Geological Survey of Finland

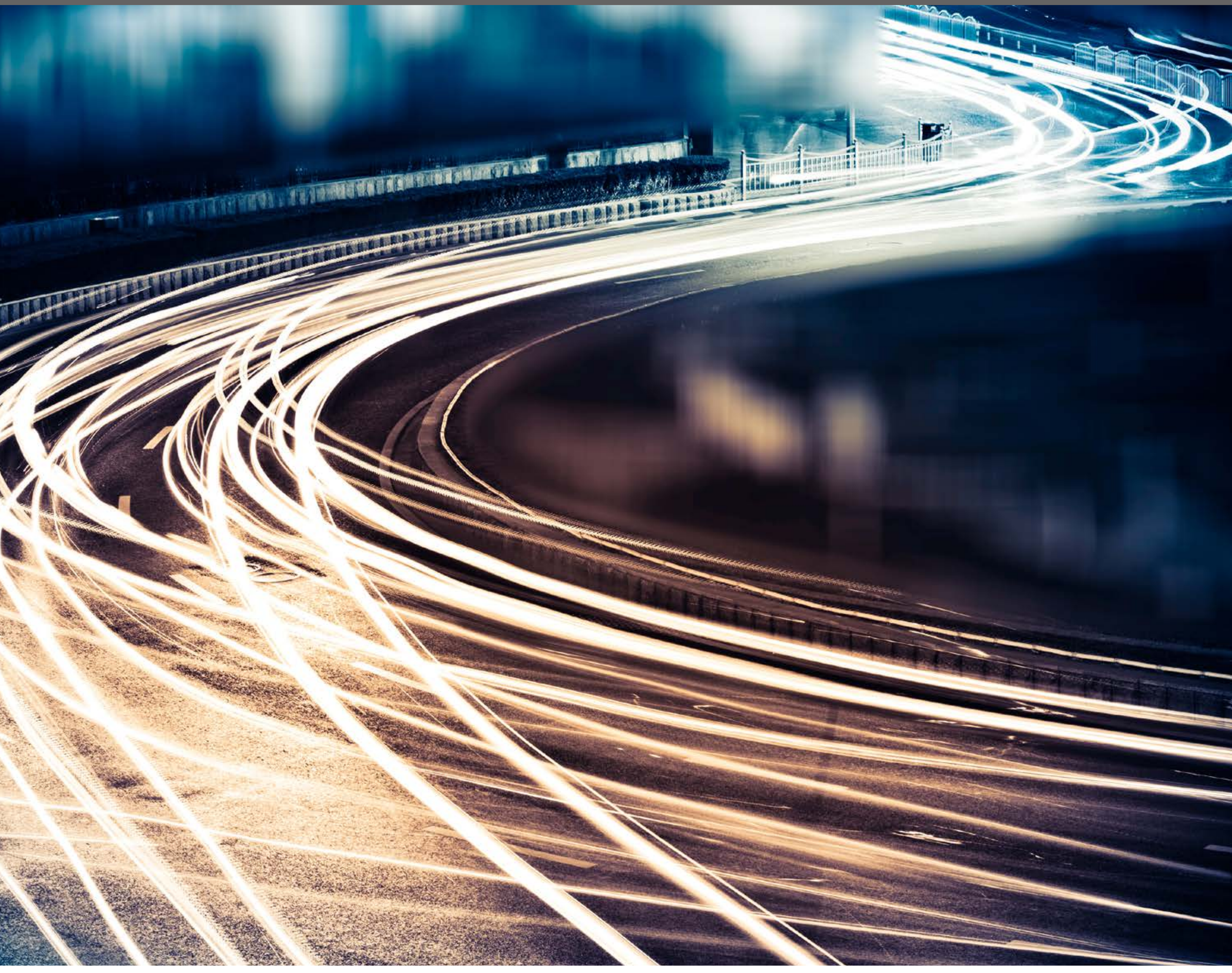
2022

Traceability methods for cobalt, lithium, and graphite production in battery supply chains

Assessing geo-based fingerprinting as a method for battery raw materials' traceability

Harri Kaikkonen, Mari Kivinen, Quentin Dehaine, Jussi Pokki, Toni Eerola, Martina Bertelli and Patrick Friedrichs

GTK Open File Research Report 20/2022



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GEOLOGICAL SURVEY OF FINLAND

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Layout: Elvi Turtiainen Oy

Espoo 2022

Kaikkonen, H., Kivinen, M., Dehaine, Q., Pokki, J., Eerola, T., Bertelli, M. & Friedrichs, P. 2022. Traceability methods for cobalt, lithium, and graphite production in battery supply chains. Assessing geo-based fingerprinting as a method for battery raw materials' traceability. *Geological Survey of Finland, Open File Research Report 20/2022,* 49 pages, 11 figures and 10 tables.

Current trends in transport electrification and mobile technologies have created an increasing demand for raw materials needed for battery production. The supply chains involved are global, complex, non-transparent and sometimes associated with unsustainable production practices. To improve on the current situation, it is essential to trace battery raw materials back to their origins to verify the conditions in which they were produced. This demand for increased transparency has triggered actions in European Union legislation and among companies operating within battery supply chains.

In this report, we review the current landscape for the application of traceability methods to battery supply chains. The report begins with a global overview of selected battery metals and minerals and their related sustainability issues. As sustainability is an integral goal for traceability, sustainability reporting systems for mining are reviewed from the perspective of traceability. Existing traceability methods and case studies in battery supply chains are reviewed, including the geo-based fingerprinting method (laboratory technology) that is being developed in the BATTRACE research project. We also discuss the business potential of the geo-based fingerprinting method.

Several drivers are identified for traceability. The main driver comes from regulatory development, such as the EU's battery directives. Customer awareness of sustainability issues is also beginning to influence manufacturers (OEMs) to invest in the transparency of their battery metal supply chains. In addition, the producers of sustainable and low emission raw materials have identified the commercial benefit of tracing the greenhouse gas emissions of their products along the supply chain. Current sustainability and reporting systems used within the mining industry are inadequate to comply with the increased traceability needs, as their focus is limited to the beginning of the supply chain.

The traceability pilots that are currently in use are still limited in scope. For traceability to become commonplace in mining supply chains, OEMs will need to recognize the overall commercial benefits of traceability. Ethical questions dominate in the sustainability considerations on cobalt production, and there are indications that the cobalt market may be separating into traceable and certified cobalt, and bulk cobalt. For lithium and graphite production, the dominating sustainability considerations relate to water and energy consumption and dust. Lithium and graphite are not currently communicated to be included in any digital traceability solution under preparation, but they have been included in BATTRACE research for the geo-based fingerprinting method.

Geo-based fingerprinting has considerable commercial potential as a traceability method and a verification tool. As the geological and elemental characteristics of a sample cannot be falsified, the method has unique potential as a stand-alone traceability technology, or as a complementary verification method with any other traceability system. The method could also serve as a verification tool in the "Metals from Finland" certificate, which could sharpen the marketing of sustainable and traceable battery metals production from Finland.

Keywords: cobalt, lithium, graphite, ore mining, refining, supply chains, traceability, certification, Finland, digitalisation, management systems, batteries, sustainable development, digital data, trace elements, isotopes

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1 INTRODUCTION

1.1 Drivers and motivation for traceability

Minerals are part of our everyday life and modern society, and are present in all industrial supply chains and activities. However, minerals and their importance remain unperceived by many, including the complexity of their global supply chains.

The transition to a decreased dependency on fossil fuels in the global energy system is a current global development. The consumption of metallic raw materials necessary for wind turbines, PV panels, batteries and hydrogen production and storage, among other systems, will markedly increase (Bobba et al. 2020). The shift to electronic mobility will require batteries, fuel cells and lightweight traction motors, cars, and heavy duty and lightweight transport. According to IEA (2021a), the fastest growing markets for electronic mobility are in China and Europe.

Lithium-ion batteries are currently the most applied technology for batteries. Despite their name, these batteries also include several other elements, many of which have been identified as critical to EU economies (Bobba et al. 2020). As the currently ongoing development requires a huge increase in battery production, the demand for battery raw materials is similarly intense. According to IEA (2021a), automotive lithium-ion battery production totalled 160 gigawatt-hours (GWh) in 2020, up 33% from 2019. To meet the raw materials requirements of the green energy transition, IEA (2021b) forecasts a 2–4-fold increase in the mineral demand until 2040, depending on the scenario. The relative demand growth will be particularly high for the battery-related minerals lithium, graphite, cobalt and nickel (IEA 2021b, Bobba et al. 2020). The European Battery Alliance (EBA 2022) estimates that the value of the battery market in Europe will increase to €250 billion annually by 2025. The aim of Finland and the European Union is to gain a significantly larger share of the battery market, which is currently focused on Asia, and to reduce the import dependency for batteries.

Although batteries themselves are seen as one solution in the green energy transition, their production does not currently come without other problems (Hodgkinson & Smith 2021, Dolega et al. 2020, Petavratzi et al. 2019). Supply chains for batteries, from the mining of raw materials to manufacturing and end use, involve several countries and companies and are anything else but straightforward. Mining always has environmental, social and economic impacts. However, human rights violations, environmental degradation and the so-called 'resource curse' effect on producing economies have particularly been connected with these supply chains, especially in the Global South (Petavratzi et al. 2019). In practice, some of these supply chains are better managed in terms of sustainability than others. However, as the supply chains currently lack transparency and traceability, customers have no possibility to know under what conditions the raw materials of their daily used equipment have been produced.

In addition to increased customer awareness, regulatory developments are influencing the entire industry around battery metals. In December 2020, the European Commission (2020a) proposed new battery regulations in response to the new developments around technological development, markets and the use of batteries (European Commission 2020b). These new regulations include an increased demand for sustainability and traceability within battery supply chains and will possibly dictate much of the global development around battery supply chain traceability.

Solutions to bring traceability to the battery supply chains are currently being developed in several companies and research projects. These solutions rely on big data and cloud technologies and are connected to the overall digital development in different industrial sectors and transportation. In addition, laboratory technologies for the physical identification of raw materials are under development. Traceability technologies connected to product passports and certificates may increase the transparency of battery production conditions to customers and reduce the human and environmental costs related to them in the future, although this development has also been challenged (see, e.g., Calvao & Archer 2021). The commercial and technological potential of any new traceability solution is dependent on the landscape of currently available solutions and future markets within the supply chain. The increased interest in sustainability among consumers and the push for sustainable and responsible business operations from market regulators such as the EU will drive the need for traceability solutions in the long term. In this report, we highlight the current methods and use of traceability for selected battery raw materials and their supply chains, and the motivation for traceability as part of sustainable operations. In doing so, we establish the current landscape of traceability in battery supply chains.

For companies that can meet sustainability criteria in their actions and shorten their supply chains, the current development towards traceability provides an opportunity to stand out. It is also a great business opportunity for companies providing and developing new digital services. Solutions to deal with the sustainable processing and traceability of battery raw materials also provide clear economic and environmental benefits to improve the competitiveness of the mining industry and technology providers in Finland. The battery strategy for Finland was published in 2021 to strengthen the innovative environment of the battery sector, accelerate Finland's sustainable and low-carbon economic growth and support the achievement of climate objectives in transport (Työ- ja elinkeinoministeriö 2021a).

Within the European Union, the European Battery Alliance was launched in October 2017. The purpose of this alliance is to ensure European benefits from safer traffic, cleaner vehicles and more sustainable technological solutions. According to the EBA, this will be achieved by creating a competitive and sustainable battery cell manufacturing value chain in Europe. Currently, the factory capacity for battery production is booming in the European Union and multiple new battery factories have either started production or are in the pipeline (Transport & Environment 2021, Tuomela et al. 2021). In addition, new capacity in other steps of the battery value chain is building up in Europe and in Finland (Tuomela et al. 2021).

In this report, we review the upstream supply chains for cobalt, lithium and graphite used in batteries, and the landscape of traceability solutions in these supply chains. Here, we refer to these supply chains as "battery material supply chains". As the sustainability component is an integral part of traceability, sustainability reporting systems for mining are reviewed from the perspective of traceability. Existing traceability methods and case studies in battery material supply chains are presented, including the geo-based fingerprinting method (laboratory technology) that is being developed in the BATTRACE research project. We also discuss the business potential of the geo-based fingerprinting method.

1.2 The BATTRACE project

This report is one deliverable of a Finnish national Business Finland co-innovation project called "Sustainable processing and traceability of battery metals, minerals and materials" or "BATTRACE" in short. The project is focused on the traceability of battery metals, minerals and materials and the optimization of production processes. The project involves several industrial partners who, in addition to research partners and Business Finland, act as project financiers. The industrial partners in this EUR 5.8 million project include the Finnish Minerals Group, Finnish Battery Chemicals, Keliber Technology, Outotec, Valmet Automation, Latitude 66 Cobalt, Grafintec, Mawson and FinnCobalt (Fig. 1).

A major part of the BATTRACE project is the development of a novel method for battery mineral traceability based on a method called geo-based fingerprinting. In geo-based fingerprinting, a material's origin can be traced back to its source based on certain material characteristics, such as the mineralogical and elemental compositions. A description of this method can be found in this report in chapter 6. The report also provides a preliminary analysis of how geo-based fingerprinting could be used for supply chain traceability or complement other existing solutions.

Fig. 1. The BATTRACE project involves several research and industrial partners.

2 COBALT PRODUCTION

The BATTRACE project is investigating the possibilities to trace the origin of battery raw materials towards the upstream direction in the supply chain (the direction of decreased refining, i.e., from products to raw materials). This chapter describes the general features of material flow in the supply chains of cobalt, covering aspects such as:

- the distribution of global and European mine production and refined production (countries, production figures)
- the most important mines and mining companies on global and European scales
- the most important refineries or production plants on global and European scales
- the source of raw material for these production plants and what their products are
- mine production and refined production in Finland.

Chapters 3 and 4 contain corresponding descriptions for lithium and graphite, respectively, but in less detail. The supply chains of cobalt are more complex than those of lithium and graphite in the sense that about two-thirds of the global production of refined cobalt takes place in different countries from the mining (Darton Commodities Ltd. 2020, Dehaine et al. 2021). Large-scale copper and nickel mines, mostly in the Democratic Republic of the Congo (DRC), provide most of the mined cobalt, while most of the cobalt processing is concentrated in China. For cobalt, international statistics on mineral and metal production separately contain mine production and refined production, but only mine production is included for lithium and graphite. Of the three commodities, only cobalt is currently produced in Finland. Concerning lithium, Keliber owns a mine project that is planned to start lithium hydroxide production in the coming years. Aitolampi is the most advanced graphite project in Finland, but is still in the exploration stage.

Cobalt is widely used as lithium cobalt oxide (LiCoO2) in lithium-ion battery cathodes. The material is composed of cobalt oxide layers with the lithium intercalated. Although in 2018 most cobalt in batteries was used in mobile phones and other electronic devices, the application of cobalt in rechargeable batteries for electric vehicles (EV) is rapidly growing. This industry has increased five-fold in its demand for cobalt (Cleantechnica 2017). The cobalt supply chain shows high complexity due to different sources of mining, including artisanal and small-scale mining (ASM), specialized ways of refining and the number of applications.

2.1 Mine production: top producing countries, mines and companies in the world

Global mine production of cobalt was 144 000 t Co in 2019 and estimated production in 2020 was 140 000 t Co (USGS 2021a). Two-thirds of the global cobalt production originates from the DRC, and the share of other countries is less than 5% each. In 2019, the five biggest producers were the DRC (71%), Russia (4%), Australia (4%), the Philippines (4%) and Cuba (3%). The DRC produced 100 000 t Co while the Rest of the World (RoW) produced 44 000 t Co.

All five top-producing cobalt mines are located in the DRC. These five mines accounted 45% of the global mine production of cobalt in 2020 (Table 1). The Kamoto Mine, controlled by Glencore Plc and Gécamines SA, produced the highest amount of cobalt, with 23 900 t Co or 17% of global production. Tenke Fungurume, controlled by China Molybdenum Co. Ltd and Gécamines SA, showed the second highest cobalt production, with 15 400 t Co or 11% of global production.

Table 1. The ten top-ranking cobalt mines in 2020 (S&P 2021a).

Rank	Project	Country	Current Controlling Company(s)	Production: Cobalt (tonnes) E = Estimation	Production Value: Cobalt ($M)	Global Production Share: Cobalt (%)	Cumulative Global Production Share:Cobalt (%)
1	Kamoto	DRC	Glencore Plc, Gécamines SA	23 900	751	17.2	17.2
2	Tenke Fungurume	DRC	China Molybdenum Co. Ltd., Gécamines SA	15 436	485	11.1	28.4
3	Metalkol RTR	DRC	Eurasian Group LLP	10 500E	330	7.6	35.9
4	Etoile	DRC	Shalina Resources Ltd	7 000E	220	5.0	41.0
5	Luiswishi	DRC	Zhejiang Huayou Cobalt Co. Ltd	5 390E	169	3.9	44.9
6	Sudbury Operations	Canada	Glencore Plc	4 400	138	3.9	48.0
7	Ruashi	DRC	Jinchuan Grp Intl Rsrc Co. Ltd, Gécamines SA	4 158	131	3.0	51.0
8	Lubumbashi Slag Hill	DRC	Groupe Forrest Intl S.A., Gécamines SA	4 000E	126	2.9	53.9
8	Mutoshi	DRC	Chemaf SPRL	4 000E	126	2.9	56.8
10	Moa Bay	Cuba	Sherritt International Corp., General Nickel Co SA	3 370	106	2.4	59.2

Glencore is clearly the most important company in the mine production of cobalt, with a global share of 26% in 2018 (Table 2). As stated above, Glencore is the owner of the highest producing cobalt mine in the world. In addition to the DRC, Glencore has mine production of cobalt in Canada (Sudbury operations, Raglan) and Australia (Murrin Murrin). Glencore is a company producing and marketing a diverse range of metals and minerals, such as copper, cobalt, zinc, nickel and ferroalloys, and it also markets aluminium/alumina and iron ore from third parties.

Glencore is followed by China Molybdenum Co., Ltd., with a global share of 8% of cobalt mine production. It is the main owner of the second highest producing cobalt mine in the world. All five top-producing companies operate in the DRC. PJSC MMC Norilsk Nickel is the biggest cobalt producing mining company that does not operate in the DRC; its main mining operations are in Russia. Terrafame Oy is ranked 19 on this list and Boliden AB is ranked 23. Umicore is not among the 54 top-producing companies.

Table 2. The twenty top-ranking companies in cobalt mine production in 2020 (S&P 2021a).

Global Rank	Company	Attributable Production – (tonnes) E = Estimation	Production Value ($M)	Global Production Share (%)	Cumulative Global Production Share (%)
1	Glencore Plc	25 946	815	18.7	18.7
2	China Molybdenum Co. Ltd. (CMOC)	12 349	388	8.9	27.6
3	Gécamines SA	11 663	366	8.4	36.0
4	Eurasian Group LLP	10 500E	330	7.6	43.6
5	Shalina Resources Ltd	6 650E	209	4.8	48.4
6	Zhejiang Huayou Cobalt Co. Ltd	5 390E	169	3.9	52.3
7	Vale S.A.	4 192	132	3.0	55.3
8	PJSC MMC Norilsk Nickel	4 102E	129	3.0	58.3
9	Chemaf SPRL	4 000E	126	2.9	61.1
10	Jinchuan Grp Intl Rsrc Co. Ltd	3 293	103	2.4	63.5
11	Nickel Asia Corp.	2 848E	90	2.1	65.6
12	Groupe Forrest Intl S.A.	2 800E	88	2.0	67.6
13	Managem S.A.	2 411	76	1.7	69.3
14	CN Nonferrous Mining Corp. Ltd	2 097E	66	1.5	70.8
15	Jinchuan Group Co. Ltd.	1 911E	60	1.4	72.2
16	Sherritt International Corp.	1 685	53	1.2	73.4
16	General Nickel Co SA	1 685	53	1.2	74.6
18	Metallurgical Corp. of CN Ltd.	1 875	53	1.2	75.9
19	Pacific Metals Co.	1 569E	49	1.1	77.0
20	Sumitomo Corp.	1 550E	49	1.1	78.0
...	...	...	...	...	...
22	Terrafame Oy	1 215E	38	0.9	79.9

2.2 Mine production of cobalt in Finland

In Europe, current cobalt mine production is concentrated in Russia and Finland (Brown et al. 2021). In Finland, cobalt mine production increased from 1377 t in 2018 to 1559 t in 2020 (Tukes & GTK 2021), only as a by-product and mainly from the Kevitsa Ni–Cu–PGE mine (Boliden) and the Sotkamo Zn–Ni–Cu–Co mine (Terrafame). The production of cobalt by the Kylylahti Zn–Cu–Au mine (Boliden) ended in 2020. In Finland, cobalt mine production is closely connected with nickel mining, because both metals occur in the same geological environment and sometimes the same ore minerals. Indeed, the Kevitsa deposit is hosted by mafic to ultramafic sulphidic rocks and the Talvivaara deposit by black schists (Sotkamo mine). The ore at the Kylylahti mine is a typical Outokumpu-type ore, in which the main metals are copper and zinc.

Kevitsa mine produced 495 t Co in 2020 (Table 3) (Boliden 2021). The main products of the mine are a nickel(–cobalt) concentrate and a copper concentrate, which are respectively refined at Boliden's Harjavalta smelter in Finland and Boliden's Rönnskär smelter in Sweden (Boliden 2020b).

Kylylahti mine produced 447 t Co in 2020 (Table 3), but the production ended in 2020 due to mine closure (Boliden 2021). The ore was processed at the Boliden Luikonlahti concentrator, where four types of concentrates were produced: 1) a gravity gold concentrate, 2) a copper concentrate, 3) a zinc concentrate transported by trucks to Boliden's smelters in Finland and 4) a nickel–cobalt concentrate transported by trucks to Kokkola port and from there onwards for refining outside Finland (Boliden 2020a). Prior to that, the nickel–cobalt concentrate was apparently transported to Boliden's smelter in Harjavalta (Savon Sanomat 2018). The production of nickel–cobalt concentrate was started in 2017. In addition, ores processed to produce a zinc concentrate generate a sulphur concentrate also containing some cobalt and nickel, mostly in pyrite. The sulphur concentrate was deposited in the sulphur tailings pond. There is an ongoing project to find an economically feasible process to recover refractory cobalt and nickel from these tailings (Boliden 2020a).

Table 3. Mine production of cobalt in Finland in 2018-2020 (Boliden 2021, Tukes & GTK 2021).

Mine	Company	2018 (tCo)	2019 (tCo)	2020 (tCo)	Co-containing product	Product refined at
Kevitsa	Boliden	591	445	495	Ni-PGE-Co concentrate	Harjavalta smelter
Kylylahti	Boliden	278	425	447	Ni-Co concentrate	Abroad
Sotkamo	Terrafame	500–600	500–600	500–700	Starting from early 2021: Ni-Co sulphide is refined onsite to Ni sulphate and Co sulphate	Starting from early 2021: Terrafame battery chemical plant (earlier sold to Trafigura and refined abroad)

Terrafame does not publish figures for cobalt mine production at the Sotkamo mine, but national statistics indicate that the annual production has been within the range of 500 to 700 t Co during recent years (Tukes & GTK 2021). Earlier, the company produced nickel–cobalt sulphide, zinc sulphide and copper sulphide, and the final products were sold for refining. A significant proportion of nickel–cobalt sulphide was processed elsewhere, mainly in Asia, into the battery chemicals nickel sulphate and cobalt sulphate to be used for electric vehicle batteries (Terrafame 2020).

Terrafame is about to become an industrial giant on a global scale in the manufacture of battery chemicals. In 2018, Terrafame decided to construct a battery chemicals plant, one of the largest in the world, within the mining site. The production of battery chemicals at the plant started in 2021, and currently, nickel–cobalt sulphide is used as a raw material to produce nickel sulphate and cobalt sulphate. Ammonium sulphate is produced as a by-product of nickel and cobalt sulphate in the battery chemicals plant. The production of zinc sulphide continues as before. This unique integrated production process from open pit to battery chemicals expands Terrafame's coverage a step forward in the downstream value chain. The value chain is short, transparent and 'traceable' (in the sense that the exact origin is known; this does not refer, e.g., to geochemical traceability). The target for the year 2024 is to annually produce 170 000 t of nickel sulphate and 7400 t of cobalt sulphate. These quantities are sufficient for about one million and 300 000 electric cars, respectively. Terrafame has the largest nickel ore reserves in Europe, and due to its huge size, the utilization of the deposit may continue for more than half a century (Terrafame 2020).

2.3 Refined production: top producing countries and companies in the world

Global production of refined cobalt was 127 000 t Co in 2018 and 138 000 t Co in 2019 (Brown et al. 2021, Tukes & GTK 2021). Most of the global refined cobalt is produced in China. In 2019, the five biggest producers were China (62%), Finland (10%), Belgium (5%), Canada (4%) and Japan (4%) (Table 4). China was estimated to produce 86 000 t Co and all other countries together 52 000 t Co.

Major international trade flows of cobalt raw materials are revealed by comparing the countries having the top mine production and the top refined production of cobalt. Although the DRC produces the most cobalt ores in the world, its share in the production of refined cobalt is diminutive (between 0 and 120 t during 2016-2019) (Brown et al. 2021). This means that the DRC exports nearly all its cobalt raw materials to be refined in other countries. The top producer of refined cobalt, China, is likewise diminutive in the global mine production of cobalt, accounting for 1.7% in 2019 (USGS 2021a). This means that China imports nearly all its cobalt raw materials. The mine production of cobalt in other countries than the DRC is only half of the amount of refined cobalt that China produces. Therefore, the DRC must be the most important source of cobalt for China.

Table 4. The top countries in mine production (USGS 2021a, Tukes & GTK 2021) and refined production (Brown et al. 2021, Tukes & GTK 2021) of cobalt and the main cobalt refining companies (Cobalt Institute 2020, The Balance 2020).

Mine production of cobalt in 2019			Refined production of cobalt in 2019			Main cobalt refining companies
DRC	69%	100 000 t	**China**	62%	86 000 t	• Jinchuan Nonferrous Metals Corp. • Huayou Cobalt Co., Ltd., • Jiangsu Cobalt Nickel Metal Co., Ltd. • Shenzhen Green Eco-manufacture Hi-tech Co., Ltd. • Umicore
Russia	4%	6 300 t	**Finland**	10%	14 283 t	• Umicore (owner since 2019) (Kokkola) • Norilsk Nickel (Harjavalta)
Australia	4%	5 740 t	**Belgium**	5%	6 500 t	• *Umicore (Olen)*
Philippines	4%	5 100 t	**Canada**	4%	6 075 t	• Vale • NPMC • Sherrit International Corp. (Fort Saskatchewan)
Cuba	3%	3 800 t	**Japan**	4%	5 900 t	• Sumitomo Metal Mining Co. (Niihama Nickel Refinery)
Madagascar	2%	3 400 t	**Norway**	3%	4 354 t	• Glencore (Nikkelverk)
Canada	2%	3 340 t	**Australia**	3%	3 700 t	• Queenland Nickel (Palmer Nickel and Cobalt Refinery)
Papua New Guinea	2%	2 910 t	**Madagascar**	2%	2 900 t	• Ambatovy
China	2%	2 500 t	**Morocco**	2%	2 397 t	
South Africa	1%	2 100 t	**Russia**	1%	2 000 t	
Finland	1%	1 454 t	**Zambia**	1%	1 271 t	

2.3.1 Cobalt refining in China

Cobalt refining in China has increased dramatically during past three decades. According to Petavratzi et al. (2019), the reported production of refined cobalt in China was 750 tonnes in 1993, rising to 69 600 tonnes in 2017. Of the 32 cobalt smelters listed by the Responsible Minerals Initiative, 22 are located in China.

- China's largest cobalt producers include:
- Jinchuan Nonferrous Metals Corp.
- Huayou Cobalt Co., Ltd.,
- Jiangsu Cobalt Nickel Metal Co., Ltd.
- Shenzhen Green Eco-manufacture Hi-tech Co., Ltd.

Each of these companies has an annual refined cobalt production capacity of over 7000 t (The Balance 2020). Jinchuan Group Co., Ltd. has the annual capacity to produce 10 000 t refined cobalt. It is the fourth largest cobalt producer in the world (Jinchuan 2020). Recycled or scrap material may now be becoming an important source of cobalt units in China (Cobalt Institute 2020).

2.3.2 Umicore is the leading cobalt refining company outside China

As Finland is the second biggest producer of refined cobalt in the world and Umicore produces >90% of the refined cobalt in Finland, Umicore is the most important producer of refined cobalt outside China. Umicore is a global materials technology and recycling group (Umicore 2019b). It focuses on application areas such as materials science, chemistry and metallurgy.

Umicore has plants in China, Korea, Finland (Kokkola), Belgium (Olen) and Poland (Nysa). All of these appear to be involved in the cobalt value chain. Some of Umicore's production recorded for Belgium takes place in China (Cobalt Institute 2020, Brown et al. 2021). However, Umicore's share in the production of refined cobalt in China is small.

With R&D, refining, precursor production, cathode materials production and battery recycling operations located in Europe, Umicore serves its European battery cell and automotive customers with a fully integrated, sustainable and local battery materials supply chain. Through this European battery materials supply chain, Umicore will contribute significantly to the European Union's plans to create a competitive and sustainable battery ecosystem in Europe (Umicore 2020).

According to Umicore (2020),

- Umicore signed a long-term supply agreement with China Molybdenum Co. Ltd. (CMOC) for sustainable cobalt. CMOC is a company with the second highest mine production of cobalt in the world and operates at Tenke Fungurume mine, in the DRC (Table 1).
- During 2019, Umicore announced partnerships for the supply of nickel manganese cobalt (NMC) cathode materials.
- Umicore and LG Chem concluded a multi-year strategic supply agreement for cathode materials to serve LG Chem's needs from Umicore plants in Poland, Korea and China (i.e., Umicore delivers products from its plants in Poland, Korea and China to LG Chem).

2.3.2.1 Umicore's cobalt refinery in Kokkola, Finland

Umicore announced on 2 December 2019 that it had completed the acquisition of the cobalt refining and cathode precursor activities in Kokkola, Finland, from Freeport Cobalt (Umicore 2019a). The Kokkola refinery has been in operation since 1968 and is one of the world's biggest cobalt refineries. The annual production of refined cobalt in Kokkola ranged between 11 000 t and 14 000 t during 2016–2020. These figures indicate contained cobalt in different metal products (cobalt powders) and chemical compounds. Currently the production is divided between Umicore and Freeport cobalt, the share of Umicore being slightly larger.

In May 2019, Umicore and Glencore announced that they had entered into a long-term revolving agreement for the supply of cobalt hydroxide[1] to Umicore's battery materials supply chain. The cobalt will be sourced from Glencore's state-of-the art industrial mining operations, Kamato Copper Company (KCC) and Mutanda, located in the DRC. In 2020, the Kamoto mine, started in 2007, showed the highest cobalt production in the world (Table 1). Mutanda was the top cobalt producing mine in 2018 but was in care and maintenance during 2020–2021. Mutanda's contained cobalt resources and reserves were 6.2 Mt Cu and 2.5 Mt Co at the end of 2019. The estimated closure year is 2040. In 2019, the mine produced 103 200 t Cu and 25 100 t Co (S&P 2021).

The cobalt units will be shipped from KCC and Mutanda to Umicore's cobalt refineries globally, including the Kokkola refinery in Finland (Umicore 2019b). The DRC has been the most important source of cobalt raw material for the Kokkola refinery during earlier years and it continues to be so. It may be that the flow of cobalt raw materials from other countries than the DRC to Kokkola is insignificant: even though Umicore's supplier, Glencore, also produces cobalt ore in Canada and Australia, this ore is probably refined in these respective countries, which have cobalt refining facilities of their own and are among the top seven producers of refined cobalt in the world (Table 4).

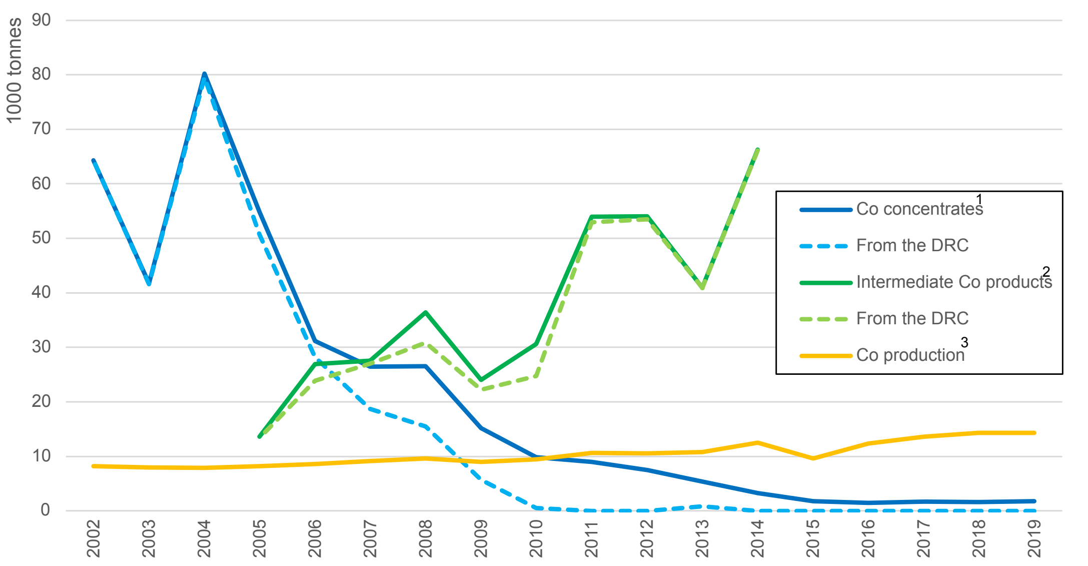
During the second part of 2020, the Kokkola refinery also started supplying precursors for cathode material production to the new Umicore plant in Nysa, Poland (Umicore 2019b).

Foreign Trade Statistics of the Finnish Customs show that the DRC has clearly been the most important source country for cobalt raw materials imported to Finland, at least from 2002 to 2014 (Fig. 2). In 2005, item 81052000 in the CN8 classification (cobalt mattes and other intermediate products of

[1] In the International Trade Statistics of the Finnish Customs, the imported material is not classified as cobalt hydroxides (28220000 in CN8 classification), but cobalt mattes and other intermediate products of cobalt metallurgy; unwrought cobalt; cobalt powders (81052000 in CN8).

cobalt metallurgy; unwrought cobalt; cobalt powders) started to increasingly replace cobalt ores and concentrates as the most important form of import of cobalt raw materials. The development after 2014 is more difficult to follow, because the mass as well as the source country of imported intermediate cobalt products (item 81052000) became confidential information. However, the monetary value of imports continued to be public and the peak was very high in 2018 (Fig. 3). The main reason for this peak was an increase in the cobalt price, which in 2017 was more than two times higher than in 2016. Nowadays, the import of cobalt ores and concentrates is rather insignificant compared to that of intermediate cobalt products.

Figure 3 further suggests that at least a significant part of the imported intermediate cobalt products was exported at a higher price. Earlier, exported material was refined but still exported with the same trade item code. Around 2013, this pattern showed a transition from a positive to a neutral trade balance, and in 2017 the balance was about €300 M negative. This type of transition could be explained in at least two ways: an increasing portion of the exports started to take place as a different trade item or the product was increasingly used in the same country.



[1] Co ores and concentrates (CN8: 26050000).
[2] Cobalt mattes and other intermediate products of cobalt metallurgy; unwrought cobalt; cobalt powders (CN8: 81052000). Data for 2002–2004 and 2015–2019 are classified.
[3] Co content in cobalt powders, oxides and asetates produced in Finland.

Fig. 2. Imports (1000 t) of the two most important trade items of cobalt raw materials (26050000 cobalt ores and concentrates, 81052000 intermediate cobalt products) to Finland between 2002 and 2019 (ULJAS – International Trade Statistics of Finnish Customs).

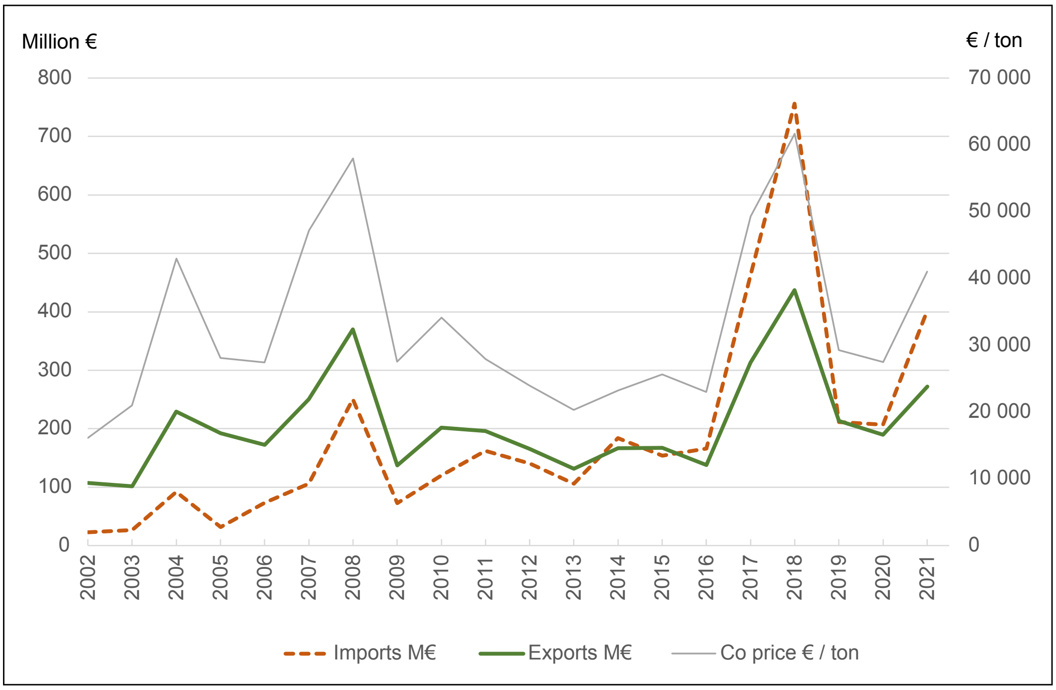


Fig. 3. The import and export value (€ million) of intermediate cobalt products (item 81052000) to and from Finland between 2002 and 2021 (ULJAS – International Trade Statistics of Finnish Customs). Variation in the annual price of cobalt (€/ton) is an important reason for the peak in recent years. Note the transitions of the trade balance for intermediate cobalt products from positive to negative.

In summary, cobalt ore produced by Glencore in the DRC is refined and imported as intermediate cobalt products to Finland and to Umicore's Kokkola refinery. After further refining, at least a major share is exported as other intermediate cobalt products. In 2020, the Kokkola refinery started supplying precursors for cathode material production to the new Umicore plant in Nysa, Poland.

2.3.2.2 Umicore Olen cobalt refinery in Belgium

Belgium has no mine production of cobalt, but it is one of the top countries producing refined cobalt in the world. In 2019, 6500 t Co or 5% of the global share was produced in Belgium (Table 4, Brown et al. 2021). In Belgium, the refined cobalt is produced by Umicore (Cobalt Institute 2020). Umicore processes precious and specialty metals, including cobalt, from both primary and secondary sources at five locations in Belgium (European Commission 2017). One of these is Umicore Olen, which was approved as the first cobalt refinery in the world to conform with the Responsible Minerals Initiative (RMI).

2.3.3 Other cobalt refining locations

Canada produced 6075 t Co or 4% of the global share in 2019 (Table 4, Brown et al. 2021). The two main producers of refined cobalt are NPMC (formerly International Cobalt Company Inc., ICCI) and Vale (Cobalt Institute 2020). Vale produces cobalt cathodes, oxides and alloys. In addition, Sherrit International Corporation produces cobalt powders and briquettes.

2.3.3.1 Ambatovy's cobalt refinery in Madagascar

Ambatovy is a partnership of four companies: Sherritt International Corporation and SNC-Lavalin Incorporated from Canada, Sumitomo Corporation from Japan, and Korea Resources Corporation from Korea (The Balance 2020). Ambatovy produces cobalt that is 99.8% pure. Ambatovy's cobalt is sold in powdered form and as 40-gram briquettes and is packaged in 250-kg drums (Ambatovy 2020).

Norway is a significant producer of refined cobalt, with the production of 4354 t Co or a 3% global share in 2019 (Table 4, Brown et al. 2021).

In Norway, the refined cobalt is produced as a by-product in Glencore's Nikkelverk refinery, which is the largest nickel refinery in the western world. Nickel concentrates are imported from Canada (Sudbury and Raglan) (The Balance 2020, Cobalt Institute 2020). With the mine production of 4400 t Co in 2020, Sudbury Operations, controlled by Glencore in Canada is the highest-producing cobalt mine outside the DRC (Table 1).

2.3.3.2 Nornickel Harjavalta in Finland

PJSC MMC Norilsk Nickel is a diversified mining and metallurgical company, the world's largest producer of palladium and high-grade metal nickel and a major producer of platinum and copper. The company also produces cobalt, rhodium, silver, gold, iridium, ruthenium, selenium, tellurium, sulphur and other products (NORNICKEL 2020a). Its main cobalt mining operation takes place in Russia, and in 2020 it had the second highest mine production of cobalt among companies that do not mine cobalt in the DRC (Table 2). In 2020, the Nornickel Harjavalta plant in Finland produced 63 352 t nickel, 2491 t copper, 17 koz palladium and 4 koz platinum (NORNICKEL 2021a). Nickel briquettes (58%) are the main nickel products and other products are nickel cathodes (29%) and nickel chemicals (13%), as well as nickel sulphates, hydroxides and hydroxycarbonates. Since 2014, the plant has also produced cobalt sulphate as a by-product, but the amounts are not reported. The cobalt is used for rechargeable batteries, as a binding agent in tyres and as an additive in animal feed (NORNICKEL 2021b). Most of the raw material originates from the company's Russian feed.

In Russia, production of refined cobalt ranged from 1800 to 3092 t Co between 2015 and 2019 (Brown et al. 2021). No statistics were found on the ratio of Russian production between European and Asian regions.

In France, the production figures are rather low, ranging from 0 t to 277 t between 2015 and 2019 (Brown et al. 2021). At its Sandouville-Le Havre refinery, Eramet produces fine cobalt powders as a by-product from refining nickel matte imported from New Caledonia, France (European Commission 2017). No mine production of cobalt is reported in continental France (Brown et al. 2021).

2.4 Sustainability aspects of cobalt production

With the aim of moving towards a cleaner environment and a greener economy, it is crucial to consider the process across the whole supply chain (e.g., Dolega et al. 2020, Graham et al. 2021, Hodgkinson & Smith 2021). Numerous factors could be considered in relation to the sustainability of production of a raw material. Those that could possibly be influenced by means of traceability are the most relevant in the context of the BATTRACE project. Production utilizing unethical methods in relation to the environment, local communities or the labour force and financing conflicts could be the most obvious examples. Ideally, geo-based traceability could verify that the raw material originates from a believed sustainable source, or verify the absence of a signature from an unwanted source with sustainability issues.

Child and slave labour, which have been repeatedly reported in cobalt mining, primarily in the artisanal mines of the DRC, is a drastic example of unethical production (e.g., Amnesty International 2016). However, cobalt is not one of the defined 'conflict minerals' (tantalum, tungsten, tin, and gold; 3TG), because it is produced in the south-eastern province of the DRC, Katanga, where there are no armed conflicts (European Commission 2017).

Umicore is among the technology companies that has started to develop procedures that could verify that artisanally mined cobalt is excluded from the supply chain, as well as any form of child labour (Umicore 2019c). In May 2019, Umicore Olen Belgium was approved as the first Responsible Minerals Initiative (RMI) conformant cobalt refinery worldwide. This requires an annual certification process. The Umicore Kokkola refinery is also RMI conformant. Child labour is linked with illegal or poorly regulated artisanal mining, rather than with the large-scale mining industry (European Commission 2017). Therefore, Umicore's approach to use Glencore as the supplier in the DRC sounds like a welcomed improvement. Umicore, however, is only a minor producer of refined cobalt in China, which is the biggest producer of refined cobalt in the world. Therefore, the key question concerning the ethical aspects of exploitation of the world's cobalt resources is to what extent the biggest cobalt refineries in China are committed to ethical values.

Even with proper working conditions ensured, one can always ask whether it is ethical that global industrial giants exploit the raw materials of one of the poorest developing countries in the world. Countries where the downstream refining as well as manufacturing and use of the end-products take place are obvious beneficiaries. The downsides of mining, such as environmental impacts and problems related to landowning in a densely populated country, fall for the DRC to bear.

It should be ensured that the country of origin sufficiently benefits from the exploitation of its resources. Proper tax and royalty regimes, legislation and its compliance, hiring local labour with appropriate wages and safety measures, using local services as much as possible and contributing to infrastructure, such as the construction of hospitals, roads and schools, are among the benefit-sharing activities to achieve this in the form of distributive fairness. Refineries and metallurgical plants could also be built in the DRC, adding value to the primary production. In any case, considering its dominance in global production (70%), it is unlikely that the DRC would cease to be the most important source of cobalt for the world in the near future. However, due to the huge dominance of mining in the DRC's industrial production and export revenues and importance of its cobalt for the green energy transition, multinational companies have a great responsibility in contributing to the sustainable development and economic and political stability of the DRC. At the least, it should be expected that they do not make matters worse therein.

The security of supply of raw materials is also a sustainability issue. It involves certain risks that the mine production of cobalt is dependent on one single country and refined production is controlled by another single country. This is even more so, as the countries in question are the DRC and China, and the demand for battery raw materials is expected to peak. Currently, political and operational risks for the mining industry have been assessed as high in the DRC and medium in China (S&P 2021b). However, in certain provinces of the DRC, political, operational and security risks are assessed as extreme. If materialized, these risks may cause disruptions in the global supply of cobalt. Tensions between superpowers may also cause complications in the trade with China.

The European Union has defined cobalt (in addition to natural graphite and 12 other commodities) as a critical raw material (CRM) in all four CRM listings, carried out in 2011, 2014, 2017 and 2020. The main parameters in identifying CRMs are the importance of a material for the EU economy and risk of a disruption in the EU supply of the material (European Commission 2020a). Of these, only the latter is related to sustainability. In the 2020 assessment, the index for the supply risk of cobalt was 2.5, which is higher than that of natural graphite (2.3) or lithium (1.6). The highest supply risk index in the assessment was 6.2, assigned to cerium and dysprosium (rare earth elements). EU import, EU export, EU production and the scaled World Governance Index (WGI) are some of the parameters incorporated in the rather complicated formula used to calculate the supply risk index.

An obvious measure of mitigation for supply issues is to place more emphasis on mineral exploration and start mining operations in new sites where economic mineral deposits are found. The opening of the three cobalt-producing mines in Finland within the last 10 years serves as an example here, setting Finland as the top mine producer of cobalt among the EU countries (Horn et al. 2021). One of these, the Talvivaara mine, suffered a leakage of its gypsum pond in 2012, which formed the key event of the mining debate in Finland (Sairinen et al. 2017). Talvivaara mining company subsequently went into bankruptcy and operations in the mine were taken over by the state-owned company Terrafame. The new company has been able to improve the sustainability of the mine.

The battery minerals boom has increased mineral exploration in sensitive areas such as those of nature conservation, tourism destinations, reindeer herding and the indigenous Sámi homeland in Finland (Tolvanen et al. 2019, Kivinen et al. 2021). This has expanded the number of mining disputes in the country, also including the cobalt mine projects of Juomasuo in Kuusamo and Rompas-Rajapalot in Ylitornio (Eerola 2022).

However, beyond the evident social and environmental impacts of mineral exploration and mining, one fundamental question that remains regarding the whole supply chain of battery minerals is the sufficiency of raw materials for the green energy transition. In fact, there are quite recent estimations that not enough production can be ramped up in the necessary time to achieve carbon neutrality and that other solutions should be sought beyond traffic electrification and wind turbines, such as a systemic societal change in which consumption is reduced and the circular economy is strengthened (Granvik et al. 2021, IEA 2021b, Michaux 2021).

3 LITHIUM PRODUCTION

Lithium is a soft metal, the lightest in the periodic table. Lithium also has the highest electrochemical potential, which enables it to achieve very high energy and power densities. It has the highest specific heat capacity among solids and a low density (0.53 g/cm^3), making it highly applicable to a long useful life in small and lightweight batteries.

Lithium is sourced from hard rock mines, evaporite lakes and salars (salt flats). Typical grades in hard rock ores are in the range of 0.9–1.6% Li_2O. The salars of Chile and Argentina have the highest lithium concentrations, in the range of 680–1570 ppm (<0.000157% Li_2O). Lithium carbonate is the most widely produced and consumed lithium compound, followed by lithium mineral concentrates, lithium hydroxide and lithium bromide. The most common process to convert lithium mineral concentrates to lithium carbonate or hydroxide is the acid-roast method. There are a wide variety of lithium compounds, so it is commonplace to refer to the lithium content in terms of the lithium carbonate equivalent ("LCE"). The conversion is directly based on the chemical formula and atomic weights: 5.323 t LCE = 1 t Li and 1 t Li = 0.188 t LCE.

On a global basis, China is the largest consumer of lithium, with approximately 40% of consumption in 2015. Europe is the second largest, with 21%, followed by Japan and South Korea. Several lithium battery plant projects have been announced in Europe, which will considerably increase European lithium demand. Currently, the only European supply for lithium comes from Portugal, producing lepidolite for local ceramics or glass. Major development projects for lithium mining and processing are under preparation in Finland and Austria to produce lithium hydroxide. The pricing of lithium is negotiated off-market and based on customer specifications, with price information rarely reported.

3.1 Mine production: top producing countries, mines and companies in the world

Global mine production of lithium was 95 000 t Li or 505 718 t LCE in 2018 and it is estimated to have been 77 000 t Li or 409 897 t LCE in 2019 (USGS 2020a). The production is forecasted to be as high as 900 000 t LCE by 2027 and 2.8 million t LCE by 2040. More than half of the lithium in the world originates from Australia. There are four major lithium producers globally, three of which are brine producers and one a hard rock producer. In 2019, the five biggest producers were Australia (55%), Chile (23%), China (10%), Argentina (8%) and Zimbabwe (2%). Australia alone produced 42 000 t Li and all other countries together 35 000 t Li.

All six top-producing lithium mines are in Australia or Chile. These six mines accounted for 75% of the global mine production of lithium in 2018 (Tables 5, 6 and 7). The Greenbushes mine, controlled by Chengdu Tianqi Industry Grp Co and Albemarle Corp, showed the highest lithium production, with an estimated 120 000 t Lithium Carbonate Equivalent (LCE) or 25% of global production. Wodgina, controlled by Albemarle Corp and Mineral Resources Ltd., showed the second highest lithium production, with an estimated 69 000 t LCE or 15% of global production.

Table 5. The ten top-ranking lithium projects in 2018 (S&P 2020). LCE = Lithium Carbonate Equivalent.

Global Rank	Mine	Country	Current Controlling Company(s)	Production LCE (tonnes) E = Estimation	Pro-duction Value LCE $M)	Global Production Share LCE (%)	Cumulative Global Pro-duction Share LCE (%)
1	Greenbushes	Australia	Chengdu Tianqi Industry Grp Co, Albemarle Corp.	120 123 E	1905.29	25	25
2	Wodgina	Australia	Albemarle Corp., Mineral Resources Ltd.	69 497E	1102.3	15	40
3	Mount Marion	Australia	Mineral Resources Ltd., Ganfeng Lithium Co. Ltd.	55 693 E	883.35	12	51
4	Salar de Atacama	Chile	Sociedad Quimica y Minera	50 400	799.4	11	62
5	Salar de Atacama	Chile	Albemarle Corp.	37 681 E	597.66	8	70
6	Mt Cattlin	Australia	Galaxy Resources Ltd.	22 319 E	354	5	75
7	Salar del Hombre Muerto	Argentina	Livent Corp.	21 597	342.55	5	79
8	Pilgangoora	Australia	Pilbara Minerals Ltd.	21 044 E	333.78	4	84
9	Salar de Olaroz	Argentina	Orocobre Ltd., Toyota Tsusho Corp., Jujuy Energia y Mineria	12 413 E	196.88	3	86
10	Yichun	China	Yichun Tantalum Co Ltd	11 293 E	179.12	2	89

Table 6. The twenty top-ranking companies in lithium mine production in 2018 (S&P 2020).

Global Rank	Company	Attributable Production (tonnes LCE) E = Estimation	Production Value LCE ($M)	Global Production Share LCE (%)	Cumulative Global Production Share (%)
1	**Albemarle Corp.**	102 368	1623.68	21	21
2	Mineral Resources Ltd.	93 501	1483.03	20	41
3	Chengdu Tianqi Industry Grp Co	61 263	971.70	13	54
4	Sociedad Quimica y Minera	50 400	799.40	11	65
5	Ganfeng Lithium Co. Ltd.	24 004	380.73	5	70
6	Galaxy Resources Ltd.	22 319	354.00	5	74
7	FMC Corp.	21 597	342.55	5	79
8	Pilbara Minerals Ltd.	21 044	333.78	4	83
9	Yichun Tantalum Co Ltd	11 293	179.12	2	85
10	Western Mining Group	9 937	157.61	2	88
11	Orocobre Ltd.	8 255	130.93	2	91
12	Qinghai Salt Lake Industry Co.	8 000	126.89	2	92
13	Neometals Ltd.	7 686	121.90	2	94
14	Alita Resources Ltd.	6 450	102.30	1	95
15	Bikita Minerals Ltd	6 232	98.85	1	96
16	Tibet Mineral Dev. Co. LTD	4 190	66.45	1	97
17	Toyota Tsusho Corp.	3 103	49.22	1	97
18	Altura Mining Ltd.	2 057	32.63	0	97
19	Cia Brasileira de Litio	1459	23.14	0	98
20	Lepidico Ltd.	1236	19.60	0	98

Table 7. Distribution of the mine production of lithium globally and in Europe in 2019 (USGS 2020a).

Global mining of lithium in 2019			European mining of lithium in 2019		
Country	**Global share**	**Metric tonne**	**Country**	**Global share**	**Metric tonne**
Australia	55%	42 000 t	**Portugal**	2%	1 200 t
Chile	23%	18 000 t			
China	10%	7 500 t			
Argentina	8%	6 400 t			
Zimbabwe	2%	1 600 t			
Brazil	0.4%	300 t			
Canada	0.4%	200 t			

According to USGS (2021b), Zimbabwe is the world's fifth largest lithium mine producer after Australia, Chile, China and Argentina, respectively having produced 1600 metric tonnes in 2019, with the potential to account for 20% of the global lithium demand. The country's privately owned Bikita Minerals is currently the only lithium producer, and reportedly holds one of the world's largest-known lithium deposits at over a million tonnes, while three other miners are working towards production (Mabunda 2020).

According to Graham et al. (2021), instead of giving strong priority to lithium mining, Chinese companies, supported by Chinese banks and the central government, have purchased substantial interests in the major lithium mines of Australia, South America and Africa. Even in the United States, Chinese companies are seeking an interest in nascent lithium mines. In addition, China has sought and established a global leadership position in lithium processing. This is consistent with the country's industrial policy, China 2025, which seeks to emphasize those parts of the industrial supply chain that have high value-added and a limited environmental impact. In 2018, for example, China accounted for a much larger share of the world's lithium processing than lithium mining (see Table 7). Most of the lithium mined in Australia is shipped to China for processing before being used in the production of cathodes for lithium-ion battery (LIB) cells.

Europe is the second largest consumer of lithium, with 21% of the global demand. Currently, the only European supply for lithium comes from Portugal, producing lepidolite for local ceramics or glass. However, there are also several lithium exploration and mine projects in Portugal in the central and northern parts of the country. In addition to Portugal, new lithium mining projects are underway in Finland, Austria, Germany, the United Kingdom, the Czech Republic, Spain and Serbia (Graham et al. 2021).

3.1.1 Lithium production in Finland

Keliber Oy is a Finnish mining and chemical company. In the future, it will start to supply lithium hydroxide, especially for the rapidly growing international lithium battery markets. Keliber aims to be the first company in Europe supplying very pure lithium chemicals produced from its own ore. Its proven hard rock ore reserves in Kaustinen, Ostrobothnia, have been estimated as the most significant in Europe. This is currently also the most advanced lithium project in Europe. Once started, the estimated period of operation will be 20 years.

The concentrator will be located at the mining site in Päiväneva, adjacent to the largest ore deposit. The concentrate will be refined into lithium hydroxide suitable for batteries (to be more specific, lithium hydroxide monohydrate $LiOH{\cdot}H_2O$) in a chemical factory that will be located in the industrial area in the vicinity of the Kokkola Port, about 50 km to the NW. An environmental impact assessment of the chemical factory was completed in 2020, and the construction of the factory is estimated to start in 2022.

A production pilot carried out by Outotec in January 2020 proved the production method successful on a small scale. According to plans, the factory will produce 15 000 tpa lithium hydroxide, equalling 13 200 tpa LCE. The environmental impacts were assessed for an even higher production capacity of 25 000 tpa lithium hydroxide. Concentrating the spodumene ore will also produce quartz-feldspar sand as a by-product. Further processing will turn this concentrate into analcime sand (Na zeolite) and lithium carbonate, and the latter will react with lime milk to produce lithium hydroxide. The analcime sand will be utilized in the construction works of the expanding Kokkola Port.

Valmet Automotive started the production of automotive lithium-ion batteries at its new plant in Salo, Finland, in November 2019 (Valmet Automotive 2020). The planned production level was expected to be reached in early 2020. In Salo, Valmet Automotive has converted a former cell phone manufacturing plant completely to meet the requirements of high-volume automotive battery pack production. The construction of the new plant started in May 2019. Car manufacturing takes place in the Uusikaupunki car plant, where the annual car production reached a record volume of 114 000 vehicles in 2019. In 2017, Valmet Automotive and Contemporary Amperex Technology Limited (CATL), China's leading manufacturer of electric vehicle battery cells, began a strategic partnership. The company is now owned by Pontos Group, Tesi (38.46% each) and CATL (23.08%).

During recent years, particularly lithium-ion accumulators (batteries) as well as lithium cells and batteries have been the main lithium products imported to Finland, whereas the import of lithium compounds (lithium oxide, hydroxide and carbonates) has been rather moderate. The new battery plant in Salo will probably change this pattern to some extent. In 2019, the value of imported lithium-ion accumulators (CN8: 85065090) was €49.9 M and the combined value of three different lithium cells and batteries (CN8: 85065010, 85065030, 85065090) was €5.6 M. The value of imported lithium carbonates (CN8: 28369100) was €653 000, whereas the value of lithium oxide and hydroxides (CN8: 28252000) was only €174 000.

3.2 Sustainability aspects of lithium production

Regarding the sustainable supply of lithium in Europe, there is currently no European mine production of battery-grade lithium. However, the new European lithium projects (e.g., Keliber in Finland) may influence this situation. Despite the lack of European mine production, the supply risk for lithium was relatively low (1.6) in the criticality assessment of the European Union carried out in 2020 (European Commission 2020a). This indicates the lack of identified major risks related to procurement via imports. Among the three battery minerals cobalt, lithium and graphite, lithium has the lowest indexes for both supply risk and economic importance. However, both indexes increased for lithium between 2017 and 2020, for which it was listed as a CRM in the 2020 study.

According to Sanderson (2021), lithium extraction is associated with several environmental problems. Lithium extraction via evaporating from salt flats in Argentina and Chile uses large quantities of water, with consequences for local wildlife and human populations. As an alternative, lithium extraction from spodumene mineral (e.g., in Australia) needs very high temperatures of over 1000 °C, using vast amounts of energy. Although the socio-environmental impacts of mining and processing of lithium minerals are basically understood, the geographically specific environmental and social impacts associated with expansion in the mining and processing of lithium are currently poorly studied (Graham et al. 2021).

The adverse environmental impacts of lithium mining could be reduced by investing in more sustainable mining techniques and technologies that can more effectively recycle the raw materials found in spent lithium-ion batteries (UNCTAD 2020). Each of these advances has a different time frame for possible implementation, uncertain technical costs, and variable environmental impacts, all of which will entail trade-offs with respect to sustainability. Between now and 2030, these technologies are unlikely to significantly curb the explosive growth in the global demand for newly mined and processed lithium (Graham et al. 2021).

Zimbabwe is believed to hold among the world's largest deposits of lithium, hosting an estimated 23 000 Mt in reserves (USGS 2021b). However, the country has mostly the same problems regarding its mining industry as the DRC: corruption, uncontrolled artisanal mining, human rights abuses, forced labour and violence. The International Institute for Sustainable Development predicted (IISD 2018) that these problems may hinder large-scale lithium production in the country. More recently, this concern was also shared by the London School of Economics (LSE 2021). The lack of transparency, an effective mineral policy, governance, a tax regime and accountability may favour the dominant party and cause grievances and elevation of tension among the affected communities towards the state, particularly if these communities do not see visible development benefits (including jobs, infrastructure and investments in health and education) coming out of the mining sector (IISD 2018). To protect Zimbabwe's miners, as well as ensure that lithium mining contributes to the country's development, all affected stakeholders—including the government and foreign investors—should work towards reforming the sector to strengthen its governance (IISD 2018). LSE (2021) has also provided a set of recommendations to improve the mining sector's sustainability and governance in Zimbabwe together with the support of the EU.

China has large lithium reserves and some production, but the country imports more lithium than it produces domestically. In recent years, China has imported more than 80% of the lithium it consumes (mostly from Australia). Lithium mining in China has been associated with environmental and social problems, and Katwala (2018) lists several local protests that have taken place against environmental harm caused by lithium mining in the eastern edge of the Tibetan plateau. The area has seen a sharp rise in mining activity lately.

Portugal has a large, untapped potential to produce high-grade lithium in the central and northern parts of the country. However, lithium mine and exploration projects face resistance from local communities and non-governmental organizations (NGO), which have formed mining-sceptical groups in several localities (Chaves et al. 2021); there are fears of environmental impacts, which may allegedly damage protected areas and local livelihoods. Similarly to Finland, the mining-sceptical movement of Portugal has requested a renovation of the Mining Act, including more rigorous environmental impact assessments, major royalties to local communities, and a municipal-level veto of mining projects (Graham et al. 2021). The Portuguese mining-sceptical movement and consequent lack of a social license to operate (SLO) may challenge or even hamper Portuguese ambitions to become an important lithium producer in the EU. If the experience in Portugal is indicative of what will happen to other projects in Europe, it is safe to predict that Europe's lithium production initiative will progress slowly (Graham et al. 2021). However, In Finland, Keliber's lithium mine project is currently not involved in SLO disputes or sensitive issues (Eerola 2022).

4 GRAPHITE PRODUCTION

Graphite is a naturally formed polymer of carbon and is the only non-metallic element that is an excellent conductor of electricity and heat. It is mostly used for refractories, in foundry facings, steel making, brake linings, pencils and in lubricants. More recently, however, the use of graphite in lithium-ion batteries has seen a surge in the global demand for graphite. In a lithium-ion battery, graphite is typically the material used at the negative electrode, whereas intercalated lithium compounds are used at the positive electrode.

Battery-grade graphite can be produced from natural graphite or synthetic graphite. Of natural graphite, only flake graphite can be used in the production of batteries. It occurs in high-grade metamorphic rocks (e.g., marbles, schists, gneisses), where it was generated by either fluid deposition or graphitisation. Amorphous (microcrystalline) graphite and vein (lump) graphite are other forms of natural graphite. Battery grade graphite requires high purity (>99.95 wt% C) spheroidal particles with sizes in the range of 10–25 µm for effective operation. Spherical graphite is made by micronizing, purifying and rounding flake graphite. Spheroidal graphite can also be produced from synthetic graphite (European Commission 2017).

4.1 Mine production: top producing countries, mines and companies in the world

Global mine production of graphite was 1 120 000 t in 2018 and it is estimated to have been 1 100 000 t in 2019 (USGS 2020b). More than half of the graphite in the world originates from China, which clearly dominates the global mine production of graphite. Together with Mozambique and Brazil, these three countries produce about 80% of the graphite in the world (Table 8). China alone produced 700 000 t graphite and all other countries together 400 000 t graphite. According to Pistilli (2021), for any investor following the sector, it will come as no surprise that the Asian country is leading the way: China is known to dominate both the mining and refining side of the graphite market. In 2014, 52% of the graphite was globally used for steelmaking and the share of use in batteries was 8% (European Commission 2017).

Table 8. Distribution of the mine production of graphite globally and in Europe in 2019 (USGS 2020b).

Global mining of graphite in 2019			European mining of graphite in 2019		
Country	**Global share**	**Metric tonne**	**Country**	**Global share**	**Metric tonne**
China	64%	700 000 t	**Ukraine**	2%	20 000 t
Mozambique	9%	100 000 t	**Norway**	1%	16 000 t
Brazil	9%	96 000 t	**Austria**	0.1%	1 000 t
Madagascar	4%	47 000 t	**Germany**	0.1%	800 t
Canada	4%	40 000 t			
India	3%	35 000 t			
Russia	2%	25 000 t			

Mozambique has made huge gains in graphite production over the past few years, with 2020 output rising to 120 000 Mt. The country is home to two main graphite miners: Syrah Resources (ASX:SYR,OTC Pink:SYAAF) and Triton Minerals (ASX:TON). Large-scale operations include Syrah Resources' Balama project, which carries a graphite production capacity of 350 000 tpa and accounts for 40% of the global graphite market, exporting primarily to China and the US (Goodrich 2021). As the USGS (2020c) states, "A graphite mine project in Mozambique commenced operations at the start of 2018 and was ramping up production during 2018 and 2019 at a high-grade graphite deposit, which was reportedly the largest natural graphite mine globally. The mine cut back production during 2019 in an effort to stabilize graphite prices. The mine is expected to operate for 50 years."

According to Pistilli (2021), little information is available about the Brazilian graphite-mining industry, as the country's top producers of the metal are private. However, ETF.com (2012) does state that the country's two largest graphite producers are Extrativa Metalquimica and Nacional de Grafite.

Madagascar produced much less graphite (47 000 Mt) than the three top graphite-producing countries in 2020, but it is still the world's fourth largest producer of the metal. According to USGS (2020c), some mines in Madagascar began ramping up production in 2018, while additional large graphite deposits are currently under development in the East African nation.

India's total graphite output in 2020 came to 35 000 Mt, slightly lower than the amount it put out in 2019. The top graphite-producing country's reserves vary widely from state to state, with Arunachal Pradesh holding nearly half of India's graphite reserves. India has eight main producers, including Tirupati Carbons & Chemicals, Chotanagpur Graphite Industries and Carbon & Graphite Products. HEG (NSE:HEG) is a small graphite electrode producer in India that made record profit in 2018 (Business Standard 2018).

In 2020, Russia's graphite output totalled 24 000 Mt, slightly down from 25 100 Mt in 2019. Despite this plateau, the country expected to significantly increase its production during the next years due to the implementation of two investment projects, Dalgrafit and Uralgraphite. As with many of the countries on this list, little further information is available on graphite mining in Russia.

4.1.1 Graphite production in Europe

Ukraine and Norway are the most important producers of graphite in Europe. Ukraine produced 19 000 Mt of graphite in 2020, lower than the 20,000 Mt in 2019, accounting for 2% of the global share (Pistilli 2021). Zavalyevskiy Graphite is a large producer in Ukraine. It has been in operation since 1934 and produces up to 30 000 t of natural flake graphite annually.

Norway's graphite-mining output was almost flat from 2019 to 2020, going from 16 000 Mt to 15 000 Mt (1% of the global share). All graphite deposits in the country contain flake graphite and are generally low tonnage, but many are in favourable locations (e.g., close to the sea or the electrical grid).

Within the EU, there is only minor graphite production in Austria (1000 t) and Germany (800 t) (USGS 2020b), and the EU is therefore very highly dependent on imports. In Austria, graphite is mined in the Kaiserberg mine (Grafitbergbau Kaiserberg GmbH) and in the Kropfmüh mine (Graphit Kropfmühl, a subsidiary of AMG Advanced Metallurgical Group). The apparent EU consumption of natural graphite was about 91 000 tpa on average over the period 2010-2014.

Currently, there is no mine production of graphite in Finland. The Aitolampi deposit in Heinävesi is the most advanced exploration project for graphite in Finland. The mineral resources (indicated + inferred) of 19.3 Mt are estimated to contain 878 000 t graphite. Grafintec (formerly Fennoscandian Resources), a subsidiary of the British company Beowulf Ltd., is carrying out characterization tests on the concentrates to determine potential industrial applications of the graphite (Beowulf Mining 2020). The project is located within the scenic Finnish landscape of Saimaa Lake region, a popular summer holiday destination with many vacation homes, and is opposed by local communities (Leino & Miettinen 2020, Eerola 2022).

In 2022, Grafintec also announced its intention to establish a battery anode materials factory in the Vaasa region in Finland (Grafintec 2022). The anode material plant is a joint venture with an Indian company, Epsilon Advances Materials. According to Beowulf Mining's press release (Beowulf Mining 2022), the overall production capacity of the anode material factory could be up to 50 000 tpa, which would make the factory a very considerable size on a global level.

4.2 Sustainability aspects of graphite production

Although graphite as material is nontoxic to humans and the environment, its mining and subsequent processing produces emissions that can have negative impacts on human health and the environment (Dolega et al. 2020). Natural graphite mining can cause dust emissions (Whoriskey 2016), and the purification of battery-grade anode products requires high quantities of reagents such as sodium hydroxide and hydrofluoric acid (Pell et al. 2021). As an example, graphite mining and processing in China is associated with dust problems, with negative impacts on human health and the environment (Whoriskey 2016).

A recent study by Pell et al. (2021) revealed that the climate impact of graphite production might be ten times higher than previously reported, as most of the published life cycle assessment (LCA) studies for graphite production do not sufficiently represent the sizeable contribution of different electricity scenarios to the overall impact of operations. Regarding synthetic graphite, most of the impacts are the result of the vast energy consumption during graphitization and roasting processes, in addition to embodied impacts associated with calcined petroleum coke production, which is the synthetic graphite feedstock (Pell et al. 2021). According to Pell et al. (2021), the production of graphite in high-climate-impact grid regions creates a challenging economic–environmental trade-off. Even though battery-grade graphite producers benefit from operating in low-cost, fossil-dominated areas, their production will inevitably generate the highest environmental impacts, which may not be acceptable for LIBs or EV customers.

In order to reduce the adverse impacts of mining, UNCTAD (2020a) recommends that the industry finds ways to reduce the need for mining in the first place. For example, scientists are testing the possibility of replacing graphite in batteries with widely available silicon. Reducing the use of the minerals found in only a few countries could lead to lower prices for the batteries, which could in turn lead to even more electric cars on the road (UNCTAD 2020).

Battery and EV manufactures are fuelling the shift towards greener mobility and need to achieve this with minimal adverse effects on the environment. Therefore, the current discussions surrounding supply chain transparency will become even more important. Many companies, enterprises and initiatives have committed to responsible sourcing of minerals. As battery cell manufacturing is currently gaining importance in Europe, it will be the key matter to face sustainability issues along the whole battery supply chain. (Dolega et al. 2021)

5 TRACEABILITY IN BATTERY SUPPLY CHAINS

Traceability has become an integral element for many global industries with complex supply chains, such as food production and logistics. However, no comprehensive traceability systems for battery supply chains are currently available. There are several on-going development projects to tackle this issue, and many companies working within the mining industry have taken the challenge on and developed intercompany systems to trace raw materials within their processes. As the demand for battery materials grows exponentially, so will the importance of environmental, social and governance (ESG) systems used within the mining sector. In business and consumer markets, there is also a logical need to develop functioning traceability systems for battery supply chains.

Traceability in supply chains should provide a tool to identify the origin of the raw materials used, and the location of the upgrading and manufacturing plants along the supply chain. This, in turn, will provide a possibility to consider the level of sustainability of supply chains by tracking, for example, carbon footprints, human rights and quality of governance.

This chapter discusses selected methods for traceability in battery mineral supply chains, including enabling factors such as chain-of-custody models and existing sustainability and reporting systems used in the mining industry.

5.1 Different chain-of-custody models for different needs

Traceability solutions rely on a chain-of-custody (CoC), which means the documentation of all organizations having ownership or control of a product during production, processing, shipping and retail (physically and/or administratively) (ISEAL 2016). Different chain of custody models have been developed to fit different industries and to fulfil different needs (ISEAL 2016). Their application to mineral-based value chains has also been discussed by Svemin (2019) and Höjvall and Rissanen (2019).

Figure 4 presents four different CoC models applied to the minerals industry. In the identity preservation model (A), a product or raw material can be traced back to the original source. Identity preservation is widely used in food industries to provide information on the production site, for example, of meat products. In the segregation model (B), only materials with equal properties, for example, certification, are mixed. Segregation is applicable to value chains where sustainable and unsustainable streams of materials can be separated. In the mass-balance model (C), materials from both sustainable and unsustainable sources are mixed during production. The mass balance principle requires that an equal volume of material claimed to be sustainable enters and leaves the process. The certification programmes UTZ2 and Fairtrade3 apply mass balance in the labelling of cocoa products. Cocoa beans are generally supplied in bulk and mixed during shipping and manufacturing. Mass balance is also an option in the Forest Stewardship Council, FSC4 chain of custody standard. The certificate trading model (D) is an approach to reward sustainable production when tracing products or materials is difficult or impossible. The sustainability claims are completely decoupled from the material and the sustainability claims are traded as certificates or credits. In certificate trading, the buyer is blind to the actual sustainability of a product or material, but the certificate guarantees that somewhere in the world an equal amount has been produced sustainably. (Svemin 2019)

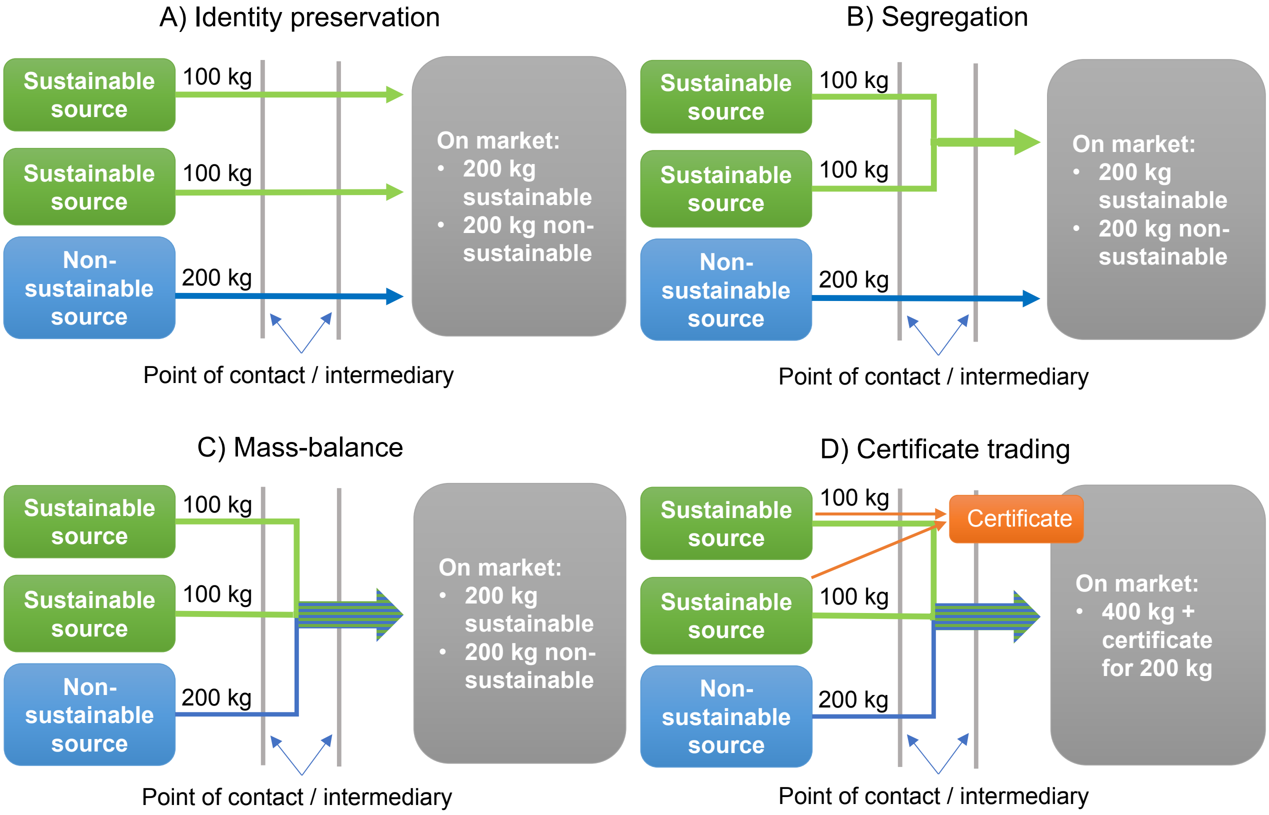


Fig. 4. Four different models for a chain of custody system. (Svemin 2019, modified).

5.2 Traceability is built on digitalization combined with sustainability reporting

The ability to prove the sustainability of a production process or a supply chain with measurable metrics is an integral element in the traceability paradigm. The most common sustainability metrics for mineral-based supply chains are currently related to ethical production, the carbon footprint and recycling content. The solutions for traceability are built, on the one hand, on the overall trend for digitalization of the entire supply chain and processes within it (e.g., digital twinning) and, on the other hand, on standardized sustainability reporting on mine sites and downstream processing sites. In addition, widespread digitalization offers new possibilities for data-intensive environmental impact assessment methods such as LCA.

Figure 5 contextualizes the emerging traceability solutions and applications in relation to established sustainability reporting standards. Sustainability reporting in the mining industry is mine site focused and offers a comprehensive understanding of the sustainability performance at a specific mine site (e.g., TSM, RMI, GRI). Traceability solutions, in comparison, aim to cover the entire supply chain of a particular product or an intermediate product. These solutions do not include comprehensive sustainability metrics but typically focus on a specific sustainability aspect with data based on existing sustainability reporting. The carbon footprint, ethical production and recycled content in raw materials have been popular metrics to apply thus far. Currently, the market for traceability solutions and applications for battery products is evolving, and several companies and consortiums are working in this field. It is evident that this development will eventually lead to standardized product passports for batteries. The basis for this development has already been laid by the new EU Batteries Regulation.

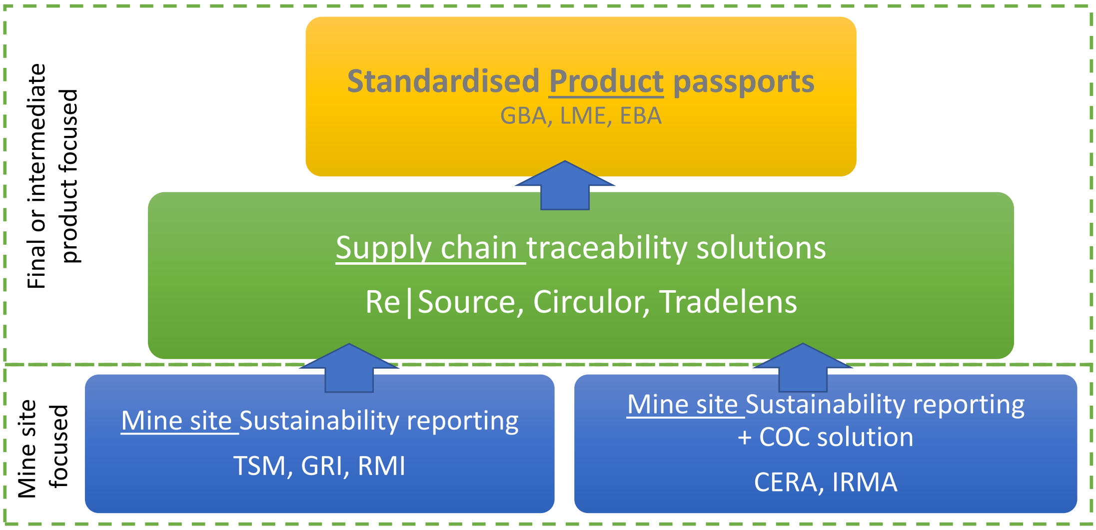


Fig. 5. Relationship between product passports, traceability solutions and mine site sustainability reporting. Each of these has a different focus and purpose. The presented solutions and reporting codes are examples. CoC = chain of custody.

5.3 Mine site-focused sustainability reporting

Communication and transparency are typical challenges for industries that cause social and environmental impacts and may depend on the stakeholders' and local communities' acceptance of their activities, such as mining (Lodhia & Hess 2014). In fact, a multitude of different types of responsibility reporting systems and guidelines for mining have been launched by mining associations and international entities since the end of the 1990s. At that time, mine accidents, conflicts and scandals (e.g., Bre-X) caused opposition to mining to increase all over the world (Hilson 2002). The mining industry realized that there was a need to change the industrial practices towards more sustainable performance and transparency in order to maintain the viability of its business (Hilson & Murck 2000). In this sense, the foundation of the International Council for Metals and Minerals (ICMM) in 1998 was one of the first responses of the mining industry to the increasing global opposition to mining during the 1990s. The ICMM was founded by ten major mining companies with the aim of improving their social and environmental performance.

The mining industry reacted to general criticism fairly late, only at the end of the 1990s and the beginning of the 2000s, due to increased resistance to mining all over the world (Hilson 2012). This reaction occurred only a few years before the sudden increase in demand for natural resources as a result of the economic growth in China. This caused a global mining boom in the 2000s and, as a result, mining conflicts multiplied all over the world (Conde 2017).

To improve the acceptance of the mining industry, tools for sustainable and socially responsible mining have been deployed by companies to varying degrees. Social values have rapidly changed, which has also had an impact on attitudes towards mining and its acceptance. For instance, a battery mineral boom is currently ongoing because of the green energy transition, which has expanded the number of mining-related disputes in Finland (Eerola 2022). The development and comparison of different methods, tools, reporting standards, best practices and traceability that promote the corporate social responsibility (CSR) of mining companies and their acceptance is still important. Discussion related to these will probably continue for as long as there are problems and conflicts related to mining.

In order to develop the transparency issue of primary natural resource production, some of the main sustainability reporting systems were reviewed determine whether these are related to traceability issues. The reviewed sustainability report systems used by the mining industry are presented in Table 9. These were classified according to their focus and geographic cover.

Table 9. Sustainability reporting and guidance systems according to their focus and geographic cover.

Global South	Financing	Regional/ National	Guidelines	General & Global
IFC	EITI	Enduring value (Australia)	e3Plus (exploration)	GRI
UN Global Compact	IFC	TSM (Canada)	Equator Principles	ISO 26000
JSE	JSE	JSE (S. Africa)	OECD	IRMA
		UNE 22470, 22480 (Spain)	ICMM	RMI

IFC = Internal Financial Control; UN = United Nations; JSE = Johannesburg Stock Exchange; EITI = Extractive Industrial Transparency Initiative; TSM = Towards Sustainable Mining; OECD = Organization for Economic Co-operation and Development; GRI = Global Reporting Initiative; ICMM = International Council of Metals and Minerals; IRMA = The Initiative for Responsible Mining Assurance; ISO = International Organization for Standardization; UNE = Unión de Normalización de España.

Several sustainability reporting systems are presented in Table 9. Some of these are national, to be applied for members of industrial associations, such as the South African Johannesburg Stock Exchange (JSE), or related to the countries of the Global South, such as the UN Global Compact and Internal Financial Control (IFC). Some of these may also focus on financial or fiscal aspects, such as the JSE, Extractive Industrial Transparency Initiative (EITI) and IFC, whereas some are guidelines (e.g., e3Plus, Equator Principles, ICMM Mining Principles). Therefore, attention was given here to the general and global sustainability reporting systems, such as the Global Reporting Initiative (GRI) and Towards Sustainable Mining (TSM). The International Council of Mining and Metals (ICMM) Mining Principles are mentioned due to their historical importance.

Although the others may also be widely used in the mining industry, the GRI is certainly the widely most used by the mining industry (Fonseca et al. 2012). Although TSM is mostly used by Canadian companies, these companies operate in many countries all around the world, and for this reason, TSM is also one of the most widely used global systems. Therefore, it is also included here to be examined regarding the traceability issue. The mentioned systems are briefly reviewed below and comments on their suitability for traceability are provided.

5.3.1 Towards Sustainable Mining

Towards Sustainable Mining (TSM) is a Canadian responsibility reporting system launched by the Mining Association of Canada (MAC). TSM was the first mining sustainability standard in the world to require site-level assessments and is mandatory for all companies that are members of implementing associations. Through TSM, nine critical aspects of social and environmental performance are evaluated, independently validated, and publicly reported against 30 distinct performance indicators. The principles are

- Indigenous and Community Relationships
- Energy and greenhouse gas (GHG) Emissions Management
- Tailings Management Protocol
- Biodiversity Conservation Management
- Safety and Health
- Crisis Management and Communications Planning
- Mine Closure Framework
- Preventing Child and Forced Labour
- Water Stewardship

TSM is a quite simple sustainability evaluation system in which legislation sets the bottom line level of C, while the highest level is AAA, and it is comprised by voluntary actions. This means that compliance with legislation is the lowest level and a pre-requisite of any sustainability evaluation in the TSM. The following categories of B, A, AA, and AAA require an ascending order of responsibility and the following of best practices set by the standard. TSM was created only for mining.

In Finland, TSM is used by Canadian mining companies, such as Agnico Eagle, which runs the Kittilä gold mine in Lapland. The TSM was also adapted to mining in Finland by the Finnish Network for Sustainable Mining (FNSM). Based on this, a sustainability evaluation system was additionally created for mineral exploration by the FNSM.

TSM has no appropriate principle or criteria for traceability. Instead, it does include CoC data standards, which can then be used as a part of any other traceability system along the supply chain. The possibility to introduce traceability into the TSM is being considered in Canada and Finland (Finnish Network for Sustainable Mining).

5.3.2 Global Reporting Initiative

The Global Reporting Initiative (GRI) is one of the most widely used global reporting systems that supports mining companies in managing key environmental and social risks (Fonseca et al. 2012). The GRI is an independent international organization that helps businesses and other organizations take responsibility for their impacts by providing them with the global common language to communicate these impacts. It provides standards for sustainability reporting: the GRI Standards.

The GRI Standards enable any organization to understand and report on their impacts on the economy, the environment and people in a comparable and credible way, thereby increasing transparency concerning their contribution to sustainable development. In addition to reporting companies, the standards are highly relevant to many stakeholders, including investors, policymakers, capital markets and civil society. The GRI reporting standards are applied by most of the mining companies in Finland.

The GRI has also developed sector-specific standards, in which mining is included. Mining is within the priority Group 1: Basic Materials and Needs, which comprises the sectors that were considered to have the largest sustainability impacts. The Mining Sector Standard is the fourth standard developed under the Sector Program. This new programme identifies a sector's most significant impacts and reflects stakeholder expectations for sustainability reporting. Its elaboration is still in progress.

Among its numerous principles and criteria, there are many that can be used or adapted to deal with traceability issues. These include disclosure of the location of operations, the geographic location of suppliers, customer access to the social impacts of products and information on the sourcing of components.

5.3.3 Responsible Minerals Initiative

Founded in 2008, the Responsible Minerals Initiative (RMI) is one of the world's widest networks regarding sustainability within the mining sector. The RMI provides companies in the mining sector with independent third-party audits and templates for responsible mineral sourcing in their supply chains. According to the RMI, more than 400 companies and associations from over 10 industries participate in the initiative. The network includes a wide range of companies both upstream and downstream in the mineral supply chains.

Mining companies often refer to their compliance with RMI's Responsible Minerals Assurance Process (RMAP) as a guarantee of their supply chain's sustainability. According to the RMI, RMAP offers companies and their suppliers an independent audit that determines which smelters and refiners can be verified as having systems in place to responsibly source minerals in line with current global standards, such as the OECD Due Diligence Guidelines, EU regulations and US legislation.

RMI provides public reporting templates and other tools such as due diligence guidelines for increasing sustainability in the mining industry. RMI also participates in various public forums around responsible and sustainable mining. However, the assurance processes of RMI do not require traceability from the mining companies as part of their sustainable operations. Instead, the RMI standards and processes equate CoC data to be a similar demand to traceability (RCI 2021).

5.3.4 Certifying of Raw Materials (CERA 4in1)

The CERA 4in1 project had been in private development since 2015, before a formal project consortium, partly funded by EIT Raw Materials, was formed in 2017. The project created the CERA 4in1 certification system. The CERA 4in1 certification scheme is the first global scheme of its kind to universalize and standardize the evaluation of social, environmental and ethical practices across the raw materials value chain. CERA 4in1 uses sub-standards according to the value chain, allowing the certification system to prove the sustainability of products along the entire value chain, from mineral exploration to the final product. The CERA 4in1 certification comprises four standards along the mining life cycle: the CERA Readiness Standard (CRS), CERA Performance

Standard (CPS), CERA Chain of Custody Standard (CCS) and CERA Final Product Standard (CFS).

The CERA Chain of Custody Standard (CCS) refers to traded commodities: run-of-mine, concentrate, primary and secondary raw materials. The CERA CCS defines criteria for ensuring appropriate management systems for the traceability of responsibly sourced commodities.

The CCS sets out requirements for the management of traded commodities, defining commodity-specific accounting methods and chain of custody eligibility. CERA certification under the CCS allows manufacturers, traders and handlers to ensure that raw materials purchased have not been mixed with products resulting from conflict-affected mining, processing and refining activities.

The Final Product Standard (CFS) considers the end product and certifies that constituent components consist of materials that have been sourced and traded in accordance with sustainability principles, enabling informed decision-making by consumers.

CFS Certification establishes clear rules on how responsibly sourced materials are declared when included in consumer goods, enabling the consumer to identify where and in what concentration certified materials are present in an item's makeup. From these, the Chain of Custody and Final Product Standards are the most appropriate regarding traceability, but of course, this also involves the Performance Standard.

5.3.5 Initiative for Responsible Mining Assurance (IRMA)

Founded in 2006, the Initiative for Responsible Mining Assurance (IRMA) is dedicated to a global demand for socially and environmentally more responsible mining. IRMA offers independent third-party verification and certification against a comprehensive standard for all mined materials that provide 'one-stop coverage' of the full range of issues related to the impacts of industrial-scale mines.

IRMA is a multi-stakeholder-led organization, meaning that it must be accountable to all. IRMA's governance is equitable and shared by civil society, communities and organized labour, alongside the private sector. The member organizations of IRMA represent the entire mining supply chain, from mining companies to OEMs.

IRMA's Standard for Responsible Mining defines good practices regarding what responsible mining should look like at the industrial scale. It provides a list of expectations that independent auditors will use as the benchmark for responsible mines. The standard includes four main elements:
- Business integrity;
- Planning for positive legacies;
- Social responsibility;
- Environmental responsibility.

The IRMA standard does not yet include traceability or a CoC standard, but a draft version of the IRMA Chain of Custody Standard for Responsibly Mined Materials has recently been published in response to the need for transparency and identification of the origin of raw materials (IRMA 2020). The IRMA CoC standard provides a framework and lays out specific requirements for tracking IRMA-conformant responsibly mined materials from mine to market. It also enables organizations operating within the supply chain and end users to make credible claims about IRMA-conformant responsibly mined materials.

The standard has been developed to work in concert with existing and emerging traceability services and technologies (e.g., blockchain, mineral ID scanning, testing). In fact, the standard does not require traceability, but "was developed to provide the base-level requirements for traceability for any mined material from the mine through the downstream chain of custody to the end consumer," again highlighting the limitation of mining-level standards for supply chain traceability.

5.4 Digital traceability solutions and case studies for mining supply chains

As the market potential for traceability is increasing, an increasing number of solutions are becoming available for supply chain traceability. Most of the currently available commercial solutions do not focus on mining, but other industries such as retail and fashion, where logistical forecasting and consumer interest in sustainability push commercial operators to have more transparency in their supply chains. There are several networks among mining companies for digital traceability (e.g., WEF Mining and Metals Blockchain Consortium, Responsible Sourcing Blockchain Network), but large, standardized solutions within the mining sector are still unavailable.

The current potential of digital devices, readily available mobile networks and cloud-based software have made the application of digital traceability solutions possible anywhere on the planet. Traceability solutions are mainly marketed as third-party data aggregators, which can use the different management information systems within the supply chain to integrate available knowledge into a traceable data set. With this approach, data ownership is one large issue surrounding the traceability solutions today and in the future; can a large downstream operator (such as a car manufacturer) demand all other upstream operators to give their data to a third-party traceability provider? And if they do, who controls access to these data? Data ownership can be seen as one major driver for large commercial operators to partner in providing traceability solutions (e.g., IBM and Maersk with Tradelens), so that they have access to an increasing amount of data on worldwide logistical operations.

Many, if not most, of the digital traceability solutions available market themselves as blockchain-based solutions providing immutable records for traceability (e.g., Circulor, Xylene, Minespider). Blockchain is also often mentioned as one key element of supply chain traceability. While blockchain can increase trust in certain applications for traceability, it does not provide a silver-bullet solution for the mining industry. The following sub-chapters present an overview of the use of blockchain technology in traceability and include an overview of selected case studies for traceability within the mining industry.

5.4.1 Blockchain technology as an enabler of traceability

Blockchain is a digital technology that has been proposed as a basis for technological solutions to provide traceability within supply chains for mining and other industries (Gaur & Gaiha 2020). The term blockchain refers to blocks of data, which are chained together via encryption algorithms (Fig. 6).

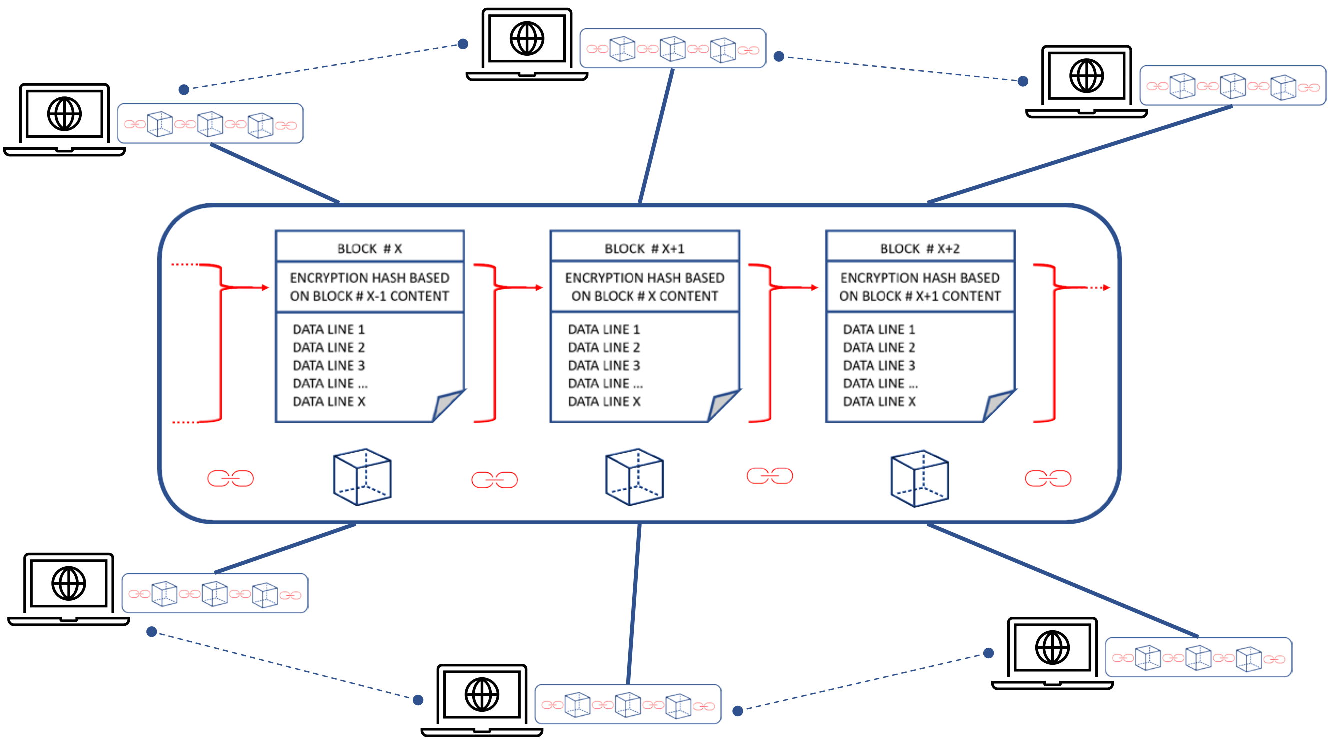


Fig. 6. Illustration of blockchain technology.

In basic terms, blockchains are decentralized databases to store information, and there are several different blockchains for different purposes. Typically, a blockchain's content is distributed between hundreds or thousands of users, which means that one user cannot alter any data after it has been written to the database. This makes the data written into the blockchain immutable, which induces trust in the data entered into the blockchain. Depending on technical solutions and user needs, data within the blockchain database can be open to anyone, or can be encrypted to be shared with restricted access.

Like other databases, a blockchain database provides a platform in which supply chain transactions can be recorded from mine to smelter and beyond. Data including weight, quantity and grade, but also provenance information and responsible production certificates can be uploaded to the system and validated at the appropriate supply chain points, and then linked to the physical material using bar codes, tags, or other internet of things (IoT) applications (such as RFID tags). This information could then be shared with downstream buyers and other third parties (RCS Global 2017).

The value of a blockchain-based database for traceability comes from the fact that data stored within it cannot be changed. This means that any data stored and verified in the blockchain database, such as a starting location and quantity of a material shipment, can be trusted to be unaltered. This enables all partners within a complex supply chain to trust each other's data, even if they may not interact together.

An increasing number of both public and private blockchains are becoming available, and many of the public blockchains have been developed with the support of large technology companies such as IBM and Oracle. When promoting their commercial solutions, companies may use this as a marketing advantage by promoting their service as "based on IBM's blockchain technology". This does not mean that IBM has taken part in developing the solutions in any way or is even aware of its use.

It should also be noted that although many commercial solutions promote themselves as "blockchain based", they cannot typically place all raw material data within the blockchain because of technical limitations. Instead, they may only store certain information or events in the blockchain, such as change of ownership. In addition to storing certain information in the blockchain, other types of supply chain data are available to relevant stakeholders through web services and other applications.

In addition to some technical limitations, blockchains are also subject to the same garbage in, garbage out (GIGO) limitation as other large data systems. Although the data within a blockchain cannot be altered, the use of a blockchain does not verify that it is correct to begin with. This means that there are commercial opportunities for technical solutions that can complement existing traceability solutions with the means to verify the data within the system.

5.4.2 Case: Circulor

Circulor is a third-party traceability service provider with a focus on the mining industry and battery metals and chemicals. It has a wide variety of reference customers within the battery supply chains, from mining companies and traders all the way to OEMs.

Circulor's traceability solution is based on data aggregation from multiple supply chain points, where commodities are given a digital, dynamic twin (Hyperledger 2020). Using data from several management information systems throughout the supply chain, Circulor can demonstrate the origin of materials. The use of a digital system also allows the use of artificial intelligence to detect possible issues within the data and flag them for review. Circulor also promotes the use of the Hyperledger blockchain as part of its traceability solution (Hyperledger 2020).

Interestingly, Circulor has demonstrated its capability to trace conflict minerals that are sourced through artisanal mining (Hyperledger 2019). A common issue with data aggregation systems is that they rely on existing production systems to provide a starting point for traceability. With artisanal mining, these systems lack information on the collection of the material and therefore lack reliability on the original source of raw materials. Partnering with a tantalum mining operator (Power Resources Group), Circulor worked to provide a starting point for artisanal mining traceability by using QR codes and facial recognition of miners to create provenance data for their traceability solution. Similar methods could be used in the future in cobalt supply chains, which have considerable input from artisanal and small-scale mining.

In 2021, Circulor and FMG also introduced a long-term collaboration in providing traceability along the battery value chains. In this collaboration, Circulor's solution is used to both track the materials and to calculate the CO2 emissions along the value chain (FMG 2021). This type of use for traceability provides evidence of the increased interest among battery raw material producers in using the traceability of the carbon emissions to gain increased commercial opportunities in the global marketplace.

5.4.3 Case: Terrafame

In addition to digital solutions, a simpler way to ensure traceability is by limiting several parts of the supply chain to a single site. Terrafame Ltd. is a battery chemical producer located in Eastern Finland that can market its own battery chemical products as traceable by refining the products within its mining site.

Terrafame delivers nickel–cobalt, zinc and copper products for downstream operators. However, in addition to the mining operation, Terrafame runs an integrated production process from in-house mining to battery chemicals on its mining site, thus ensuring traceability from mine to battery chemicals. In addition, the Finnish Minerals Group (majority owner of Terrafame) has on-going technology development collaboration with Circulor, a digital traceability solution provider (FMG 2021). The companies are aiming towards large-scale multi-user solutions for traceability further along the supply chain, which will enable further traceability of Terrafame's battery chemicals along the supply chain.

Production ramp up of the company's new battery chemicals plant started in June 2021. At the time of its completion, the battery chemicals plant had will have globally one of the highest production capacities. The company claims its process to be a "unique and energy-efficient production chain that provides customers battery chemicals with carbon footprint among the smallest in the world" (Terrafame 2021).

The integrated production process provides Terrafame an opportunity to claim its products to be traceable within the identity preservation mode (Fig. 4), as the full supply chain from the mine to battery chemicals is known. This, together with a low carbon footprint of the products, gives the company an advantage amongst battery chemical producers. In October 2021, Terrafame and Renault Group published a Memorandum of Understanding for the future supply of nickel sulphate for electric vehicle batteries. According to their press release (Renault Group 2021), the partners are aiming towards a sustainable and fully transparent European battery value chain.

5.4.4 Case: Re|Source

Umicore, Glencore, CMOC, Eurasian Resources Group (ERG), Tesla and others have joined in collaboration to pilot a solution called Re|Source to trace responsibly produced cobalt from the mine to the electric car (Umicore 2021a, b). In addition to these companies, the RMI and the Cobalt Institute have joined Re|Source as strategic advisors. The pilot includes the entire Tesla supply chain and ran until the end of 2021. The launch of the final industry solution is expected in 2022.

The blockchain-based solution is being tested under real operating conditions from cobalt production sites at DRC to downstream electric vehicle production sites. For the traceability of cobalt supply chains, this collaboration is significant, as Umicore and Glencore are major companies of the global cobalt supply chain (see Chapter 3). The pilot is also investigating how aspects of the related GHG emissions along the supply chain can be traced and disclosed. To support this purpose, Re|Source integrates a comprehensive set of industrial sustainable mining and sourcing standards and frameworks, such as ICMM, RMI, IRMA CIRAF, Copper Mark and others.

As Re|Source partners are also involved in the Global Battery Alliance, it is possible that the Re|Source traceability solution will additionally serve as part of the GBA Battery Passport, which is currently under construction. The Re|Source solution is also a considerable development when considering traceability in complex cobalt supply chains.

5.4.5 Case: TraceMet

TraceMet is a traceability system developed in a research project by a Sweden-based organization, SVEMIN, in co-operation with several industrial actors. TraceMet is based on blockchain technology and includes the certification of metals in terms of the carbon footprint and the amount of recycled materials. The purpose of TraceMet is to develop a simplified but fully functional IT system to trace certified metals from mining to end use. The piloting of TraceMet has thus far included copper and steel. The study found a mass-balance chain-of-custody model to be the most feasible type to realize for copper (Svemin 2019). This is based on the complex value chains of copper, in which raw materials including mineral concentrates and recycled scrap from several sources are mixed in smelters. In this option, information on the exact origin of the material is lost, but the promise to the customer is that the same amount of certified material has been produced. TraceMet certification is focused on climate actions and the circular economy, but omits metrics on social sustainability.

5.5 Current battery passport initiatives

Several "battery passport" initiatives are currently being developed within European and global markets. These include the EU Battery Passport (or the Electronic Exchange System [EES]), Global Battery Alliance's (GBA) battery passport and the LME Passport. In many ways, the goals and development of these battery passport initiatives are interconnected, with many organizations being involved with several passport initiatives. Several smaller businesses are also promoting commercial battery passport solutions, but these currently lack the widescale adoption and credibility of larger, industry-wide solutions.

The EES's characteristics as proposed by the EU's upcoming battery directive are probably going to have a significant influence on other battery passport initiatives, as it will be defined by legislation. Therefore, the other systems will most probably comply with the specifications of the EES and their data will be interchangeable with it. For the companies working within the battery supply chains, standardization of data between the systems is a critical factor in increasing their deployment, especially if several passport systems will be required by regional legislation in the future.

It remains to be seen whether some of the "battery passports" becomes a standard model of deployment but based on the fragmentation of the mining industry's sustainability standards, it will also be probable that several passport systems will exist globally in the future.

5.5.1 European Electronic Exchange System (EU Battery Passport)

As part of EU's new Green Deal, in December of 2020, the European Commission (2020a) proposed a new Batteries Regulation in response to the new developments around technological development, markets and use of batteries (European Commission 2020b). Instead of earlier battery regulations, which focused more on the end-of-life stages of batteries and their recycling, the new regulations focus more on the entire value chain from raw materials, to the design and repurposing of the batteries. The new regulations are applicable to all batteries entering the EU market, independently of their origin. For batteries manufactured outside the EU, the importer or distributor of the batteries needs to ensure their compliance.

The battery regulations suggest mandatory requirements for:

- Sustainability and safety (such as carbon footprint rules, minimum recycled content, performance and durability criteria, safety parameters);
- Labelling and information (such as storing of information on sustainability and data on the state of health and expected lifetime of batteries);
- End-of-life management (such as extended producer responsibility, collection targets and obligations, targets for recycling efficiencies and levels of recovered materials);
- Obligations of economic operators linked to product requirements and due diligence schemes;
- Electronic exchange of information.

Regarding the traceability of battery raw materials, the new regulations establish a common 'Electronic Exchange System' (EES) for batteries, which will provide public information on all batteries placed on the market. This system has been dubbed in many sources as the 'EU Battery Passport'.

According to the European Commission's (2020c) press release, individual batteries can be linked to the EES via QR codes for traceability and management. In the proposed regulation (European Commission 2020b), article 65 states that rechargeable "industrial batteries and electric-vehicle batteries shall have an electronic record for each individual battery placed on the market," and the record is required from batteries larger than 2 kWh.

In the proposed regulation, the EES is required to be in use from 1 January 2026. The architecture of the EES and formats for data and information will be made available by the end of December 2024 (Article 64). All information on what data the systems will include are defined in Annex XIII of the regulation (ibid.) (Fig. 7).

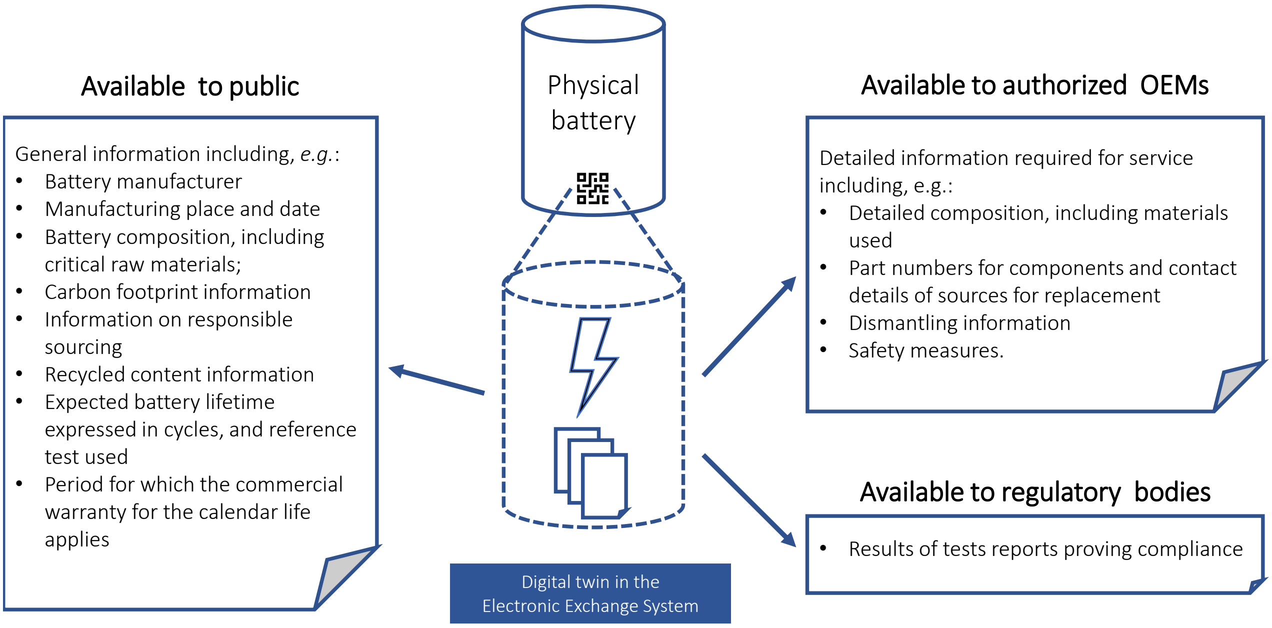


Fig. 7. Illustration of the three levels of information in the Electronic Exchange System (EES) for batteries.

Based on the proposed regulation, the EES will have information available on three levels. Public information should be accessible by anyone through a battery's electronic identifier, such as a QR code. This information will include detailed information on the battery, such as its manufacturer, type, capacity, manufacturing location and warranty. In addition, it should include information on the environmental impacts of the battery, such as the carbon footprint, recycled content and information on responsible sourcing of raw materials. Detailed information on the format or quality of the public environmental information is not yet available.

In addition to the public information, the EES will also include restricted levels of information, such as detailed product breakdowns, schematics, recycling instructions and testing reports for regulatory officials.

5.5.2 GBA Battery Passport

The Global Battery Alliance (GBA) is a partnership of over 70 organizations across the battery supply chain founded in 2017 under the World Economic Forum (WEF). The self-proclaimed goal of the alliance is to increase battery deployment and create responsible and sustainable battery production to realize the goals of the Paris climate agreement. In relation to many other initiatives surrounding the battery supply chains, GBA has a major advantage of including a wide variety of companies and organizations, from mining to OEMs. It also has a wide public organization backing with the support of the WEF. This lends significant credibility to GBA as a guiding factor in driving sustainability and traceability in the battery sector.

In early 2020, GBA launched 10 guiding principles together with a vision for sustainable battery value chains by 2023. The principles, agreed by the member organizations in January 2020, cover a wide range of sustainability topics, from promoting circular value chains to safeguarding human rights.

As a key initiative to their guiding principles, GBA has introduced the concept of a 'Battery Passport' (Fig. 8). The idea of the Battery Passport is to act as a digital platform to exchange data among all authorized lifecycle stakeholders to support a sustainable supply chain for EV and stationary batteries. It would verify material provenance, disclose the GHG footprint, measure sustainability and general environmental impacts, and advance battery life extension and recycling. Based on GBA's own material, the traceability specifications for their Battery Passport go beyond the requirements of EU's EES by also specifying the original source of raw materials used in the batteries.

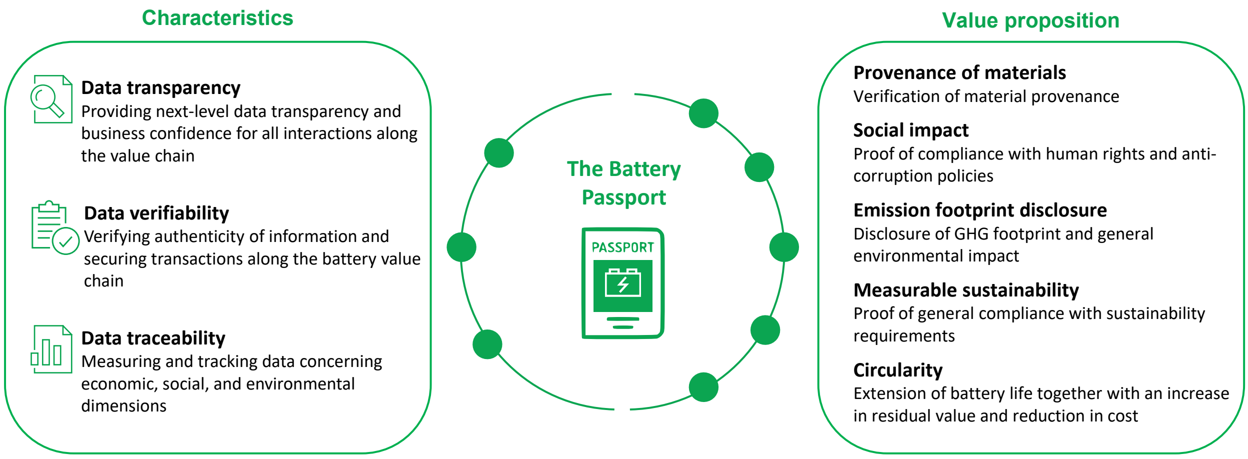


Fig. 8. Characteristics and value proposition of the Battery Passport (GBA 2020a, modified).

Only a limited amount of public information is available on the Battery Passport platform and its features. According to the GBA briefing paper (GBA 2020b), the Battery Passport is not intended to be a commercial product but a platform that offers a solution for securely sharing information and data. The Battery Passport can include a variety of types of information, which can be made available according to the needs of a stakeholder or consumer. As of April 2022, GBA has not announced detailed specifications for the Battery Passport, such as who would act as a service provider for the platform, or how it will be technically implemented.

Initially, a Battery Passport prototype was planned to be introduced in 2020. In November 2020, GBA estimated that a "vision demonstration" of the passport would be available in Q2 of 2021, a functional version 1.0 in Q4 of 2021, and that the Battery Passport would launch with full functionality in Q4 2022.

5.5.3 LME sustainability and traceability initiatives and the LME Passport

Among the drivers for sustainability in the mining sector, commercial exchanges are starting to require sustainability from the companies trading through them. The London Metal Exchange (LME) is one of the most significant worldwide exchanges for industrial metals. Previously, it has only had metallurgical standards for products traded through it. In 2019, LME published a position paper also describing new responsible sourcing requirements that the brands must meet to be traded through it (LME 2022).

In short, LME has set the following responsible sourcing requirements based on the OECD guidance:

1. Establish strong company management systems
2. Identify risks in the supply chain
3. Identify the appropriate track for compliance and follow the steps set out in that track
4. Adopt ISO 14001 and OHSAS / ISO 45001 (or equivalent) certifications

LME has stated that companies have until June 2022 to notify LME of their compliance with the requirements and has given the companies until the end of 2023 to fully implement all required changes.

The sustainability requirements that LME has set are based on current OECD due diligence guidelines, and as such do not propose major changes for well-established mining organizations. However, they do require all parts of the brands' supply chain to commit to the same quality, environmental and occupational, health and safety (OHS) standards and red flag assessments transparently, which should broaden the adoption of the requirements.

5.5.3.1 LMEpassport

Although the responsible sourcing requirements of LME are not directly related to traceability, in the future, LME will move further forwards in its 'sustainability strategy'. In August 2020, LME published a discussion paper on an "LMEpassport", a digital credentials register with further plans to accommodate traceability and provenance information on traded metals (LME 2020). The LMEpassport (Fig. 9) is proposed to serve both as a certificate of analysis (CoA) utility service and as a safeguarded library of provenance information. Although the primary driver of the LMEpassport is to serve as a central utility service for CoAs, the secondary function of the service is to provide traceability for brands as "a growing demand for provenance information from consumers across industries is increasingly evident."

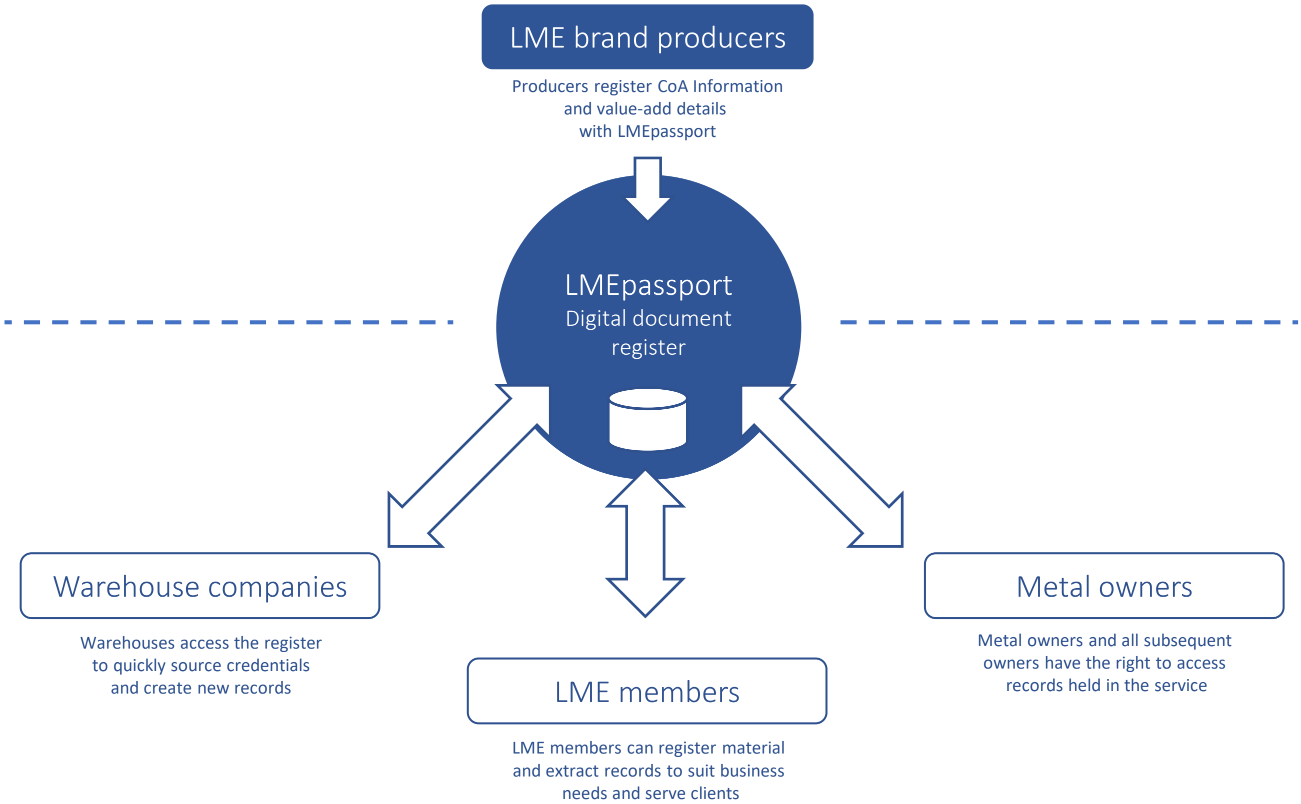


Fig. 9. Overall depiction of the LMEpassport (LME 2020, modified).

Currently available information on the traceability aspects of the LMEpassport is limited. The discussion paper refers to the LMEpassport as a "digital, immutable register", which could indicate the use of a blockchain as part of the technological architecture of the system. The LMEpassport went live in August 2021, and the system should be fully implemented and required of producers in 2024. In terms of battery metals, the LMEpassport will be implemented for nickel and cobalt at the beginning of 2023 (Fig. 10).

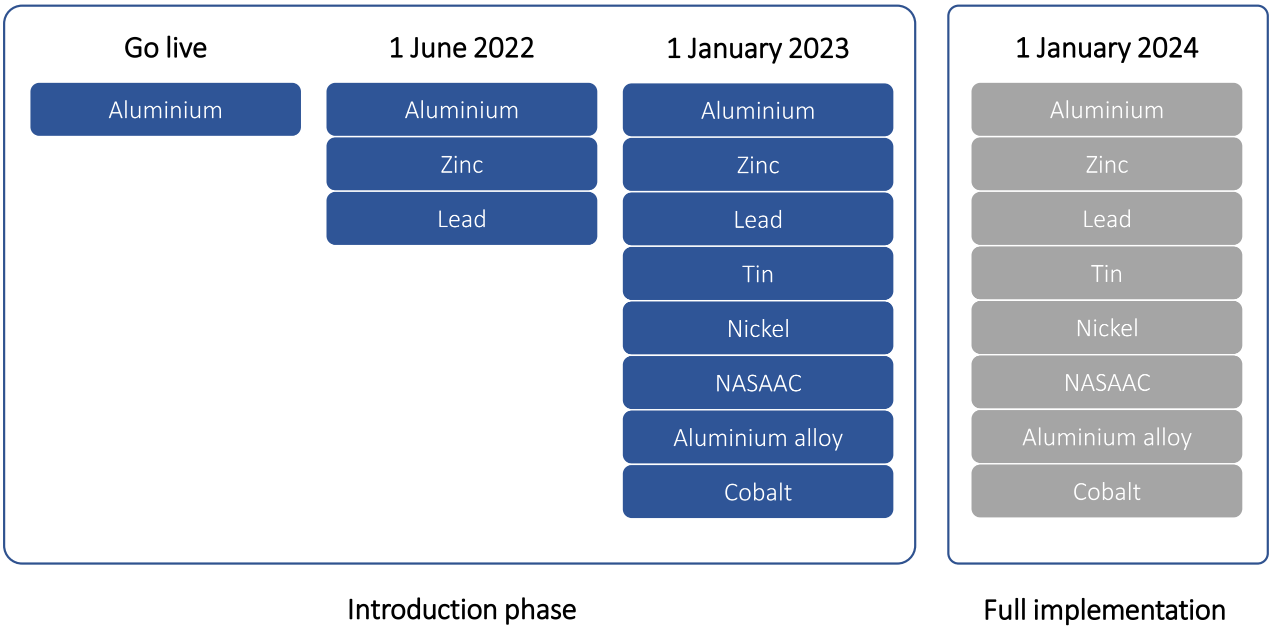


Fig. 10. Proposed timeline for the LMEpassport (LME 2020, modified).

5.5.3.2 LME spot-trading platform and new contracts for sustainable metals

In their 2020 sustainability discussion paper (LME 2020), LME introduced other initiatives towards sustainability as well. Two of these are of particular interest in relation to future markets for sustainable battery metals.

Firstly, LME discussed the possible adoption of new contracts for "low-carbon" aluminium, which would allow producers to set a price premium for their product based on sustainability criteria. LME does not intend to adopt this for aluminium at this point, since the production levels of low-carbon aluminium are not sufficiently high to warrant this change yet. Nevertheless, the discussion on the topic does provide a possible indication that there may be separate contracts and price premiums for verifiably sustainable metals in the future.

Second, LME is launching a voluntary spot-trading platform for aluminium contracts in which producers can include additional information on their products (e.g., carbon offsets, provenance and amount of recycled content) to influence the pricing of their contracts.

The spot-trading platform introduces a new mechanism for demand-based pricing for sustainable products. Although it was introduced with aluminium, if the platform moves further towards battery metals, it will offer a system for buyers to pay a premium for sustainable and traceable metals. However, as discussed previously, buyers are rarely willing to pay premiums for sustainability unless forced by regulatory development.

6 PROVENANCING AND BATTRACE'S GEO-BASED TRACEABILITY THROUGH ANALYTICAL FINGERPRINTING

The traditional traceability systems are essentially paper-based or document-based following the usual "bag, seal and tag" routine to trace the origin of a truckload, shipment or cargo. These documents can be corrupted, thus making these traceability systems highly susceptible to fraud and adulteration. Several projects to control provenance using digital technologies such as blockchain or QR codes are being explored beyond the traditional current paper-based systems. These approaches are costly in terms of computing power and face technical challenges related to corruptible data input ('garbage in, garbage out'), with complex points of aggregation, mixing and processing, thus making the control of material flows difficult (RCS Global 2017).

Several digital-based commercial solutions are available and under investigation for supply chain traceability, but they are all sensitive to the reliability of the data input. Physical fingerprinting based on the geological characteristics of raw materials may assist in the establishment of a verification instrument in a certification procedure for the battery raw materials supply chain. With this objective, geo-based fingerprinting could complement a digital traceability system by allowing the control, verification or certification of materials' declared origin. The robustness of data-based traceability systems may be significantly enhanced through independent assessment based on the analysis of intrinsic properties of the ores and minerals to allege their declared origin, and therefore strengthen the digital traceability systems. Demonstrating physical fingerprinting verification methods for cobalt, lithium and graphite supply chains is one target of the BATTRACE project.

6.1 Principle

Physical fingerprinting, in the present context, is the process of determining the origin of a given sample (ore, concentrate, material/product) by analysing its properties or characteristics. One has to differentiate between "natural" fingerprinting, for which these properties are intrinsic to the material (e.g., geochemistry, mineralogy), and artificial fingerprinting, whereby the material is artificially altered (e.g., addition of particles or taggants with unique properties to a shipment, laser inscription and marking of gemstones) in order to certify its origin and ensure traceability. Physical fingerprinting is a well-known practice in archaeometallurgy, where the provenance of the raw materials used to manufacture ancient tools can often be established using trace elements patterns and lead isotope ratios (Pernicka 2014).

The so-called natural properties of ores include a range of geochemical and mineral properties, such as bulk chemistry, mineralogy and textures, as well as in situ properties, including mineral properties such as minor and trace elements, or stable and radiogenic isotopes in specific minerals. These ore properties are linked to the geological setting and geological history of the deposits in which these ores are found. Some of these properties may be site-specific to a deposit or mining district and can therefore be used for traceability. By comparing

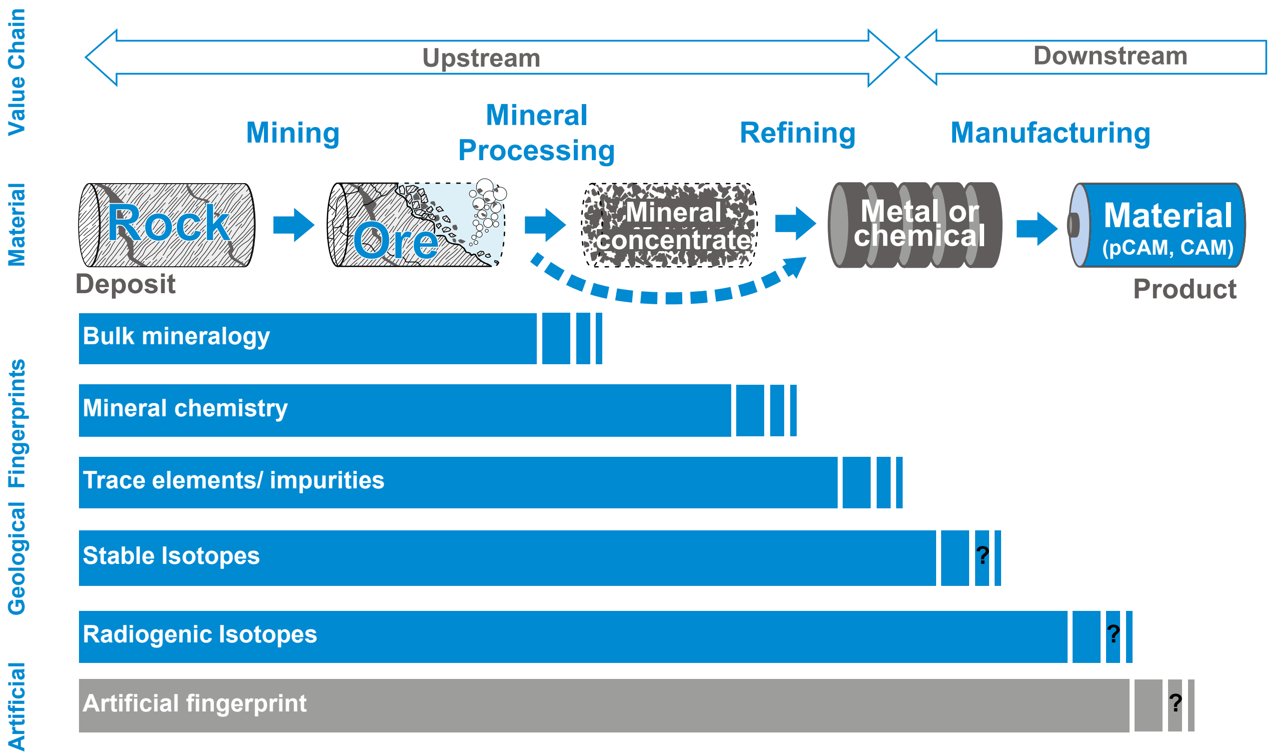


Fig. 11. Principle of the BATTRACE physical fingerprinting approach, modified after Dehaine et al. (2020).

these fingerprints with a database or reference samples, one can then certify the origin of the sample analysed. The final comparison of these features between the control and reference sample is achieved by applied, often multivariate statistics (Schütte et al. 2018).

Figure 11 illustrates the principle of the physical fingerprinting approach investigated in the BATTRACE project and notably the issue of conservation of the different fingerprints along the battery raw materials value chain. Indeed, some if not all the geological fingerprints are lost at some stage of the value chain, which may limit their use for traceability purposes. These aspects are discussed in more detail in section 6.3.

6.2 Case studies and examples

Physical traceability systems to define the origin of minerals and other raw materials based on intrinsic properties have already been developed for various minerals and materials, such as gemstones, gold, uranium/yellow cake or base metals, amongst others (Table 10). The approach generally requires the development of a workflow involving several steps, including sample preparation, the measurement of selected parameters (i.e., modal mineralogy, mineral chemistry, etc.) by specific analytical methods (i.e., automated mineralogy, LA-ICP-MS), the construction of a reference database and, finally, the statistical investigation of the results. A brief overview of selected analytical fingerprint workflows developed in recent years is provided below.

6.2.1 The Analytical Fingerprinting (AFP) Method – Bundesanstalt für Geowissenschaften und Rohstoffe (BGR)

The Federal Institute for Geosciences and Natural Resources (BGR) developed an analytical fingerprint (AFP) protocol to aid the traceability of 3T conflict minerals in the Great Lakes region in Africa (Schütte et al. 2018). Details of the approach can be found in several published articles (Gäbler et al. 2011, 2020, 2017, 2013, Martyna et al. 2018, Melcher et al. 2008, Schütte et al. 2018) and are briefly summarized here. The method focuses on the analysis of mineral concentrates from mine sites in the Great Lakes region in Africa and includes four stages: 1) sampling and sample preparation, 2) definition of the modal mineralogy of the samples by scanning electron microscopy (SEM) coupled with energy-dispersive X-ray spectrometry (EDX), 3) determination of mineral chemistry and isotope composition of individual grains by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) and 4) evaluation of the results through statistical analysis. The latter is undertaken in order to 1) define the signature of specific deposits based on samples of known origin (reference samples) and 2) certify the origin of samples under investigation, generally employing the Kolmogorov-Smirnov test (KS-d) (Schütte et al. 2018).

6.2.2 Characterization of gold concentrate and gold bars from Guyana – Bureau de Recherche Géologique et Minière (BRGM)

Between 2013 and 2015, the French Geological Survey (BRGM) participated in a pilot project funded by the WWF aimed at verifying the possibility of characterizing gold concentrates and gold bars from Guyana and Suriname and identifying their origin (Augé et al. 2015). The study included a first phase involving sampling and the morphological and chemical characterization of gold grains by optical microscopy, SEM and microprobe analysis (EPMA), followed by a second stage aiming at completing the chemical characterization of the grains using LA-ICP-MS for the determination of trace elements and MC-ICP-MS for the measurement of Pb, Cu and Ag isotopes. The approach has evolved over the years and now also includes laser-induced breakdown spectrometry (LIBS) for the determination of Hg (Pochon et al. 2021). Gold certification is generally achieved through the determination of Ag by EPMA or LIBS, followed by statistical analysis to compare the acquired results with a reference database (Pochon et al. 2021).

6.2.3 Geoforensic passport for gold – University of Lausanne (UNIL) and Metalor

In March 2021, Metalor and the University of Lausanne (UNIL) announced the development of a geoforensic passport for gold doré. Their protocol includes three levels of investigation. The first step consists of the chemical characterization of gold doré by EDS XRF analysis. The analysis is followed by evaluation of the results by multivariate statistical analysis (e.g., principal component analysis, linear discriminant analysis) to validate the origin of unknown samples. If the analysis is conclusive, i.e., the origin of the gold can be certified, then then no further investigation is undertaken. If the analysis is inconclusive, the samples are then analysed for the determination of Pb isotopes, followed by further statistical investigation of the newly acquired results. As with other techniques already mentioned, if the unknown analysed material is matched with the reference samples in the reference database, the analysis is considered conclusive and the material is able to be certified. Otherwise, the analysis is deemed as inconclusive and further analyses are required in order to verify the origin of the samples under investigation.

Table 10. Examples of the application of physical fingerprinting for minerals or raw materials.

Commodity/ Mineral	Scope & Scale	Supply chain coverage	Fingerprints	Technology*	References
Gemstones	Local to International	Product	Trace elements	LA-ICP-MS	(Dalpé et al. 2010, Pornwilard et al. 2011)blue, purple, yellow
Gemstones	Local to International	Product (Natural & synthetic)	Minor elements, Trace elements (Be in particular, Ga, Zn, Li)	LIBS, LA-ICP-MS, SIMS	(Abduriyim & Kitawaki 2006)
Base metals	Local to International	Ore	Micro-textures, Bulk mineralogy, Mineral chemistry, Minor elements	SEM, EPMA, pXRF	(Machault et al. 2014
Tin/Cassiterite, Nb-Ta/ Coltan	*Local to Regional*	*Ore to concentrate*	*Trace elements*	*LA-ICP-MS*	*(Gäbler et al. 2011, 2020, 2013)*
Nb-Ta/Coltan	*Local to Regional*	*Ore to concentrate*	*Bulk mineralogy, Mineral chemistry, Trace elements, Radiogenic isotopes (U/Pb)*	*QXRD, SEM/MLA, EPMA, ICP-MS, LA-ICP-MS, TIMS*	*(Melcher et al. 2008)*
Tungsten/ Wolframite	*Local to Regional*	*Ore to concentrate*	*Trace elements*	*LA-ICP-MS*	*(Gäbler et al. 2017, Martyna et al. 2018)*
Uranium/ Uraninite & yellowcake	*Local*	*Ore to product*	*Bulk mineralogy, Grain morphology, Trace elements*	*DRS, LIBS, SEM, XRD, ICP-SFMS, Leach tests*	*(Keegan et al. 2012, 2008, Sirven et al. 2009, Wotherspoon et al. 2014)*
Gold	*Local to International*	*Ore to product*	*Bulk geochemistry, isotopes*	*ED XRF, MC-ICP-MS*	*(Metalor 2021)*
Gold	*Local to Regional*	*Ore to product*	*Grain morphology, Mineral chemistry, isotopes (Pb, Cu, Ag)*	*SEM, EPMA, LIBS, LA-ICP-MS, MC-ICP-MS*	*(Augé et al. 2015, Pochon et al. 2021)*

*Abbreviations: DRS: Differential Reflectance Spectroscopy, EDS-: Energy Dispersive, EPMA: Electron Probe Micro-Analyser ICP: Inductively Coupled Plasma, LA-: Laser Ablation, LIBS: Laser Induced Breakdown Spectroscopy, -MS: Mass Spectrometry, MLA: Mineral Liberation Analyzer, SIMS: Secondary Ion Mass Spectroscopy, TIMS: Thermal Ionization Mass Spectrometry, XCT: X-ray Computed Tomography, (p-)XRF: (Portable) X-Ray Fluorescence, (Q-)XRD: (Quantitative) X-Ray Diffraction.

6.3 Current limitations

There are at least two potential limitations of the physical traceability approach: (i) the stage of the value chain up to which physical traceability can be applied and (ii) the "spatial" resolution.

6.3.1 At which stage of the value chain does physical traceability stop working?

First, the stage of the value chain up to which physical traceability may apply is one of the most important limitations. Indeed, as explained before, the robustness of this approach decreases along the value chain because of the metallurgical processes that may alter the fingerprints on which the method is based. The amplitude and importance of this phenomenon varies significantly depending on the commodity and processing route. For instance, the impact of the processing and refining processes on the production of purified (natural) graphite is expected to be relatively limited. On the contrary, high pressure and high temperature processes are involved in the refining of nickel and cobalt that are very likely to alter the original fingerprints, hindering the applicability of the physical traceability method. Therefore, the integrity of the fingerprints downstream of the value chain for intermediary or final products/materials depends on both the original fingerprints of the source ore and the processes that led to the production of these materials. This means that when the impact of these processes is known and can be quantified, the overprint of the refining processes could be used as an additional means of tracing the origin of the raw materials by being able to trace the likely origin of the source material and the associated refining processes.

In addition, depending on the suppliers and products, raw materials of different sources may be mixed. This makes physical tracing more complex, as the fingerprints of the different sources are then mixed. However, the distinction of multiple sources may be possible, provided a complete fingerprint of the end members exists in the data base (Melcher et al. 2008).

For these reasons, the physical fingerprint has so far been applied in a relatively limited way to the upstream raw material supply chain (e.g., to ores and mineral concentrates), before materials from different sources are mixed or transformed during a refining process, which tends to decrease or alter the concentration of fingerprints and hence the efficacy of the fingerprinting process (Epstein & Yuthas 2011, Melcher et al. 2008). The only commodities for which physical fingerprinting has been applied down to the product level are gold doré (Augé et al. 2015, Metalor 2021) and yellow cake (Sirven et al. 2009)produced with the uranium ore. It is the first step in the fabrication of nuclear fuel. As it contains fissile material its circulation needs to be controlled in order to avoid proliferation. In particular there is an interest in onsite determination of the geographical origin of a sample. The yellow cake elemental composition depends on its production site and can therefore be used to identify its origin. In this work laser-induced breakdown spectroscopy (LIBS, although only local to regional application and limited published data or peer-reviewed publications exist in the case of gold (for commercial and security reasons).

6.3.2 How precise is the identification of the source in analytical fingerprinting?

The "spatial" resolution (or precision) of the fingerprinting approach is also an important consideration. The source of the material can be identified, in increasing order of precision, in terms of:

- Geological context (e.g., magmatic, sedimentary, metamorphic, placer, etc.)
- Continent
- Country
- District
- Deposit
- Mine

The precision of the method will depend on numerous aspects:

- The number and relevance of fingerprints available
- The completeness of the reference database and the presence of similar reference material
- The stage of the value chain at which the method is applied, as discussed above
- The complexity of the production and trade
- The absence or presence of context, additional (certified) information about the material being analysed.

6.3.3 Can physical traceability be used as a one-off solution?

Due to the aforementioned considerations of analytical fingerprinting, it is unlikely that this method will become a unique solution to traceability systems along the whole battery raw materials supply chain (Epstein & Yuthas 2011, Melcher et al. 2008). However, because this method is incorruptible, it offers considerable forensic potential for verification and quality control purposes. It is suggested that analytical fingerprinting can assist in the establishment of a control instrument in a certification procedure for the production and trade chains (Melcher et al. 2008). With this objective, this fingerprinting method could be used to check the results of another verification process, or as a forensic tool in their auditing procedures (Epstein & Yuthas 2011). BATTRACE's fingerprinting technology may provide an answer to the GIGO dilemma in traceability systems. One potential use case for mineral fingerprinting may be as a verification tool for quality assurance and auditing purposes.

7 CONCLUDING DISCUSSION

Traceability is one of the ways to increase transparency along the raw materials supply chain. Ideally, however, traceability of raw materials would not be required if there was global trust that all mining companies act in a socially, environmentally and economically sustainable way. When in place, sustainability and responsibility standards should ensure transparency and trust along the mining supply chains. However, as the global demand for battery minerals is expected to grow exponentially, the increased demand may introduce financial incentives for some companies or actors with poor performance to adopt unsustainable business practices. The traceability of raw materials to their origin, i.e., verification methods regarding the reported origin, would work as a barrier against these actors with poor performance entering their products on the market.

Although the current proposals for battery directives within the EU show signs of requirements for responsible sourcing of materials, there is currently no information on whether there is a legislative or regulatory demand for traceability of battery metals all the way to down to the mines from which they are extracted. Instead, the upcoming 'battery passport' systems will only require information about where the battery cells themselves have been manufactured. If the directives included a requirement for raw material traceability, this would have wide-scale effects either through mandating raw material producers to adopt traceability systems to remain competitive, or through a market split into traceable and un-traceable commodities.

7.1 Traceability and geo-based fingerprinting as part of existing sustainability systems

One objective of the BATTRACE project is to analyse the compatibility of geo-based fingerprinting with currently adopted sustainability and responsibility systems. Compatibility with existing systems would enable easier adoption of the novel traceability technology for companies that already have existing systems in place. However, the adoption of geological fingerprinting as a method for traceability or verification would require the existing systems to demand traceability as part of sustainable and responsible mining.

As the nature and scope of the sustainability systems and reporting standards vary greatly, comparisons between the systems and their relationship with traceability are difficult. Analysis of the fitness of geo-based fingerprinting with currently used sustainability and certification systems is therefore qualitative in nature. The differences between the sustainability systems and their rate of adoption does not enable a set of quantitative benchmarking criteria to be used in comparing the fit between the systems.

There are clear limitations regarding the traceability of raw materials in most of the currently adopted sustainability and reporting systems, standards and certifications. Some of them are intended as standards as a basis for internal process development, while others involve third-party audits and provide commercial value for business purposes.

Currently, the focus of the mining sustainability systems is on the mining companies and mine sites only up to the point where the products are moved to the next step in the supply chain. Some of these systems have standards and guidelines for producing high-quality data that can then be used in any CoC (or traceability) solution, but these standards are limited to the scope of a single company.

Because traceability must be ensured throughout the supply chain to be meaningful, it becomes the responsibility of the OEM or the battery manufacturer to demand traceability from its upstream partners. This is the same for all traceability solutions, including geo-based fingerprinting. This also means that the geo-based fingerprinting solution developed in BATTRACE does not currently fit into the existing sustainability systems used in the mining industry. Traceability will, however, be increasingly demanded by OEMs, which will increase the demand for traceable raw materials and force mining companies to adopt some traceability practices. If there is sufficient market pull, the need for traceability may also influence the existing sustainability systems to include a standardized data model for traceability in compliance with upcoming battery passports. The use of a standardized data model would also ensure the ability of traceability providers to use these data directly with their solutions.

7.2 Traceability solutions for cobalt, lithium and graphite

There are currently many on-going initiatives to introduce traceability solutions to battery mineral supply chains. As batteries contain several metals with different supply chains, the best traceability methods would be able to embrace this variability. Currently, the different solutions are not very transparent, most probably due to commercial competition. Geo-based fingerprinting could be used as a method for traceability for all the battery raw materials presented in this report (Co, Li and graphite). Naturally, the commercial applicability of the method depends on the regulatory development of batteries and the severity of sustainability issues related to each individual element.

As ethical questions dominate in the sustainability considerations concerning cobalt production, the applied CoC model for this metal should be based on a segregation model or identity preservation model (see Fig. 4). This would physically separate ethical production from unethical production and guarantee consumers the ethical production of cobalt in consumables. There are signs that the cobalt market may be separating into traceable and certified cobalt produced by companies such as Umicore, Boliden and Terrafame, and a bulk cobalt for which the ethicality or sustainability of the supply chain cannot be guaranteed. This will also create a natural basis for differentiated pricing for cobalt with commodity brokers, such as LME.

For lithium production, the dominating sustainability considerations relate to water and energy consumption. In addition, ethical questions are also emerging in connection with lithium mining projects in Zimbabwe and the Latin American lithium triangle (Bolivia, Peru and Chile). Currently, however, the ethical questions in the production of lithium are not so dominating as for cobalt. In this sense, the CoC model for traceability solutions in lithium production could be any of those presented in Figure 4. As lithium production from pegmatite ores is energy intensive, the CO2eq intensity of the products may serve as a competitive advantage for those companies with lower-than-average climatic impacts. Currently, however, lithium is not communicated to be included in any digital traceability solution under preparation.

Graphite production is currently globally dominated by China and Chinese companies, but the ethical considerations regarding graphite production are mostly revolving around work safety. The limited production capability outside China and high demand for graphite dictate that there are limited opportunities for battery producers to influence sustainability considerations by limiting their sourcing to other countries. China has initiated advances in more sustainable and responsible graphite production, which should improve sustainability considerations in the future.

7.3 Commercial aspects of traceability and geo-based fingerprinting in battery metals

Although the current main driver for traceability is to ensure responsible and sustainable mining practices, the carbon emissions of the products will probably become the main currency of traceability technologies in terms of commercial applications. This is because the currently adopted business practices around sustainability (and some pilots around traceability) revolve around carbon emissions, since there is a lack of other business metrics regarding sustainability and responsible mining.

Consumer interest is increasingly pushing mining producers and equipment manufacturers towards sustainability and traceability. However, there is a possibility that the cost of traceability will be pushed downwards in the supply chain towards end products and, ultimately, the consumer. Currently, battery producers are not willing to pay a price premium for traceability without any identified additional business benefits. The main driver for traceability comes from regulatory developments such as the EU's forthcoming battery directives.

If traceability is seen only as a separate addition to business operations, the mainstream adoption of any traceability technologies will be difficult. In contrast, if traceability is considered as a logical part of the overall digitalization of entire supply chains, with additional benefits such as inventory management, forecasting, and a carbon emission price premium, its application will appear more appealing for companies. Therefore, mining companies and other supply chain operators would benefit from full consideration of the business benefits of traceability. The possibility of additional profits through lower carbon emissions of raw materials should be communicated by those producers that can trace their products, so that other operators will start to recognize the benefits of traceability and drive the market towards this goal.

Legal and consumer pressure on companies to control their supply chains may lead to the shortening and simplification of these chains. This could mean, for example, fewer (but larger) companies participating in the supply chains and a reduction in the sources of raw materials.

Traceability itself does not guarantee sustainable production but could help to identify companies and operators that do not follow sustainability principles or need improvement in their operations. It also gives a marketing advantage to those companies that can prove the traceability of their products. Greater pressure towards transparency would also create pressure towards increased sustainability actions for those companies that are not yet fully implementing a sustainability mentality in their actions. The demand for transparency and sustainability in international mineral markets could also create pressure on those countries and regions where sustainability is not taken as a priority value.

Many of the digital solutions for traceability are currently based on blockchain technologies, and more applications for the new technology are being developed in relation to supply chain management. However, basing traceability solutions on blockchain does not remove all doubt from the solutions and it does not provide a "silver bullet" solution to traceability. Blockchain technology may help induce trust in information along complex supply chains, but it does not remove the GIGO dilemma of data reliability at the source of the information. It should therefore be noted that while blockchain does add certain value to traceability, it does not solve it directly.

Moreover, many of the companies currently offering traceability solutions also lack the resources and knowhow to incorporate it along entire supply chains and will need to partner with large systems providers to penetrate the traceability market (e.g., Tradelens & IBM). Currently, the traceability of battery raw materials or otherwise is not standardized in any way. The traceability initiatives and pilots that are currently in use are often limited in scope between individual companies and are executed in many cases by smaller start-ups attempting to leverage the new market potential. If traceability becomes commonplace in mining supply chains, it is expected that the market will be consolidated by bigger operators through standardization or acquisitions.

Although geo-based fingerprinting does not currently fit into the existing sustainability systems used in mining, it does have considerable commercial potential as a traceability method and a verification tool. As the geological and elemental characteristics of a sample cannot be altered, the geo-based fingerprinting method developed in BATTRACE has a unique potential in working as a stand-alone traceability technology, or as a complementary verification method with any other traceability system. This includes any digital systems based on blockchain technologies, which may suffer from the GIGO issues, as mentioned in chapter 6.

There are several opportunities for the commercialization of geo-based fingerprinting, which requires further research to fully compare the business potential between different options. Potential avenues for commercialization include setting up a new company to provide sample verification as a service, incorporating the technology as part of other sustainability systems that are in use by battery manufacturers, technology licensing or partnering with existing laboratory service providers, to name a few.

7.4 Sustainable metals from Finland: An opportunity for branding

The EU's goal of reducing its dependence on imports from singular geographical areas outside the EU provides Finnish battery metal and mineral producers a great opportunity for increased market share within the EU. As an example, China holds global dominance over a major part of battery supply chains. This includes graphite production, amongst several other critical minerals, and lithium and cobalt refining. China's dominance in the critical minerals sector has been identified as a potential trade policy threat for the EU economy, and already for a decade the EU commission has acted to lessen its dependency on China in the minerals sector.

In addition to trade policy issues, increased demands to guarantee sustainable practices along supply chains tighten the freedom of action for companies in global markets. An example of this development is the new EU regulations for batteries.

These developments bring an opportunity for Finland´s minerals and metals industry. The country has established geological, technological and societal conditions to support sustainable battery metals production. A new battery strategy for Finland has recently been published and new industrial activities created and investigated in this sector. Companies operating in lithium and cobalt supply chains have arranged their operations so that circulating materials from China is not necessary. Volumes are small at the global level, but the supply chains are shorter and straighter. This creates an advantage in an emerging regulatory environment demanding transparency and sustainability along the supply chain.

One option for Finland to strengthen its position within European battery supply chains would be the introduction of a "Metals from Finland" or a "Metals from Nordic" certificate, in addition to the 'Batteries from Finland' initiative launched in 2021 (Työ- ja elinkeinoministeriö 2021b). With all the positive socio-economic and environmental indicators, raw materials produced by Nordic countries can have added commercial value. The certificate could serve as a proof of origin, but also include a sustainability component. Sustainability could be included, for example, by introducing sustainability threshold conditions that should be met for the certificate. Mass-balance CoC could be used for plants mixing concentrates from different sources. With the certificate, Finland and Finnish companies could sharpen their marketing in the changing operational environment by emphasising their unique position in Europe in battery metals production.

Geo-based fingerprinting could be used as part of such certificates as a verification method by providing the service of a fingerprint or a catalogue of the geological fingerprints of Finland-based metals and minerals. By providing a 'recipe' for Finnish battery metals with a verification option, any battery manufacturer or commodities broker would have the option to verify the source of battery metals marketed with the certificate.

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