ difference and are inconclusive. Curtin's John de Laeter Centre (JdLC) measurement of spodumene from the Greenbushes pegmatite (+5.4 ± 0.2‰) compares very well with literature data (5.96 ± 0.18‰), and attests to the narrow-expected range of δ^7Li in fresh spodumene for a given location.

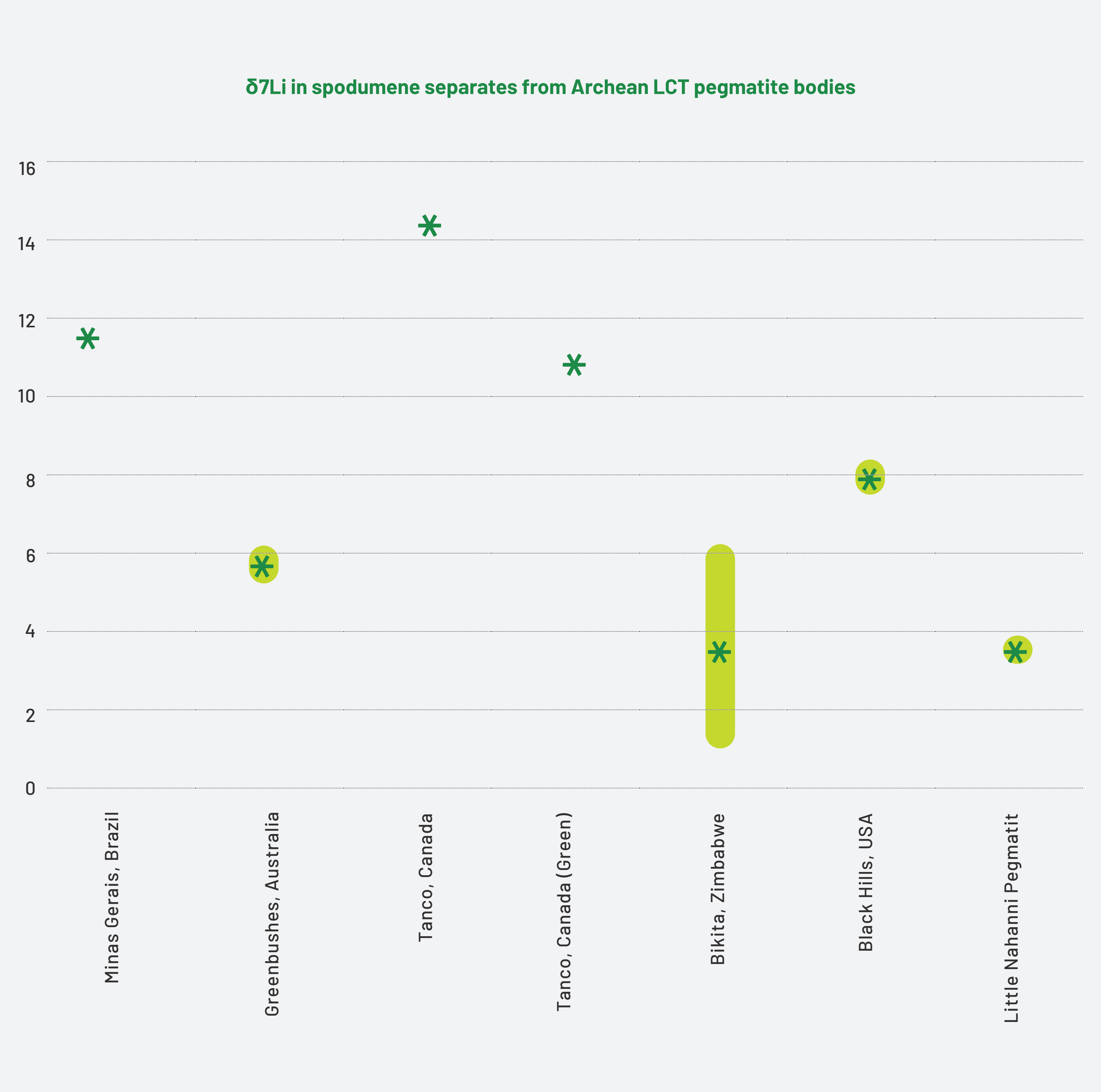


Figure 9: δ^7Li in spodumene separates from Archean LCT pegmatite bodies worldwide.

The project further proposes to investigate how those source characteristics translate through the Li supply chain (spodumene to ore to concentrate to chemical), and how a refined Li product (LiOH or $LiCO_3$) can then be clearly assigned to a specific source locality through a multidisciplinary approach.

PROPOSED WORKFLOW OF GFP ON AUSTRALIAN BATTERY RESOURCES

There are no provenance verification case studies available for Australian battery material exports in the economically significant Li, Co, Ni and Mn supply chains. It is proposed that the initial focus of development of an FBI CRC provenance verification tool be carried out on the Australian Li mineral supply chain. Successful geochemical fingerprinting needs to be based on a comprehensive geochemical database of Li sources.

Therefore, it is essential to analyse a broad range of critical Li minerals (spodumene, lepidolite, petalite etc.), and salts (mostly from Latin America). For Australian pegmatites, there is already geological, mineralogical, and metallurgical information available through MRIWA's project M532, which aimed to develop a geometallurgical framework to improve efficiencies in Li economic recovery. The FBICRC project will employ the accumulated geological and resource knowledge of Australian Li ores to distinguish geochemical signatures for critical provenance information of strategic Li ores. The collection of worldwide Li samples was initiated with LiOH, and Li_2CO_3 samples derived from South American Li brines.

The provenance verification workflow and development of GFP will follow three parallel paths:

- Lithium isotopic signatures – the primary characteristic of the element
- Trace element patterns – the secondary characteristics of associated elements in material impurities
- Physical, mineralogical and isotopic process signatures

The project will primarily utilise the laser ablation ICP-MS (GeoHistory) facilities, John de Laeter Centre (JdLC) at Curtin University. JdLC is a modern centralised research infrastructure facility founded in 1992 by Professor John de Laeter in co-operation with UWA and the Geological Survey of Western Australia. The laboratory led by Prof. Noreen Evans is equipped with two RESOlution 193 nm excimer laser ablation systems coupled to NU Plasma II MC-ICP-MS for the precise determination of Li isotopic fingerprinting signatures. The instrument offers detection limits down to ~50 ppt for a wide range of elements, which is critical for the determination of ultra-trace element contents in battery precursor materials. The supporting trace element fingerprinting analysis of solution-based samples will identify host gangue and impurity phases for the signature trace elements using ICP-MS equipment.

The transformational challenge of supply chain manufacturing processes will be studied by determining physical, mineralogical and isotopic characteristics of Australian lithium concentrates and LiOH/$LICO_3$ chemicals and establish the effect of transformational chemical processes on geochemical signatures. This will be conducted by Murdoch University (MU), with state-of-the-art analytical equipment and experience in Li concentrate characterisation and processing in a two-directional workflow for concentrate conversion into chemicals and source material chemical signatures in manufactured battery components (battery pouches and active materials), supported by industry partners Tianqi and BASF, respectively. Precipitation experiments using a dedicated reactor and vacuum oven will identify the effect of process parameters for geochemical signatures that are critical for provenance verification.

The combination of multidisciplinary analytical techniques and experimental methods will provide the necessary understanding on Li provenance chemical profiles and material transformation due to supply chain processes to develop a comprehensive forensic tool for downstream actors to obtain critical source information.

POTENTIAL RISKS OF PROPOSED WORKFLOW AND SOLUTIONS

The risk of failure in the analytical protocol development is minimal. All participating parties involved are experts in their fields, samples are readily available today, and pilot project results have shown promising results. There is evidence in the literature that Li ores of various origins can be chemically differentiated (Duuring, 2020), so all that remains is to begin building a database of geochemical signatures. The risk of the material transformational aspect will be minimised with precipitation experiments under a controlled environment conducted by Murdoch University to reflect the real supply chain processes.

However, the transformational processes for Co, Ni and Mn are different to Li material processing, especially in the upstream parts (Talbot and Watts, 2020). The engagement with Ni-Co-Mn mining and processing companies will provide a critical understanding of mineral processing, and with the support of other projects in the FBI CRC portfolio, the issue will be addressed in the following years after the initial first year pilot project on the Li supply chain. Ultimately, the aim of the project is to establish a provenance verification method for the entire battery supply chain, relating to Li, Ni, Co and Mn.

Feedback through personal connections on the existing provenance verification methods on the mineral supply chain suggests the cost factor on less successful market deployment was the analytical cost. The project will develop a business model with a principal industry partner, to address the issue of analytical costs by balancing output precision and deployed methods. The analytical results return time will also be a factor to resolve during the development stage.

The acceptance of provenance verification depends on communication with battery supply chain stakeholders. Communication and connection of stakeholders are primarily delivered by a traceability solution. Therefore, the systematic integration of a provenance verification method and an analytical fingerprinting tool is necessary for successful acceptance by end-users.

The results of provenance verification work will be documented in a dynamic data management system developed by a data science team at the Curtin Institute for Computation (CIC) to form the data management basis of a traceability solution and framework that can be expanded to other critical elements, such as Co and Ni. The generated raw analytical data for metal, stable isotopic ratios and trace element profiles from project participants will be processed with a descriptive statistical approach to summarise the information features. The chemical fingerprinting of transformational changes (chemical reactions) along the supply chain will be reflected as mathematical equations for a digital traceability solution.

To address universal adoption by supply chain stakeholders and especially the battery end-users, the provenance verification data management system will be developed according to responsible sourcing certification standards (developed in partnership with the FBI CRC “Certification and LCA” project) to create a database of high-quality analytical data, chemical fingerprinting methods and open access provenance/processing information with the involvement of the traceability solution provider.

Verification through chemical assay

Provenance verification technology is based upon chemical information and is independent of conventional shipping documentation and tagging procedures, thus allowing for more robust verification of product provenance.

5. CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations are based on the review and solutions proposed by the study:

- Lithium-ion batteries will play a critical role in bringing the transportation and energy sectors to carbon emission neutrality by transforming 'renewable energy' from a perceived 'alternate' source to a genuinely accepted 'primary' source. This need for fundamental change in perception and its associated societal benefits drives the development of new battery technologies.

- By volume/value Li is the key element in the Australian battery material supply market today. A framework of source verification for Australian Li products will provide the technological guidelines for expanding protocols into other raw battery materials (e.g., Ni, Co, Mn) and to international sources for broader comparison and verification.

- Existing responsible sourcing initiatives focus predominantly on 3TG from the Central Africa region and are designed to minimise risk by avoiding the negative impact of conflict minerals. For the far-reaching impact of responsible sourcing through the mineral supply chain, provenance verification and traceability solution are essential to provide trust in the sourcing claim and to transfer critical information through the supply chain to end-users, respectively.

- Countries and regions with existing high standards of mining and processing of battery minerals and metals, such as Australia, could derive market advantage and potentially value through highlighting responsible production practices. This will require demonstration of responsible sourcing data within globally recognised certification schemes, such as IRMA or CERA, through the supply chain.

- Traditional supply chain traceability methods (e.g. paper-based labels) and some novel technological solutions offer compliance and varying degrees of transparency with pay offs around accessibility, privacy, and efficiency. However, industries are addressing increasing supply chain requirements by undergoing digital transformation through the use of emerging technologies, such as blockchain technologies, to create improvements in consumer satisfaction, logistical and economic efficiencies. Currently, a public, open-source and scalable blockchain technology is a digital traceability standard for service providers that provides transparency with regards to data transactions and storage through the chain of custody.

- A traceability solution based on blockchain technology with a massbalance model approach increases trust and consensus along the chain of custody and minimises fraud risk with tamperproof verification methods, and provides secure data sharing. Mineral supply chain challenges such as scalability, confidentiality and accessibility should be addressed in the platform development proposal, prepared in close interaction with service industry partners.

- The concept of provenance verification is at the core of a trust-building strategy for a responsible supply chain and offers a highly auditable process to minimize perceived financial, social, performance and physical risks. Provenance verification technology is based upon chemical information and is independent of conventional shipping documentation and tagging procedures, thus allowing for more robust verification of product provenance. The existing provenance verification methods focus predominantly on the mining side of a mineral supply chain and are employed in case of disputes through the highly auditable and often costly process. The suggested provenance verification method of battery materials and elements aims for the systematic and secure integration of the method in the chain of custody traceability solution. This will provide time and cost-effective audit capabilities for supply chain actors, which is necessary for successful acceptance by end users.

- Geological processes impart a chemical 'fingerprint' on minerals that can be used to develop a geochemical fingerprinting (GFP) database. Unknown product/samples accompanied by a provenance claim can be chemically compared against this database for source verification. Fingerprints may be isotopic or elemental, or a combination of both. An effective facilitated verification will connect upstream and downstream products using chemical signatures that retain their voracity throughout the supply and production chain.

- The implication of battery material chemical fingerprinting has a potential beyond source and supply chain tracing. The provenance and fingerprinting proxy information of the "end-of-life" battery materials and recycled chemicals should provide critical information in establishing standards for recycled battery elements and separation of virgin and recycled materials in the end product from the LCA perspective.

6. ENDNOTES

Adamas Intelligence (2019) NCM 811 Commands an 18% Market Share in China in September 2019 https://www.adamasintel.com/subscription/ev-battery-capacity-monthly/

Airbus (2017) Supplier Code of Conduct. (Accessed 20 June 2018). https://www.airbus.com/sites/g/files/jlcbta136/files/2021-07/Airbus-Supplier-Code-of-Conduct.pdf

Ali, S., Giurco, D., Arndt, N. et al. (2017) Mineral supply for sustainable development requires resource governance. Nature 543, 367–372

Apple Inc. (2019) Conflict Minerals Report https://www.apple.com/supplierresponsibility/pdf/Apple-Conflict-Minerals-Report.pdf

Araoka D, Kawahata H, Takagi T, Watanabe Y, Nishimura K, Nishio Y (2014) Lithium and strontium isotopic systematics in playas in Nevada, USA: constraints on the origin of lithium. Mineral Deposita 49:371–379

Astill, J. (2019) Transparency in food supply chains: A review of enabling technology solutions. Trends in Food Science & Technology 91:240-247

Austrade (2018) The Lithium-Ion Battery Value Chain – New Economy Opportunities for Australia https://www.austrade.gov.au/ArticleDocuments/5572/Lithium-Ion Battery Value Chain report.pdf.aspx

Benchmark Minerals (2019) after Co, industry focus shifts to other battery minerals in responsible sourcing https://www.benchmarkminerals.com/after-cobalt-industry-focus-shifts-to-other-battery-minerals-in-responsible-sourcing/

Berthon, P., Pitt L., Parent M., and Berthon J.P. (2009) Aesthetics and ephemerality: Observing and preserving the luxury brand, California Management Review, 52(1), 45-66

Best, A. and Vernon, C. (2020) State of Play, Australia's Battery Industries as at March 2020. CSIRO, Australia.

BGR: Bundesanstalt für Geowissenschaften und Rohstoffe (2008) Certified Trading Chains https://www.bgr.bund.de/EN/Themen/Min_rohstoffe/CTC/Concept_MC/CTC-Standards-Principles/ctc_standards-principles_node_en.html

BGR (2013). "Terms & Definitions": Mineral Certification in Central Africa. Brochure for distribution

BGR (2018) The Analytical Fingerprint (AFP) Method and Application Process Manual Version 1.4 https://www.bgr.bund.de/EN/Themen/Min_rohstoffe/

CTC/Downloads/AFP_Manual.html

BMW (2020) BMW Group uses blockchain to drive supply chain transparency https://www.press.bmwgroup.com/global/article/detail/T0307164EN?language=en

CIPRS (2020) Canadian Identity Preserved Recognition System https://grainscanada.gc.ca/en/industry/grain-safety/ciprs.html

Curtin University (2019) Blockchain & Provenance Oranges https://businesslaw.curtin.edu.au/wp-content/uploads/sites/5/2019/10/OrangeBlockchain-Provenance.pdf

Chapron, G. (2017). The environment needs cryptogovernance. Nature 545 (7655), 403–405.

Diamond Trading Company (2013) Provenance Claims – 'Diamonds from DTC' – Guidance https://www.dtc.com/~/media/Files/D/Debeers-DTC/documents/Retailers/Provenance%20Claims%20%20Diamonds%20from%20DTC%20-%20Guidance%20for%20third%20parties%20and%20retailers.pdf

DMT Group (2019) New raw materials certificate to guarantee universal standard of ethics, sustainability and environmental impact, Press release. https://www.dmt-group.com/news-info/press/press-release/archive/2019/10/31/new-raw-materials-certificate-to-guarantee-universal-standard-of-ethics-sustainability-and-environm.html?cHash=4abc7cfc97370aa39ef2dc3c68916138

Duuring, P (2020) Rare-element pegmatites: a mineral systems analysis: Geological Survey of Western Australia, Record 2020/7, 6p

EDRM (2017). Chain of Custody. http://www.edrm.net/glossary/chain-of-custody/.

Estelle Levin LTD (2017) Comparative study of certification and traceability systems https://www.levinsources.com/assets/pages/report-promines-comparative-study-certification-traceability-systems-drc-congo.pdf

Esty D. (2003) Environmental Protection in the Information Age. SSRN Electron. J.

Equita (2018) Electric Vehicles Update report https://www.equita.eu/static/upload/ele/electric-vehicles.pdf

European Parliament and the council of the European Union (2017) supply chain due diligence obligations for Union importers of tin, tantalum and tungsten, their ores, and Gold originating from conflict-affected and high-risk areas https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32017R0821

Everledger (2020) Batteries Life Cycle Management https://everledger.io/batteries-life-cycle-management/

Falkheimer, J. and Heide, M. (2015) Trust and brand recovery campaigns in crisis: Findus Nordic and the horsemeat scandal, International Journal of Strategic Communication, 9(2), 134-147

Flexer V., Baspineiro C., Galli C. (2018) Lithium recovery from brines: A vital raw material for green energies with a potential environmental impact in its mining and processing, Science of The Total Environment, 639, 1188-1204

Grewal D., Gotlieb, J. and Marmorstein H. (1994) The moderating effects of message framing and source credibility on the price-perceived risk relationship, Journal of Consumer Research 21(1) 145-153

Grimstad Bang T., Johansson A. (2019) Responsible Sourcing via Blockchain in Mineral Supply Chains. TRITA-EECS-EX 242

Guardian (2019) Apple and Google named in US lawsuit over Congolese child Co mining deaths https://www.theguardian.com/global-development/2019/dec/16/apple-and-google-named-in-us-lawsuit-over-congolese-child-Comining-deaths

Harmon, R.S., Shughrue, K.M., Remus, J.J. (2011) Can the provenance of the conflict minerals columbite and tantalite be ascertained by laser-induced breakdown spectroscopy? Analytical Bioanal Chem 400, 3377–3382

Hofmann, H., Schleper, M.C. and Blome, C. (2015) Conflict minerals and supply chain due diligence: an exploratory study of multi-tier supply chains. J. Bus. Ethics 1–27.

Houston J., Butcher A., Ehren P., Evans K., Godfrey L. (2011) The evaluation of brine prospects and the requirement for modifications to filing standards, Econ. Geol., 106(7),1125-1239

IBM (2019) IBM Food Trust.
A new era for the world's food supply
https://www.ibm.com/blockchain/solutions/food-trust

IEA (2020), Global EV Outlook 2020, IEA, Paris https://www.iea.org/reports/global-ev-outlook-2020

Kesler S., Gruber P., Medina P., Keoleian G., Everson M., Wallington T. (2012) Global Li resources: Relative importance of pegmatite, brine and other deposits. Ore Geology Reviews 48, 55–69

Ledger Insights (2019) Novartis to go live with blockchain network in 2020 https://www.ledgerinsights.com/novartis-live-blockchain-network-2020/

Manning, L. and Soon, JM (2014) Developing systems to control food adulteration. Food Policy, 49, 23–32.

Marschall HR, Pogge von Strandmann PAE, Seitz HM, Elliott T, Niu YL (2007) The lithium isotopic composition of orogenic eclogites and deep subducted slabs. Earth Planet Sci Lett 262:563–580

Mckinsey (2018) Lithium and cobalt - a tale of two commodities, https://www.mckinsey.com/industries/metals-and-mining/our-insights/lithium-and-cobalt-a-tale-of-two-commodities

Misra S, Froelich PN (2012) Lithium isotope history of Cenozoic seawater: changes in silicate weathering and reverse weathering. Science 335, 818–823

Mitchell, V.-W. and Greatorex, M. (1988) Consumer risk perception in the UK wine market, European Journal of Marketing, 22 (9) 5-15

Mol, A.P.J.; Oosterveer, P. (2019) Certification of Markets, Markets of Certificates: Tracing Sustainability in Global Agro-Food Value Chains. Sustainability, 7, 12258-12278

National Geographic (2019) This metal is powering today's technology—at what price? https://www.nationalgeographic.com/magazine/article/lithium-is-fueling-technology-today-at-what-cost

Organisation for Economic Co-operation and Development (2020) OECD Due Diligence Guidance for Responsible Supply Chains of Minerals from Conflict-Affected and High-Risk Areas https://www.oecd.org/corporate/mne/mining.htm

Potts, J. et al. (2018) Standards and the Extractive Economy. Intergovernmental Forum on Mining, Minerals, Metals and Sustainable Development.

RCS Global Group (2019) Saving the EV Revolution. Better Mining: Digital monitoring, data-driven risk management and positive impact generation in Co, copper and 3TG ASM supply chains. https://www.rcsglobal.com/pdfs/20191810%20RCS%20Global%20Group%20Better%20Mining%20Saving%20EVs%20Report%20Public.pdf

Roskill (2020) Lithium's growing CO2 footprint. An analysis of energy consumption and emissions intensity from the global lithium supply. White Paper.

RCS Global (2017) Blockchain for Traceability in Minerals and Metals Supply Chains: Opportunities and Challenges. ICMM https://www.rcsglobal.com/wp-content/uploads/2018/09/ICMM-Blockchain-for-Traceability-in-Minerals-and-Metal-Supply-Chains.pdf

Rutovitz J., Dominish E., Li W., Farjana S., Northey S., Giurco D. (2020). Certification and LCA of Australian Battery Materials – Drivers and Options. Prepared for Future Batteries Industry CRC by the Institute for Sustainable Futures, University of Technology Sydney and The University of Melbourne.

SAP (2020) Blockchain Applications and Services https://www.sap.com/products/intelligent-technologies/blockchain.html

SMM (2020) China's nickel sulphate market roughly balanced in 2020-2022, https://news.metal.com/newscontent/101009397/chinas-nickel-sulphate-market-roughly-balanced-in-2020-2022/

Staaij, J.; van den Bos, A.; Toop, G.; Alberici, S.; Yildiz, I. (2012) Analysis of the Operation of the Mass Balance System and Alternatives; Ecofys: Utrecht, The Netherlands

Strade (2018) Successful implementation of conflict mineral certification and due diligence schemes and the European Union's role: lessons learned for responsible mineral supply https://www.stradeproject.eu/fileadmin/user_upload/pdf/STRADE_Report_D4.19_Due_Diligence_Certification.pdf

SustainBlock (2020) Blockchain-assisted Mineral Supply Chain Due Diligence https://www.sustainblock.org

Swain, B. (2017) Recovery and recycling of lithium: A review. Separation and Purification Technology, 172 (388-403)

Tang YJ, Zhang HF, Nakamura E, Moriguti T, Kobayashi K, Ying JF (2007) Lithium isotopic systematics of peridotitexenoliths from Hannuoba, North China Craton: Implications for melt-rock interaction in the considerably thinned lithospheric mantle. Geochim Cosmochim Acta 71:4327–4341

Talbot, P. and Watts J. (2020) Future Battery Industries "Li-ion battery cathode manufacture in Australia" a scene setting project report, QUT, Australia

Tesla Impact Report (2019) https://www.tesla.com/ns_videos/2019-tesla-impact-report.pdf

UNFCC (2015) Paris Agreement https://unfccc.int/sites/default/files/english_paris_agreement.pdf

US Securities and Exchange Commission (2012) Section 1502 of the DoddFrank Act https://www.sec.gov/spotlight/dodd-frank-section.shtml#1502

van den Brink R., Kleijn A., Tukker J and Huisman S. (2019) Approaches to responsible sourcing in mineral supply chains. Resour Conserv Recycl. 145, 389–398.

Vikström H., Davidsson S., Höök M. (2013) Lithium availability and future production outlooks Appl. Energy, 110, 252-266

Williams A. (2017) "Diamonds on the Blockchain: Building a Global Digital ledger for Valuable Assets," foreword by Don Tapscott, Blockchain Research Institute
Williams N. (2018) MineSpider: Protocol for Due Diligence in the Raw Material Supply Chain https://uploads-ssl.webflow.com/5bb20121ca2e96ee01db29bc/5c0fa81d4a4585e37ea764b7_Minespider_Whitepaper.pdf

Wilson, J. and Martinus, K. (2020) The governance of battery value chains: Security, sustainability and Australian policy options Prepared for Future Batteries Industry CRC by the institute for Sustainable Futures, University of Technology Sydney and The University of Melbourne, Perth USAsia Centre

World Economic Forum and Resolve Solutions Network (2015) Voluntary Responsible Mining Initiatives: A Review https://www3.weforum.org/docs/Voluntary_Responsible_Mining_Initiatives_2016.pdf

World Economic Forum (2020) A Vision for a Sustainable Battery Value Chain in 2030 Unlocking the Full Potential to Power Sustainable Development and Climate Change Mitigation, Insight Report, Global Battery Alliance http://www3.weforum.org/docs/WEF_A_Vision_for_a_Sustainable_Battery_Value_Chain_in_2030_Report.pdf

Wunder B, Meixner A, Romer RL, Heinrich W (2006) Temperature-dependent isotopic fractionation of lithium between clinopyroxene and high-pressure hydrous fluids. Contrib Mineral Petrol 151:112–120

Young, S.B. (2018) Responsible sourcing of metals: certification approaches for conflict minerals and conflict-free metals. Int J Life Cycle Assess 23, 1429–1447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