MaDiTraCe project roadmap

Deliverable D4.5

Final Version

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Summary

The MaDiTraCe research project, funded by the Horizon Europe programme, was launched in January 2023 and concluded in June 2026. Its objective was to test and develop solutions for the traceability of minerals, materials, and metals—from the mine to the end product.

This deliverable serves as the project's final output, summarizing the key results from its technical work packages:

- The integration of minerals traceability into policies (e.g., the EU Battery Regulation, the Corporate Sustainable Due Diligence Directive) and international initiatives (UN, OECD, and G7);
- The development of the CERA 4-in-1 certification scheme for the mineral raw material sector;
- The testing and development of material fingerprinting solutions for four substances (lithium, cobalt, natural graphite, and neodymium), including as well artificial fingerprints;
- The integration of all these elements into a digital ecosystem and digital material/product passports.

Additionally, this document does a review of different ongoing traceability roadmaps and national initiatives and benchmarks with the situation in other supply chains (timber, textile, food, gemstones). It proposes implementation scenarios that combine all the concepts. These scenarios form the basis for the implementation roadmap. Finally, the project provides policy-oriented recommendations, both within the "Made in Europe" framework and for broader traceability discussions, such as the G7 traceability roadmap.

Keywords

Traceability, roadmap, policy, critical raw materials, due diligence, responsible sourcing, energy transition

Abbreviations and acronyms

Acronym	Description
AFP	Artificial Fingerprinting
ATP	Artificial Tracking Particle
CAB	Conformity Assessment Body
CCS	Chain of Custody Standard
CoC	Chain of Custody
DPP	Digital Product Passport

EoL	End-of-life
FSC	Forest Stewardship Council
GSO	Geological Survey Organisations
ISO	International Organization for Standardization
LCA	Life Cycle Analysis
MFP	Material Fingerprinting
RJC	Responsible Jewellery Council
TIC	Testing, Inspection and Certification
TP	Tracer Particle
UV	Ultraviolet
WP	Work Package

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1 Introduction and purposes

1.1 Introduction to the MaDiTraCe project

MaDiTraCe was a research project funded by the Horizon Europe programme, that took place from January 2023 to June 2026. The objectives of the project were clearly identified since the beginning as stated in the public abstract of the project:

Reliable access to raw materials is essential to Europe's economy and its ability to meet global challenges such as the energy transition. Some critical raw materials (CRMs) are essential to meet these strategic goals. Moreover, demonstrating sustainable sourcing will be required in the future. Reducing risk and enhancing security through better tracking these CRMs which are essential for low-carbon technologies (lithium, cobalt, natural graphite, REEs) as well as improving transparency of their supply chains is the focus of the EU-funded MaDiTraCe project. MaDiTraCe will develop and test digital, geochemical and artificial fingerprinting approaches for CRM traceability and integrate them with a generic certification scheme. It will enhance the reliable supply of these CRMs and support compliance with current and future regulations.

Project objectives are presented in Figure 1 as well.

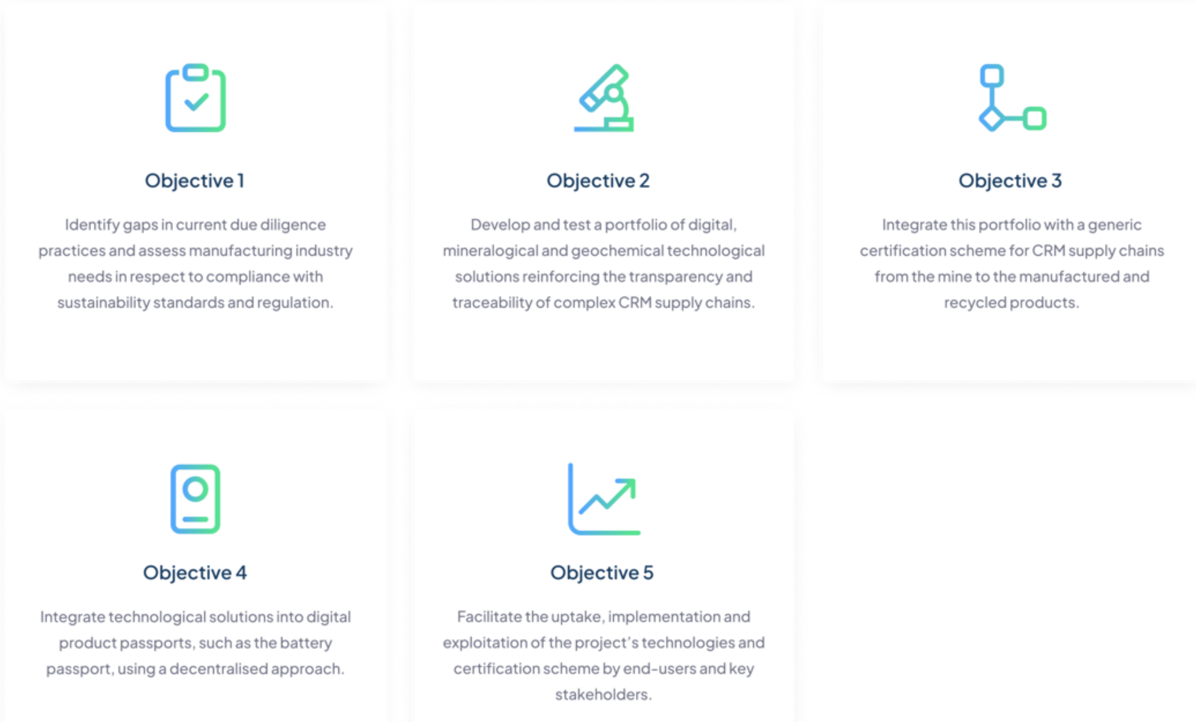

Figure 1: MaDiTraCe project initial objectives

1.2 Purpose of this document

MaDiTraCe project achieved several technical deliverables related to four technical work packages. The present deliverable acts as a final deliverable of the project. The purpose of this document is to:

- Integrate critical raw materials traceability in the landscape of current and future regulations
- Present several of the main results of different work packages of the project
- Present scenarios of application
- Present an implementation roadmap
- Give recommendations oriented to policy

1.3 What is traceability

The term traceability applied to minerals has been defined in several documents, and it has been the subject of recent studies. The multiplicity of the definitions highlights the political stakes of the subject, as it defines the extent to which transparency is required. We prefer to refer to the documents that already exist and clarify the concept. Traceability has become a policy salient term for corporate and policy actors, due to rising legal obligations (Corporate Sustainability Due Diligence Directive (CSDDD) or Battery Regulation) to conduct risk based-due diligence, geopolitical concerns for access to critical minerals, and the International Organization for Standardization (ISO) created several working groups addressing this topic[1]. Traceability of mineral supply chains is one of the main points in G7 countries "Roadmap to Promote Standards-based Markets for Critical Minerals"[2].

The OECD-IEA report published in 2025 made a clarification and an overview of several definitions of traceability that we copy here.

The most used definition of "traceability" is the one developed by the International Organization for Standardization (ISO), which defines traceability as *"[t]he ability to trace the history, application or location of an object". The ISO definition further specifies that "[w]hen considering a product or a service, traceability can relate to: the origin of materials and parts; the processing history; [or] the distribution and location of the product or service after delivery"*.

The International Social and Environmental Accreditation and Labelling Alliance has used the ISO definition to develop its own definition of traceability, which it defines as *"[t]he ability to verify the history, location, or application of an item by means of documented recorded identification"*. In a similar vein, the non-governmental organization Business for Social Responsibility defines traceability as *"the process of tracking the provenance and journey of products and their inputs, from the very start of the supply chain through to end-use"*.

In the food safety context, the United Nations Codex Alimentarius Commission's Procedural Manual defines traceability as *"the ability to follow the movement of a food through specified stage(s) of production, processing, and distribution"*.

The European Union's General Food Law defines traceability as *"the ability to trace and follow a food, feed, food-producing animal or substance intended to be, or expected to be incorporated into a food or feed, through all stages of production, processing and distribution"*.

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[1] https://www.iso.org/standard/85076.html

[2] https://www.canada.ca/en/natural-resources-canada/news/2025/10/roadmap-to-promote-standards-based-markets-for-critical-minerals.html

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In the minerals context, the Responsible Minerals Initiative has previously defined traceability as *"the capacity to preserve and verify the chain of custody of goods – their flow from one end of the supply chain to the other"*.

Similarly, BRGM defines traceability as *"the ability to identify a product's source and trace or reconstruct its path, from the initial raw material through to the distributed manufactured product"*.

Inside traceability, we often identify connected concepts.

Digital traceability and blockchain technology: refers to the use of interoperable information systems to record, store, and transmit data on material flows and transactions along the value chain, with blockchain technologies offering enhanced data integrity, transparency, and resistance to tampering through decentralized and immutable records.

Geoforensic and material fingerprinting: analytical methods that use the intrinsic physical, chemical, and isotopic characteristics of raw materials to determine their geographical origin and reconstruct their transformation pathway, thereby enabling scientific verification of provenance independent of documentary evidence (Desaulty et al 2022).

Artificial fingerprinting: the artificial alteration of raw materials through the addition of chemical or physical particles or tracers (hereon referred to as artificial taggant particles (ATPs) or tracer particles (TPs)) with unique functional properties to the raw material itself or its container. TPs are used to demarcate materials and objects for the purpose of identification, anti-counterfeiting and tracking (Donnelly et al., 2023).

1.4 Why traceability?

According to the OECD, traceability for minerals is essential for several key reasons:

1. **Risk Mitigation**: Mineral supply chains can be linked to human rights abuses (e.g., child labor, forced labor), conflict financing, corruption, money laundering, and environmental harm. Traceability systems help companies identify, prevent, and mitigate these risks by providing reliable data on the origin, evolution, and ownership of minerals, enabling meaningful risk assessments and remediation.
2. **Policy and Compliance**: Traceability supports emerging policy goals by integrating data on mineral origins and transformations, ensuring compliance with regulations like CSDDD or battery regulation. OECD Due Diligence Guidance for Responsible Supply Chains of Minerals is widely adopted in laws across Europe, Africa, the Middle East, and the Americas, requiring companies to address adverse impacts in their supply chains.
3. **Supply Chain Resilience**: Overlooking risks in mineral supply chains can disrupt the supply of critical materials needed for clean energy technologies and other strategic industries. Traceability helps maintain stable, ethical, and sustainable supply chains, which are vital for the green transition.
4. **Transparency and Accountability**: The lack of reliable information on material origin, geographical path, chain of custody, and physical transformation hinders risk assessments and mitigation. Traceability systems provide the transparency needed for credible due diligence and stakeholder trust.

5. **Supporting Clear Objectives**: The OECD emphasizes that traceability should not be an end in itself but should serve clear objectives, such as improving sustainability, ethical sourcing, and circular economy practices. It should be deployed progressively and inclusively to avoid market fragmentation.

This roadmap is being published and presented in a very particular moment (June 2026) when geopolitics and particularly raw materials are in the middle of tensions. Associated to that we observe a proliferation of documents from public agencies (OECD, IEA, EU Commission, G7, think tanks, NGOs) as well as a plethora of scientific articles on this topic. Unfortunately, it was therefore impossible to integrate here the most recent developments in the field.

According to a recent IEA (2026) report addressing traceability of critical raw materials for energy sector, there are two major drivers for adoption of traceability policies depending on the position of a country in the supply chain, a major distinction being between mining countries and consuming countries:

- Mining countries encourage policies or roadmaps based on proof on the geographical origin and encourage domestic use. Australian traceability roadmap and the consultation for a "Mined in Canada" credential are initiatives going in this direction, both led by mining OECD countries
- Consuming countries, have focused more on the introduction of sourcing requirements
    - Traceability as a tool for enabling supply chain diversification, reducing concentration. In this particular point we can cite regulations such as EU CRM Act or USA Inflation Act.
    - Promoting responsible practices across global mineral supply chains like Corporate Sustainability Due Diligence Directive. Here, however, we observe as well a reduction of certain policy ambitions like in recent omnibus debates related to responsible due diligence directive in Europe.

From a company perspective, referring once again to IEA report (2026), we can cite two main drivers for traceability, with a big distinction between downstream companies and upstream. Reputational considerations and customer demand are mostly the drivers for traceability for downstream companies whereas compliance with regulatory requirements is the main driver for upstream sector.

1.4.1 Traceability in EU regulation

Mineral raw materials traceability is related mainly to three EU regulations: EU battery regulation (EBR), Corporate Sustainability Due Diligence Directive (CSDDD) and Critical Raw Materials Act (CRMA).

The **European Battery Regulation** (EU) 2023/1542 (EBR), enacted in 2023, introduces comprehensive requirements for sustainable and safe battery production. Its scope spans the entire product lifecycle and addresses the performance standards, the end-of-life solutions, and the recycling (European Union, 2023). Traceability is one of the objectives of this regulation.

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"Ensuring traceability of a battery throughout the whole supply chain helps to make market surveillance simpler and more efficient and provides transparency to consumers. ***An efficient traceability system facilitates*** *the market surveillance authorities' task of tracing economic operators who have placed on the market, made available on the market, or put into service non-compliant batteries. Economic operators should therefore be required to keep information on their transactions involving batteries for a certain period, including in electronic form*".

In particular, CHAPTER VII, covering Articles 47 through 53, establishes a due diligence framework, representing a transformative development for the battery industry. This framework ensures the effective management of supply chains for critical raw materials, such as cobalt, nickel, lithium and natural graphite, and of chemical compounds based on them (EBR, 2023; Mattea, 2023). From 18 August 2027 (Council of the EU, 2025), economic operators placing batteries on the market or putting them into service shall comply with the due diligence obligations set out in the Regulation by implementing specific battery due diligence policies to ensure responsible sourcing and sustainable, circular management of supply chains ensure responsible sourcing and sustainable management of the supply chain recycling (EBR, 2023). CSDDD identifies traceability technical solutions as follows: "*Digital tools and technologies, such as those used for tracking, surveillance or tracing raw materials, goods and products throughout value chains, for instance satellites, drones, radars, or platform-based solutions, could support and reduce the cost of data gathering for value chain management, including the identification and assessment of adverse impacts, prevention and mitigation, and monitoring of the effectiveness of due diligence measures. In order to help companies fulfil their due diligence obligations along their value chain, the use of such tools and technologies should be encouraged and promoted. To that end, the Commission should issue guidelines with useful information and references to appropriate resources. When using digital tools and technologies, companies should take into account and appropriately address possible risks associated therewith and put in place mechanisms to verify the appropriateness of the information obtained.*" (European Union, 2024).

It should be noted that the Omnibus Directive (European Commission, 2024) introduced simplifications to the scope and implementation of the CSDDD. These adjustments reduced the number of companies falling under the directive by raising the employee and turnover thresholds, narrowed the scope of systematic due diligence primarily to direct business partners, and extended the review period for risk assessments from annual to every five years. They also postponed the timeline for climate-related obligations and overall application deadlines, giving companies more time to prepare. In addition, the Omnibus removed the draft's EU-wide civil liability regime and streamlined stakeholder engagement obligations, while capping the information large firms can request from SMEs to avoid excessive reporting burdens.

CRMA is not an act that addresses directly traceability purposes. In fact, the word traceability is not mentioned in the final text of the CRMA. However, CRMA recognizes and encourages certification schemes that meet criteria fixed in Annex IV of CRMA. A recognized certification scheme shall meet the following criteria:

1. It is open under transparent, fair, and non-discriminatory terms to all economic operators willing and able to comply with the scheme's requirements and subject to multi-stakeholder governance.

2. Verification and monitoring of compliance is objective, based on international, Union or national standards, requirements and procedures and carried out independently from the relevant economic operator.
3. It includes sufficient requirements and procedures to ensure the competence and independence of the verifiers responsible.
4. It includes requirements to ensure an audit report is established at the site level.

To summarize, the place of traceability if those regularity texts is as follows:

- **EU Battery regulation**. Fixes a required digital product passport for battery production. The traceability system would be at the heart of the regulation and ensure the reliability of the passport and hence, the proper application of the regulation.
- **CSDDD**. Traceability is encouraged. Those solutions would help companies address data gaps and risk assessment. For digital tools, companies should take into account mechanisms of verification.
- **CRM Act**. Fixes the conditions for critical raw materials certification schemes in Europe. Those certification schemes would request traceability systems and differentiate between certified and non-certified CRM sources.

1.5 Drivers for material traceability for different groups of stakeholders

As stated by IEA (2026), currently, companies across the mineral supply chain—from upstream to downstream—often lack strong incentives to collect, share, or demand verified traceability data. To change this, governments can integrate traceability incentives directly into critical mineral policies. By combining regulatory, financial, and market-based measures, they can drive adoption throughout the supply chain. A strategic mix of "push" (mandates) and "pull" (incentives) mechanisms can further amplify impact and effectiveness.

The following chapter identifies motivations, incentives, and drivers for the upstream, midstream, and downstream industrial sectors to adhere to a traceability system, but also identifies threats and challenges.

1.5.1 Upstream sector

Upstream sector in Europe.

For the MaDiTraCe project assessed substances (lithium, natural graphite, cobalt, and rare earths), the local primary production in Europe is very low, but there is the possibility of increased production if CRM Act strategic projects become viable. However, the degree of dependence on midstream/refining outside Europe is very high.

In any case, for the upstream European industry, a traceability system can be a competitive advantage if local criteria become a market criterion for key sectors such as energy, battery, or automobile. With the EU Industrial Accelerator Act and the introduction of "Made in Europe" criteria, there is a clear possibility for a geographical guarantee of origin. This Made in Europe mechanism could engage the attribution of public funding or public purchasing

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linked to “Made in Europe” criteria, like a minimal European material content. However, the Industrial Accelerator Act is at the level of a project under discussion, and in the current debate (in March-April 2026), the concept of what is Made in Europe is under debate. So, there is a clear possibility and interest for upstream sectors in Europe, but the real interest would depend on the final decision and definition of the Made in Europe criteria. If the “Made in Europe” criteria tend to dilute or downsize expectations of upstream industry, then the interest in a traceability system with proof of origin will decrease.

Sustainably sourced materials could be associated with a price premium as it seems to be already the case (IEA 2026). In this case, de facto, traceability systems would appear necessary as a mechanism for validating and controlling any fraud risk.

Global upstream sector

The integration of a “Mined in” credential system and the resulting access to markets where geographic origin is a key criterion would be a major driver for the deployment of traceability systems and for increasing interest across the global upstream sector. Consequently, the level of interest in the upstream sector is likely to vary significantly between regions, depending on geographic context and the extent to which sustainable practices are implemented.

Upstream companies following voluntary sustainability standards (VSS) can have an interest in participating in global traceability systems, as the labelling or certification following VSS can be a competitive criterion. The investment and application of any VSS is an effort that upstream companies would like to valorise to downstream actors. The global upstream sector would be interested as well in a premium when sustainability criteria are requested.

In mining OECD countries such as Australia and Canada, there are already initiatives going in the direction of “proof of origin” with different traceability initiatives. The ambition is to connect national proof of origin initiatives with global traceability systems, and here, the European battery passport is systematically mentioned as a key system. A particular attention to it will be showed in sections 2.2 and 2.5.

However, those initiatives are very focused on the origin of primary commodities, face difficulties as the main metal refining capacities are located in third countries, mostly in China. The proof of origin could be maintained downstream in the supply chain but that would require a traceability system that integrates and addresses interoperability with the Chinese material/product passport system.

1.5.2 Midstream sector

The midstream sector for electric vehicles and batteries includes metal refining/processing and precursors manufacturing (e.g., pCAM), cell components (e.g., cathode, anode) (IEA 2025).

European midstream sector

The current midstream capacity for battery (metal processing, pCAM, anode, cell components, battery cell) or magnet production in Europe is very low. Several European lithium extraction projects include lithium refining capacity as well (Cinovec, Emili, Ageli, Vulcan, and Keliber plans lithium process). However, stages such as the processing of other metals into sulfates, as well as pCAM production and anode fabrication, remain largely concentrated in China. For magnets there is a similar situation, with several projects planned, but presently the EU depends totally on China (IEA 2024).

The emerging midstream battery and magnet sector in Europe could be favourable to a traceability system, especially if they are closely associated with raw material extraction projects. In addition, a framework such as "Made in Europe" would be a booster for this traceability system, but at the same time, the realism, at least in the short term, would be to connect and interact with other systems worldwide, especially Chinese digital passports.

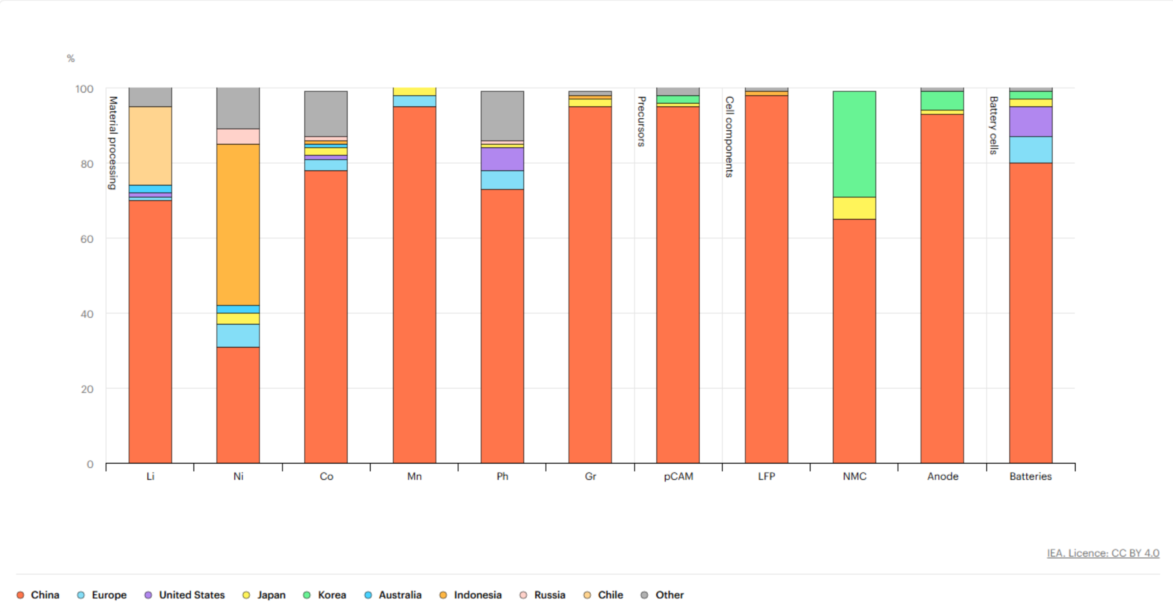

Figure 2: midstream and downstream global supply chain capacity in 2024 (source IEA 2025).

Global midstream sector

At a global scale, the midstream sector can share the same motivations than global upstream sector, to have access to European market or the standard based market.

However, the current midstream capacity means are located in China. Upstream proof of origin initiatives (like Canada and Australia) risk being diluted or missed when materials are processed and mixed in China. When the midstream sector is considered, any international traceability system must be compatible and interoperable with the Chinese digital material/product system. Without that, traceability would only cover a few material flows within OECD countries.

The existence of a traceability system is not going to solve the diversification objective of the midstream industry.

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1.5.3 Downstream sector

European downstream sector

The European downstream sector could be interested in a Made in Europe system but recent position papers from industrial alliances like ACEA (European Automobile Manufacturers) debate about it. More particularly, the introduction of a local content requirement generates a debate as European material content can generate over-costs:

"However, the introduction of Local Content Requirements (LCRs) must be handled carefully to avoid negative impacts on competitiveness, supply chain efficiency, and market dynamics. The lack of clarity around the scope, definitions, and timelines of these requirements makes it difficult to assess their full impact."

"Introducing leaner and fairer rules of calculating "local content", recognising the significant value added by vehicle manufacturers in vehicle production, and the important economic role of vehicles manufactured in Europe for exports."

However, as stated by several authors and EIA (2026), the main driver for traceability for the downstream sector is reputational and here traceability is a reality. With or without "Made in Europe" possibility, traceability under the umbrella on existing regulations is already implemented.

Global downstream sector

The accessibility to the European market under EU regulations and the alignment within a standard-based market could be the main motivation and driver for the downstream sector.

Inside the community of the battery passport and service providers consulted during MaDiTraCe project events, there is an expectation to know how the first battery passports in Europe in February 2027 would be reported, and the degree of information communicated by OEMs around the world commercializing batteries in Europe. As observed by Evans (2026) Europe picked batteries—a complex technology requiring 80+ data points—as the first DPP pilot, yet the sector is dominated by Chinese manufacturers. This means foreign firms have outsized influence over the EU's first DPP rollout. The risk of interoperability fails is there.

The next table identifies opportunities and threats/challenges related to raw materials traceability for the three levels of the supply chain. We also differentiate EU actors and OECD countries as certain initiatives can generate different positions.

Sector	Opportunities	Threats
Upstream – EU	- "Made in Europe" criteria cover explicitly mining activity - Sustainable premium - Standards are supposed to be applied by default/regulation	- Battery supply chain still not in Europe - "Made in Europe" criteria are mostly for midstream and downstream - Small refining capacity in Europe, refining happens elsewhere. Paradox: mined in Europe, refined

Sector	Opportunities	Threats
		elsewhere. Proof of origin information is diluted or lost
Upstream – OECD	- Mining companies with VSS see traceability as an opportunity - Initiatives in Canada and Australia (proof of origin) - G7 roadmap & Standard based market - Sustainable premium	- High dependency to midstream industry in China. Proof of origin information is diluted or lost
Upstream – global	- Mining companies with VSS see traceability as an opportunity - Interest in having access to the EU market - Global VSS initiatives – ISO	- Interoperability between systems
Midstream – EU	- CO2 footprint in Europe vs. the rest of the world in some cases. - Made in Europe - Recycled content	- Global efforts reducing carbon footprint - Competitive with Asian companies - Interoperability between systems
Midstream - OECD	- Standard-based market	- Interoperability between systems
Midstream – global	- Interest in having access to EU market	- Recycled content - Interoperability between systems
Downstream – EU	- Made in Europe advantage - Encompass with due diligence & battery regulation and reputation risk	- Status quo situation. Made in Europe, mined elsewhere - Interoperability between systems
Downstream - OECD	- Interest in having access to EU market - Standard based market	- Interoperability between systems
Downstream - Global	- Interest in having access to EU market	- Interoperability between systems

Table 1: Opportunities and threats for the adoption of a mineral traceability system for upstream/midstream/downstream companies.

2 Review of recent documents, works and initiatives about mineral raw materials traceability

2.1 IEA-OECD documents

In 2025, the International Energy Agency (IEA) and the Organisation for Economic Co-operation and Development (OECD) jointly published "The Role of Traceability in Critical Mineral Supply Chains" (OECD & IEA, 2025), a report prepared under the guidance of a dedicated Task Force of the IEA Working Party on Critical Minerals. The report was developed in consultation with governments, civil society, including organisations representing Indigenous Peoples, industry associations, and industry representatives.

The report is based on the premise that supply chains for critical minerals cannot be truly secure, reliable and resilient unless they are also sustainable and responsible. As the energy transition accelerates demand for minerals such as lithium, cobalt, nickel, copper, graphite, and rare earth elements, in the IEA's Net Zero Emissions by 2050 Scenario, mineral demand nearly triples by 2030, which would mean the development of about 150 average-sized new mines, processing facilities and refineries.

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The report provides a working definition of traceability as the capacity to determine where a particular product originates, where it has travelled, who has handled it, and what modifications it has undergone, covering four core informational elements: i) Origin, ii) Geographical path; iii) Chain of custody, and iv) Physical evolution. It further clarifies the relationship between traceability and related concepts such as due diligence, supply chain mapping, chain of custody, and product transparency, emphasising that traceability is not equivalent to due diligence, instead, it is one approach for achieving the level of transparency necessary to identify, prevent, mitigate and account for how companies address actual and potential adverse impacts.

On the regulatory landscape, the report finds that since 2010, regulations requiring supply chain due diligence have encouraged new industry efforts to map targeted mineral supply chains and use information on the country and mine of origin to mitigate risks, with mineral due diligence measures expanding in number and scope since then. Key regulatory instruments reviewed include the EU Batteries Regulation[3], the US Inflation Reduction Act[4], the Uyghur Forced Labor Prevention Act[5], China's Rare Earth Management Regulation[6], and Indonesia's SIMBARA platform[7], among others.

The report identifies four key components of an effective mineral traceability system: appropriate technical infrastructure, standardised data collection, supply chain collaboration, and governance and verification (see Figure 3). On technology, it notes that while digital tools such as blockchain, RFID, AI, and fingerprinting offer significant benefits, blockchain is only as good as the data entered. It cannot provide certainty about the quality of the data entered. On interoperability, it highlights the role of the UN Transparency Protocol as a standardised technical toolkit enabling different systems to exchange data through digital product passports and conformity credentials.

[3] https://eur-lex.europa.eu/eli/reg/2023/1542/oj/eng
[4] https://www.iea.org/policies/25161-final-rules-on-the-clean-vehicle-provisions-of-the-inflation-reduction-act
[5] https://www.iea.org/policies/18020-uyghur-forced-labor-prevention-act
[6] https://www.iea.org/policies/25387-regulations-on-the-management-of-rare-earths
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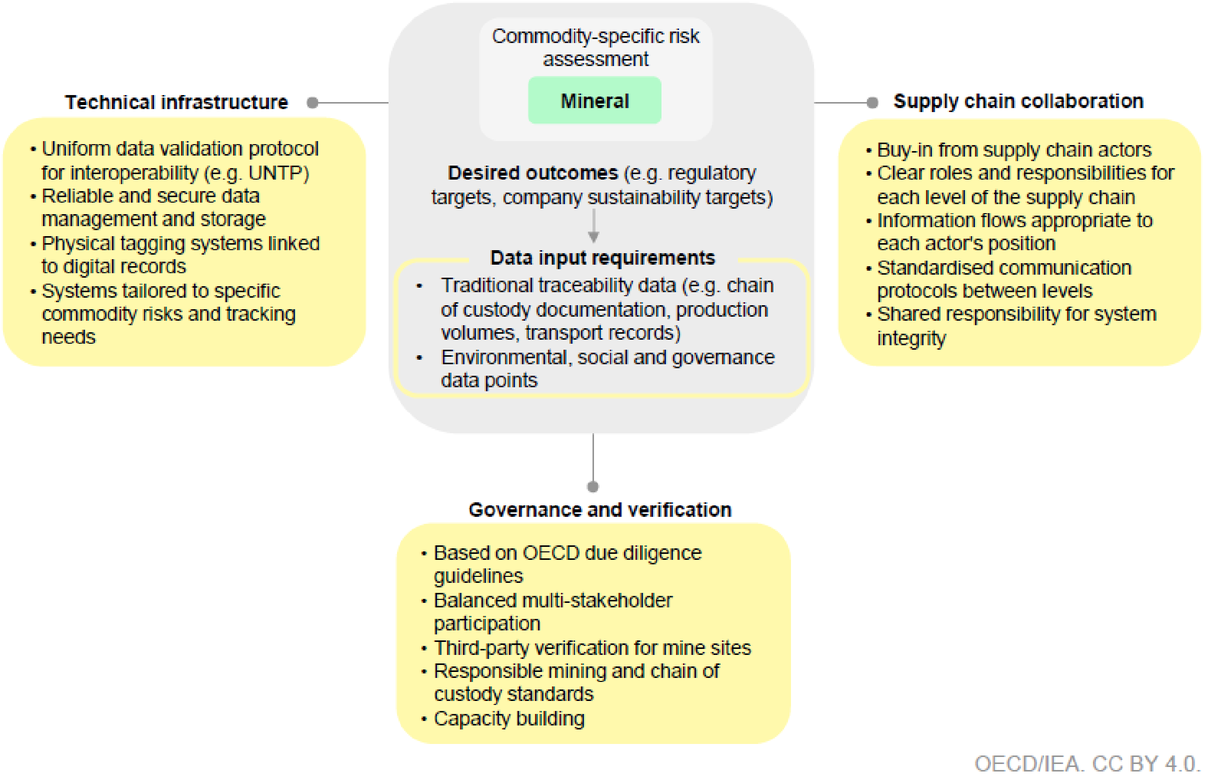

Figure 3: Conceptualising a critical mineral traceability system. Source: OECD & IEA (2025).

The report also provides a mineral-by-mineral analysis of traceability challenges for six key energy transition minerals. It notes, for example, that graphite is the most geographically concentrated mineral, with about 80% of mining and almost 100% of refining occurring in China, and with almost 300 companies in its supply chain, making full traceability extremely difficult and costly. For cobalt, it warns that disengaging from the artisanal and small-scale mining sector due to the challenges of achieving full traceability does not constitute responsible sourcing and may exacerbate the root causes of child labour.

The report concludes with a practical eight-step roadmap for policy makers:

1. Determine the policy objectives and understand the supply chain context
2. Choose which products to focus on
3. Determine which information should be collected and shared
4. Choose which operators to focus on
5. Promote the development and use of interoperability protocols
6. Establish trust mechanisms
7. Create incentives for increasing traceability.
8. Engage with stakeholders in foreign jurisdictions

Throughout, the report stresses that traceability should not be seen as the goal in and of itself. Traceability systems should aim to support clear objectives and a measured, progressive approach, rather than prescriptive mandates for immediate end-to-end traceability, to maintain smooth market functioning and ensure inclusive participation by source countries and smaller operators.

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More recently, in May 2026, IEA with the collaboration of OECD published a new report mapping different traceability initiatives and presents the result of a survey of companies about the implementation of traceability tools in their respective supply chains. This report covers only main energy transition related commodities: copper, lithium, graphite, rare earths and nickel.

50% of surveyed companies uses document paper or digital information tools and more than 25% use XRF or laboratory analyse of random sample. Less than 25% uses material fingerprinting. Between 15 and 20% of surveyed companies indicated price premiums.

Around 90% of companies with a traceability system declared to know the country of origin of materials and the location of the mine around 80%. Corporate transparency information (ownership of mine, taxes, sanction checks) and environmental (scope 1 and 2 GHG emissions, environmental audits, biodiversity impact) are disclosed for less than 50%. So, inside the group of companies with a traceability system, geographical origin at country level is well addressed, even at mine level, but ESG criteria is only present in less than 50% of those traceability systems.

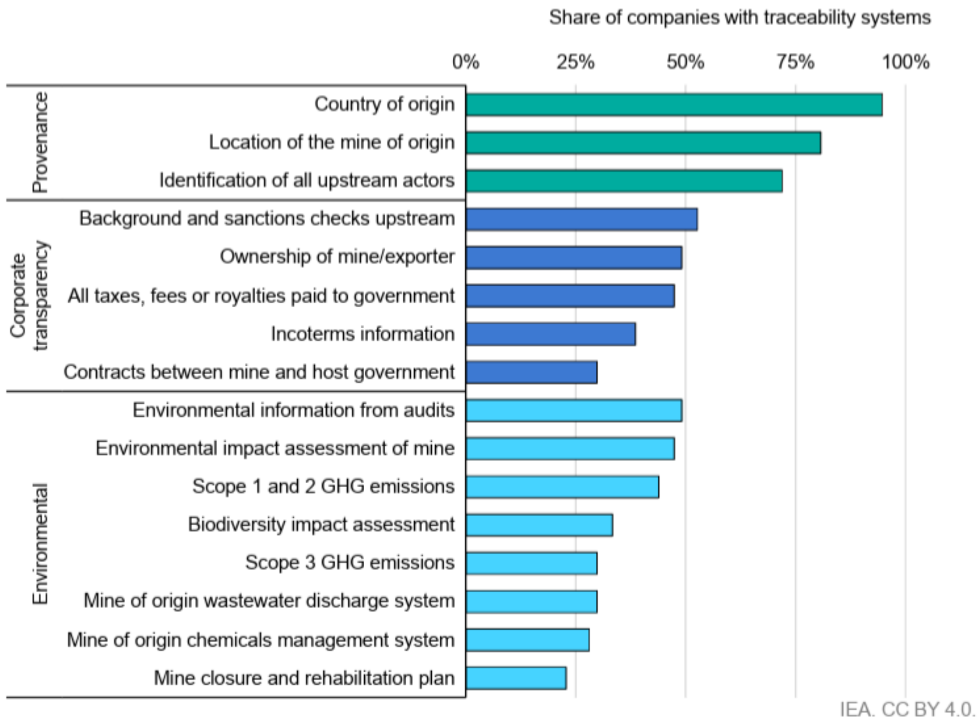

Figure 4: share of companies with traceability systems and the type of information contained in these systems. Source: IEA (2026).

The report identifies four main challenges or barriers for traceability in mineral supply chains and proposes four solutions for it, basically consisting in more collaboration upstream-downstream and internationally, strength policy instruments and financial support for technical infrastructure.

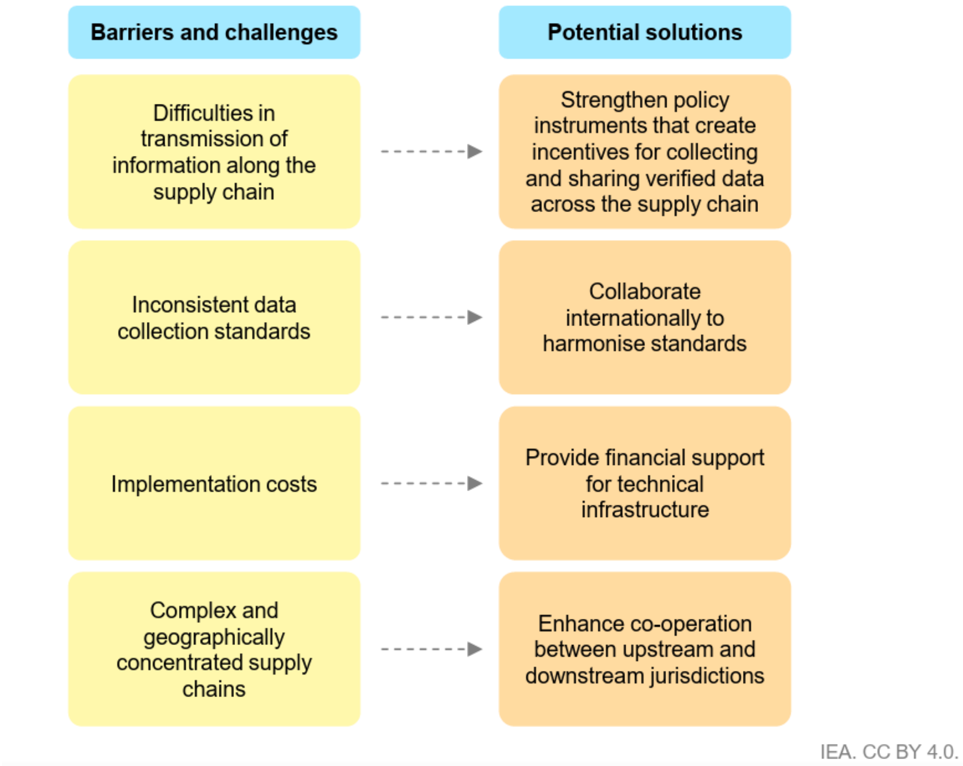

Figure 5: barriers, challenges and potential solutions for the adoption of traceability systems for mineral supply chains. Source: IEA (2026).

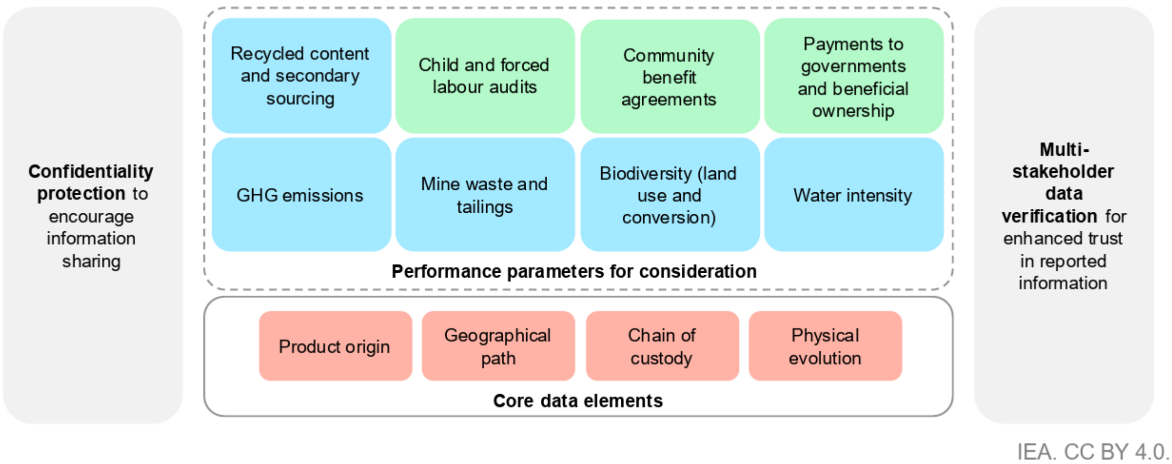

Figure 6: core data elements in traceability systems and performance parameters that shall be included/considered. Source: IEA (2026).

Insights for a MaDiTraCe roadmap

Those IEA-OECD documents are very relevant for MaDiTraCe project objectives and the project roadmap.

First, they bring strong recommendations in terms of policy, even though those recommendations are well known since the beginning: the implementation of those traceability systems requires more collaboration between upstream-midstream-downstream and at international level, with more interoperability between systems.

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Last IEA report indicates also the place for improvement into those current systems, as the study clearly shows that ESG reporting and performance parameters (environmental and social) are still absent in more than half of companies with a traceability system.

2.2 Australian roadmap

In 2024 a report from FrontierSI for Queensland government and Queensland geological survey presented a roadmap for critical raw materials traceability for Australia. This roadmap presents a 5-level roadmap from a first level where a framework for a provenance and traceability system in Australia is defined (with a governance structure) and the last level is a optimised system, with equivalent systems elsewhere.

The objectives of this roadmap are:

- To provide a framework for critical minerals' provenance and traceability ecosystem in Australia.
- To demonstrate provenance as a nationally endorsed credential.
- To provide a framework for supply chain traceability.
- To realise economic benefits from data-driven decision-making.
- To benefit from the circularity of a sustainable mineral supply chain.
- To ensure participation and benefit sharing to First Nations groups.

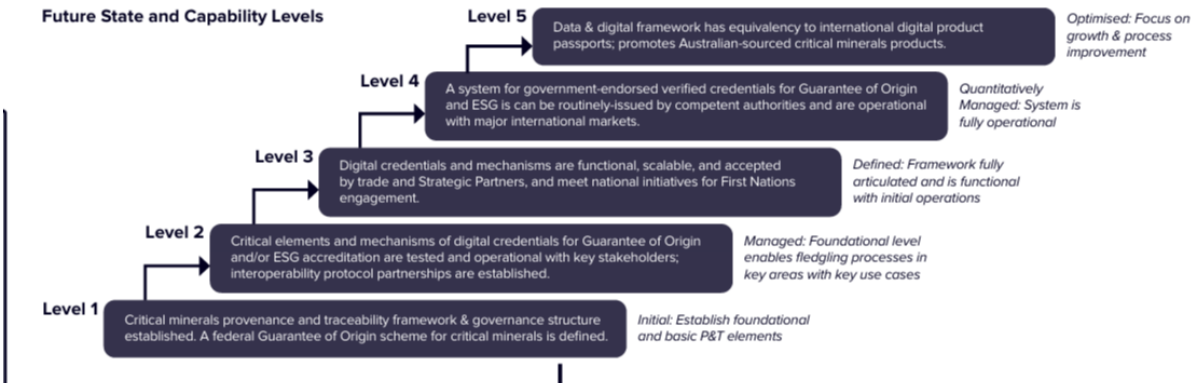

Figure 7: five capability levels from the Australia roadmap for critical raw materials traceability. Source: FrontierSI (2024).

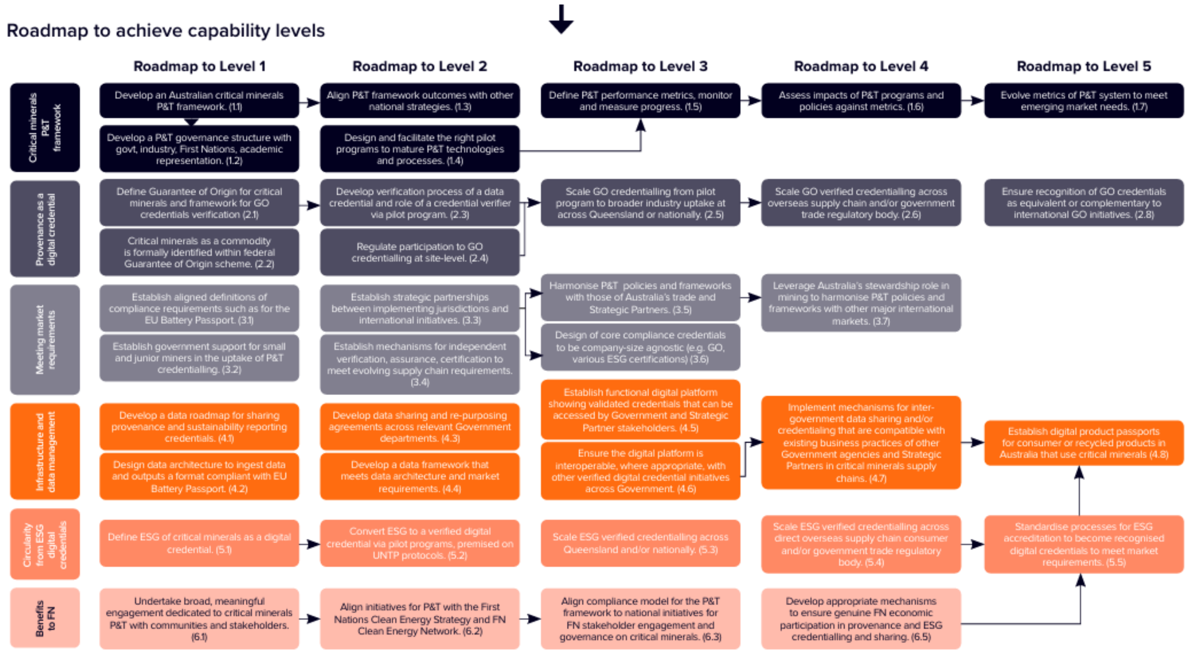

Figure 8: Australian roadmap to achieve capability levels. Source: FrontierSI (2024).

Insights to MaDiTraCe and European context

This roadmap has the particularity of being designed for an upstream country. The Australian roadmap clearly identifies the provenance of materials from Australia as an essential element of the strategy. With certain exceptions, Europe does not directly import unprocessed materials from Australia but rather processed products containing materials mined there. Midstream metal smelting mostly takes place in China.

In the current situation, any verified credential proving the Australian origin of materials (for example lithium) would naturally end up in the Chinese material passport system. If this information were later included in the battery passports of batteries commercialized in Europe, following the EU battery passport system, it would represent a perfect example of interoperability between the Australian, Chinese, and EU systems. However, MaDiTraCe authors we assume a clear risk that any proof-of-origin credential for materials from Australia could be lost or diluted once those materials are processed in China.

This roadmap clearly identifies the establishment of a Verified Credential system for materials mined in Australia, including a governance framework and body, where ESG aspects are key components. The ambition is to connect upstream, midstream, and downstream actors, with the clear goal of gaining access to the European market.

From a due diligence and chain-of-custody perspective, country-level credentials are not sufficient. Within a country, different practices can coexist among different companies. Taking the example of Australia and its lithium mines, there are several hard-rock projects in joint ventures with Chinese mining companies, and these projects claim compliance with various voluntary sustainability standards. The country origin by itself is not a guarantee of any ESG criteria.

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2.3 UN CEFACT

UN/CEFACT (United Nations Centre for Trade Facilitation and Electronic Business) is a subsidiary body of the United Nations Economic Commission for Europe (UNECE) that focuses on simplifying and harmonizing international trade procedures and information exchange. They work in traceability to enhance transparency, efficiency, and trust in global supply chains by developing standards and recommendations that enable the tracking of goods and transactions across borders, ensuring compliance, reducing fraud, and improving trade facilitation.

In July 2025, UNECE published a white paper where they identified cross-border cooperation solutions regarding DPPs and CRMs for batteries. Figure 9 summarizes the main outcomes of this work, where interoperability, mutual recognition and cooperation are keywords.

1 **Digital Product Passports should be** designed to support sustainability and circularity by facilitating the easy tracking of products and the sharing of information across international and multi-sector value chains**. (Chapters 2,3, and 4)**

2 **Legal conflicts in implementing DPPs (Chapter 5)**

- States define and regulate CRMs differently. Different DPPs and traceability systems in the EU, China, and the US lack interoperability. Both create confusion and increase costs in business compliance.
- Jurisdiction tensions exist between states when regulating data required by DPPs, illustrated by the competing demands of data transparency, privacy, security, and business confidentiality and incoherent regulations of cross-border data flows.
- Confusions in applicable laws causing uncertainties to the CRM-Battery value chains with DPPs and circular industries.
- When enforcing DPPs, measures need to be taken to engage SMEs and the Global South countries.

3 **To address these multifaceted conflicts, five principles are proposed to enhance legal coordination between states or businesses in the CRM-Battery value chains (Chapter 6):**

- Leverage existing legal framework and develop international law for digital traceability
- Respect mandatory laws and public policy exceptions
- Maintain certainty and predictability
- Ensure inclusivity and support for SMEs and developing countries
- Achieve mutual recognition of regulatory outcomes across jurisdictions

Figure 9: UNECE white paper outcomes and recommendations.

In addition to this white paper UN CEFACT developed UNTP. UNTP stands for United Nations Transparency Protocol, an initiative developed under UN/CEFACT to enhance transparency and trust in global trade. It works in traceability by providing a standardized, interoperable protocol that allows supply chain data to be shared and verified across borders and platforms, helping to combat greenwashing and ensure the credibility of sustainability claims. The UNTP is designed to be compatible with existing standards like GS1 and supports the creation of Digital Product Passports, making it easier to track and verify product information throughout the supply chain

Insights for MaDiTraCe project roadmap

Main insights of UNECE/UN CEFACT white paper are oriented for a policy public, MaDiTraCe is only a research project. However, main insights of this white paper should be a sort of baseline for traceability systems. International cooperation and legal conflicts are one of the main issues where MaDiTraCe project identifies those challenges and threats as well.

The technical integration of UNTP into MaDiTraCe would be described later in chapter 4.4.

2.4 G7 countries roadmap

On June 17, at the 2025 G7 Summit in Kananaskis, Canada, G7 Leaders announced the Critical Minerals Action Plan[8], which tasked relevant Ministers with developing a Roadmap to advance standards-based markets for critical minerals. Leaders committed to transparency, diversification, security, sustainable mining practices, trustworthiness, and reliability as essential principles for resilient critical minerals supply chains.

This action plan identifies actions to strengthen supply chain resilience, reliability, traceability and transparency.

Accordingly, the G7 called in October 2025 for the following:

- Strengthening requirements for traceability and transparency within strategic supply chains, including defence.
- The development of a global framework for the interoperability of digital credentials and digital product passport compatibility aligned with the UN Transparency Protocol.
- Improved traceability for critical minerals supply chains for off-exchange trading aligned with practices carried out through mineral and metal commodity exchanges and other platforms.
- As appropriate, and in accordance with domestic laws, provide consideration of sovereign tools to review, on national and economic security grounds, the disposition of critical minerals assets.
- Encouraging private and public sector investment in critical minerals recycling technology.
- Collaborating to ensure management of critical minerals and rare earth scrap that supports supply chain diversification.
- In order to achieve these goals, G7 members will advance actions to:
    - Assess the performance of Sustainability Metals Premia, engaging with relevant private sector-led initiatives as appropriate such as the LME sustainable metals premium market.

[8] https://g7.canada.ca/en/news-and-media/news/roadmap-to-promote-standards-based-markets-for-critical-minerals

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- Publish the results of pilot studies that test and demonstrate the feasibility of data collection requirements, identify gaps in data needs, and provide recommendations for the interoperability of digital credentials between G7 members and partners.
- Propose a plan for the G7 to increase transparency, traceability, resilience and reliability to diversify and reduce dependence on unreliable sourcing throughout specific critical mineral supply chains in consultation with the private sector, including to establish a data governance framework pertaining to digital traceability tools.
- Undertake member-specific initiatives to increase user uptake of traceability tools and systems.

In June 2026 G7 meeting in Evian (France), G7 countries discussed and decide the implementation of this mineral traceability roadmap under G7 group for lithium and nickel, with the objective to add other five commodities in the future. We copy here the main outcomes of this declaration in terms of traceability:

- *We recognize the importance of strong transparency and traceability frameworks to ensure supply chain security and the compliance with high standards in resilient market environments, as well as tackling illegal trafficking of critical minerals. Acknowledging ongoing work by the Organisation for Economic Cooperation and Development (OECD) and International Energy Agency (IEA), we are committed to working towards establishing harmonized, interoperable mechanisms aligned with our interests that ensure traceability and transparency regarding the origin of critical minerals. This would start with two pilot critical minerals – lithium and nickel – and aim to avoid undermining competitiveness or imposing excessive cost burdens. We will seek to extend the pilot to five new critical minerals each year with particular attention given to rare earths.*

- *We will work towards improved knowledge transparency of global raw material markets and supply chains, including through the development, voluntary and confidential exchange and publication of shared analytical tools, market indicators and better visibility on prices, supply, demand and processing capacities. We recognize the indispensable role of data in underpinning this work. To reach those goals, we commit to working together through the platform below, that marshals existing work and capabilities in the OECD and the IEA Critical Minerals Security Program including in a structured dialogue with businesses.*

- *We will seek to promote a level playing field in the extraction of critical minerals by aligning practices with internationally recognized labour standards and encouraging coordinated action to address systemic risks of forced labour, in accordance with the "G7 Toolkit for Standards-Based Criteria to Identify Risks of Forced Labour in the Extraction of Critical Minerals", adopted in June 2026.*

Insights for MaDiTraCe project roadmap

G7 declaration in June 2027 was released after main developments of MaDiTraCe project. However, the conclusions of G7 declaration in 2026 which are aligned with previous declarations open a clear opportunity for MaDiTraCe project results such as cases studies for lithium.

2.5 "Mined in Canada" credential

Natural Resources Canada (NRCan), public authority in Canada in charge of natural resources governance, is exploring the feasibility and design of a "Mined in Canada" digital credential—a secure, verifiable proof of Canadian provenance for minerals. The goal is to:

- Enhance supply chain transparency
- Support trade compliance
- Strengthen Canada's position in global critical mineral markets

A Request for Information (RFI)[9] seeks stakeholder input to inform the development of this credential and potential future tools (e.g., digital credentials for mineral processing).

NRCan proposes:

- Current Gap: Canadian mining companies lack a consistent method to prove the origin of their minerals to downstream actors (processors, refineries, manufacturers, border agencies, international partners).
- Digital Credential: A portable, tamper-evident digital record (like a certificate) issued by a trusted authority (e.g., Government of Canada). It can be shared via QR codes or digital wallets, offering a secure, verifiable solution for provenance.
- Potential Benefits:
    - Global recognition of Canadian minerals
    - Support for trade agreements, stockpiling, and market access
    - Voluntary integration with supply chain traceability systems

This initiative aligns with:
    - Canadian Critical Minerals Strategy (2022): Market transparency
    - G7 Roadmap: Supply chain traceability and provenance
    - Canada-EU Digital Trade Agreement: Interoperability of digital credentials

They identify several risks and challenges:
- Coordination: Requires collaboration across stakeholders (companies, industry associations, international partners) and jurisdictions (provinces/territories).
- Cost & Viability: Need to assess cost models for issuance, verification, and compliance.
- Technical Complexity: Integration with supply chain systems and ESG frameworks; cybersecurity risks.
- Adoption: Depends on perceived value, ease of use, and compatibility with existing systems.

NRCan will use the public consultation feedback to decide on the best path forward for the credential, potentially laying the groundwork for future digital credentials (e.g., mineral processing).

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[9] https://natural-resources.canada.ca/minerals-mining/request-information-mined-canada-digital-credential

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Insights for MaDiTraCe project roadmap

This initiative from Canada is clearly with what MaDiTraCe project sent an answer to this consultation. In its response, the consortium welcomed the Canadian initiative, which it believes should inspire other initiatives in Europe, but also pointed out some limitations or warnings. These verified credentials measures should be accompanied by control mechanisms, as materials extracted in Canada may have been extracted under very different conditions, applying different standards in addition to Canadian law. Furthermore, given that Canada has companies operating worldwide, great care must be taken to avoid mixing these materials with those mined elsewhere by Canadian companies. MaDiTraCe project concept

In the framework of one scientific article published by MaDiTraCe team, Fernandez et al (2026) presented a conceptual framework for mineral supply chains traceability (Figure 10). This conceptual scheme is the result of consultation of different stakeholders that achieved in this result and this framework is also connected to different international agencies work that revisit and bring new concepts (cf. chapter 2).

As other authors also refer to (IEA 2026), traceability by itself is not the final objective. Supply chain management is in the middle of the system. This supply chain management integrates compliance with regulations, and the compliance of those regulations enables the need of a set of technologies and analytics and in consequence traceability.

Traceability can be seen as a set of tools, including inside different technologies, to enhance supply chain management and ensure performance monitoring. MaDiTraCe project developed and worked mostly in this part of the system but working under the umbrella of several regulation (cf. section 1.4).

Environmental and social impacts are crucial in this conceptual schema. Firstly, in the EU regulation requires transparency and verification about those impacts. Secondly, markets and downstream industry require transparency as well and ESG reporting. And thirdly, companies are in continuous improvement. Any performance and monitoring is evaluated based on environmental and social criteria. Traceability technologies appear here, once again, as a tools for verification, validation and data exchange.

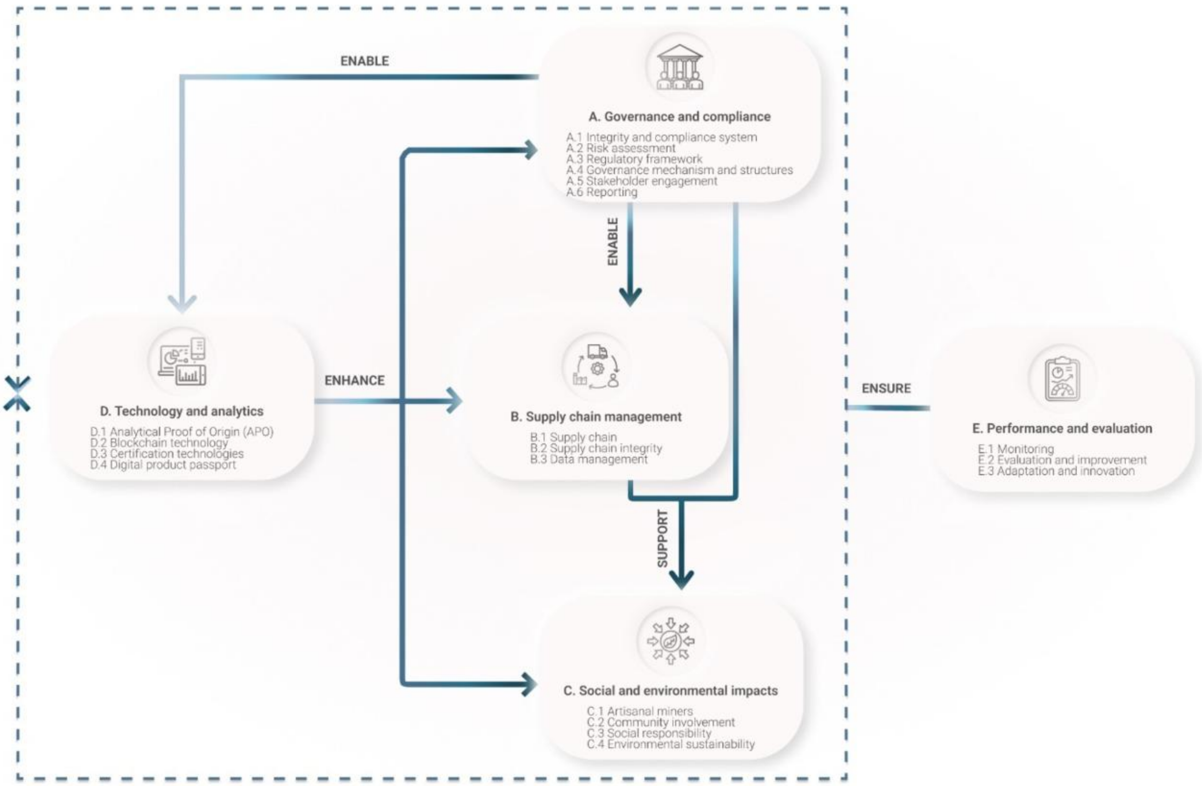

Figure 10: conceptual framework for traceability from Fernandez et al (2026).

2.6 Three pillars for traceability tools in MaDiTraCe

The set of technologies investigated and developed in MaDiTraCe project covered mainly three pillars.

- **Proof of origin, material fingerprints (MFP) and artificial material tagging or fingerprint (AFP)**

Analytical techniques, geoforensic and material science present methods allowing to characterize or determine a material origin, or the presence of a material in a determined place.

The project worked at the same time on material fingerprints based on natural/intrinsic material characteristics (MFPO) and artificial tagging techniques or artificial fingerprint (AFP). MaDiTraCe project assessed four substances: lithium, cobalt, neodymium and natural graphite.

Chapter 4 in this document would present some results of those developments and presents next requirements for a larger deployment of those solutions.

- **Digital product/material passport and blockchain**

This pillar includes all digital traceability solutions. Inside, we must distinguish between digital product/material passport, the assignation of Verified Credentials to all three actors across the traceability system and blockchain technology solutions.

This aspect of MaDiTraCe is covered in chapter 4.

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- **Certification**

Traceability for MaDiTraCe is not only the proof of geographical origin of materials (country or mine level) but the association to materials of a certification delivering guarantees of responsible practices based on a system of audits and certifications.

In MaDiTraCe project certification is the result of the work of DMT company developing a family of standards called CERA 4in1. CERA 4in1 is the result of the integration of 4 single certifications into a single system, covering exploration, raw material processing and extraction, chain of custody and final product standard.

In a world where the proliferation of standards/certifications applicable to raw materials is important (Zhang et al 2026, Nouvel et al 2026), MaDiTraCe project looked to this global panorama of those voluntary standards as well.

Chapter 5 presents this aspect of MaDiTraCe project and its roadmap.

3 Material fingerprinting and Artificial Fingerprinting

3.1 MFP using intrinsic material properties

Material Fingerprinting (MFP) based on intrinsic material properties is one of the core innovations investigated within the MaDiTraCe project. The approach relies on the fact that geological materials inherit unique signatures from their formation environment and geological history. These signatures can be measured using analytical techniques and subsequently used to establish provenance, verify origin claims, or assess consistency with declared supply chain information. The MaDiTraCe project investigated several categories of intrinsic signatures across four strategic critical raw materials: lithium, natural graphite, cobalt, and neodymium. Depending on the commodity and the stage of the value chain, different analytical parameters were evaluated, including isotopic compositions, trace element distributions, mineralogical assemblages, spectroscopic responses, and microstructural characteristics.

3.1.1 Upstream stages: mining and concentrate production

The highest discrimination power is generally achieved during the upstream stages of the value chain, including mining, beneficiation and concentrate production. At these stages, materials still preserve most of their original geological characteristics and only limited chemical transformations have occurred. Consequently, trace element compositions, mineralogical assemblages, isotopic signatures, spectroscopic responses and textural properties can often be used to identify the geographical origin of a material with a high level of confidence. However, the most suitable analytical approach strongly depends on the commodity considered, as the nature and preservation of intrinsic signatures vary significantly from one raw material to another.

Lithium
For lithium-bearing ores and concentrates, MaDiTraCe demonstrated that several complementary fingerprinting approaches can be applied. Lithium isotope compositions

allow discrimination between major resource types such as hard-rock deposits, continental brines and geothermal resources. In addition, trace element compositions measured by XRF and ICP-MS provide valuable provenance information at the deposit level. Spatially resolved techniques such as µLIBS mapping revealed characteristic elemental associations that can be exploited through machine-learning classification models, while ultraviolet (UV)-bench and cathodoluminescence imaging showed promising capabilities for distinguishing spodumene concentrates from different geological sources. The combination of these datasets provides a robust multi-parameter fingerprinting strategy applicable to both ore and concentrate stages.

Natural graphite

For natural graphite, provenance determination relies on structural, mineralogical and geochemical signatures preserved within graphite concentrates. Carbon isotope compositions remain largely unaffected by beneficiation processes, however, they show no notable difference between the most important flake graphite deposits worldwide due to the fact that they mostly formed in a relatively narrow time interval between 2.1 and 1.8 Ga (e.g., Parnell et al., 2021) from the same primitive organisms. At the same time, mineral impurities are always associated with graphite flakes and preserve distinctive mineralogical and trace-element signatures. Mineral impurities can be separated from the concentrates and can be characterised using SEM-EDS and other in-situ methods, while XRF, solution ICP-MS, LIBS LA-ICP-MSand XRD can be used to analyse bulk graphitic samples. These signatures enable discrimination between deposits and graphite concentrate sources from different geographical regions.

Cobalt

For cobalt-bearing ores and concentrates, trace element compositions and sulphur isotopes represent the most promising intrinsic tracers. Multi-element datasets measured in bulk ores and sulphide minerals allow discrimination between magmatic sulphide deposits, sediment-hosted Cu-Co systems and lateritic ores. Sulphur isotope compositions provide an additional independent tracer linked to ore-forming processes and significantly strengthen provenance assessments when combined with trace-element data.

Neodymium

For rare earth elements, and particularly neodymium, isotopic compositions constitute the most powerful fingerprinting parameter identified within MaDiTraCe. Nd isotopic signatures reflect the geological evolution of the source deposits and provide strong discrimination between major REE provinces. Rare earth element patterns offer complementary information and can further strengthen provenance assessments when combined with isotopic data**.**

These stages correspond to the highest maturity level currently demonstrated by MaDiTraCe, as most intrinsic geological signatures remain preserved and measurable before extensive metallurgical transformations occur.

3.1.2 Refining and chemical conversion stages

Refining and chemical conversion represent a critical transition point for material fingerprinting. Unlike mining and beneficiation stages, where materials largely preserve their original geological characteristics, metallurgical processing introduces physical and chemical transformations that may alter, dilute or even erase some intrinsic signatures.

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Consequently, the applicability of material fingerprinting at this stage strongly depends on both the commodity considered and the analytical parameter used. One of the main findings of the MaDiTraCe project is that there is no universal behaviour of intrinsic tracers during refining. While some isotopic signatures remain remarkably stable through complex industrial processes, other geochemical parameters are progressively modified by purification, precipitation, solvent extraction, crystallisation or alloy production steps. As a result, the objective of material fingerprinting evolves from precise mine-of-origin determination towards verification of supply-chain consistency and validation of declared feedstocks.

Lithium

The MaDiTraCe project investigated lithium isotope compositions along several industrial processing routes, including hard-rock, brine and geothermal resources, as well as the subsequent conversion into battery-grade lithium chemicals. The results demonstrate that lithium isotopes are generally preserved throughout most refining and chemical conversion stages. Lithium hydroxide and lithium carbonate produced from different feedstocks maintain isotopic signatures that remain representative of their original sources. This preservation enables discrimination between major source categories even after chemical processing. However, the project also identified situations where isotopic fractionation may occur. Measurable variations were observed during certain hard-rock processing routes involving mineral conversion and lithium extraction. Other processes induced little or no measurable isotopic fractionation. These observations indicate that the behaviour of lithium isotopes depends on the extraction and refining technology employed and therefore requires commodity-specific reference databases covering different industrial pathways. Overall, the MaDiTraCe results suggest that lithium isotope compositions remain one of the few intrinsic tracers capable of preserving provenance information from the geological resource to battery-grade lithium chemicals, making lithium one of the most favourable commodities for downstream material fingerprinting applications.

Natural graphite

During flotation, purification and spheroidisation processes, the graphite matrix itself remains essentially unchanged. Carbon isotope compositions therefore remain relatively stable throughout the refining chain and continue to reflect the original graphite formation environment. However, the principal challenge lies in the progressive removal of mineral impurities during purification. Many of the most discriminating signatures identified upstream, such as accessory minerals and their associated trace element compositions, become less abundant as graphite purity increases. Consequently, provenance determination becomes increasingly difficult for highly refined graphite products. The MaDiTraCe results nevertheless indicate that certain resistant mineral phases, including zircon, rutile and titanite, may survive purification processes and continue to preserve useful geochemical information. In addition, trace element patterns measured at very low concentrations may still provide discrimination between source regions. Therefore, while fingerprinting performance decreases with increasing purification levels, graphite retains a significant traceability potential during refining provided that sufficiently sensitive analytical techniques are used.

Cobalt

The MaDiTraCe project followed samples throughout a complete Ni-Co processing route and demonstrated that substantial modifications occur in trace element compositions during both pyrometallurgical and hydrometallurgical stages. Progressive purification removes many of the trace element signatures that originally characterize the ore deposit, leading to a significant reduction in provenance resolution. Sulphur isotopes exhibit greater resilience than trace element compositions and remain relatively stable throughout several processing stages. Nevertheless, significant changes were observed during the production of sulphates, indicating that even isotopic tracers may eventually be affected by industrial transformations.

Neodymium

The MaDiTraCe project obtained samples from concentrates and downstream stages of the Nd value chain, but only limited access was available to intermediate products generated during rare earth separation and metal production. As a result, the evolution of Nd isotopic compositions and REE patterns during cracking, leaching, solvent extraction, precipitation and metal production could not be fully assessed. Rare earth refining therefore remains one of the main knowledge gaps identified by MaDiTraCe. Future work should focus on documenting the behaviour of isotopic and elemental signatures throughout the complete refining chain, from mineral concentrates to separated rare earth oxides and metallic neodymium. Such studies will be essential for evaluating the feasibility of material fingerprinting during rare earth refining and for identifying tracers capable of surviving these highly selective purification processes.

3.1.3 Component manufacturing

During component manufacturing, materials undergo additional chemical and physical transformations to produce battery components such as cathode active materials (CAMs), anodes (AAMs) and magnet alloys. At this stage, materials originating from different sources may also be blended together, making provenance determination increasingly complex. Consequently, the performance of material fingerprinting depends not only on the preservation of intrinsic signatures during processing but also on the degree of mixing occurring within industrial supply chains.

Lithium

The MaDiTraCe project investigated whether lithium isotopic signatures are preserved during the conversion of battery-grade lithium chemicals into cathode active materials. Results obtained on NMC cathode materials synthesized from lithium hydroxides and lithium carbonates of different origins demonstrated that no significant isotopic fractionation occurs during CAM production. The isotopic composition of the final cathode material remains directly linked to that of the lithium precursor. These results indicate that lithium isotopes constitute one of the most robust intrinsic tracers identified within MaDiTraCe. At the component manufacturing stage, lithium isotopic compositions can therefore still provide information regarding the origin and nature of the lithium feedstock used for cathode production. However, the increasing use of blended feedstocks may progressively reduce the ability to identify a single geological source.

Natural graphite

For natural graphite, MaDiTraCe primarily focused on mining, concentrate production and purification stages. Limited data were available regarding the evolution of intrinsic signatures during the production of battery-grade anode materials. Nevertheless, because the graphite isotopic composition itself remains largely unchanged during spheroidisation and coating processes, carbon isotope compositions are expected to remain relatively

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stable. In contrast, many of the mineralogical and trace element signatures identified upstream are likely to become less informative due to the high degree of purification and processing required for battery applications. Additional work is therefore required to evaluate the persistence of graphite fingerprints throughout anode manufacturing.

Cobalt
For cobalt, component manufacturing occurs after extensive refining and chemical conversion stages that have already modified a significant part of the original geological signature. The cobalt incorporated into cathode active materials is generally present in the form of highly purified chemical compounds, reducing the discrimination power of many trace element-based tracers. Consequently, the ability to link a cathode material to a specific cobalt deposit is expected to be limited.

Neodymium
For Neodymium, no sufficient dataset was available within MaDiTraCe to assess the behaviour of Nd isotopic signatures during the transition from metallic neodymium to Nd-based alloys. Consequently, the applicability of material fingerprinting at this stage of the value chain remains to be investigated.

3.1.4 End product

At the end-product stage, materials have undergone multiple refining, manufacturing and assembly steps and are incorporated into complex products such as lithium-ion batteries and permanent magnets. At this stage, material mixing and successive industrial transformations may significantly affect the preservation and interpretation of intrinsic signatures. Consequently, material fingerprinting is generally no longer intended to determine a specific mine origin, but rather to evaluate whether a product remains consistent with its declared feedstocks and supply chain history.

Lithium
For lithium, MaDiTraCe investigated the evolution of lithium isotopic signatures between cathode active materials and assembled battery cells. The results demonstrated that no significant isotopic fractionation occurs during electrode preparation and cell manufacturing. Consequently, the isotopic composition measured in cathode active materials is preserved in the final battery prior to cycling. Battery assembly therefore does not appear to represent a major limitation for lithium traceability. In contrast, subsequent electrochemical cycling was shown to induce measurable isotopic fractionation between battery compartments. This indicates that the main modifications of lithium isotopic signatures occur during battery use rather than during battery manufacturing itself.

Cobalt
The MaDiTraCe project did not specifically investigate the evolution of cobalt fingerprints during the transition from cathode materials to assembled battery cells. Consequently, no conclusion can currently be drawn regarding the preservation or modification of cobalt-related signatures during battery manufacturing. This stage therefore remains a knowledge gap requiring further investigation.

Natural graphite
The downstream stages of the graphite value chain were only partially covered within MaDiTraCe. In particular, the behaviour of graphite fingerprints during electrode fabrication

and battery assembly was not investigated. Further work is therefore needed to determine whether the signatures identified in purified graphite and anode active materials remain detectable and discriminant in finished battery cells.

Neodymium

For neodymium, MaDiTraCe demonstrated that Nd isotopic compositions remain stable between the alloy stage and the final NdFeB magnet. No significant isotopic modification was observed during magnet manufacturing processes, indicating that the isotopic signature inherited from the alloy is preserved in the final product. In addition, rare earth element (REE) compositions were also investigated throughout the magnet production chain. The results indicate that REE patterns remain measurable in the final magnet and provide complementary information on the composition of the feedstock used during alloy production. Although REE distributions are generally less discriminating than Nd isotopic signatures for provenance purposes, they may contribute to assessing the consistency between intermediate products, alloys and final magnets.

3.1.5 MFP summary

Table 2 presents main intrinsic properties (trace elements, mineralogy, isotopes) that fits better for 4 stages: mining concentrate, refining, components manufacture and end-product.

<table>
<tr><td>Commodity</td><td>Mining concentrate</td><td>Refining / chemical conversion</td><td>Component manufacturing</td><td>End product</td></tr>
<tr><td>Lithium</td><td>Luminescence properties + Trace elements + Li isotopes</td><td colspan="2">Lithium isotopes + trace & ultra trace elements</td><td>Battery cycling induces isotopic fractionation</td></tr>
<tr><td>Natural graphite</td><td colspan="2">Mineral impurities + trace elements</td><td colspan="2">No tested</td></tr>
<tr><td>Cobalt</td><td>S/Ni isotopes
Trace elements
Mineralogy</td><td>Trace elements + S isotopes</td><td>Highly pure Co form. Difficult</td><td>No tested</td></tr>
<tr><td>Neodymium</td><td colspan="4">Nd isotopes. Maintained along the supply chain. Limited dataset</td></tr>
</table>

Table 2: summary of MFP techniques per product stage.

More details about the different analytical techniques and radar diagrams to assess the different criteria are presented in D2.3, D2.4 and D2.5.

3.2 AFP using artificial tagging

MaDiTraCe research into MFP along the lithium-ion battery supply chain shows both high promise, but also variable discriminatory power and alteration, dilution and erasure of intrinsic isotopic signatures depending on the minerals and processes undergone. Artificial fingerprinting (AFP) research was integrated into the MaDiTraCe work plan to determine the potential for using such methods to a) substitute for MFP at steps where those methods no longer work well, allowing traceability to continue, and b) potentially physically encode

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information that could be followed along the supply chain, complementarily to the digital information of the Digital Product Passport.

In MaDiTraCe, taggants or tracer particles were the chosen method of artificial fingerprinting – the addition of particles other than those of the material being tracked. AFP and taggants/artificial tracking particles (ATPs)/tracer particles (TPs) have been to date little used for the minerals, metals, compounds and chemicals in the lithium-ion battery supply chain, and there is very little scientific literature based around their behaviour, performance and longevity. The planned research for MaDiTraCe therefore focused on a) determination of the current state of the art of AFP in other industries, and b) development and testing of tailored ATPs, and testing of commercial ATPs, in the battery lithium-ion supply chain at low technology ready levels (TRL).

3.2.1 Current state of the art of AFP

The state of the art for AFP was reviewed in MaDiTraCe deliverable D2.1 (Donnelly et al. 2023). A broad range of AFP methods, including taggants/ATPs, was found to be used for property marking, anti-counterfeiting and tracking/monitoring of numerous commodities and finished goods. These include food, fuel, currency, clothing, pharmaceuticals, chemicals, explosives, electronics, vehicles, raw materials etc.

Donnelly at al. (2023) reviewed a large number of existing AFP technologies. A questionnaire was produced for key stakeholders and industry members to outline the types of material that are both acceptable and unacceptable at various stages of the lithium-ion battery supply chain. Further, penalty element tables from industry detailing materials that are not permitted at certain stages of mining and refining in the supply chain were examined.

On the basis of the AFP review (Donnelly et al. 2023), questionnaire, and penalty element tables, it was concluded that there may be no currently commercially available existing ATPs that are directly applicable to MaDiTraCe lithium-ion battery supply chain materials. This is due to a range of factors, including:

- cost (since especially early-stage mineral products are often of large quantity/mass but relatively low value, whereas many of the products currently traced using AFP are of lower quantity and relatively high value e.g. electronics, cars etc.)

- the inclusion of components which may not be acceptable to the minerals and metals industries and the rest of the lithium-ion battery supply chain, either because of the materials involved or, even if found in such low concentrations that they are both safe and within required penalty limits, the perception of their inclusion. Such components include particular metals, rare earth elements, or toxic elements and compounds

- complex detection procedures which may be impracticable in the lithium-ion battery supply chain, especially the large quantities of early-stage mineral ores and concentrates

- lack of knowledge about the behaviour of ATPs in lithium-ion battery supply chain materials, and a lack of tailored ATPs for this purpose

3D printing was examined in Donnelly et al. (2023) as a technology that could potentially be used for manufacture of ATPs for the lithium-ion battery supply chain. This was due to the potential for:

1. incorporating materials considered acceptable within the lithium-ion battery supply chain within ATPs

2. production of ATPs with shapes designed for optimal dispersion within various lithium-ion battery supply chain materials and at different stages, for instance by producing ATPs matching the shape of particles of these materials

3.2.2 Tailored ATP production

Because of the lack of prior data about the behaviour of ATPs in the mineral industry in general and the lithium-ion battery supply chain in particular, a broad range of concepts, designs and technologies for the production of tailored AFPs were investigated, concentrating on the following parameters:

1. Shape. Alternative concepts investigated included production of tailored ATPs matching commodity particle shape, alongside basic shapes (spheres, cubes) to test their distribution within host material and movement under transport behaviours.
2. Size. Due to the limitations of available 3D printing equipment, and depending on the host material and supply chain stage, tailored ATPs were either similar in size to the larger particles of host material, or larger than particles of the host material.
3. Material. A range of materials and production methods was trialled, including composites of host material and biopolymer, polymer only, and metals.
4. Data encoding. Both overt and covert methods of data encoding, using lettering or micro QR codes, were tested.
5. Detection. Different concepts for detection were used, including addition of small commercial ATPs of known detection parameters within larger tailored ATPs, testing and use of UV fluorescent materials, and particle size or magnetic separation of ATPs from host materials.
6. Recoverability. Two methods of ATP particle recoverability were tested: particle size and magnetic separation of ATPs from host materials.

In total, 18 types of tailored ATP prototypes were produced by 3D printing (both inhouse and outsourced).

3.2.3 Lab and field testing of tailored and commercial ATPs

Based on production feasibility and initial performance, nine types of 3D printed ATPs were produced in sufficient quantity for lab and limited field testing, though not all ATP types underwent all tests. A range of tests of both these tailored ATPs and existing commercially

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available ATPs were carried out, to determine the behaviour, detectability and robustness of ATPs in parts of the lithium-ion battery supply chain. These included:

- Preliminary tests to evaluate the effectiveness of different methods of application, mixing and detection.
- Natural ageing tests.
- Photooxidative ageing tests.
- Artificial climate ageing tests.
- Real-world and simulated transportation tests.
- Minimum effective dosage tests.

The results of the tests conducted on ATPs are outlined within D2.6 of the MaDiTraCe project.

3.3 Benchmark with other sectors using MFP/AFP based traceability

The use of MFP and AFP technologies is already applied by industry. The purpose of this section is to show how those techniques are implemented in other supply chains, what is covered and which is the data exchange between actors.

3.3.1 Gemstones

Gemstones are a product where MFP/AFP are being used for a while with several companies providing traceability tools. Gubelin is a jewellery and gemstone company with a Gubelin Gem Lab who address traceability and product tagging. This company example can be used as an example of integration of MFP/AFP techniques into product traceability.

- *How they work?* Combination of DNA nanoparticle tagging, gemmological/geochemical properties, Gemtelligence™, deep-learning interpretation of analytical data (spectra, chemistry)
- *Why does it work?* reference stone collection > 30,000 gemstones from all commercially relevant mines, analyses of tens of thousands of high-grade customers' stones analysed since the 1970s, available for AI training, deep learning on standard analyses avoids work-intensive examination (microscopic, LA-ICPMS…).
- *Segments of supply chain?* All, but gemstones are simple (only extraction, cutting, eventually treatments (heat…)
- *Links to certification?* „Gem Passport" (Gübelin gemmology in-house)
- Use of AFP. DNA encryption of information about the mining location, miner, and mining time. Encrypted data encapsulated in a durable sphere of amorphous silica, protected from sunlight, temperature, and humidity…. carrier liquid to transfer this information onto rough crystals and gems. Nanoparticles penetrate even the smallest of fissures and adhere tightly to the walls of the gemstones.
- Tagging by independent auditor at the mine before any cleaning and sorting, DNA tags remain intact during cutting, polishing, and even re-oiling processes!

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Insights for MaDiTraCe

One private company and a big player of gemstones sector has a huge gemstone database. This situation is difficult to compare with battery raw materials, however, big mining and refining companies operating in different countries could internalize this work and made an equivalent MFP database and provide in-house material passport

3.3.2 Gold

Gold is another commodity where several companies apply MFP/AFP methods to ensure traceability.

Argor Heraeus, Haelixa and Axedras companies communicate examples of MFP/AFP methods.

- *How?* geoforensic analysis including XRF (Argor-H.), DNA tagging (Haelixa), Bullion Integrity Ledger™ : distributed ledger technology (DLT)-based business network (Axedras)
- *Why does it work?* Trace element signatures (MFP), unique DNA spray on site (AFP), provenance claim validated at refinery, new spray for downstream chain.
- *Segments of supply chain?* primary gold ==> doré ==> refining ==> bullions

Metalor company (Figure 11) have a MFP procedure based on MFP and consulting addressing following questions:

- *How?* "geoforensic passport" 2021 (Barbara Beck) + BullionProtect® high sec. ink
- *Why does it work?* 3-tier approach ED-XRF, 20 trace elements and Pb isotopes. Comparison to Metalor database of doré
- *Segments of supply chain? MFP:* primary gold until doré but not beyond refining,
- *Links in-house standard in Metalor*

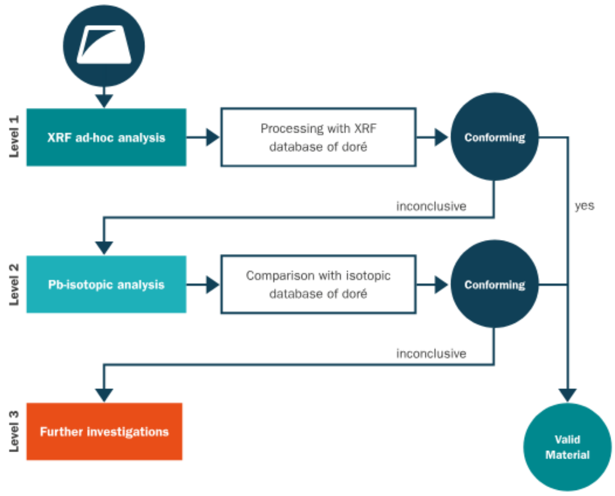

Figure 11: Three levels of investigations put in place by Metalor traceability system.

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In addition to those works, some research (Pochon et al 2021) work as well in gold characterisation with the particular focus on mercury utilisation.

Insights for MaDiTraCe project

- Even for a gold for jewellery supply chain which is simpler than battery one, the MFP applies mostly for stages around mining-doré-bullion
- Companies such as Metalor have their own database and propose in-house standard
- The importance in gold market for fair/responsible certification is high
- A challenge remains about the integration of artisanal and small mining gold into it.

3.4 Material tagging contribution for a roadmap

Until now MFP or AFP techniques are not explicitly referred into mineral traceability's roadmaps.

However, the deployment and integration of MFP/AFP techniques into a global traceability system requires a specific sub-roadmap and specifically to address and clarify the role of conformity assessment bodies, that could be based on public agencies such as geological survey organisations (GSO) or testing, inspection and certification companies (TIC).

3.4.1 Role of Conformity Assessment Bodies

3.4.1.1 Roles for Geological survey organisations

A geological survey organisation (GSO) is a government or public institution responsible for studying and mapping the Earth's structure, composition, and processes. These organizations serve as the authoritative source of geological information for a country or region, providing essential data and expertise that supports decision-making across many sectors of society. Mineral resource assessment is a traditional function. Geological surveys inventory and evaluate mineral deposits within their territory, providing information that supports responsible mining and resource extraction. This work helps nations understand their resource endowment and plan for sustainable use of non-renewable geological resources.

Scientific research underpins all these activities. Geological surveys conduct both fundamental and applied research in earth sciences, studying topics ranging from plate tectonics to climate change impacts on geological systems. They develop new methods and technologies for exploring and understanding the subsurface, often collaborating with universities and research institutions worldwide.

Public service and expertise provision round out their mission. Geological surveys provide technical advice to governments, policymakers, and regulators on matters ranging from environmental protection to infrastructure development. They make their data and publications openly accessible to researchers, businesses, and citizens. Many also engage in educational activities to improve public understanding of geosciences and their relevance to everyday life.

Two partners of MaDiTraCe are GSO: BRGM and GTK.

Those organisations have analytical laboratory devices, have a strong relation to mining authorities or even in some countries GSO integrates mining authority inside the organisation and are at the same time research and development teams. In a situation where material traceability became a mission for GSOs in a Made in Europe/RESourcEU framework, we identify next steps.

- GSOs have a clear mandate to collect material samples in a way and a frequency to be defined from mining companies operating within Europe
- Establish a collaboration between European GSO participating to a material system, under the umbrella of the future Geological Survey for Europe organisation
- GSO would update and maintain material fingerprint databases in a structured and confidential way, ensuring company level data protection
- Verified Credentials for GSO participating to material fingerprint and integration into a DPP system
- Continuous R&D development, continuity of partnership with universities and other research institutions

3.4.1.2 Role of testing, inspection and certification companies

The testing, inspection and certification (TIC) sector would play a critical role in implementing MFP and AFP traceability systems. TIC companies, which are accredited and certified independent third parties such as Alfred H Knight, are appointed at critical points along CRM supply chains for the purposes of verifying and certifying the quantity and quality of raw materials. TIC companies possess expertise that is directly transferable for MFP-AFP traceability system implementation, specifically in the areas of inspection, sampling, analysis and reporting. TIC companies are also part of traceability systems for existing sustainability initiatives for various industries including the mining industry (Assurance Services International, 2026). Furthermore, TIC companies such as Alfred H Knight can be well-established globally and have interconnected offices and laboratories.

Stakeholders can contract TIC companies to provide services for MFP or AFP verification. TIC companies can also provide “outsourced” regulatory enforcement for governmental organisations or in collaboration with GSOs.

3.4.1.3 Common elements for MFP and AFP conformity assessment bodies

For both TIC companies and GSOs, we identify next steps that any further system based on MFP and AFP would require:

- Establish the procedure for material sample collection, frequency, data protection, confidentiality and ethics for MFP and AFP
- Build a standardisation roadmap to establish a recognition of laboratory methods tested and implemented in MaDiTraCe project and other projects for an international standard recognition (ISO)

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- Define responsibilities and risk assessment for laboratories participating to material fingerprint analysis
- Establish a business model: identify who pays MFP or material tagging, if those costs are reported to premium prices, etc
- Investments. Need for new analytical means in relation to commodities assessed.

4 Use of Digital Product Passports in MaDiTraCe Traceability Framework

4.1 Overview of Traceability Architecture

At its core, the DPP is structured around the concepts of Self-Sovereign Identities (SSI)[10], Verifiable Credentials (VCs) (W3C 2021), and Decentralized Identifiers (DIDs) (W3C 2022). The MaDiTraCe system architecture is based on principles supporting these concepts to ensure that all data is accurate and traceable back to a verifiable identity, issued by a legitimate source, to meet regulatory compliance with verification workflows. MaDiTraCe utilizes Open API documentation for secure API endpoints and open standards like W3C Verifiable Credentials (World Wide Web Consortium [W3C], 2023), to ensure different certification systems work together in a semantically interoperable manner. The building blocks of the architecture are depicted in the Figure below and are further explained in detail throughout this subchapter.

10 https://github.com/WebOfTrustInfo/self-sovereign-identity/blob/master/self-sovereign-identity-principles.md

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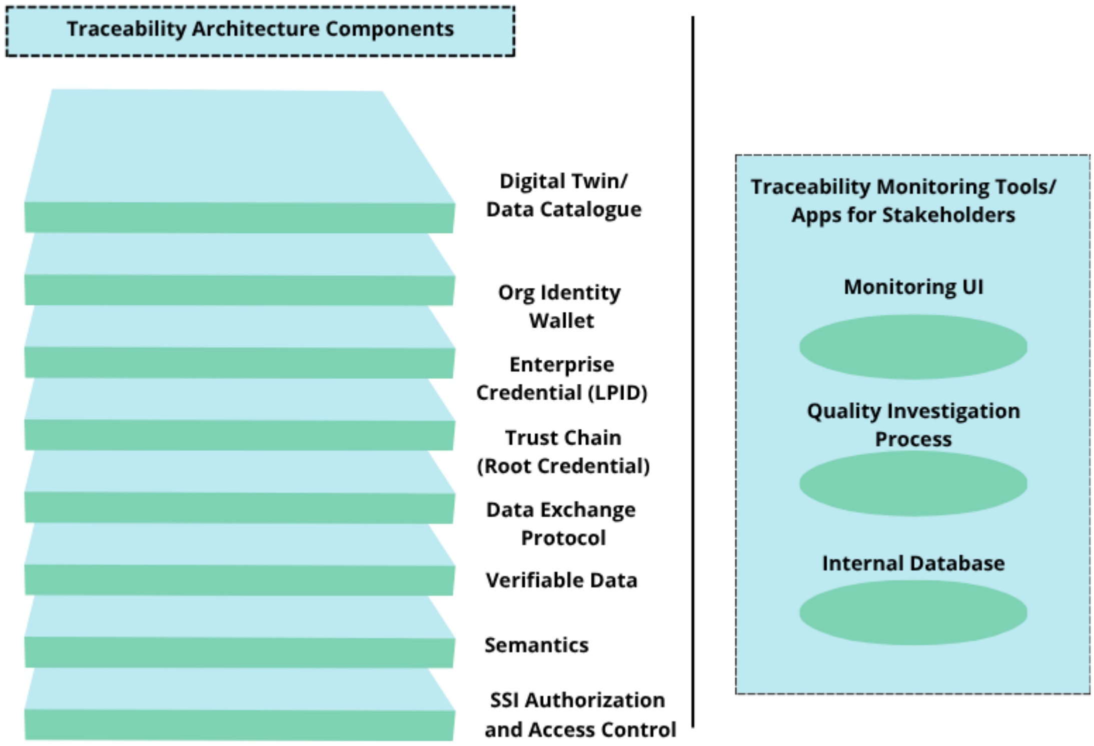

Figure 12: Building blocks of DPP architecture

A central element of the architecture is the implementation of enterprise credentials, which are digital credentials that uniquely identify an organization as a legal entity. W3C VCs shall be used for enterprise credentials to enable interoperable data exchange among all supply chain stakeholders. Furthermore, this identity credential requires the establishment of a hierarchy of trust called a trust chain, by creating a trusted authority to which credentials can be traced (e.g., chambers of commerce for legal person identities).

SSI principles are used to establish trust for presentation of identity claims as a verifiable credential. For this reason, an organization identity wallet is required in this traceability architecture to store, manage, and present organizational credentials, as well as supply chain certificates such as CERA4in1 certification currently being developed under the MaDiTraCe project together with other compliance certificates. In MaDiTraCe system architecture, it is foreseen that an EUDI Wallet (European Commission, 2024) stores both foundational legal entity credentials and other organizational conformity credentials linked to the organization's identity and supports the issuance of verifiable DPPs containing these credentials.

To establish a DPP that serves as a crucial tool to improve the traceability of products along the value chain, as stated in the ESPR regulation (European Commission, 2022), the economic operator requires data exchange mechanisms between all partners inside the supply chain. For this reason, MaDiTraCe system architecture has to consider data exchange protocols that provide secure communication and data transfer between stakeholders. The Catena-X dataspace project (Catena-X, 2023) provides an example architecture that consists of a control plane for policy management that uses Eclipse Dataspace Connector protocol (Eclipse Foundation, 2025) and a separate data plane for data exchange between entities. In the control plane, SSI authorization and access control principles are used to

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enable decentralized, enterprise credential-based authorization. In this step, the requesting economic operator proves that they are a valid organization and a dataspace participant by presenting the required credentials from their organizational identity wallet. After contract agreement, the actual data exchange takes place through the dataspace transfer protocol under the conditions defined in the negotiated contract.

The Digital Twin serves as a repository for raw material data coming either from the product itself or acquired through supply chain stakeholders. As part of this role, it also acts as a Data Catalogue that provides the discovery layer for DPP assets and linked evidence. It allows stakeholders to locate material batches, retrieve associated credentials, and navigate supply chain relationships. In this context, the DPP can also be considered as the software tool that visualizes the digital twin of a product. For this reason, the establishment of a digital twin for static and dynamic data access should be considered as part of the architecture. The digital twin interacts with other components to provide up-to-date records essential for decision making.

The components within the architecture interact to facilitate secure data exchange and maintain traceability. The Data Exchange Protocol governs the flow of data between systems and supports controlled exchange of verifiable information. The Digital Twin/Data Catalogue interacts with other components by providing up-to-date records that are essential for decision-making. The Organization Identity Wallet stores credentials that support the authentication processes defined by the SSI Authorization layer. The Trust Chain verifies the legitimacy of these credentials, while the Verifiable Data concept ensures that exchanged data retains its integrity and authenticity, thereby promoting trust among stakeholders in the supply chain.

To ensure interoperability and machine-readable interpretation of data, semantic standards and shared vocabularies are required within the architecture. For this reason, the architecture may include a governed semantic hub[11]. Such a hub provides shared, versioned data models and credential schemas so that issuers and verifiers interpret certificate, chain-of-custody, and due diligence data consistently. This component supports both machine-readable verification and a common understanding of exchanged traceability data across stakeholders.

The system architecture depicts on the right-hand side monitoring tools and applications for the economic operators that want to make use of the traceability data. A foundational component of the economic operator for storing, managing, and retrieving data related to raw materials is the internal database, providing an organized record that supports traceability efforts. Additionally, a quality investigation process should be designed to analyse and address quality issues within the supply chain, utilizing data to ensure compliance with standards and regulatory requirements. Finally, a monitoring user interface provides visibility into raw material data and traceability information to users. The monitoring, quality assurance, and internal data management components are implementation-specific responsibilities of the respective economic operators utilizing the traceability infrastructure.

[11] https://userguide.cofinity-x.com/en/articles/312999-semantic-hub

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4.2 Integration of Material Fingerprint information into DPP

The material fingerprinting credential developed in MaDiTraCe project is a verifiable digital proof that supports origin claims for a raw material batch by linking the material's measurable physical properties to its digital traceability record. Material Fingerprinting credentials are used to validate declared origin claims without relying only on documents or identifiers, which can be copied, reused, or relabelled.

Figure 13: Process of integration of MFP into DPP

As seen in the Figure above, the process begins with laboratory analysis of representative samples using chemical, isotopic, or spectral methods. The analytical results are then compared against validated reference datasets maintained by an authoritative assessment body to determine whether the measured material signature is consistent with its declared geographic or geological origin. Instead of producing a binary result, the outcome is expressed as a probability-based origin assessment, making scientific uncertainty explicit and allowing downstream actors to make risk-based decisions. This assessment is issued as a cryptographically signed Verifiable Credential and linked to the Raw Material Digital Product Passport, where it can be retrieved and independently verified. The credential also includes supporting information such as the methodology used, the reference database, the laboratory or assessment body involved, accreditation details, false positive risk, and sample representativity. In this way, a material fingerprinting credential strengthens provenance assurance. It does not replace traceability records, but complements them with tamper-evident, machine-verifiable evidence that makes origin claims more transparent, and harder to falsify.

Regarding the issuance of material fingerprinting credentials, EBSI provides a useful European example of how a blockchain-based trust infrastructure can support these credentials through clearly separated accreditation, issuance, and passport integration roles (EBSI). In EBSI, a Trusted Accreditation Organisation (TAO) accredits issuers to issue certain types of verifiable credentials, while a Trusted Issuer (TI) issues domain-specific credentials to holders. This trust model allows verifiers to rely not only on the credential signature itself, but also on a publicly verifiable accreditation chain and issuer status.

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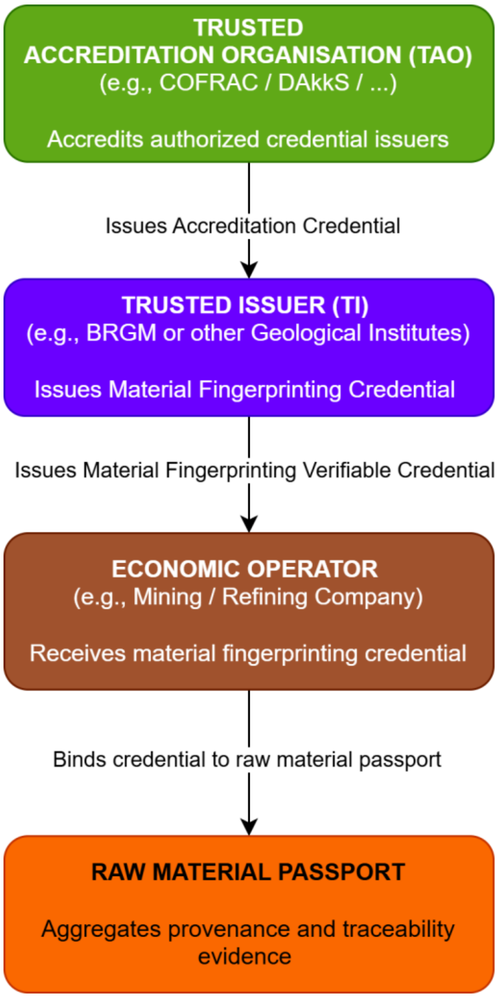

Figure 14: EBSI process

Using EBSI as a reference, the trust framework model behind material fingerprinting can work as follows: A national accreditation body plays the accreditation role by authorizing qualified institutions to issue material fingerprinting credentials. In the French example, this role would be played by COFRAC[12], the French accreditation body member of European Accreditation (EA). An authoritative scientific institution such as BRGM acts as the Trusted Issuer, issuing a material fingerprinting credential for a specific raw material batch based on analytical material data and validated reference datasets. The raw material manufacturer then receives that material fingerprinting credential and adds it to its raw material passport, where it becomes part of the passport's evidence layer.

The value of such a model is that it creates a publicly verifiable trust chain for provenance. A downstream buyer, auditor, or regulator can inspect the raw material passport, verify the fingerprinting credential, and confirm through this trust infrastructure that the issuer was properly accredited to issue that credential type. In line with SSI principles, trust is distributed across clearly defined roles rather than concentrated in a single central platform. The accreditation authority would not issue the scientific result itself; it would establish trust by accrediting who is authorized to issue such credentials. The trusted issuer does not control the passport; it issues the scientifically grounded credential under its own verifiable

[12] https://www.cofrac.fr/en/

identity. The manufacturer does not perform the authoritative assessment; it holds and reuses the issued credential by binding it to the raw material passport for downstream use. This separation of roles, combined with verifiable credentials and decentralized identifiers, supports tamper-evident evidence exchange, independent verification, and organizational control over issued and presented data. EBSI therefore serves as a concrete European reference point as a blockchain-based trust infrastructure for a credential system.

4.3 Integration of certification to DPPs

Certification information is a key element for making DPPs useful for traceability in critical raw material supply chains. In conventional supply chains, certification evidence is often generated and exchanged as separate files. These documents, such as audit reports, certificates of assay, inspection reports, and due-diligence statements, are usually produced by different actors and may be transferred independently from the material batch or product they belong to. This creates a risk that certification evidence becomes difficult to verify and detached from the physical material flow.

The MaDiTraCe approach addresses this challenge by linking certification evidence directly to the DPP (Figure 15). The DPP is therefore not only a digital access point for product data, but also a structured evidence container for certification, traceability, and due-diligence information. In this model, certificate documents remain available as human-readable evidence, while the corresponding metadata and document references are represented in machine-readable and signed verifiable credentials. As a result, certification evidence can be accessed through the DPP, checked by human auditors, and verified by digital systems across the supply chain.

Load Port

Loading Location	Lobito Port, Avenida da Independencia, CP 16, Lobito, Angola
Mode of Transport	Freight Train
Quality Loading	6% Li2O
Certificate of Assay	Alfred H Knight Certificate of Assay
Quantity/Volume	10000
Quantity Unit	dmt
Artificial Fingerprint	ATP-SP-04456
Verification Report	Alfred H Knight Inspection Report
Load Port PDF	Link
Load Port Certificate PDF	Link

CoC General Information

Unique ID	DE-HRB-45821
CERA 4in1 CoC Certificate ID	COC-2026-0147
Certification Start Date	2026-03-15
Certification End Date	2029-03-14
Organization Name	DMT
Organization Address	Zollvereinstr. 45, 45141 Essen, Germany
Claim Type	MB
% Claim	0.65
Country of Origin	n/a
CERA 4in1 Certificate	Link
Certificate File Name	TN CCS Certificate example.pdf

Figure 15: example of material passport.

In the MaDiTraCe implementation, certificate-related information is represented through W3C Verifiable Credentials. A credential binds together the issuer, the subject material batch or product, certificate metadata, and a cryptographic proof (i.e., issuer's signature). The subject of the credential is the DPP identifier, which ensures that the certification evidence is explicitly linked to the corresponding material or product. The proof section of the credential provides the technical basis for checking data integrity, meaning that

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downstream actors can verify who issued the certification-related evidence, which product it refers to, and whether the credential content has been altered after issuance.

Within this traceability solution, it is important to distinguish between the original certificate document and the verifiable credential that references it. A PDF audit report, inspection report, or certificate of assay is not automatically transformed into a digital credential. Instead, the credential contains structured metadata about the certificate and a reference to the original document. This makes the certificate claim and the document reference issuer-bound and tamper-evident, while still preserving the original human-readable document for auditors, buyers, certification bodies, and other stakeholders who may need to inspect it directly. The DPP therefore combines documentary evidence with digital verification mechanisms, rather than replacing one with the other. From a chain-of-custody perspective, this approach is particularly relevant because it makes certification evidence more reusable and easier to verify across supply-chain tiers. Instead of repeatedly exchanging documents manually, authorized actors can access the DPP and retrieve the relevant evidence in a structured format. They can check the issuing organization, the credential subject, the cryptographic proof, and the referenced documents before accepting a claim.

4.4 Relations with UN CEFACT and other initiatives

The MaDiTraCe traceability architecture is designed to align with emerging European and international initiatives for DPPs. A central reference point for MaDiTraCe is the work of UN/CEFACT (2026) as it provides international recommendations for cross-border trade facilitation and interoperable data exchange. The transparency protocol of UN/CEFACT (UNTP) (2024) is a voluntary, globally applicable B2B traceability framework that enables downstream actors to verify provenance and chain-of-custody continuity. MaDiTraCe aligns with this approach by using UNTP concepts to represent traceability events as verifiable digital evidence attached to the Raw Material DPPs.

In the MaDiTrace architecture (Figure 16), UNTP-aligned traceability events are used to document relevant lifecycle steps across the raw material supply chain. These events may include transaction, transformation, aggregation, and association events. Together, such events can form a transparency graph that links input materials to output products through verifiable lineage relationships. This is particularly relevant for critical raw materials, where downstream manufacturers, auditors, and regulators need to understand not only where a material originated, but also how it moved, changed, and was handled across multiple supply-chain tiers.

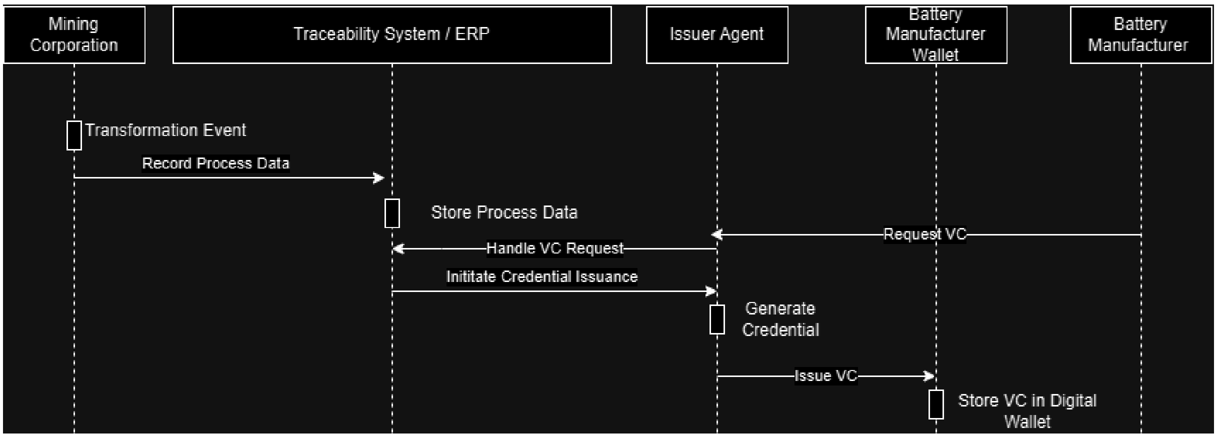

Figure 16: MaDiTraCe digital architecture.

MaDiTraCe implements this logic by linking traceability-event evidence to the raw material's DID-based identifier. When a relevant lifecycle step occurs, the responsible supply-chain actor records the corresponding process or custody information. This information can then be encoded as a verifiable credential and linked to the Raw Material DPP. The DPP becomes the access point through which downstream actors can discover and verify the UNTP traceability evidence. This approach is closely connected to the wider MaDiTraCe evidence model, as the same architectural mechanism is used for material fingerprinting, certification, and UNTP-aligned traceability events. In each case, evidence is issued by an accountable actor, cryptographically protected, linked to a product identifier, and made retrievable through the Raw Material DPP.

In addition to UN/CEFACT and UNTP, MaDiTraCe also relates to several European DPP and data-space initiatives, such as the Battery Pass Consortium (2024), CIRPASS (2024), Catena-X (N.d.), and CEN/CENELEC JTC 24 (2025a to 2025f). The Battery Pass Consortium provides relevant guidance for battery passport data attributes, material composition, and the separation of public and restricted data. CIRPASS provides a cross-sectoral reference for DPP interoperability and supports vendor-neutral architectures based on open standards for identifiers and data carriers. Catena-X provides a reference architecture for data-space-based exchange, including the use of dataspace governance and Eclipse Dataspace Connector concepts.

The relation to CEN/CENELEC JTC 24 is particularly important for European DPP alignment. Although EU DPP obligations are not yet broadly binding for standalone raw materials, MaDiTraCe aligns with the emerging JTC 24 framework for DPP systems. This includes alignment with principles for secure data exchange, persistent unique identifiers, physical data carriers, data persistence, APIs, and system interoperability. In the MaDiTraCe PoC, DID-based identifiers are used for products and organizations, QR codes can resolve to Raw Material DPPs, API-based access supports retrieval of DPP data and linked evidence, and JSON-LD is used to support semantic interoperability.

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5 Certification

5.1 The CERA 4in1 Certification System

The CERA 4in1 certification system (CERA 4in1) for responsible mineral raw materials supply chains was developed to contribute to achieving the SDGs. CERA 4in1 aims to establish requirements for the implementation of responsible production practices as well as for the traceability of responsibly sourced materials.

The TÜV NORD GROUP has taken a leading role in the development of the CERA 4in1 research initiative from the very beginning through its subsidiaries TN CERT (as certification body) and DMT (as a consultant in exploration, mining, processing, and sustainability). The concept of an accessible, universally applicable, and standardised certification programme was developed by the TÜV NORD GROUP in 2015. It was then further developed into a research project from 2017, with the financial support of EIT RawMaterials - a leading global consortium in the field of raw materials - until 2021. This collaboration involved several prestigious academic and institutional partners, including the Universiteit Leiden, Montanuniversität Leoben, LTU Business AB, Research Institutes Sweden (RISE), DMT (Project Leader) as well as TÜV NORD CERT GmbH (Certification).

The completion of all CERA 4in1 standards is conducted within the framework of "MaDiTraCe Project".

The CERA 4in1 development is based on the following principles:

Full Value Chain Coverage: CERA 4in1 is a pioneering certification system that provides tangible proof of environmental and social responsibility and corporate governance along the entire mineral raw material value chain, from exploration to final products;

Traceability: CERA 4in1 implements solutions for tracking certified mineral raw materials along the entire supply chain;

Universal Certification Solution: CERA 4in1 provides a holistic solution for comprehensive certification through the value chain; allowing existing schemes to coexist by considering their implementation as evidentiary support for CERA 4in1 requirements during the CERA 4in1 certification process, leading to top-quality standards and benefiting all stakeholders;

Involvement: CERA 4in1 allows every consultant and certification body, which meets the requirements as listed in this document, to register. The participation of a wide range of consultants and certification bodies ensures that companies have access to a homogeneous market and a diverse range of expertise. Furthermore, stakeholders are consulted during development processes and included during audit processes;

Applicability: CERA 4in1 targets all minerals globally excluding deep-sea mining;

Inclusiveness: CERA 4in1 is available to companies of all sizes. While the applicability of requirements is independent of company size, the evidence required for certification can vary significantly. This flexibility enables small and medium-sized enterprises (SMEs) to participate in the dynamic certification process, so that companies of all sizes can benefit from CERA 4in1; and

Risk Mitigation: CERA 4in1certification can secure investment value with greater transparency and responsibility by minimizing reputational and financial risk[13].

CERA 4in1 features a set of four standards, as shown in the Figure below. Each of these standards focuses on a different interface of the value chain, providing different certification solutions that promote both responsible mineral raw materials production and well-informed decision making by customers.

Figure 17: CERA 4in1 certification system

The CERA 4in1 standards are further described as:

CERA 4in1 Readiness Standard (CRS) defines environmental, social and governance (ESG) criteria for responsible conduct of mineral exploration and mine development projects prior to the operational phases.

CERA 4in1 Performance Standard – upstream (CPS) defines the ESG criteria, for a production facility or a group of production facilities that cover the operations of mining, processing, smelting, and/or refining.

CERA 4in1 Performance Standard – downstream (CPS-II) defines the ESG criteria for a manufacturing facility and covers the manufacturing of semi-finished products.

CERA 4in1 Chain of Custody Standard (CCS) applies to traded commodities and defines criteria for ensuring appropriate management systems for the traceability of responsibly sourced minerals, commodity-specific accounting methods, and chain of custody (CoC) material eligibility.

CERA 4in1 Final Product Standard (CFS) establishes the criteria necessary to label final consumer goods, empowering consumers to make informed purchasing decisions.

5.1.1 Focus - The CERA 4in1 Final Product Standard

The CERA 4in1 Final Product Standard (CFS) defines how certified supply chain actors communicate and make public claims about minerals and products that have been verified under the CERA 4in1 certification system. It does not certify companies or products directly; instead, it establishes the rules that govern who can use CERA trust marks, what they can

[13] Fu, C.; Yu, C.; Guo, M. & Zhang, L (2024): ESG rating and financial risk of mining industry companies. Resources Policy, 88, 104308. https://doi.org/10.1016/j.resourpol.2023.104308.

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say, and how they must back up those statements. Claims under the CFS always relate to specific attributes, such as the presence of certified material, ESG performance at a facility, or verified recycled content, and must clearly define their scope

The standard applies to:

- Brand owners, manufacturers, retailers and distributors using CERA certified inputs
- Sustainability, compliance, marketing and procurement teams responsible for ESG claims
- Auditors and certification bodies verifying CFS compliance

Before any public claim can be made under the CERA 4in1 system, whether on a product label, website, ESG report, or B2B contract, it must go through an approval process. The CFS distinguishes between pre-approved claim templates and new claims that require individual review.

Step 1. Verify Upstream Certification

The company must hold, or be able to demonstrate sourcing from, valid certification under at least one CERA 4in1 standard (CCS, CPS-I, CPS-II, or CRS). Non-certified entities such as brand owners or retailers must also sign a CFS Licensing Agreement with the CERA 4in1 Secretariat before making any claim.

Step 2. Select the Claim Type and CoC Model

The company identifies which of the approved claim categories applies (certified material, recycled content, ESG performance, etc.) and determines the Chain of Custody model used to track certified material. The CoC model directly determines the required disclaimer wording.

The Chain of Custody model plays a critical role in how claims can be interpreted. Not all models guarantee physical traceability. For example, mass balance and book and claim models allow for administrative allocation of certified material, which requires disclaimers to avoid misleading interpretations.

Step 3. Check Whether the Claim Is Pre-Approved

The CFS provides a library of approved claim templates with standardized wording for common scenarios. If the claim the company wants to make matches a pre-approved template exactly, the company may proceed to documentation and label preparation without submitting individual review. If the claim is new, or does not match an existing template, for example, an adapted ESG performance statement, a combined claim across multiple CoC models, or a claim referencing a specific emission reduction figure, it must be submitted for formal approval.

Step 4. Prepare Documentation and Label

The company collects the required evidence package and prepares label artwork or claim, including correct disclaimer placement, language consistency, and logo format.

Step 5. Ongoing Monitoring and Renewal

Once approved, claims are subject to periodic review and spot checks. Claims must be resubmitted whenever the product, CoC model, supplier, or certified scope changes. Licenses are time limited and must be renewed in line with certification of renewal cycles.

Once the process flow is understood, companies need to identify which claim category and format applies to their situation. Claims under CFS fall into two broad format categories:

On-product communication refers to information displayed directly on the product or its packaging, such as physical labels, hang tags, QR codes, part markings, or rating plates. In these cases, the approved CERA label must be clearly shown, and any claim must be accompanied by a disclaimer placed directly next to it. Off-product communication includes channels such as websites, annual or ESG reports, B2B contracts, advertising materials, and press releases. For these formats, written preapproval is required, and the same substantiation rules as for on-product claims must be followed.

All CFS claims must be supported by audit ready documentation retained for a minimum of five years. Key evidence requirements by claim type can be found in the Audit Catalogue. Core requirements across all claim types include:

- Valid CERA CCS, CPS, or CRS certificate for the relevant certified entity
- Complete CoC documentation tracing certified material from origin to point of claim
- Internal traceability logs (batch records, inventory, flow diagrams)
- Supplier certificates and transaction/shipping documents
- Signed declarations confirming claim accuracy and current certification status
- For ESG performance claims: GHG inventory, KPI data, and independent verification
- For Book & Claim: credit registry records and retirement confirmations

Three levels of non-conformance are defined based on severity and impact.

Minor non-conformances include issues such as using an incorrect font in the logo or applying an outdated claim format. These result in a Notice of Non-Conformance and require correction within a defined timeframe.

Major non-conformances involve more significant breaches, such as making public claims without proper traceability of documentation or using a mass balance claim without the required disclaimer. These trigger a Corrective Action Request and require a root-cause analysis. Critical non-conformances refer to serious violations, including falsely claiming certification or using fraudulent certificates or credits. These may result in revocation of the license, public delisting, and may result in legal action.

Governance is managed by the CERA 4in1 Secretariat, which manages licensing agreements, claim pre-approvals, periodic standard reviews (minimum every three years), and stakeholder grievance procedures. All public claims must receive written approval before use. Licenses are time limited and non-transferable. Also, the company making the claim remains responsible for its accuracy, even when certification and approval processes are in place.

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5.1.2 Focus - The CERA 4in1 Chain-of-Custody

The CERA 4in1 CCS is divided into four topics: Responsible Sourcing, Operations, Handling and Claims to demarcate the scope of the CoC system.

Responsible Sourcing:

Responsible sourcing is about ensuring not only that the materials received conform to the applicable CoC requirements, but that the supplier complies with the environmental, social, and governance (ESG) requirements outlined in the standard. This topic addresses both certified and non-certified materials procured by the organization. The certified materials have fewer requirements, mainly covering qualitative and quantitative information about the materials, as well as verification of the certification documents and the relevant data received on sustainability and the materials' origin. Whereas, for non-certified materials, the organization must conduct due diligence in line with the OECD Due Diligence Guidance for Responsible Supply Chains of Minerals from Conflict-Affected and High-Risk Areas (CAHRA) for the materials in the document and in addition, a minimum set of ESG principles established in the standard must be implemented to attain the controlled status of the materials.

Responsible Operations

Apart from ensuring their suppliers meet the minimum requirements in the standards, the Responsible Operations part is to ensure that the organization itself operates in accordance with the applicable ESG criteria. This standard also follows a modular structure, which means that under Responsible Operations, if the organization is already certified to the CERA 4in1 Performance Standard (Upstream or Downstream), they are exempt from fulfilling the requirements of this section. The majority of the chain of custody (CoC) standards in the mining industry are add-ons to the performance standard. In contrast, the CERA 4in1 CCS is a standalone standard that integrates the minimum ESG criteria into the CoC framework, making it distinct in its approach.

Responsible Handling and Claims

Responsible Handling includes the following CoC models and aligns with ISO 22095:2020. The following table represents the different models and the controls required, as well as the corresponding claims that can be made:

CoC model	Controls	Claims
Identity Preserved	Separation of certified materials from one origin from certified materials from other origins and non-certified materials. The certified outputs must be equal to or less than the certified inputs, taking the conversion factors into account.	Origin of the material

Segregation	Separation of certified and non-certified materials. The certified outputs must be equal to or less than the certified inputs, taking the conversion factors into account.	100% of the material is certified
Controlled blending	Mixing certified and non-certified materials is allowed, but the percentage of certified material mixed must always be accurately determined and recorded. The certified outputs must be equal to or less than the certified inputs, taking the conversion factors into account.	X% of the material is certified.
Mass balance	Allows mixing of certified and non-certified materials and reconciliation of certified materials within the accounting period to ensure certified outputs do not exceed certified inputs. Additionally, the certified inputs procured over the accounting period must correspond to the claims made. Includes the rolling average percentage method and the credit method.	X% of responsibly sourced materials over a defined period

Table 3: CoC models and controls required

Another method is the book-and-claim method, where there is no traceability of the certified material, and the material claims are sold as credits on a trading platform that the organization can buy to make relevant claims. This approach has both advantages, such as the ability to sell credits where there is no demand for certified materials and disadvantages like the loss of traceability of certified materials. This method has not been considered as part of the CERA 4in1 CCS because it requires a credit-trading platform.

5.1.3 Challenges of conventional certification process

Limited adoption

Regulatory instruments outline the requirements for responsible practices in the mining industry, but often provide limited guidance on implementation, demonstration and verification, for which industry actors generally rely on voluntary standards to fulfil. One example is the EU Battery Regulation, which requires organizations to establish a CoC or traceability system, whereas voluntary standards provide guidance and, through audits, help verify that they have the systems in place to meet the defined requirements. However, these standards, which help bridge the gap between regulatory requirements and industry practices, are not enforced by regulations; as a result, their adoption largely depends on the willingness of organizations and stakeholders, as well as market pressure.

Paper-based systems

As highlighted in the IEA and OECD (2025) report, paper-based systems are still widely used in industry. These systems are cheap, convenient, do not require complex

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infrastructure or high-skilled personnel to implement, and are easy to adopt. But these paper-based systems are susceptible to forgery and manipulation and are more prone to manual errors when handling information than digital systems. Such systems record information at aggregated shipment or batch levels, limit the ability to collect and record information at a granular level, and make it difficult to maintain continuous oversight of material transformation and movement across supply chain actors. Furthermore, CoC systems not only generate large volumes of information about the material and processes, but also about due diligence practices, which are necessary to ensure responsible sourcing or handling of materials. Linking all this information and reviewing the documents makes auditing time-consuming and challenging to verify. In short, even if paper-based systems are easy to implement, they are often associated with limitations and drawbacks when collecting, recording, linking, and transmitting information to all involved stakeholders.

Oversight of certification bodies

The certification is achieved when the organization meets the requirements defined in the standard, and following that, surveillance audits are conducted annually to ensure that the organization continues to maintain the CoC systems and in certain cases, are also required to annually or at the end of the accounting period, report on the reconciliation of the certified materials and provide information about the origin of the materials procured. However, the materials are continuously procured, handled (which may involve mixing with non-certified materials), and transferred to the next actor in the supply chain. The data on the origin, volume of certified materials, and transaction records are only available to the certification body at the end of the accounting period or annually. Therefore, any inconsistencies may only be detected after a significant delay. This creates a temporal gap between the movement of materials and the verification of information. Therefore, certification bodies would require real-time access to material volumes and transaction information to identify instances of overdraws, inconsistencies of claims, etc., to ensure the credibility of the claims.

5.2 Lessons Learned from the Pilot Program conducted in Africa and Georgia and Contribution to the Development of the CERA 4in1 Certification Framework

Within the MaDiTraCe project, some pilots were undertaken to validate different components of the CERA 4in1 certification framework across multiple stages of the mineral value chain.

The pilots were the following:

- **CRS Pilot**: validation of the CERA Readiness Standard (CRS) at an exploration and mine development project in Georgia to assess the applicability of ESG readiness requirements during the early stages of mining projects.
- **CPS-II Pilot**: implementation of the CERA Performance Standard for Downstream Manufacturing (CPS-II) at a manufacturing facility (Sakcable/Georgia, see Figure 18) using mineral raw materials to evaluate ESG performance requirements.

- **CCS Pilot Manufacturing**: Assessment of Chain of Custody requirements within the downstream manufacturing (Sakcable/Georgia) environment to evaluate material traceability, inventory management, and the integration of traceability requirements with ESG performance verification.
- **CCS Pilot Artisanal and Small-Scale Mining (ASM)**: Benchmarking of an existing traceability system for mica originating from ASM operations (Madagascar & Tanzania) against the principles and requirements of the CERA 4in1 Chain of Custody Standard.

Figure 18: Main entrance of the Sakcable manufacturing facility in Tbilisi, Georgia, where the CPS-II and CCS pilot activities were conducted.

Together, these pilot activities provided practical validation of the certification framework across exploration, mining, downstream manufacturing, and supply chain traceability. They also enabled the project consortium to identify implementation challenges, assess the auditability of the proposed requirements, and refine the standards based on practical experience obtained under different operating conditions.

The objective of this section is to summarize the principal lessons learned during the pilot program and describe how these findings contributed to the further development and improvement of the CERA 4in1 framework, with particular emphasis on the Chain of Custody Standard (CCS) and the Downstream Manufacturing Performance Standard (CPS-II). Furthermore, it is also to be noted that the objective of the pilot program was not to provide any certification to the pilot partners, and the pilot was not intended to replicate the processes of a full certification audit.

5.2.1 Overview of Pilot Activities

CRS Pilot Exploration and Mine Development Project

The CERA Readiness Standard (CRS) pilot was conducted to evaluate the applicability of ESG requirements within an exploration and mine development project and to assess the effectiveness of the readiness assessment methodology prior to full certification.

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The assessment included a review of project documentation, interviews with project personnel, and onsite verification of project activities. The pilot evaluated governance, environmental and social management systems, stakeholder engagement processes, risk management practices, operational controls, and project planning activities.

A key objective of the pilot was to test the progressive certification concept adopted within the CRS. The pilot assessed the suitability of the maturity-based approach and the practicality of determining which requirements should apply according to the project's development stage.

The findings provided valuable insights into the definition of assessment scope, evidence requirements, auditor guidance, and the implementation of readiness assessments across projects with varying levels of maturity.

Figure 19: DMT auditors Luisa and Lukas conducting the CRS pilot audit during the site.

CPS-II Pilot Downstream Manufacturing Facility

The CPS-II pilot focused on validating the applicability and auditability of the CERA Performance Standard for Downstream Manufacturing at a manufacturing facility utilizing mineral raw materials.

The pilot followed the proposed conformity assessment methodology and included document review, interviews with management and operational personnel, onsite verification activities, and testing of the audit catalogue. Requirements covering governance, responsible sourcing, environmental management, climate change, occupational health and safety, labour practices, circular economy, data governance, and disclosure were assessed against available objective evidence.

The pilot also served as an opportunity to evaluate the integration of ESG performance verification with traceability requirements under the broader CERA 4in1 framework.

Figure 20: Samuel discussing the CPS-II Standard requirements during the pilot implementation and validation process.

CCS Pilot Manufacturing Supply Chain

The first Chain of Custody pilot was conducted alongside the CPS-II assessment to evaluate the applicability of CCS requirements within a downstream manufacturing environment.

The assessment focused on the traceability of mineral raw materials throughout the manufacturing process, including supplier documentation, material identification procedures, inventory management, production records, warehouse controls, and batch tracking mechanisms.

The objective was to determine whether existing operational systems could effectively support the implementation of the CERA 4in1 Chain of Custody Standard.

The pilot demonstrated that many manufacturing organizations already possess mature operational systems capable of supporting Chain of Custody implementation. Existing enterprise resource planning systems, inventory management procedures, production records, and quality management processes provided a strong basis for material traceability and verification activities.

The findings from this pilot contributed to the refinement of the CCS audit methodology, verification requirements, and implementation guidance for downstream manufacturing facilities.

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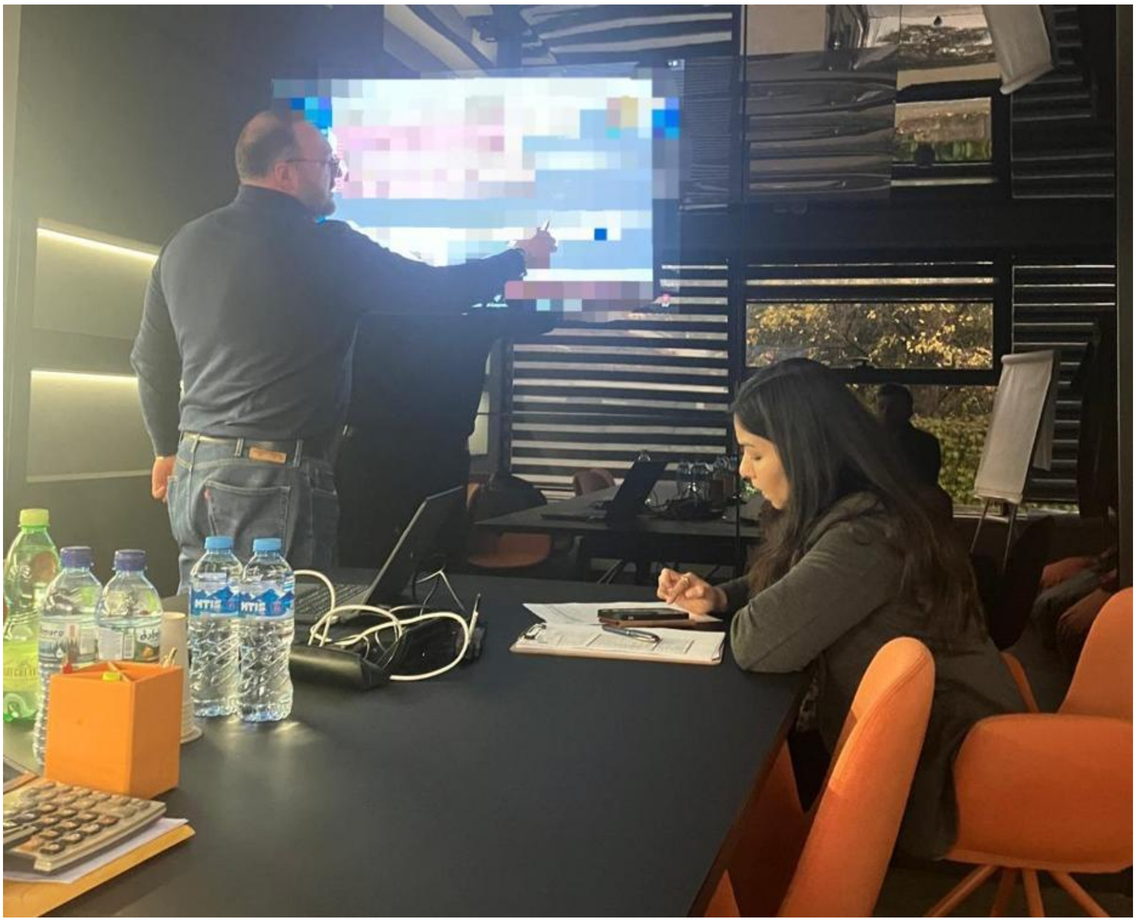

Figure 21: Thania conducting interviews as part of the Chain of Custody Standard (CCS) pilot to assess traceability practices.

CCS Pilot ASM Supply Chain

A second Chain of Custody pilot was conducted within an artisanal and small-scale mining (ASM) supply chain to evaluate the applicability of CCS requirements under significantly different operating conditions.

The participating organization is a Chinese manufacturer producing mica shielding products for electric vehicle batteries, sourcing mica from ASM operations in Madagascar and Tanzania. In response to customer requirements regarding responsible sourcing and transparency, the company had developed its own traceability system based on QR-code technology and material tracking procedures.

As there is currently no internationally recognised Chain of Custody system specifically addressing ASM-derived mica, the objective of the pilot was not to validate the complete CCS audit catalogue but rather to benchmark the company's traceability approach against the principles and requirements of the CERA 4in1 Chain of Custody Standard.

The assessment included a desktop review of the traceability system, interviews with relevant personnel, and a site visit to evaluate how materials originating from ASM operations could be traced and controlled before entering global supply chains.

Figure 22: CCS pilot – from left to right (Tanzania – raw mica, Tanzania – stock, Madagascar – mine)

The pilot provided valuable insights into the practical challenges associated with implementing Chain of Custody systems in ASM environments, particularly regarding scope definition, eligibility of materials, evidence requirements, documentation practices, and verification of cash transactions. Rather than questioning the relevance of the existing CCS requirements, the pilot demonstrated that additional implementation guidance is necessary to ensure that the standard can be applied effectively within ASM contexts while maintaining the credibility and integrity of responsible sourcing claims.

Collectively, the four pilot activities validated different components of the CERA 4in1 framework and demonstrated the value of testing the standards across diverse operational environments. The lessons learned from these pilots informed the refinement of the standards.

5.2.2 Key Lessons Learned from the Pilot Program

The pilot program provided practical experience regarding the implementation of the CERA 4in1 certification framework under different operational conditions. Although each pilot addressed different stages of the mineral value chain, several common themes emerged regarding auditability, evidence collection, risk management, traceability, and implementation practicality. The lessons learned contributed to the refinement of the standards.

Audit Planning and Evidence Collection Require Additional Flexibility

One of the most important observations from the pilot program concerned the collection and verification of objective evidence during onsite assessments.

During the CRS pilot, it became evident that discussing findings during the onsite audit can be challenging because supporting documentation may not always be immediately available. In several cases, project personnel were able to locate additional records after discussions with the audit team, resulting in the closure of initially identified gaps.

This demonstrated the importance of providing organizations with sufficient opportunity to review preliminary findings and submit additional evidence before final audit conclusions are reached. It was concluded that providing a summary of findings at the end of each audit

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day would improve the efficiency and fairness of the assessment process by allowing organizations adequate time to review documentation and provide supporting evidence where appropriate.

The CPS-II pilot produced similar observations. Although many management systems and operational controls already existed, supporting documentation was not always maintained in a format that directly corresponded to the requirements of the standard. This reinforced the importance of clearly defining evidence expectations within the audit catalogue and providing auditors with greater flexibility when assessing objective evidence.

Language and Cultural Considerations Influence Audit Effectiveness

Language barriers were identified as a recurring challenge during pilot implementation.

During the CRS pilot, documentation was frequently maintained in the local language, requiring translation before it could be assessed. Interviews often required additional explanation and interpretation to ensure that both auditors and auditees shared a common understanding of the requirements.

These activities proved to be considerably more time-consuming than anticipated and highlighted the importance of incorporating translation requirements into audit planning. Future implementations should allocate sufficient time and resources for translation activities and, where appropriate, involve local language support to improve both efficiency and consistency during the assessment process.

Maintaining Auditor Independence While Supporting Continuous Improvement

The pilot program also highlighted the importance of maintaining an appropriate balance between providing guidance and preserving auditor independence.

During both the CRS and CPS-II pilots, pilot partners frequently requested clarification, suggestions, or recommendations regarding how identified gaps could be addressed. While these discussions support organizational learning and continuous improvement, certification systems must clearly distinguish between conformity assessment and consultancy activities.

The pilots demonstrated that the extent to which clarifications, suggestions, or recommendations can be provided remains a sensitive issue within any certification scheme. Additional guidance was developed to clarify the role of auditors, ensuring that impartiality is maintained while still allowing auditors to explain the intent of requirements and the basis for assessment findings.

Scope Definition Is Critical for Consistent Assessments

A key lesson from the CRS pilot concerned the importance of clearly defining the assessment scope. An exploration project frequently consists of activities at different stages of maturity. While the primary project may still be considered an exploration project, it may simultaneously include construction activities, development-stage infrastructure, demonstration processing plants, or other operational facilities.

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That is why selecting the appropriate requirements according to the maturity stage of the project becomes considerably more complex. Also, determining whether existing facilities should be included within or excluded from the assessment scope requires clear justification and consistent decision-making.

The pilot demonstrated that additional guidance on scope determination was required to improve consistency between assessments and ensure that organizations are evaluated against requirements appropriate to their stage of development.

Existing Management Systems Provide a Strong Foundation for Certification

One of the most positive findings across the pilot program was that many organizations already possess management systems capable of supporting certification.

Within the CPS-II pilot, existing quality management, environmental management, occupational health and safety, procurement, inventory management, and production control systems provided a strong basis for demonstrating conformity with ESG requirements.

Similarly, the manufacturing CCS pilot demonstrated that existing traceability systems, enterprise resource planning systems, production records, warehouse controls, and batch identification procedures already provide many of the controls required by the Chain of Custody Standard.

These findings validated the design adopted within the CERA 4in1 framework, namely that the standards should build upon existing operational systems wherever possible rather than requiring organizations to establish entirely new management structures.

Requirement addressing the definition of the scope of the Chain of Custody system in ASM Operations

In the general case of the CERA4in1 Chain of Custody standard, the scope is defined by the organization, and the auditor assesses whether the scope is appropriate and whether all activities conducted within the scope support the chain of custody claim. However, during the pilot it was observed that the scope definition needs to be more explicit in the case of ASM. Within this scope, the miners involved, the mining areas, the materials/products, and the activities within the boundaries need to be included. What was further observed was the presence of non-registered miners on site during the pilot. So, it requires that the scope should be defined explicitly to not only cover what is included, but in addition, if a specific area, activity, or person is excluded from the scope, a reasonable justification for the exclusion must be provided, as exclusion should not be a shortcut to simplify compliance and avoid difficult areas.

Therefore, in addition to the definition of scope, in the CERA 4in1 CCS standard should include further clarification on what the scope in case of ASM must include and should justify any exclusions (such as any miners who are excluded or any areas etc.) and also address the reasonable measures that were taken to include them, and why the inclusion was not feasible at the time of the assessment. When assessing, the auditor will need to monitor how materials originating outside the scope are prevented from mixing with eligible materials.

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Eligibility of Materials Originating from ASM Operations

In the case of CERA 4in1 CCS, the mine is the starting point of the chain of custody, and it should be having a certified status, meaning that it has fulfilled all the requirements of the standard. However, during the pilot, it was observed that the current evidence required to satisfy CERA 4in1 requirements may be challenging to apply directly in the context of an ASM. For instance, in the CERA 4in1 standard it is required that the organization identify all the critical control points where certified and non-certified materials may be mixed, altered or compromised and in a large scale operation the auditor will be able to assess through the documented procedures and fixed production lines or the presence of a process map where such points could possibly be and also assess the controls in place by the organization to prevent the event from taking place. However, in the ASM pilot there was no formal process map or documentation available, and no fixed facility layout. Material handling was more on a day-to-day basis than following a standard operating procedure. The assessment on site had to be adapted accordingly by reconstructing the material flow (where the mica was extracted, how the materials are sorted according to grades, how eligible materials are kept separate from the ones originating from out of scope, etc.) through observations and interviews rather than reviewing documentation.

Furthermore, detailed documentation on material reconciliation is required by the standard for the material integrity and this includes recording the inputs, outputs, conversion factors, waste or losses. Similarly, this requirement was difficult to apply and verify as the material is manually extracted and sorted, and the quality grading is done visually and are also handled in small batches by the processors. Weight changes do occur from the extracted mica to processed mica but these losses in each of these transformation steps are not recorded. So, it became challenging to verify the balance between the input and output quantities. The requirement for material reconciliation is certainly valid but needed to be adapted to fit the context of ASMs.

In this case, consideration should be given to what could reasonably serve as minimum evidence for compliance and the objective should not be to burden ASM with additional administrative requirements. Rather, the focus should be, for instance, on whether the material can be traced to the registered miner, defining the minimum due diligence requirements and whether they have sufficient controls to prevent mixing of materials from unknown or non-eligible sources and if such controls are in place then the material originating from such sources could be considered eligible to serve as the point of entry into the CoC system.

Cash Transactions within ASM Supply Chains

The requirement related to cash transactions in CERA 4in1 CCS states that such transactions should not exceed the legal limits or USD 10,000, whichever is lower and that it must be thoroughly documented. Because with cash transactions there is a risk of information on the records being manipulated. It was, however, observed during the pilot, payments are made to the miners in cash, and such cash transactions are unavoidable due to the limited availability of banking infrastructure and the distance to the financial services. Therefore, the issue is not that the legal limit or the USD 10,000 is exceeded, but whether this cash payment can be used as a reliable evidence that the eligible material was purchased from the registered miner as it is the first point of entry, and is connected to the miner from a defined source area and a recorded batch number.

So during the pilot, it was assessed whether these cash transactions could be verified if the payments had information related to the registered miner, quantity, grade and source area and controls were in place, for instance, include having a witness present during payment, dual sign-off by the paying person and the receiving miner. The presence of witness was not there to replace the documentation, but it serves as an additional layer of verification that the payment was in fact made to the registered miner for the recorded quantity of eligible material.

Overall it was concluded from the pilot that the existing CERA 4in1 requirements are still relevant but additional guidance will need to be developed specifically for the ASM context, and the focus should be if the material is traceable and controlled and not solely on meeting the documentation expectations.

Risk-Based Management Improves Practicality and Applicability

The pilot program confirmed the value of integrating risk management principles throughout the CERA 4in1 framework.

The CRS pilot demonstrated the importance of identifying and prioritizing ESG risks according to the maturity stage of a project, while the CPS-II pilot validated the practical application of the Bowtie methodology for identifying threats, undesirable events, preventive barriers, mitigation measures, and potential consequences associated with ESG risks.

Rather than relying exclusively on prescriptive compliance requirements, the pilots demonstrated that a risk-based approach provides greater flexibility and applicability across organizations of different sizes, operating contexts, and levels of maturity. It also supports continuous improvement by encouraging organizations to focus resources on the most significant ESG and traceability risks.

The Bowtie methodology and broader risk management principles were retained and further strengthened within the CPS-II framework, providing organizations with a structured approach to identifying, managing, and monitoring ESG risks while supporting more consistent and risk-informed assurance activities.

5.2.3 Contribution of the Pilot Program to the Development of the CERA 4in1 Framework

The pilot program provided valuable practical experience that validated the overall architecture of the CERA 4in1 certification framework while identifying opportunities to improve its clarity, consistency, and practical implementation. Rather than fundamentally changing the standards, the pilots confirmed that the proposed ESG and Chain of Custody (CoC) approach is technically robust and applicable across different stages of the mineral value chain.

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The experience gained from the CRS, CPS-II, and CCS pilots led to several refinements. Standard requirements were clarified to improve their applicability, implementation guidance, and interpretation by both organizations and auditors, particularly regarding responsible sourcing, data governance, traceability, and ASM operations. The audit methodology was strengthened by reinforcing the use of document reviews, stakeholder interviews, onsite observations, and evidence triangulation, while providing greater flexibility during evidence collection without compromising audit independence or certification integrity.

The pilots also improved the audit catalogue by providing clearer guidance on evidence. While many participating organizations demonstrated mature management systems, the pilots showed that evidence often required better documentation or contextual explanation.

Another important outcome was the validation of the framework's risk-based approach. The pilots confirmed that integrating Bowtie principles into CPS-II helps organizations better understand the relationship between ESG risks, operational controls, monitoring activities, and continuous improvement, strengthening both implementation and auditability.

Finally, the pilot program validated the strategic integration of ESG performance and traceability within a single assurance framework. The pilots demonstrated that combining ESG verification with Chain of Custody assurance increases supply chain transparency, strengthens responsible sourcing, enhances the credibility of sustainability claims, supports Digital Product Passport initiatives, aligns with emerging regulatory requirements, and reduces duplication of audits.

5.2.4 CERA 4in1 case studies conclusion

The pilot program represented a fundamental milestone in the development and validation of the CERA 4in1 certification framework.

Through the implementation of the CRS pilot, the CPS-II pilot, and two complementary CCS pilot activities covering both downstream manufacturing and artisanal and small-scale mining supply chains, the project successfully evaluated the applicability, auditability, and effectiveness of the proposed standards across multiple stages of the mineral value chain.

The pilot activities confirmed that the overall architecture of the CERA 4in1 framework is robust and applicable across diverse operational contexts while also identifying opportunities to improve implementation guidance, evidence requirements, verification procedures, and audit methodologies.

Perhaps the most important outcome of the pilot program was the confirmation that ESG performance assurance and Chain of Custody assurance should be viewed as complementary components of a single responsible sourcing framework. By integrating organizational ESG performance with material traceability, the CERA 4in1 framework provides a comprehensive assurance system capable of supporting responsible mineral production, transparent supply chains, credible sustainability claims, and emerging regulatory requirements.

Overall, the pilot program significantly enhanced the practicality, credibility, and market relevance of the CERA 4in1 framework. The resulting improvements provide a strong foundation for future implementation, independent certification, and wider market adoption across mineral value chains.

6 Integration of the three MaDiTraCe pillars

The integration of the three MaDiTraCe pillars—Chain of Custody certification, Material Fingerprinting/Artificial Fingerprinting (MFP/AFP), and the Digital Product Passport (DPP)—was based on a **Statement of Interfaces** developed jointly by the work package partners during dedicated integration workshops held during the MaDiTraCe General Assembly meetings in Leoben (2024) and Essen (2025). The objectives of these workshops were to identify how the technical outputs of WP2 and WP3 could support the development of the WP4 certification framework and to define the interactions between the different pillars.

This Statement of Interfaces established the scope, responsibilities and expected contributions of each work package, identifying the information, technical requirements and methodological outputs that needed to be exchanged to enable integration. In particular, it examined where material fingerprinting and artificial tagging could provide evidence to substantiate origin and Chain-of-Custody claims, how Digital Product Passports could support the recording, exchange and verification of traceability information, and what procedural, governance and auditing requirements would be necessary for these technologies to support certification. The statement also identified the principal challenges, boundary conditions and prerequisites associated with their implementation, thereby providing a common roadmap for the integration activities undertaken within MaDiTraCe.

The following sections build upon these interfaces by examining existing approaches from other industries, assessing the contribution of each MaDiTraCe pillar to claim validation, and proposing an integrated framework for trustworthy mineral traceability.

6.1 Lessons from other industries

6.1.1 Timber Industry

The Forest Stewardship Council (FSC) and the Programme for the Endorsement of Forest Certification (PEFC) are the two voluntary wood certification systems widely adopted by the industry to improve forest management through ESG considerations, such as illegal logging, labor conditions, biodiversity, etc., and tracking of raw materials along the supply chain using CoC (Depoorter & Marx, 2022). The former is a global standard for sustainable forestry, comprising 10 principles and 57 performance-based management criteria and is a member of the ISEAL Alliance (FSC, 2023; ISEAL, 2025). Whereas the latter seek to endorse national certification systems if they meet the requirements set by the standard (PEFC, 2018).

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In the case of the FSC CoC standard FSC-STD-40-004, it considers the segregation and mass balance models (termed as the percentage system and credit system). In addition, it includes fiber testing criteria (criteria 1.10), which the organization should comply with by providing samples and specimens of its materials and products to the certification body and to Assurance Services International for verification and identification of the genus, family, and, sometimes, the species of timber (FSC, 2011). Under the testing scheme, stable isotope and DNA analyses are used to determine the origin of the wood, depending on whether sufficient samples are available for comparison. This has been developed under the WorldForestID Project, which aims to build a georeferenced, open-source database of wood samples to eliminate wood from supply chains originating in high-risk areas associated with illegal logging practices (FSC).

Figure 23 Illustrates the method for identifying origin, where the first step is the collection and analysis of samples, followed by data modelling that combines chemical analysis results with environmental data to create spatial reference models that show chemical variability across species and geography. The final step is to compare these chemical signatures in the products or raw materials to assess consistency with the claimed origin, thereby supporting claims of origin

Figure 23: WorldForestID method for identifying origin of timber products.

The FSC CoC standard also includes core labour requirements, for which self-assessment templates are provided by region of operations. Furthermore, coupled with the CoC standard, are complementary standards such as multi-site, controlled wood and reclaimed wood standards. The CoC standard is also supported by the FSC Trace technological solution, a blockchain-based solution that enables FSC participants to securely access and exchange information in real time. It allows participants to upload transaction information (bulk upload or individual transactions), flexibility in information sharing on the platform (how much to share and for whom) and verify the claims made on the products, which helps to meet regulatory requirements such as the European Deforestation-Free Regulation (EUDR) through the reporting function (FSC).

Concerning the PEFC CoC standard, it also includes health, safety, and labour issues, and the CoC models considered in the standard are similar to those in the FSC, namely the physical separation method and the mass balance method, which consists of the percentage and credit method. PEFC is also developing an online platform that will use satellite data, such as geolocation and certified forest areas, to enhance monitoring of group certification. The approach is being piloted to make certification accessible to smallholders and, at the same time, serve as a tool for risk monitoring (PEFC).

6.1.2 Textiles

The textile supply chain is also fraught with environmental pollution and labour-related risks (McFall-Johnsen, 2020; Nguyen, 2024). Like other commodities, it has developed CoC standards to maintain records of inputs and outputs and to ensure that associated claims are legitimate. The Textile Exchange standard includes segregation, controlled blending, and mass balance, which is referred to as the alternative volume reconciliation method in the standard. Textile Exchange also developed a technological solution called Trackit, comprising Digital Trackit (dTrackit) and Electronic Trackit (eTrackit). dTrackit digitalizes transactions and provides users with information such as the scope of certification. eTrackit tracks certified materials online using a token system (one token corresponds to 1kg of material) that transfers virtual materials between supply chain actors (Textile Exchange).

Determining the provenance and validating the claims of organizations sourcing textile raw materials is important to avoid complicity in supply chain risks, and Textile Exchange, along with Fashion for Good, has initiated the Textile Tracer Assessment. This form of assessment employs forensic and additive tracers. Forensic tracers are applied at the raw material extraction phase and include isotope analysis, DNA analysis, and isotopic or elemental profiling. In contrast, for additive tracers, synthetic/artificial DNA, ink, or rare-earth fluorescents or optical fingerprints are added at any stage in the supply chain to enhance end-to-end traceability (Fashion for Good, 2022).

Better Cotton is another standard used within the fashion industry to govern the cotton supply chain. The Better Cotton CoC standard includes segregation, controlled blending, and a mass balance model (credit method denoted as Better Cotton Initiative (BCI) Claim Units). The segregation model is further subdivided into single- and multi-country models, in which the origin can be preserved if not mixed with other countries (Better Cotton Initiative, 2026). To further enhance traceability, the BCI developed the BCI platform, which allows supply chain actors to enter and monitor their transactions to verify the volumes of certified materials. For the segregation and controlled blending models, the volumes of certified materials are recorded directly from the transaction information on the platform. However, the mass balance system works differently on the platform. It uses Better Cotton Claim Units (BCCUs) (1 BCCU = 1 kg of Better Cotton lint), which are digital units used to track certified materials (Better Cotton Initiative). The standard also suggests various ways compliance should be monitored, including the use of forensic or additive tracers to assess integrity in the case of segregation (single country) claims (Better Cotton, 2023).

Among other standards in the apparel industry, the OEKO-TEX Standard also ensures that its cotton products are traceable, free of harmful substances, and produced in a sustainable manner (OEKO-TEX, 2025). The standard also relies on a digital traceability platform, TextileGenesis, which helps digitalize transaction documents (OEKO-TEX, 2026). This approach is used in conjunction with their fiber testing solution developed by Haelixa AG, which uses DNA markers to improve the traceability and reliability of claims (Haelixa, 2025).

6.1.3 Food

Food sector is a good example of interactions between traceability systems and certification schemes (fair, organic).

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For fisheries – The Marine Stewardship Council (MSC[14]) CoC standard only allows segregation of certified fish from non-certified fish. In addition, for CoC eligibility, the organization must also comply with the labour requirements. For supply chain assurance, the standard requires the organization to allow the collection of samples of certified products for DNA testing or other product authentication investigations. The sampling procedure includes clear instructions for collecting samples, selecting species from the Priority Species list, and recording and storing sample information (Marine Stewardship Council, 2023). Digital traceability is also on MSC's agenda. It will include requirements for sharing data in a standardized, digital format, taking into account the EPCIS data standard and the Global Dialogue on Seafood Traceability's interoperability standard. The standard is going to conduct pilots of their digital solution till September 2026 (Caldwell, 2026).

Soy – Round Table on Responsible Soy (RTRS[15]) Chain of Custody Standard permits the use of segregation, mass balance, and book-and-aim models to ensure soy traceability from production to the final product (Round Table on Responsible Soy, 2025). In addition, the RTRS set up an online platform for credit trading, called the Marketplace, where 1 tonne of soy is equivalent to 1 credit, and organizations can choose to trade either directly or in the blind. If credits are issued against the certified material, the physical material cannot be sold with an RTRS claim. The other transactions related to segregation and mass balance can also be recorded on the online platform, enabling traceability of physical materials throughout the supply chain (Round Table on Responsible Soy). The standard requires testing to verify non-genetically modified organism (GMO) status, using analytical methods such as real-time polymerase chain reaction (PCR) and controlled thresholds, such as the percentage of accidental presence of GMO DNA in the input material, depending on the legislation (Round Table on Responsible Soy, 2025).

Similar to the supply chain for mineral raw materials, the other supply chains for food, timber, and textiles also require end-to-end traceability solutions to comply with regulations and other stakeholder demands. As a result, the latter CoC standards have integrated, or are in the process of integrating, a range of digital and chemical technological solutions. As provided above, FSC uses fiber testing techniques, FSC Trace, textile standards, forensic and additive tracers, and dedicated online platforms such as Trackit and the BCI platform. They seek to support the CoC standard for validating claims of origin, promote greater transparency and more effective traceability, and move away from reliance on solely documentation-based traceability and claims.

6.2 Material fingerprinting and Artificial fingerprinting as tools for CoC certification

6.2.1 Utilization of MFP and AFP for different types of material claim

MFP and AFP can be used to substantiate materials claims across various CoC models, including identity preservation, segregation, controlled blending, and mass balance. Theoretically, identity preservation offers the most straightforward application for these

[14] www.msc.org
[15] https://responsiblesoy.org/

technologies. As physical mixing of the raw material is prohibited under this model, the inherent material fingerprint is maintained, allowing MFP to verify material claims. By extension, when utilising AFP, the applied TP dosage and material-specific encoding would remain unchanged. Furthermore, MFP and AFP should also reliably detect the illicit wholesale substitution of raw materials, as the material's fingerprint would be inherently different and any associated TPs would be missing.

However, MFP and AFP may fail to work as traceability tools when certain CRMs undergo transformation or beneficiation, as both the material fingerprint or the information contained within TPs may become lost or unrecognisable as part of these processes. However, in the case of AFP, as long as AFP is used alongside traceability systems which verify the material claim of a material upon entering a facility, refined raw materials which may lose TPs or origin-specific material fingerprints at the facility can subsequently have TPs reapplied before the refined material is passed onto the next stakeholder or location along the CoC.

A significant item to address when the practices of identity preservation, segregation, controlled blending or mass balance are used is the reality of mixing with certified raw material (i.e. segregation) or mixing with non-certified raw materials (e.g. during controlled blending or adulteration). Both MFP and AFP can be used to determine if and when material has been mixed, either legally or illicitly. For MFP, this is achieved by verifying the presence or absence of material fingerprints associated with CRMs from a particular mine, region or country, in particular from regions or areas where material is banned. For AFP, the extent of mixing can be evaluated by assessing the unique identities of TPs present (if multiple tagged materials have been mixed) and by quantifying any deviations between actual TP dosage and expected TP dosage based on the declared mixing ratios.

6.2.2 Utilisation of MFP/AFP per production stage per commodity

For AFP use, it is expected that the underlying mechanisms behind AFP technology will largely remain the same regardless of the product or commodity being traced. However, the AFP technology utilised may have to be adjusted according to the physical and chemical properties of the different products along a commodity's particular supply chain, for example due to product-specific penalty or impurity element/compound concentration thresholds, the various environmental or processing conditions TPs would be exposed to, and the type and volume of the raw material itself (e.g., upstream high volume particulate spodumene concentrate and downstream lower volume solid cathodes).

Figure 24 gives an example of the application of AFP technology within the lithium supply chain for lithium-ion batteries. In this scenario, the processing of raw materials will destroy any preexisting TPs and would require the addition of new TPs once the refined product is to be transported to the next location along the supply chain.

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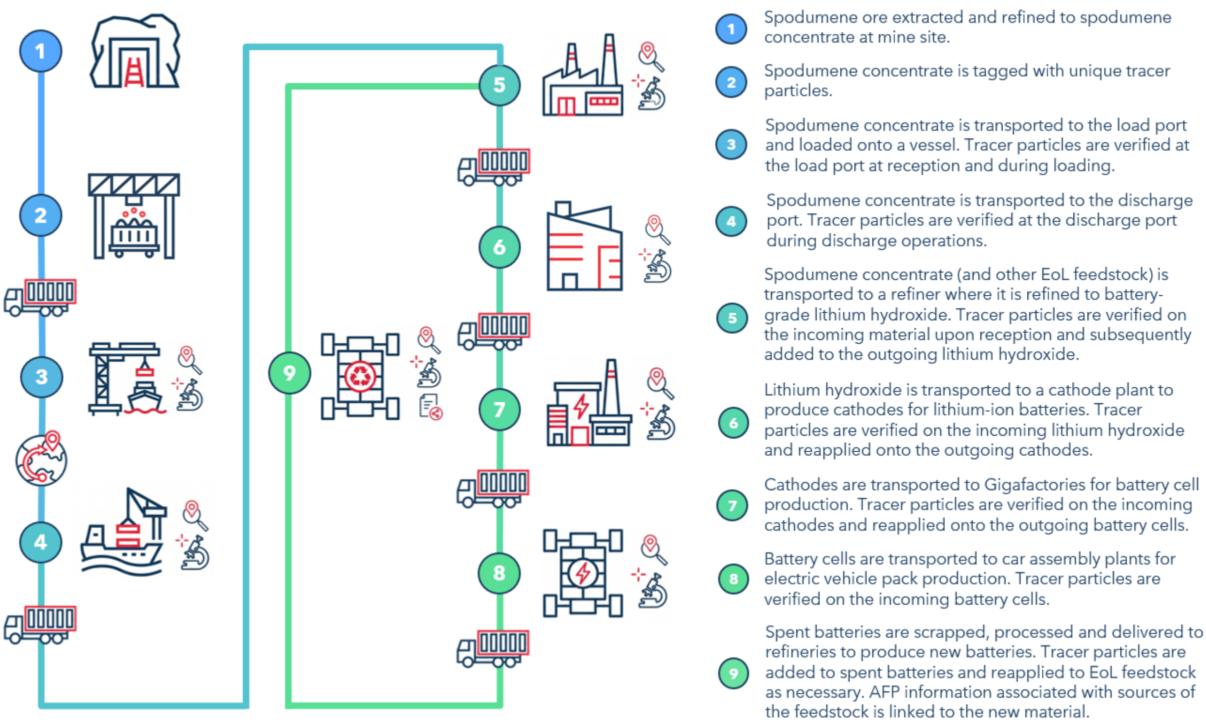

Figure 24: Example application of AFP technology for lithium within the lithium-ion battery supply chain.

Main MFP principles should be very similar to all the substances when MFP is applied in traceability between mining site and refiner.

- Upstream company sells material (ore concentrate) to a midstream company or to a trader. Material is transported to a load port, railway. Mining companies declare an ore content of their concentrate and this information if present in material passport
- When midstream or trader company receives this material a first chemical/mineralogical analyses is done. Midstream companies analyse materials with different analytical means that they have on site, the main purpose is to analyse and assess the purity of the transacted product.
- In addition to those regular and ell established analysis, midstream companies could compare those observed results (mostly based on trace elements) with a reference database. This verification would deliver or detect an anomaly.
  - If there is no anomaly, declared origin is coherent with observed/measured properties and the material can follow
  - In case of anomaly in this first test, more elaborated analysis can happen (like isotopes).

Figure 25 presents the relationship between the upstream and downstream actor (white rounds) and the construction and maintenance of MFP reference database (black rounds).

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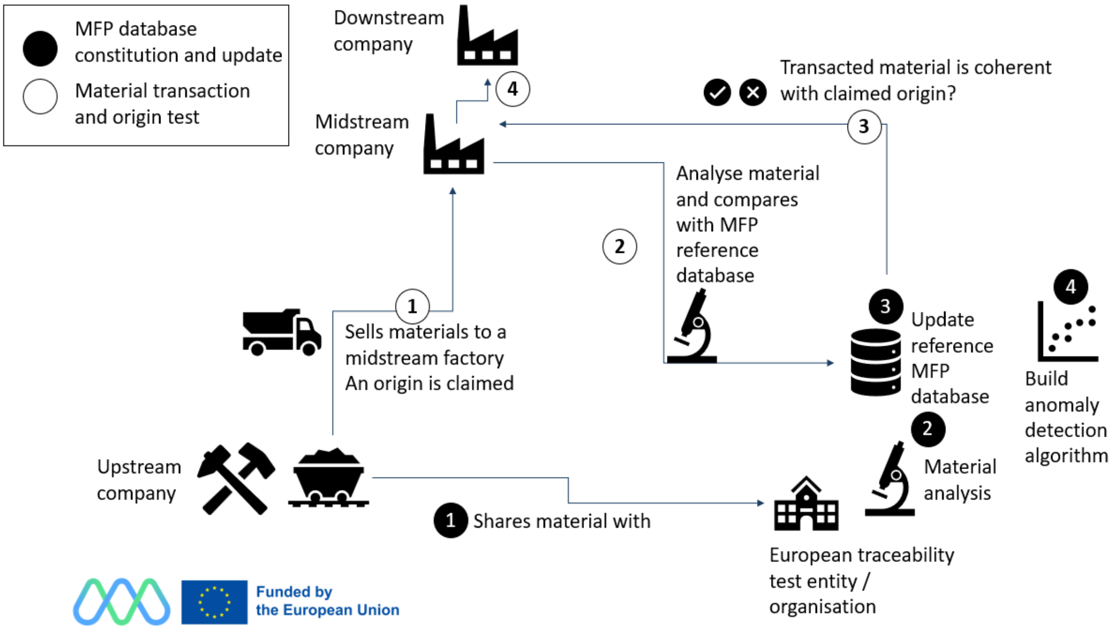

Figure 25: example of MFP application in a material transaction between an upstream and midstream company. Black rounds represent stages for the construction and maintenance of a MFP database for a certain substance. White rounds represent the material transaction and origin tests.

6.2.3 MFP and AFP as a tool for claim validation during certification

Current traceability systems for CRMs rely on extrinsic traceability and security mechanisms on industrial packaging, such as security seals on shipping containers or printed documentation on Flexible Intermediate Bulk Containers (FIBCs). While these are established methods, the integration of AFP directly into the raw material as an intrinsic traceability tool, which is currently not widely utilised within CRM supply chains and the wider mineral and metals industry, provides a further level of "truth" which complements these existing systems. AFP would be able to detect substitution, adulteration or false declarations of origin where other traceability systems, such as paper-based systems, may fail to. AFP should not be considered as a substitute for existing traceability systems but rather considered as an additional tool that can be used to strengthen the probative value of certification claims. Similarly, MFP would be able to determine discrepancies in origin claim and detect material mixes between two or more geographical provenances.

Current Approach		**MFP/AFP-supported Approach**	
Company	**Audit**	**Company**	**Audit**
Transaction information (Bill of Lading, sales invoice, delivery notes, etc) Production information ESG information Origin information Reconciliation of input and output volumes Supplier information	Documents of the information on the left	MFP/AFP information (fingerprint/encoding, dosage, etc.) Accredited independent third-party involvement	CoC and MFP/AFP documents

Table 4: Current and MFP/AFP supported approaches to audit material claims

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Additional responsibilities of suppliers, receivers and/or other stakeholders (e.g. traders) for the implementation of AFP would include the application, collection and evaluation of TPs to substantiate material claims. This would require the implementation new processes to apply and collect TPs, and to evaluate TPs and subsequently report results. For MFP, certified companies adhering to a MFP traceability scheme should be able and open to share material samples with laboratories with a MFP central entity. The share of material would a sine qua non condition for the establishment of a central MFP database.

As is the case for the existing sustainability standards, such as within the timber industry, where conformity assessment bodies (CABs) (i.e. accredited independent third parties) carry out chain of custody assessments for appointees for certification purposes (Assurance Services International, 2026), accredited third parties would need to be appointed by the stakeholders in CRM supply chains to substantiate material claims. Moreover, the CABs would themselves require regular audits by an accreditation body or by accreditation bodies to ensure CABs are conducting their responsibilities in line with any national and/or international standards.

6.2.4 Prerequisites for utilisation of MFP/AFP to support certification

Although AFP is presently marketed as a traceability tool for mined raw materials including CRMs (e.g. Microtrace, 2026), the utilisation of AFP to support certification claims requires its formal recognition as one of a suite of auditable technologies that can be used to verify material claims. This may require specific reference to AFP technology and mechanisms in standards, similar to how tamper-evident packaging, electronic tagging and other physical markers are explicitly stated within the Responsible Jewellery Council (RJC) standard and supporting guidance for precious metals CoC certification (RJC, 2024; RJC, 2025). Alternatively, if the CoC standard does not explicitly outline CoC traceability methods, which is the case for some existing standards for other industries (e.g. the FSC-STD-40-004 standard defines fibre testing broadly as "a suite of wood identification technologies"), CABs may be the responsible parties who would be required to recognise and subsequently certify against AFP. Similarly, new processes and methods to audit against and conduct oversight assessments for, situations where AFP is utilised would have to be implemented, as these have not yet been developed for CRMs.

The establishment of a central database and a common platform where different parties will record and upload AFP information may also be required. This is especially significant as, depending on the country, region or even the facility at which a single consignment of CRM passes through and is assessed, different accredited third-party verifiers and CABs may be involved in the implementation and assessment of AFP technology along the CoC. Additionally, third-party verifiers and CABs may be freely appointed by the supplier, receiver or other stakeholders who wish to make material claims which emphasises the requirement for a central database and conformity between how AFP information is collected and how it is stored. Special consideration would have to be given to who owns and manages these databases, as well as to who can access these central databases and platforms, in order for necessary parties to check and verify sustainability claims and to prevent access to parties who may wish to make unauthorised modifications to said information.

Within the wider minerals and metals industry, various national and international standards and codes exist to outline and standardise methods of sampling, chemical analysis, physical testing and moisture determination of raw materials. In certain cases, these standards are specific to particular types of raw materials, such as the standards outlining sampling procedures for the determination of the metal and moisture content of copper, lead, zinc and nickel concentrates (ISO 12743:2021) and for the determination of mass loss of bulk material on drying for copper, lead, zinc and nickel concentrates (ISO 10251:2006). To successfully utilise AFP/MFP technologies for CRMs, international or national standards may have to be developed, either for specific types of TPs, different analysis (trace elements, isotopes) and/or specific CRMs, to ensure the methods for storing, applying, mixing, sampling, detecting, analysing TPs, and reporting results of AFP/MFP are consistent between organisations that take on these responsibilities. These standards may explicitly require the use of infrastructure or equipment for the implementation of AFP/MFP technologies, such as conveyor belts, drop spreaders and industrial blenders, and in some cases, stakeholders may be required to procure these items.

MFP faces a similar situation to AFP. A main prerequisite for the utilisation of MFP into certification would be the standardisation of laboratory methods and the consequent accreditation of laboratories participating to MFP. Current MaDiTraCe project developments demonstrate a potential of MFP techniques for the 4 commodities but analytical techniques put in place are the result of research and lack of an international industrial standard recognition. Trace elements detection in different matrices (mineral concentrate, intermediate products) and isotopic analysis should be standardized and present a global recognition. To launch working groups at ISO level would be the first stage.

A further prerequisite for the utilisation of AFP/MFP will be real-time or near real-time field testing and approval or rejection of CRMs based on material tagging or fingerprinting. The physical global trade of CRMs is often carried out rapidly for financial and logistical reasons, often fuelled by commodity price volatility, high costs associated with the extensions in transportation and storage durations of these raw materials or due to companies operating on demanding logistical models where raw materials arrive at a facility only when they are required. Stakeholders or appointed service providers will have a requirement to ensure methods to analyse AFP/MFP technologies have short turnaround times, by potentially implementing quicker field verifiable tests and supporting laboratory-based tests. These turnaround times may have to be in the order of hours or days to prevent significant delays to the movement of CRMs along the CoC.

6.2.5 Risks associated with using MFP/AFP to support certification

6.2.5.1 Risks associated with using AFP to support certification

A fundamental risk associated with AFP is the lack of data demonstrating its scalability across CRM supply chains. As part of the MaDiTraCe project, the integration of TPs with CRMs has

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been conducted at low Technology Readiness Levels (TRLs), specifically TRL 3 (analytical and experimental tests to determine the technology's critical function) and TRL 4 (basic technology validation within a laboratory environment). While the laboratory tests have successfully demonstrated compatibility between specific TPs and CRMs, these tests focused on ores, concentrates and particulate secondary raw materials (i.e. black mass). Evaluation of AFP technology on other parts of CRM supply chains, especially downstream products (e.g., anodes and cathodes, battery cells, magnets) remains to be tested. Moreover, validation of AFP technology in an industrial setting is required before AFP can be recognised, standardised and accredited as a traceability method. Furthermore, as AFP is not widely commercialised for CRMs, a time lag is anticipated between validation in an industrial setting and formal adoption by jurisdiction-specific service providers, CABs, and accreditation bodies. Current ambiguities surrounding the operational obligations and legal liabilities of the entities that will manufacture, apply and evaluate results of AFP technologies, and which of these entities are accountable in the event of certification disputes, will likely delay this formal adoption. This time lag may be protracted further by stakeholder resistance within the CRM sector, for example, due to technical, logistical or financial concerns with the technology. Even localised resistance by certain jurisdictions or key actors within a CRM supply chain could result in regional bottlenecks where material traced using AFP technology cannot be verified due to a lack of local technical expertise or regulatory approvals.

The intentional or inadvertent incorporation of incorrect data in physical and/or digital records associated with AFP is a recognised risk associated with this technology and stringent access controls to associated data and documentation are required to safeguard the integrity of data. Considering in practice multiple certified service providers and CABs may be involved in the certification of a single consignment as it is transported across the globe, regular due diligence and independent third-party audits, and the standardisation of methods for AFP implementation are essential to mitigate the input of incorrect data into supporting information systems.

Locations along the CoC where CRMs undergo physical or chemical transformations at processing facilities pose an additional risk for the use of AFP technologies. At these locations, TPs may become unrecognisable or lost, and the reapplication of TPs may be required before the refined material moves down the supply chain. This creates interim periods where CRMs are physically untagged. This is compounded by processing facilities often handling and simultaneously processing raw materials from diverse origins, which increases the availability of material that can be used to substitute or adulterate consignments. To mitigate this risk, new and existing material reconciliation procedures such as facility inventory verification and consignment-specific input and output volume checks, alongside dedicated infrastructure to quarantine consignments while undergoing verification checks, may be required to ensure a consignment satisfies material claims before TPs are reapplied.

As AFP is used more frequently for CRMs, general awareness of how the technology works would also increase. Although this may be favourable for the wider adoption of the technology, this may also provide an opportunity for bad actors to develop techniques and methods to circumvent the effectiveness of AFP. Although it is not anticipated that identical clones of TPs could be produced due to their high encoding factors and the sophisticated methods to produce these TPs, bad actors may find workarounds to prevent AFP from being used as a traceability tool for particular consignments, such as by tampering with or disabling field detectors or by producing counterfeit TPs which pass first-pass verification checks which may be accepted to ensure logistics associated with the movement of CRMs are not disrupted or for certain payments to be processed.

6.2.5.2 Risks associated with using MFP to support certification

A first risk, similar to risk for AFP, is the up scalability and the demonstrability of MFP at a global scale. In MaDiTraCe only 4 substances were assessed with a quite good but not exhaustive sampling of the main exploited deposits in the world. Deposit heterogeneity, risks of false positives or true negatives exist, and the work did in MaDiTraCe task D2.5 (see Bodereau et al 2026) giving % or accuracy should be the pathway to follow. 100% certain results would be very difficult.

Another risk is the recognition of MFP results. MaDiTraCe provides research developments and results, but real world implementation of MFP would require insurance and accredited results by accredited laboratories following international recognized standards. MaDiTraCe shows it can work, but the roadmap must develop those laboratory standards. Without accredited techniques for MFP the risk of using MFP into a certification scheme is very high.

In any transaction between two actors, MFP results detecting an anomaly of a declared origin would be an additional argument. MFP anomaly detection in laboratory will not be the only argument to penalize a company in a CoC certification scheme, but this anomaly would constitute an argument in addition to other suspicions such as invoice manipulation, missing documentation, etc. The use of MFP in food sector in very similar to this situation.

6.3 DPP as a tool for CoC certification

6.3.1 Utilization of DPP in different types of material claim

Claims about sustainability regarding products and processes lack the ability to foster trust among consumers, as there is no process to verify the information. For instance, a CoC claim with 'contains responsibly sourced certified minerals' cannot be verified, as it does not specify how the materials were tracked and even if a certification number is included, limited information is readily accessible about the scope of certification, the level of assurance, if the claim refers to only a certain component of the product or the entire product. As a result, the claims may become vague, hinting at greenwashing, and prevent consumers from making informed purchase decisions.

Using a Digital Product Passport (DPP), claims approved under CFS can be converted into readily accessible information for consumers by scanning the product's QR code. The DPP can be populated with audit certificates and the accredited certification body that conducted them, so the scope of certification is accessible, as well as CoC documents, which provide information about the type of CoC model used. Furthermore, in addition to technical and ESG information, conflict-mineral declarations, due diligence statements, and material origin details can be included to satisfy consumer and regulatory requirements, especially in the case of the EU Green Claims Directive, which requires that an independent organization verify claims, and that non-compliance can have severe repercussions, including financial fines and operational consequences such as restricted market access. So, DPP is not a replacement for certification or audits, it is a tool that helps to provide support

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to enable stakeholders to verify the information on various platforms and labels, and at the same time provide a platform for the fragmented information across the supply chain to be presented in a structured and accessible format.

6.3.2 Integration of LCA into DPP: key challenges

DPP can provide information on the environmental performance of products through the integration of life cycle assessment (LCA). Current DPP initiatives primarily focus on disclosing life cycle climate change impacts (i.e., carbon footprints). However, the holistic perspective of LCA would enable the disclosure of a much broader range of environmental impact categories, including human toxicity, particulate matter formation, freshwater ecotoxicity, eutrophication, land use, water use, and mineral and metal resources use, among others. Beyond the currently limited scope of impact coverage, integrating LCA into DPPs raises two additional major challenges related to: (1) defining LCA data requirements for DPP integration, and (2) verifying the LCA data incorporated into the DPP.

A broader coverage of environmental impact categories in DPPs would better align with the fundamental objective of LCA (Berger et al., 2024; Jensen et al., 2023), namely to avoid burden shifting from one impact to another (e.g., reducing climate change impacts while increasing human toxicity). In this regard, the European Commission’s Product Environmental Footprint (PEF) methodology recommends assessing 16 impact categories. Although comprehensive environmental reporting through DPPs is desirable, it may also impose significant reporting burdens on value chain actors. Thus, a more pragmatic near-term approach may involve focusing on the most relevant impact categories for each sector. Such prioritization of impact categories should be sector specific and closely aligned with scientific evidence on the most pressing environmental issue of each sector (e.g., water and biodiversity-related impacts should not be overlooked for the mining and metals sector).

The LCA methodological guidelines developed within MaDiTraCe (D4.6) were informed by the impact category requirements and recommendations of broader and sector-specific guidelines and frameworks (e.g., the EU Batteries Regulation, metal & mining industry recommendations, product category rules (PCR) for metal products). While the selection of the most relevant impact categories ultimately depends on context and intended application, for the critical raw materials and products assessed in MaDiTraCe, the impact categories commonly recommended by the metal & mining industry (namely climate change, ozone depletion, photochemical ozone formation, acidification, eutrophication) should be complemented with indicators addressing water- and land-use impacts.

Current attempts to define DPPs data requirements often provide only limited guidance on LCA-related information, typically requiring the reporting of aggregated environmental indicators and/or product carbon footprints (PCFs), and in some cases their breakdown by life cycle stage (i.e., raw materials extraction, manufacturing, use, and end-of-life) (Chawla et al., 2026). In particular, ongoing DPP initiatives tend to focus on facilitating the exchange of PCFs across value chains. Under this approach, each actor quantifies the cradle-to-gate PCF of its product and transfers the aggregated result downstream (embedded in the DPP). Downstream actors can then calculate the PCF of their own product by combining the received PCF with the quantity of the input product used (Holzapfel et al., 2024). However, while the exchange of aggregated PCFs or LCA-based impacts reduces the reporting burden, it also creates comparability challenges due to potentially divergent methodological choices across value chain actors. Moreover, aggregated LCA results obscure the underlying processes, technological parameters, geographical conditions, and operational practices driving these impacts. These underlying details are essential for interpreting LCA results and identifying effective mitigation strategies.

To address these limitations, academic research has proposed a more comprehensive definition of LCA data requirements for DPPs (see Table 5), emphasizing the need to transparently report methodological choices (such as functional unit, system boundaries, allocation approaches, etc.) as well as the underlying inventory data (Haupt et al., 2024). The inclusion of process-specific inventory data (e.g., energy use and sources, raw materials consumption, direct emissions, etc.) within DPP is analytically more valuable because it preserves the level of detail necessary for robust modelling, interpretation, and decision-making. However, sharing such data and information poses practical challenges as it increases reporting burden, requires frequent updates, and may expose commercially sensitive information.

MaDiTraCe has adopted an alternative approach to improving comparability while also validating LCA results integrated into the DPP, without requiring extensive disclosure of sensitive inventory data. The approach involves the development of harmonized methodological guidelines on how to conduct LCA across a specific value chain alongside the establishment of certification schemes via CERA 4in1. Several sector-specific DPP initiatives already provide harmonisation guidelines for PCFs, such as the Catena-X PCF Rulebook and the Global Battery Alliance. Because compliance with these guidelines must be verified, third-party verification can ensure that LCAs are conducted in accordance with the prescribed methodological requirements and data quality criteria. In this approach, DPPs would contain not only aggregated LCA results, but also certification demonstrating that these results were generated following harmonized and verified methodologies.

LCA data category	Data attribute	Definition	Confidentiality
Methodological choices	Modelling approach	Approach followed for LCI modelling (attributional or consequential)	Low
	Functional unit	Quantitative and qualitative description of the product system's function(s), and reference to which the impacts are referred to	Low
	Reference flow	Flow to which inputs and outputs quantitatively relate	Low
	System boundaries	Which parts of the life cycle and which processes belong to the analyzed system	Low
	Cut-offs	What parts of the product system can be excluded from the system boundaries.	Low

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	Selection of impact categories	For example: climate change, acidification, ecotoxicity, etc.	Low
	Selection of impact assessment methods	Method used to translate environmental flows into potential impacts	Low
Inventory data	LCI dataset metadata	This may include dataset name, geographical location, description of the dataset, details of the technology, representativeness of the dataset (e.g., geographical and temporal), etc.	High
	Inputs and outputs flows metadata	This may include the flow name, unit, name of the upstream process that delivers the flow, and the quantity of the flow	High
	Secondary datasets metadata	Datasets obtained from background LCI databases (e.g., ecoinvent). Minimum metadata information to be provided include the exact dataset name, product, and geographical location as specified in the database. Additional information that could be included involves a description of the dataset, details of the technology, representativeness of the dataset (e.g., geographical and temporal), etc.	Low
	Multifuntionality approach	Description of the approach followed to solve multifunctionality issues alongside any underlying assumptions	Low
	Data for multifunctionality	Data used for solving multifunctionality (e.g., product-specific revenues used in economic allocation)	Medium
	Data quality requirements	Quantitative, qualitative, and semi-quantitative approaches to determine the quality of the underlying LCI data	Low
Impact results	Life cycle inventory table	Aggregated elementary flows over the life cycle of the product system	Low
	Impact results	For example: impacts on climate change, acidification, ecotoxicity, etc.	Low

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	Breakdown of impacts	Contribution of specific parts of the product system to the total impact (e.g., breakdown by life cycle stage)	Low
	Uncertainty and sensitivity analysis results	Additional analyses to test the robustness of the LCA results. It also includes the description of the analysis performed (e.g., type of sensitivity analysis or description of scenarios) as well as all the underlying assumptions	Low

Table 5: LCA data attributes and their confidentiality levels. Definitions are largely based on the ILCD Handbook (European Commission, 2010). Table adapted from D3.2

6.3.3 Integration of LCA into DPP: solutions and the way forward

The extension of the CERA 4in1 certification system in the MaDiTraCe project offers a balanced approach to addressing some of the challenges associated with integrating LCA into DPPs. By integrating LCA-related requirements within the certification scheme, CERA 4in1 can support the verification of sensitive LCA data, while ensuring compliance with methodological guidelines and reporting requirements across the supply chain (see Table 7). The key characteristic of the CERA 4in1 system that enables this approach is its full value chain coverage and applicability across all mineral commodities. This holistic coverage can promote methodological consistency among actors throughout the supply chain and across sectors. This is particularly important, as methodological inconsistencies between interconnected sectors remain a major challenge in LCA (e.g., divergent approaches to handling multifunctionality across dependent sectors within the battery value chain Husmann et al., 2025).

A key challenge of this approach lies in establishing the methodological guidelines that each actor across the supply chain should follow and that auditors should apply during verification. MaDiTraCe D4.6 provided the methodological foundation for conducting LCAs within the context of the CERA 4in1 certification system. The document focused on critical raw materials for energy applications, particularly batteries and rare earth magnets, and alignment with the EU Battery Regulation and Critical Raw Materials Act. However, the comprehensive scope of CERA 4in1, covering the entire value chain and all mineral commodities, requires methodological guidance that extends across multiple sectors and applications. This is particularly challenging given the divergence among sector-specific LCA guidelines developed by different mineral and metal industries (Berger, 2026), as well as evolving regulatory frameworks that may introduce additional requirements. Keeping pace with these developments and ongoing harmonisation efforts will therefore be essential but may also impose a substantial and continuous update burden on the certification system.

While audit and certification schemes can help overcome methodological inconsistencies, they do not address the fact that LCI data remain far more informative for LCA. Companies aiming to develop robust decarbonization roadmaps require more detailed information about their suppliers than a single aggregated carbon footprint indicator. Building and evaluating alternative decarbonization pathways require access to information on suppliers'

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processes and technologies in order to assess how changes across the supply chain may influence a company's own performance. Therefore, access to supplier-level LCI data could considerably improve assessment and scenario-modelling capabilities. This potential could be enabled through DPP architectures incorporating tiered data-access rights, an approach already being explored in initiatives like Catena-X and CIRPASS. Under such systems, detailed LCI data could be made accessible only to authorised actors, helping to balance transparency with confidentiality concerns. MaDiTraCe D3.3 explains role-based access control implementation for DPPs as part of MaDiTraCe methodology to tackle both confidentiality concerns of the economic operator and the compliance requirements of auditors and authorities, and MaDiTraCe D3.6 explains how this access control can further be enhanced with policy access mechanisms and SSI-based authorization by integrating MaDiTraCe data exchange use cases to dataspaces.

An additional challenge that will need to be addressed concerns the integration of data attributes related to the environmental performance of product end-of-life (EoL) management. This stage generally falls outside the direct control and temporal scope of the actors involved the production stages. As a result, manufacturers can, at best, report LCA results associated with scenarios of intended EoL treatment or recycling routes, whereas the actual fate of a product will depend on future collection systems, consumer behaviour, waste management practices, and recycling infrastructure. Developing protocols for the dynamic integration of product-specific EoL LCA results through active interaction with the waste management and recycling sectors is therefore of high importance. In this context, CoC systems could play a role by linking DPPs with waste operator reporting systems.

Integration approach	Advantages	Disadvantages
LCA results integrated into the DPP	• Low data requirements (for the DPP) • Low reporting burden for companies • No confidentiality concerns • Enables straightforward use by downstream actors	• Risk of methodological inconsistency across supply chains • Limited transparency regarding assumptions and modelling choices • Insufficient contextual information for interpretation
Methodological choices and LCI data integrated into the DPP	• Could enable methodological consistency across actors • Improve transparency and interpretability • Provide contextual information for downstream actors	• Highly data-intensive (for the DPP) • High reporting burden for companies • Potential confidentiality and data-sharing concerns • Increased modelling effort required for downstream actors

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LCA results combined with certified methodology integrated into the DPP	• Lower data requirements compared with full LCI integration (for the DPP) • Lower reporting burden for companies • Limited confidentiality concerns • Enables straightforward use by downstream actors • Supports methodological consistency through certification	• Requires additional resources for certification and verification • Depends on robust certification governance and auditing systems • Requires continuing update and alignment of methodological guidelines with ongoing sectoral and policy developments

Table 6: Different approaches for integrating LCA data into DPPs.

6.3.4 Prerequisites for utilization of DPP as a tool to support certification

DPP systems need to be designed not only to support consumers but also to serve a range of stakeholders, such as regulatory bodies, companies in the supply chain that handle the products, and can act as a support tool for certification. The first prerequisite is to abide by the provisions of a data governance and assurance system that addresses data quality, completeness, reliability, consistency, validity, and uniqueness, as prescribed by the standard. It must adhere to the granularity of the information that must be available on the platform, including certification details (scope, validity), audit reports, and due diligence documents, etc. The information provided should be verified by a third party to ensure it is valid and useful to the different stakeholders.

The second prerequisite is to integrate levels of accessibility, as not all information in a DPP needs to be accessible to all stakeholders. Consumers may require the information in a simplified format. In contrast, authorities and certification bodies may require access to more detailed information, such as volume balances, corrective actions, internal management system audit reports, etc. So, the DPP platform must consider the requirements and functions of the different stakeholders when determining the level of transparency. Moreover, when information is disclosed to the public, any technical aspect must be presented in clear, accessible language. For example, if a claim is based on a mass balance model, then the DPP should explain that the claim is supported through volume reconciliation rather than full physical traceability of the material.

6.3.5 Risks in using DPP as a tool to support certification

Claim's reliability: Although the DPP can help to improve the structure, accessibility to information and the ability to verify claims readily, it is also associated with risks such as the credibility of the information on the system. If DPP is used as a tool to verify claims made by suppliers without independent audits, it will simply transfer the unverified information into

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a digital format. The reliability of the information will depend on the quality of the information entered on the system and would require additional checks and a control system in place to prevent manipulation and fraudulent practices when entering data.

Harmonisation of systems: Harmonisation is of a major concern as certification systems may use different formats and definitions of terms in standards, for instance using the words 'source' and 'origin' interchangeably, making comparison of the claims information challenging. Standardization will be necessary to enable comparability of products. Moreover, this can be further complicated if each standard, sector or company start devising their own DPP structures, and the lack of interoperability between the DPP systems will contribute to more challenges for instance the certification bodies might not have access to information or might interpret data differently and add to the already fragmented systems.

Security of information on the platform: Digital systems may be prone to cyberattacks which may result in unauthorised changes to the information on the system and proper security measures need to be in place.

Granularity of information: Certification processes may require information at different levels of detail, such as product, batch, shipment, or component level. If the DPP does not provide sufficient granularity, certification bodies may not be able to determine whether a claim applies to a specific product or only to a broader product group.

Versioning and change management: Certification-relevant information may change over time, for example due to updated supplier data, corrected measurements, changed production processes, or renewed certificates. If the DPP does not include clear versioning, audit trails, and change histories, it may become difficult to determine which data was valid at the time of certification.

6.4 Envisaging the system

The three pillars of MaDiTraCe, as described in Section 2.6 can be viewed as adding trust to a traceability system by providing three levels of integrity:

- Standards/certifications provide **system integrity** by defining auditable requirements, responsibilities, claims and verification criteria.
- Material Fingerprinting and Artificial Tagging provide **material integrity** by offering physical evidence to support identity and origin claims.
- The Digital Product Passport provides **information integrity** by maintaining traceable, attributable and tamper-evident information throughout the value chain.

As already mentioned in the earlier sections, each mechanism of trust has strengths and limitations. Those are summarised in the Table below:

Mechanism	Strengths	Limitations/Risks
Standard / Certification (audit-based)	Direct observation of operational reality	• Periodic (snapshot) • Limited ability to independently authenticate external evidence and documents

Material Fingerprinting	Independent physical evidence, difficult-to-manipulate material characteristics	• Relies on representative sampling and analytical chain of custody • Applicability diminishes along the supply chain due to material transformations
Digital Product Passport	Continuous visibility of supply-chain information	• Relies on accuracy of data at entry

Table 7: Strengths and limitations of mechanisms of trust in mineral traceability systems

Audit-based certification provides evidence through direct observations of operations on the ground, where activities take place. This enables auditors to assess whether documented procedures are implemented in practice and to identify issues that may not be visible through documents or digital traceability systems alone (Levin & Cook, 2015). However, audits are typically conducted at long intervals therefore providing a periodic rather than a continuous view of operations (OECD, 2025). Furthermore, in paper-based systems auditors may have limited ability to independently authenticate information originate from actors outside the scope of the audit.

Material fingerprinting and artificial tagging provide evidence from the characteristics of the material itself. This may involve physical, chemical or isotopic signatures, or the detection of intentionally introduced markers designed to support identification and authentication. By relying on material-based evidence, these approaches provide independent means of testing traceability claims without relying on stakeholder declarations. However, their reliability depends on integrity in sample collection, handling, and analysis. In addition, material fingerprinting may be compromised when materials undergo processing, blending, or transformation that alters, dilutes, or removes the characteristics used for identification (Abdallah et al., 2026; Melcher et al., 2021).

Digital Product Passports (DPPs) allows traceability information to be shared and accessed in a regulated way across supply-chain actors. Through Verifiable Credentials, traceability claims can be cryptographically authenticated, allowing stakeholders to verify the provenance and integrity of information. However, the reliability of the system remains dependent on the accuracy and completeness of the data at the point of issuance (Abdallah et al., 2026).

Integration of the three mechanisms (audit-based certification, material fingerprinting, and Digital Product Passports) enables a more robust traceability assurance framework by combining complementary sources of evidence while mitigating the risks/limitations of each individual mechanism. The actors in a potential implementation of such a system are presented in Table 8. Certification actors—including standard owners, accreditation bodies, certification bodies, and auditors—provide governance, assurance processes, and on-the-ground verification of compliance with traceability requirements. Material fingerprinting actors—including the MFP authority, sampling and inspection bodies that ensure sampling integrity, and analytical laboratories—contribute independent material-based evidence that can corroborate traceability claims. The DPP authority supports the trusted exchange, accessibility, and cryptographic verification of traceability information across supply-chain actors. Together, these mechanisms strengthen confidence in traceability claims by

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combining direct observation of practices, evidence derived from the material itself, and verifiable digital information, thereby reducing reliance on any single source of assurance.

Mechanism	Actors	Responsibilities
Standard / Certification	Standard Owner	Defines requirements, claims, assurance processes and governance rules
	Accreditation Body	Assesses and recognizes the competence and impartiality of certification bodies
	Certification Body	Makes conformity decisions; issues, maintains, suspends or withdraws certificates
	Auditor	Collects and evaluates objective evidence against specified requirements
Material Fingerprinting	MFP/ATP Authority	Defines sampling and analytical procedures; Maintains reference datasets; evaluates consistency between analytical results and claimed origin
	Sampling / Inspection Body (TIC)	Obtains representative samples and maintains sample chain of custody
	Analytical Laboratory	Determines material characteristics through testing and analysis
Digital Product Passport	DPP Authority	Defines governance rules and maintains trusted exchange of traceability information

Table 8: Actors in a possible implementation of an integrated traceability system

The MFP Authority may be constituted by one or more Geological Survey Organisations, or by an independent body governed and technically overseen by a consortium of Geological Survey Organisations (see also Section 3.4.1.1). Accredited analytical laboratories can operate independently in this system; however, in the following implementation -for the sake of simplicity- it is assumed that analytical services are provided by Testing, Inspection and Certification companies.

A simplified visualization of actors, roles and responsibilities, procedures and decision making in a potential implementation of an integrated traceability system is provided in the following diagrams. The system presented does not address specific commodities and their challenges, nor does it consider complex supply chain scenarios. Actors depicted include the Certification Body, the Auditor, the MFP Authority, the TIC company, the Organisation (whose Chain of Custody Conformity is assessed), a Mine that supplies material to the Organisation and a Forwarder that transports this material.

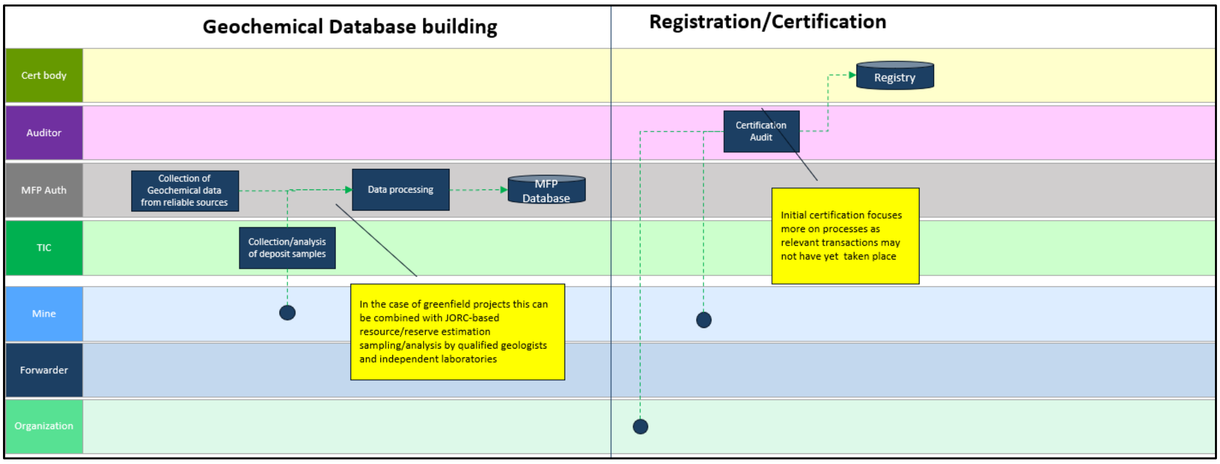

Figure 26: Integrated system: Building Stage

The building stage involves firstly the building of the geochemical/isotopic ore database which will be based on samples collected and analysed by independent 3rd parties (here TIC companies). In case of sites where JORC (or other standard) based resource/reserve estimation reporting takes place, the qualified geologists and the accredited laboratories engaged can be responsible for collecting and analysing the ore samples and reporting the results to the MFP Authority.

Furthermore, this stage includes the initial certification of the value chain actors and their registration in the registry of the Certification Body.

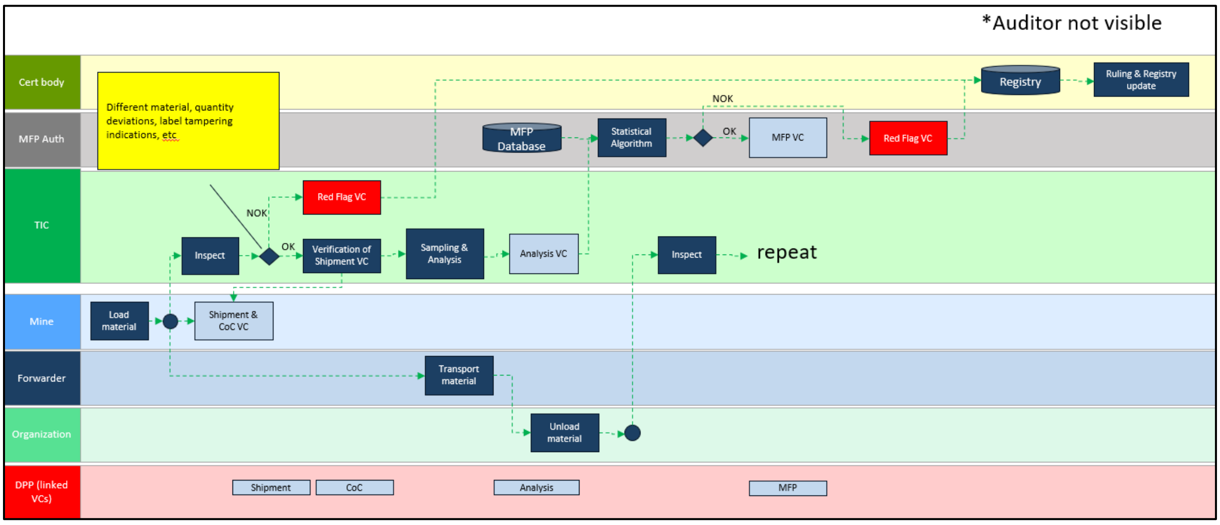

Figure 27: Integrated system: Daily operations utilising MFP/DPP technologies

For the monitoring of material transactions in daily operations, verifiable credentials created and linked to the DPP capture inspections and analyses conducted by TIC actors at critical points while and red flags (inconsistency in quantities or types of materials) are forwarded to the Certification Body for ruling and registry update. Such a system enables near real-time monitoring of supply chains and rapid detection of red-flags/deviations with immediate repercussion on the certification status of individual actors.

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In the presented implementation, samples are collected and analysed by TIC companies at critical points. Results are shared with the MFP Authority which assesses the validity of the material claims (e.g. specific origin or non-origin) and in case of a deviation informs the Certification Body. The entire process can be automated via a platform to which data are uploaded and which issues verifiable credentials with the analytical results and their assessment. This implementation also secures the confidentiality of both the deposit data and the individual supply chains.

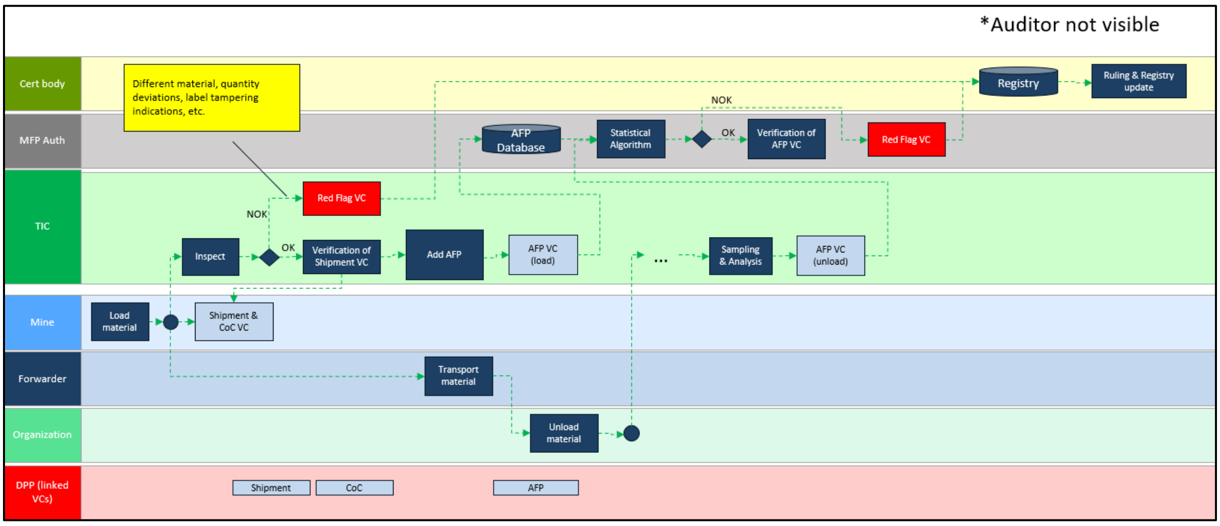

Figure 28: Integrated system: Daily operations utilising AFP/DPP technologies

The system operates in a similar way with Artificial Tagging, the sole difference being that the TIC company will also be responsible for the tagging process at critical points.

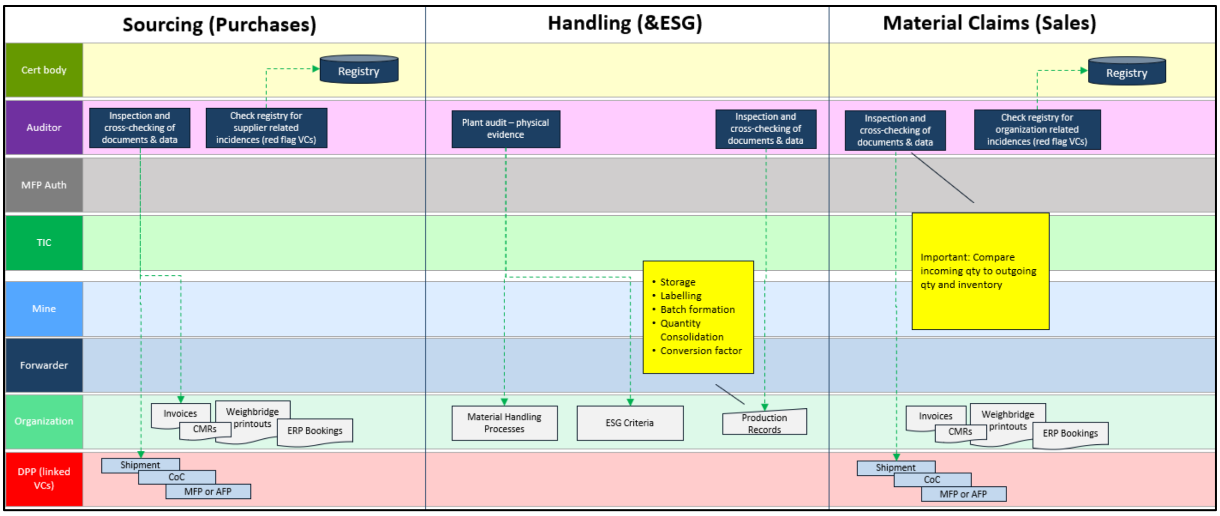

Figure 29: Integrated system: The Audit Process

Within this system, to audit responsible sourcing and material claims (for a CERA Chain-of-Custody certification) the auditor utilizes the trusted information in the Verifiable Credentials issued by the Mine, the Forwarder, The Organization, the TIC company, the MFP authority and the Certification Body, to ensure that claims are valid, and that the mass balance is

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maintained between incoming, outgoing, and stock materials. Furthermore, the auditor can access any red-flag incidences relating to past transactions, involving either the Supplier or the Organization, via the Certification Body registry.

The architecture presented above should be viewed as a generic framework rather than a specific implementation model. The purpose is to illustrate how audit-based certification, material fingerprinting or artificial tagging, and Digital Product Passports can be integrated to provide complementary layers of trust across mineral value chains. In practice, the optimal configuration of actors, controls, sampling points, analytical procedures, and digital credentials will depend on the characteristics of the specific commodity, the nature of material transformations, supply-chain complexity, and the specific traceability objectives being pursued. Consequently, different commodities and supply-chain scenarios may require different combinations of assurance mechanisms and operational procedures. Furthermore, the above implementation does not take into consideration the costs introduced by the additional actors, sampling, analysis, processing, and other procedures that should be carefully factored in any design of a sustainable traceability system. The following sections examine more specific scenarios to illustrate how the proposed framework can be adapted to different traceability challenges while maintaining the same underlying principles of system integrity, material integrity, and information integrity.

6.5 Scenarios of integration of MFP AFP, DPP and CERA perspective

6.5.1 Scenario 1 - Material sourced from the region associated with Conflict-Affected and High-Risk Areas (CAHRA)

CERA 4in1 Chain of Custody Standard perspective

From the CERA standard perspective, the organization will need to ensure it has a management system in place to prevent complicity in the human rights violations associated with CAHRA, and this provision aligns with regulatory requirements such as the Battery Regulation and the EU Conflict Minerals Regulation. For instance, the organization sourcing materials from the CAHRA regions needs to implement processes and procedures to integrate the five-step framework in line with the OECD Due Diligence Guidance for Responsible Supply Chains of Minerals from CAHRA, ensure that a responsible person is designated to conduct risk assessment procedures annually or with the change of circumstances and determine the likelihood and severity considering the risks mentioned in Annex II of the guidance. More importantly, the organization should implement processes and procedures to determine the origin of the minerals related to the CAHRA, the type of operations, quantities, form, physical description and dates of extraction and countries through which the minerals were transported and transited, which also applies to the by-products, where all the information regarding the point of separation is also maintained. Currently, the evidence primarily consists of supplier self-declarations and transaction and country-of-origin documents, which are audited to ensure that responsible sourcing practices are maintained when sourcing materials from regions related to CAHRA.

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MFP

In the example of CAHRA, this scenario must refer to previous work of BGR in Great Lake Area, where a project of MFP was implemented locally (Melcher et al 2008, Schutte et al 2020).

MFP techniques can compare, by analyzing, materials from a random sampling and benchmark it with a reference database. If an analyzed material presents a similar MFP with deposits inside CAHRA area, doubts about this origin exist. MFP can also determine that a material does not come from a certain origin, in this case MFP technique can give proofs of non-origin.

In all the cases, a scenario of implementation in a CAHRA area for MFP perspective would require an intensive field and laboratory work. It means that exploited mineral deposits in CAHRA areas would require to acquire material samples, build a MFP reference database and develop machine learning tools to determine any provenance or origin, including a calculation of false positives and true negatives. Data is owned and maintained by this entity.

Currently, those areas are heavily difficult to access with conflicts for any field work. This can be only possible under a formal framework of collaboration and cooperation with CAHRA countries.

In this case, MFP technique can work with a principle of "origin exclusion". The result of MFP is not saying the origin of material but can exclude the origin of materials from a certain area.

AFP

AFP can be used in conjunction with MFP as a physical traceability technique, to support data from MFP or in situations where one of the two technologies may fail, to verify sourcing claims for material originating from CAHRA. Tailored TPs, with declared properties associated with the TPs, such as encoding and applied dosage, would be manufactured and transported to the required point along the CoC by a certified independent party. The declared properties of the TP would be recorded in a secure database and used to verify sourcing claims further along the CoC. Specific equipment would be required to apply and blend the TPs throughout the material to ensure they are thoroughly distributed throughout a particular consignment. This is critical so that TPs can be easily detected and authenticated further along the CoC.

Physical access to the raw material at the necessary points along the CoC, for example, where material physically or legally exchanges hands, will be required to allow a certified service provider to sample the material to carry out field and/or laboratory verification of the TPs. This would require in-field personnel and the availability of appropriate equipment to process the raw material and to detect and authenticate taggants. Additionally, for laboratory verification, a secure method to transport laboratory samples using verified couriers would be used. Once results from the TPs are obtained, these will be transferred into a secure database.

If issues surrounding the AFP of a particular consignment are raised, such as non-identification of TPs or TP dosages below acceptable thresholds, red flags can be raised and transferred to the material's DPP. Additionally, as assessment of AFP technology occurs in real-time or near real-time, relevant stakeholders can be made aware of issues associated with the consignment and decisions to raise investigations, halt operations or refuse shipments can be made.

The detailed methodology used to deploy, evaluate and report AFP results would have to be declared and incorporated into verification documents and a secure database, which would ultimately be accessible in the product's DPP.

DPP

The DPP supports this scenario by linking CAHRA-related sourcing claims and due-diligence evidence to the relevant material batch or product in a structured and verifiable format. It connects country-of-origin information, supplier responsible-sourcing declarations, audit reports, and relevant certificates to the corresponding DPP identifier. In addition, MFP and AFP results can be linked as verification evidence where they are used to assess origin consistency.

In CAHRA-related sourcing scenarios, the DPP can also support red-flag assessment by making potential inconsistencies visible across the supply chain. For example, if the declared origin, chain-of-custody information, MFP result, or AFP result does not match, an authorized actor could issue a red-flag signal linked to the affected batch or product. This red flag would not automatically revoke a certificate, but it would provide structured input for the certification body or auditor to review the case, request additional evidence, or reassess the certification status. This follows the MaDiTraCe logic where red flags can be issued as verifiable non-conformity signals, while the certification body remains responsible for deciding whether a certification should be maintained, suspended, or revoked (Abdallab et al 2026).

Access rights are an important part of this scenario. Not all CAHRA-related information should be openly available, since the evidence may include sensitive supplier, transport, audit, or risk-assessment data. The DPP should therefore support controlled access, where certification bodies, auditors, competent authorities, downstream buyers, and other authorized stakeholders can access different levels of information according to their role.

6.5.2 Scenario 2 - Verification of product-level claims

CERA 4in1 Chain of Custody Standard perspective

From the CERA 4in1 standard perspective, the organization needs to demonstrate that any product level claims, be it about origin 'material is sourced from x', certified sources' material from 100% certified sources' or claims related to the percentage of certified material in the product, '30% of the product contains certified materials' should be verified and supported by documented control procedures. For instance, in the case of the identity-preserved claim, through documented processes and procedures that include linking batch numbers to transaction records, conversion factors, input and output quantities, supplier CoC certification, production records, transportation records, etc., the organization should be able to prove that the product can be traced to its origin. Furthermore, if it is about claims related to controlled blending, they must show the defined conditions under which certified and non-certified materials are mixed, along with inventory reconciliation, conversion factors, production processes, blending ratios, etc. Similar to the previous scenario, the assessment is limited to documented evidence and through the presence of appropriate controls in the organization, the CoC certificate is awarded. It does not fully verify the

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material's physical or chemical characteristics, nor does it automatically ensure that the claim is communicated to consumers in a transparent and easily understandable way. This creates an opportunity to integrate AFP, MFP, and DPP. AFP and MFP can strengthen the verification of material identity, origin, or composition by adding material-level evidence, while the DPP can support the structured communication of verified claims, certificates, and CoC information to the relevant stakeholders.

MFP

This scenario is already the reality for jewellery products where pieces contain a limited number of metals or gemstones (like gold and diamonds) and MFP techniques are already applied.

If we refer to batteries and main materials: graphite, lithium, cobalt, manganese, nickel, iron and phosphate, for much more complex products such as a smartphone or a vehicle, in all these cases, MFP integration would require next conditions.

Upstream raw material companies which are certified would adhere to share and deliver regularly material samples to build the reference database. This reference database is held and maintained by a neutral and third-party having this role (cf. conformity bodies, section 3.4.1). The willingness to share and deliver those materials is one of the conditions for upstream companies to be certified in this situation.

Material mixes and the risk of mixing between certified and non-certified materials appears in midstream (metal refining). In this scenario, midstream companies certified would take randomly material samples and make it analyzed by accredited laboratories. If MFP analyze does not identify any deviation or anomaly respect to declared origin, midstream company can accept this material and consider it as certified.

For such scenario, MFP system deployment would require:

- To establish a protocol for sampling upstream companies under the certification scheme (volume of samples, frequency)
- To establish the protocol of control and verification on midstream companies (main leverage point)
- CFS and downstream company must define criteria for materials presenting anomalies. If they are rejected (option for identify preservation or segregation) or accept material mix (material with anomaly cannot be presented as certified"
- Determine the % of accuracy of origin determination methods.

AFP

Product-level claims would be supported by the verified data generated from AFP of batches of material as these raw materials, which the final product is composed of, moved along the supply chain. As the AFP data is collated, it would undergo verification by certified independent parties, and the information would be transferred to secure databases and ultimately the DPP, where supporting documents and certificates regarding the AFP technology deployed can be accessed.

Simply, to verify product-level claims, the linked material batch AFP data can be critically assessed in association with non-AFP data (e.g. MFP data, supplier information, input and output volumes, etc.). Additionally, although potentially not operationally realistic, reserve samples from different parts of the raw material supply chain could be stored for a set period if additional AFP verification checks are required.

DPP

The DPP supports this scenario by enabling verified information to move across the supply chain together with the relevant material batch or product. As shown in the information-transfer process, data are first generated by different supply-chain actors, for example as ESG information, process data, product information, certificates, or chain-of-custody records. These data are then collected and verified through certification, assurance, or chain-of-custody procedures before being linked to the relevant material batch, intermediate product, or final product of the economic operator.

The certification workflow can also be understood as part of a wider information-transfer process. Supply-chain data are first generated by different actors, then collected and verified, linked across the chain, and finally transferred to the next actor through the DPP. Certification information follows the same logic. A certificate, report, or assessment is generated by a responsible organization, linked to the relevant material or product through the DPP, and made available to authorized stakeholders in a verifiable format. This allows certification evidence to move with the material or product across organizational boundaries without relying only on ad-hoc document exchange.

7 Timeline towards maturity (roadmap)

Based on other roadmaps such as particularly in Australian one, we identified 5 stages for the adoption of a critical raw materials traceability roadmap in Europe: planning, designing, implementation, scaling & monitoring and optimization.

For each one of those stages, we identified a set of topics that would require. We distinguish four topics or pillars: regulation, MFP/AFP, digital technologies and standard setting bodies or certification.

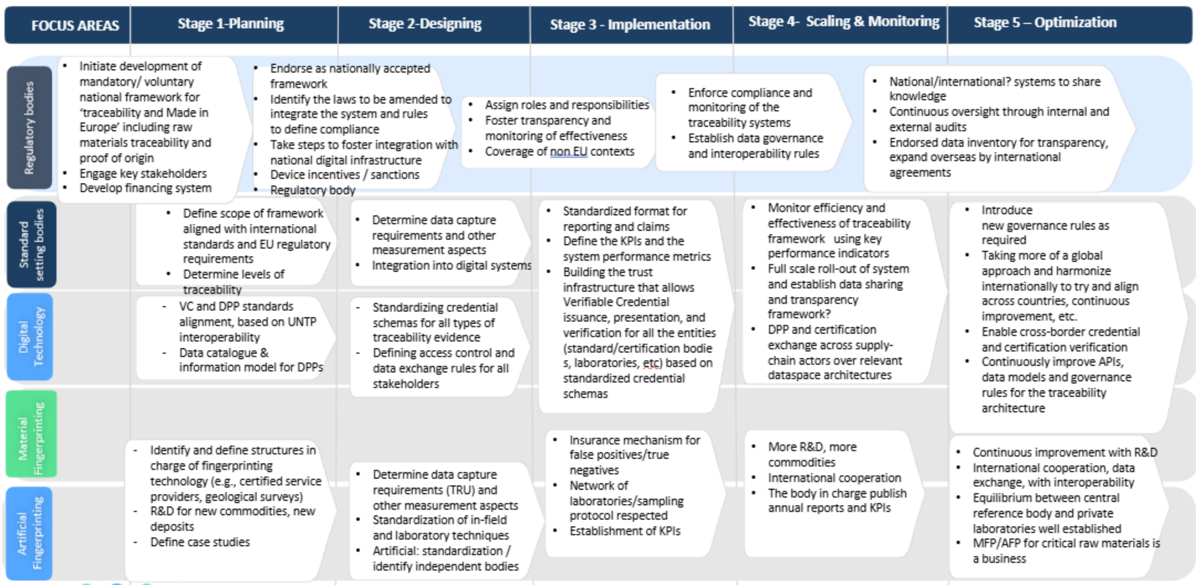

Figure 30: main inputs for MaDiTraCe roadmap.

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7.1 Stage 1- Planning

- **Timeline for regulations**

Current EU policies contain references to raw materials traceability scattered across different regulations and action plans. Planning of regulation must consist of mapping different current or ongoing policies, which are the requirements in terms of traceability, chain of custody and due diligence for minerals. Typically, this would must be a continuation of Fernandez et al 2025 (D1.1 and D1.3 deliverables) work.

This stage 1 would require the acceptation of a framework for "Made in Europe" that includes raw materials traceability and an obligation for a proof of origin. This framework must be clarified and present an alignment between different regulations such as CRMA, battery regulation and CSDDD. This regulatory framework must be linked to other traceability initiatives coming from partnership countries or the rest of the world such as G7 strategy.

The financing system for it must be identified with the negotiation with Member States and stakeholders. The costs of the implementation of traceability system were not assessed in MaDiTraCe project with the exception of first costs for ATP. It is essential to define who is paying for this system, the induced costs of traceability systems and the willingness to pay.

- **Timeline for certification**

The standard-setting body should define the scope of the Made in Europe framework, including products or raw materials, actors in the supply chain, supply chain stages to be included, and digital technologies that need to be considered. In addition, attention should be given to which minimum environmental, social, and governance (ESG) criteria should be met, as well as which relevant mandatory regulations and international standards should be included. This is important in the context of existing EU regulations like the EU Conflict Minerals and battery regulation, which already contain provisions for traceability and CoC, so rather than the framework duplicating it, efforts need to be made to build on the existing requirements.

As part of defining the framework, the required level of traceability and the CoC models that can be applied should also be determined, based on the products or raw materials. As seen in existing CoC standards, either a specific model is prescribed, or organisations are allowed to select the most appropriate one based on their mode of operations. Many factors are also considered: if the material is associated with CAHRA, additional measures are required, including, at a minimum, risk assessment of tier one suppliers. The flexibility to choose may help foster adoption of the standards, but can, at the same time, introduce risks related to inconsistencies in methods, claims across different actors, and varying levels of traceability assurance. Therefore, the framework must specify the minimum controls that must be in place, the form of evidence that will be acceptable, and the types of claims that will be allowed under the label 'Made in Europe', thereby fostering greater trust in the system and improving consistency.

- **Timeline for MFP and AFP**

National and international sustainability and traceability reporting standards must be evaluated and audited to ensure AFP-MFP satisfies stipulated compliance requirements. If as part of this evaluation it is found that AFP-MFP may not satisfy existing requirements, the planning stage should focus on identifying where current standards must be updated or outline requirements to create dedicated standards which incorporate AFP-MFP.

For AFP, as part of this review, identification of potential certifiable third parties who will have operational obligations and take legal responsibility of AFP technology will also be carried out.

For MFP as well, at this stage is essential to identify of agencies/companies having in charge the determination of reference database for MFP, establishing a protocol to collect samples/data from companies operating within Europe.

In terms of MFP, MaDiTraCe assessed 4 substances. This stage 1 must start with an assessment and the consideration to integrate other substances in a MaDiTraCe project similar work in new research programs, considering several reasons: criticality, exposition to ESG risks, strategy for EU industry, domestic production in Europe, risk of frauds, accessibility and feasibility of sample acquisition, etc.

Feasibility studies assessing the impacts of introducing AFP into CRM supply chains will also have to be carried out. These studies will identify high and low feasibility supply chains based on factors such as logistical disruption, capital requirements, and infrastructure requirements. Methods to mitigate disruption to existing supply chains should also be evaluated. Similarly, further R&D is required for a broader range of CRM commodities and products to assess the feasibility of AFP technology across a wider range of CRM supply chains. Subsequently, supply chains with technical readiness for AFP will be progressed to the designing stage.

- **Timelines for DPP**

DPP is already a reality for some products and in particular in 2027 battery passport would become a reality in the EU. The main timelines for DPP would be

- VC and DPP standards alignment, based on UNTP interoperability
- Data catalogue & information model for DPPs

7.2 Stage 2 – Designing

- **Timeline for regulations**

Once the regulatory framework is established, with an adoption of a "Made in Europe", designing phase must create public incentives to fuel the adoption of it, built lighthouse cases (like G7 roadmap) and identify early adopters.

1. Endorse as Nationally Accepted Framework

- Establish the traceability framework as the national standard for raw materials, ensuring alignment with regulatory bodies and industry stakeholders.
- Secure official endorsement from government agencies to position the framework as the benchmark for transparency and compliance in raw materials supply chains.
- Develop a certification process to validate adherence to the framework, reinforcing its credibility and national acceptance.

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2. Take Steps to Foster Integration with National Digital Infrastructure

- Collaborate with national digital platforms to embed traceability data, enabling seamless information sharing across supply chain networks.
- Design APIs and data exchange protocols to ensure interoperability between the traceability system and existing national digital infrastructure.
- Pilot integration projects with key industry players to demonstrate the framework's compatibility and scalability within the national digital ecosystem.

3. Devise Incentives to Fuel Adoption of Framework

- Introduce tax breaks or subsidies for companies that adopt the traceability framework, accelerating industry-wide participation.
- Launch a recognition program to highlight early adopters, creating a competitive advantage for businesses that embrace the framework.
- Partner with financial institutions to offer low-interest loans or grants for implementing traceability technologies, reducing barriers to adoption.
- Define an implementation calendar and delegated acts

4. Define data governance framework

- Define data ownership, access rights, and privacy protocols to ensure secure, ethical handling of traceability information.
- Develop standardized data formats and exchange protocols to guarantee seamless interoperability between different traceability systems and platforms.
- Align data governance with EU data regulation and data sovereignty frameworks

- **Timeline for certification**

Once the planning phase is completed, which tackles the governance of the system, the standard-setting body must consider the practical implementation of such a system. At this stage, it is important to determine what data needs to be captured (granularity, which will depend on the scope of the framework), the minimum system requirements to define how this data will be captured and verified. The standard-setting body needs to work in collaboration with other stakeholders involved in blockchains, tagging technologies, laboratories, and other IoT devices to establish standardised data formats, terminology, and interoperability protocols, and to design the provisions accordingly.

The design phase should also address the various issues related to trust and information verification. Many existing standards do acknowledge the use of technologies, no doubt, but the provisions related to them are often limited, and insufficient guidance is provided to stakeholders who will interact with the system. It is also often noted that a main limitation of using a technological solution is the reliability of the information entered into the system. So, the framework design should also consider, for instance, what types of evidence will be acceptable on the digital platform, who will be responsible for verifying this evidence, and how the authenticity of the information will be ensured.

- **Timeline for MFP and AFP**

The designing stage for AFP/MFP focuses on developing stage 1 results into a format suitable for identified high-feasibility supply chains. The technical standardisation of AFP as an approved traceability method would be carried out, defining standardised methodologies for AFP deployment, sampling, analysis, data collection and reporting. For MFP different analytical methods and techniques must rely on international accepted standards such as ISO.

These methodologies will also dictate the physical infrastructure requirements necessary for field implementation. Where applicable, this process will include updating existing traceability standards; if existing standards are not fit-for-purpose, new, dedicated standards will be produced. Similarly, an accreditation system for AFP/MFP will be designed to designate roles and responsibilities for third-party service providers who would undergo certification as part of this system.

Secure and centralised databases will also be established as part of this stage. These will consider the AFP data capture requirements and stakeholder access controls. These databases will also integrate MFP data, where necessary, and link with DPPs. Finally, KPIs for AFP will be defined to objectively evaluate how effective the AFP is within subsequent phases. Anomaly detection algorithms relying on high-level scientific developments must be secured and protected to avoid any fraud or corruption.

- **Timelines for DPP**

DPP designing stage is heavily based on current standardisation initiatives. We must refer to recently released CEN-CENELEC norms[16] needed for the implementation of DPP published in July 2026.

- EN 18216 'Digital product passport - Data exchange protocols'
- EN 18219 'Digital product passport - Unique identifiers'
- EN 18220 'Digital product passport - Data carriers'
- EN 18221 'Digital product passport - Data storage, archiving, and data persistence'
- EN 18222 'Digital Product Passport - Application Programming Interfaces (APIs) for the product passport lifecycle management and searchability'
- EN 18223 'Digital Product Passport - System interoperability'
- EN 18239 'Digital Product Passport - Access rights management, information system security, and business confidentiality'
- EN 18246 'Digital product passport - Data authentication, reliability and integrity'

7.3 Stage 3-Implementation

- **Timeline for regulations**

Identify the Laws That Will Need to Be Amended to Integrate the System and Rules to Define Compliance

- Conduct a legal gap analysis to pinpoint existing laws and regulations that require amendment to accommodate the new traceability system.

[16] https://www.cencenelec.eu/news-events/news/2026/en-in-the-spotlight/2026-07-15-dpp/

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- Draft proposed legislative changes to ensure the framework aligns with national and international compliance standards for raw materials.
- Define clear compliance rules, including data reporting requirements, audit protocols, and penalties for non-adherence.

Assign Roles and Responsibilities

- Designate a national oversight body to coordinate implementation, monitor progress, and enforce compliance with the traceability framework.
- Clarify the responsibilities of producers, processors, and traders in maintaining accurate, up-to-date traceability data.
- Establish cross-DG task forces to address inter-agency collaboration and resolve implementation challenges.
- Integrate traceability in an existing agency or in the new EU CRM Centre

Foster Transparency and Monitoring of Effectiveness

- Implement a public dashboard to display key traceability metrics, ensuring stakeholders can track progress and compliance in real time.
- Develop a third-party audit system to independently verify data accuracy and the effectiveness of the traceability framework.
- Publish annual reports on the system's impact, highlighting successes, challenges, and areas for improvement.

- **Timeline for certification**

Once the governance framework is designed and the technical aspects are addressed, the next phase is implementation. Under this main consideration is the development of a standardised reporting format for traceability, similar to the conventional ESG reporting format, that can be used to communicate the strategies employed in traceability, how processes are conducted, the risks, and the processes for identifying and mitigating those related to traceability. In addition, the reporting format could also include the disclosure of how traceability technologies are integrated into their systems, the stages at which they are employed, and how they contribute to varying the claims associated with their products and could provide a better understanding of the level of assurance of their traceability system to the different stakeholders.

Another critical aspect to address is the designation of Key Performance Indicators (KPIs) to monitor the efficiency and effectiveness of the traceability framework. These KPIs could include traceability coverage in the supply chain, data completeness, success rates for material origin verification, etc., and need to be assessed over time.

- **Timeline for MFP and AFP**

The implementation stage involves the trial deployment of AFP-MFP traceability systems within designated low-risk supply chains to resolve any implementation issues that may arise, using predefined KPIs to monitor the traceability systems. Newly developed accreditation systems will be made operational, and steps to verify, certify and audit participating third-party service providers and AFP/MFP traceability systems will commence. Once MFP-AFP systems have been proven within these low-risk supply chains, the systems will be scaled across more complex or high-risk supply chains as part of the subsequent scaling and monitoring stage.

- **Timelines for DPP**

As previously stated, implementation of DPP is already a reality for several fields and actors. However, timelines for DPP implementation are closely related to the integration of VC of other actors than pure raw material suppliers (certification bodies, auditors, MFP accreditations, LCA verification bodies) participating in the system.

7.4 Stage 4- Scaling and monitoring

- **Timeline for regulations**

Enforce Compliance and Monitoring of the Traceability Systems

- Deploy automated monitoring tools to continuously track compliance with traceability requirements, flagging discrepancies for immediate action.
- Empower regulatory authorities to conduct unannounced audits and impose sanctions for non-compliance with the traceability framework.
- Create a centralized compliance hub to aggregate data, analyse trends, and ensure all actors adhere to established traceability standards, associated to EU CRM centre or other public agencies
- Form a multi-stakeholder committee to oversee data governance, resolve disputes, and update interoperability standards as technology evolves.

- **Timeline for certification**

During this phase, the main role of the standard-setting body is to closely monitor KPIs and maintain oversight of the implementation of the traceability framework. This means that the challenges related to interoperability, inconsistencies in implementation, any risks that may lead to the fragmentation of the system should be closely monitored.

- **Timeline for MFP and AFP**

Once MFP and AFP have been successfully trailed within selected low-risk supply chains, these traceability systems will be expanded across wider CRM supply chains, including within higher-risk jurisdictions. The continuous monitoring of MFP-AFP systems within other supply chains will take place to ensure the systems' KPI's are operationally acceptable. Using the anomaly detection systems, this will facilitate the isolation and mitigation of anomalies as they emerge. Issues associated with data security and sharing will undergo further refinement based on the results of scaling these traceability systems, especially as these systems will become reliant on a wider range of service providers and stakeholders from more jurisdictions.

- **Timelines for DPP**

The scaling and monitoring of the DPP is closely related to other topics: monitor KPIs, interoperability and the assessment pf DPP content quality by international expert working groups or committees.

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7.5 Stage 5- Optimization

- **Timeline for regulations**

Achieve Full Interoperability: Complete the transition to harmonized technical standards enabling seamless data exchange across systems, jurisdictions, and product categories. Establish the EU as the global reference for traceability governance, attracting international alignment, with collaboration and cooperation with other countries like for example G7 or OECD countries.

Integrate Circular Economy Loops: Extend traceability systems to capture end-of-life material flows, enabling efficient recovery and recycling. Link DPPs with waste management systems and urban mining initiatives to close material loops.

Evaluate and Adapt: Conduct comprehensive assessment of traceability system effectiveness, costs, and benefits. Use findings to refine requirements, address implementation gaps, and inform next-generation policy development.

Promote Global Standards: Leverage EU market power and diplomatic channels to promote adoption of European traceability standards internationally. Work through multilateral forums to establish global frameworks that prevent regulatory fragmentation while accommodating diverse contexts.

- **Timeline for certification**

Optimisation of the framework may be needed, with the standard-setting body introducing new governance mechanisms where required, depending on circumstances, as traceability systems operate in dynamic geopolitical and technological environments that are constantly evolving. So, the framework cannot be static; it also needs to adapt to a changing environment and emerging risks related to the mineral/product and ESG. Moreover, since the framework is planned to extend and adopt a more global approach, it may present additional challenges, so it is expected that the standard-setting body will continuously support the framework's optimisation to ensure it remains efficient and effective in achieving its objective of attaining traceability even across the global context by harmonizing with international laws and standards.

- **Timeline for MFP and AFP**

MFP and AFP traceability systems will undergo continuous optimisation with more R&D to withstand attempts to circumvent these systems, to adapt to developing CRM processing methodologies, and to incorporate innovative and more sophisticated technologies to prevent technical obsolescence. AFP-MFP will also have to undergo optimisation to ensure these systems are aligned with national or international standards that undergo revision or are newly published.

At this stage, we would imagine that an ecosystem of private laboratories providing MFP/AFP services will exists, in an equilibrium with the centralised reference body.

- **Timelines for DPP**

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As for other topics, the optimization stage for DPP implementation would consist on continuous improvements actions, with more technical developments, more interoperability between systems and consequently more international cooperation.

8 Policy recommendations

8.1 Traceability within “Made in Europe” (Industrial Accelerator Act)

The "Made in Europe" initiative, part of the broader Industrial Accelerator Act (IAA), was officially proposed by the European Commission on 4 March 2026 and is now under discussion by the European Parliament and Council:

- Key Features:
    - Introduces "Made in Europe" (or "Made in EU") requirements for public procurement and support schemes, aiming to increase demand for European-made clean technologies and products.
    - Sets minimum local-content requirements for strategic sectors (e.g., steel, cement, aluminium, cars, net-zero technologies like batteries, solar PV, wind turbines, and electrolysers) when public funds are used.
    - Goals include increasing manufacturing’s share of EU GDP from 14.3% (2024) to 20% by 2035.
- Current Stage:
    - The proposal is now in the hands of the European Parliament and Council for adoption. It is expected to face intense debate, especially regarding the definition of "European" content and the balance between protectionism and competitiveness.
- Context & Objectives:
    - The IAA is designed to reduce strategic dependencies, boost EU competitiveness, and support the green transition. It follows recommendations from the Draghi report and is part of the Clean Industrial Deal.

This plan can generate an opportunity for MaDiTraCe developments as any definition of local content would require a minimum of traceability and verification along supply chain, otherwise the risk of fraud and economic consequences are too high. However, despite being an opportunity, criteria definition and the consideration of upstream industry in this plan would be key.

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Opportunities for MaDiTraCe

- Possibility for a "Mined in EU" label, inspired by Australian and Canadian documents/plans

- Verified credentials system for raw materials companies operating in the EU

- Neutral public agence(s) settling EU raw materials MFP database and delivering "proof of origin"

- Develop AFP technologies and business

- Associate “Made in Europe” with certifications, connect it with certification schemes from CRM Act

- Continuation of EU battery passport movement

- Global vision, alignment with UN CEFACT, G7 traceability roadmap and other global initiatives

- Integrate traceability for non-European materials

Needs

- Need to define a local content and define a formula and criteria for “Made in Europe”

- Local content is not synonym of certified content. Define how both criteria are considered

- Engage working groups with European raw materials sectors about their interest

- Economic impact assessment of the implementation of a traceability system

- Clarify the link with CRM Act certification schemes list

- Assess the degree of requirements

- More developments for recycled content traceability

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8.2 Standard based market – G7

G7 countries will fix a roadmap for critical raw materials traceability in Summer 2026. It represents an opportunity for MaDiTraCe project but at the same time there is a clear need of clarification as G7 discussions tend to mix different conceptualisations of traceability where responsible sourcing and ESG criteria are fundamental for such development. We observe here that in the public and international momentum traceability, as stayed also by IEA 2026, can be just a tool to demonstrate supply chain diversification or can be a tool to assess the degree of transparency and ESG of supply chain whereas extraction and processing is happening. Both conceptualisations of traceability can coexist but there is a clear need of clarification of the main purpose of those international roadmaps.

Opportunities for MaDiTraCe

- Interoperability with G7 countries initiatives under the umbrella of UN CEFACT/UNTP

- MaDiTraCe experience and case studies could be the basis for first pilot cases in G7

- Possibility for a premium price for commodities produced under standards and traced

- Launch of ISO working groups and other standardization works

Needs

- Need to clarify ESG requirements and exigences in G7 standard based market

- Traceability as a tool for supply chain diversification or traceability as a tool to demonstrate responsible sourcing whereas it happens

- Interoperability between certification standards

- Assess new substances (nickel, manganese, copper, etc.)

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8.3 Global recommendations and international cooperation

Beyond initiatives such as "Made in Europe" or G7 roadmap, traceability applied to minerals is a global concern as pointed out by international organisations such as UNECE or IEA. At this level recommendations, opportunities and needs are very similar to UNECE white paper ones. Current commercial war momentum constitutes a necessity for more international cooperation but at the same time represents a very complex situation as any dialogue is complex. However, traceability systems ignoring such complexity of supply chains cannot work.

Opportunities for MaDiTraCe

- Interoperability with countries initiatives under the umbrella of UN CEFACT/UNTP and other international initiatives

- MaDiTraCe experience and case studies could be the basis for first pilot cases

- Put responsible sourcing and ESG in the middle

- Launch of ISO working groups and other standardization works

- Alignment with ISO traceability norms

- Assess quality and content of first battery passports in Europe

- International dimension of MFP, work with main raw materials producers, assess CAHRA countries

Needs

- Associate mining countries

- Integrate artisanal and small-scale mining and SMEs

- Discussion and agreement using international agencies such as ISO

- Ensure interoperability (OECD, China), understand Chinese material traceability requirements

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