UK Critical Minerals
Intelligence Centre

Securing sustainable supply of critical raw materials for the UK: good practice and recommendations for improvement

Decarbonisation and Resource Management Programme

Commissioned Report OR/22/034

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Nickel-copper-cobalt ore and its end-products nickel (blue) and cobalt sulfates (orange) produced at the Sotkamo mine in Finland operated by Terrafame. © Terrafame Ltd.

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Securing sustainable supply of critical raw materials for the UK, current issues and recommendations for improvement

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BRITISH GEOLOGICAL SURVEY

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Summary

This report gives an assessment of the strengths and weaknesses of current approaches to managing the supply of critical raw materials (CRMs). It builds upon an initial phase of work, published in the *Overview of activities and policy report*[1]. This reviewed current global activities, research and policy leading to the identification of the key issues related to CRM resource management and the sustainability of supply. This review provided the basis for the formulation of a series of recommendations in this study.

Where appropriate, the role of the United Nations Framework Classification (UNFC) in classifying and harmonising CRM resource data is evaluated. The potential application of the United Nations Resource Management System (UNRMS), which is planned to be used as a toolkit for managing resources throughout the supply chain, is also discussed.

UK-based industry and academic experts were consulted during this research to highlight the most important issues facing the sustainable supply of CRMs to the UK. Five case studies have been developed to illustrate specific issues related to CRM resource management and to identify appropriate mitigation and best practice. Three of these focus on the supply of battery raw materials, graphite, lithium and cobalt. They cover the full raw material value chains and discuss economic aspects and environmental, social and governance (ESG) performance. The other case studies examine management of mineral exploration data and the development of traceability tools for CRM supply chains.

On this basis a series of recommendations for improving the security and sustainability of CRM supply has been developed. These encompass a wide range of activities across material value chains from mineral exploration and CRM resource definition, through processing and manufacture, to recycling and disposal. Particular consideration is given to ESG aspects throughout the CRM supply chains. Based on existing national expertise and research capacity, those topics on which the UK is particularly well suited to lead have been identified.

The recommendations include:

Theme	Recommendation
how to improve the understanding of CRM resource data	Invest in research and exploration for CRM resources in the UK to promote domestic supply.
	Develop links with overseas governments, academic institutions, and corporations active in sustainable management of CRM resources.
	Promote the use of UNFC in CRM research and encourage the minerals industry to adopt UNFC when reporting data to national governments.
how to encourage mineral exploration and economic development in the UK and overseas	Improve management of UK mineral exploration data to ensure its value is maintained and it remains accessible in the future.
	Develop collaborative partnerships with researchers and governments in Africa and Latin America to better understand global CRM resources and to identify new sources of primary supply.
	Promote the use of the UNFC and UNRMS to help with evaluating overseas projects based on their performance in sustainable and responsible sourcing.
how to improve our understanding of secondary resources as potential sources of CRMs	Undertake research into how data on waste and recycled materials is classified. Carry out detailed mapping of CRM supply chains to determine if recycling can make a significant contribution to UK CRM supply.
	Undertake research to improve waste characterisation and CRM recovery potential from disused mine sites in the UK and overseas.

	Evaluation of waste management law to ensure that re-use and recycling of CRMs from waste materials is prioritised.
	Develop improved systems for collection and sorting of end-of-life products and for the recovery of CRMs.
how to improve the ESG performance of the mineral industry and transparency along CRM supply chains	Develop harmonised and standardised reporting of ESG issues in the extraction of CRMs.
	Develop tools to foster good industry practice e.g. sustainability certificates and labels to increase consumer and investor confidence.
	Develop a standardised taxonomy for terms in the field of sustainability and ESG.
	Ensure that ESG aspects are considered throughout the life of a project via early engagement with the exploration industry.
how to improve data collection and availability	Fill data gaps in CRM supply chains through policy intervention requiring data disclosure and by fostering industry acceptance of the benefits of collecting and disseminating data.
	Promote understanding of CRM demand and supply through the planned UK critical minerals intelligence centre.
	Improve collaboration between existing UK researchers and bodies like the ONS to improve data quality, harmonisation, timeliness and accessibility on stocks and flows of CRMs.
	Elaborate the data requirements for mapping CRM supply chains and implement related changes. UK should collaborate with international organisations on trade statistics and codes.
how collaboration and communication can be improved	Develop educational materials and promotion of transparent supply chains to highlight the importance of CRMs and to demonstrate the environmental credentials of CRM supply.
	Involve social scientists in stakeholder engagement related to new projects.
	Ensure new research includes extensive stakeholder consultation and multidisciplinary expert input to augment data-driven studies.
how understanding of the entire value chain is necessary to identify circular economy interventions for CRMs	Undertake detailed mapping of complete CRM supply chains using Material Flow Analysis to identify supply barriers and opportunities for mitigation.
	Improve coordination between different national authorities, for example statistical offices, geological surveys and environment agencies, to ensure all relevant datasets are accurately and consistently used in new models.
	Ensure that systems and tools under development for sustainable management of resources such as MFA, digital twins, battery passports and any new frameworks developed by UNRMS are aligned and compatible.

This report also considers how a UK-based International Centre of Excellence (ICE) on sustainable resource management may help to mitigate risks to global CRM supply. Such a centre would contribute to further development of the UNRMS and UNFC and also benefit the UK by lowering the barriers to sustainable CRM supply. Research priorities should build on areas where the UK already has high levels of expertise and a strong track record. These include the development of geological models for CRM resources and exploration, planning and environmental protection and mapping of complete CRM value chains.

1 Introduction

1.1 AIMS OF THIS STUDY

This study aims to give an overview of the major issues related to the sustainable supply of critical raw materials (CRMs) for the UK. Selected case studies are used to highlight specific challenges and to identify best practice. These examples cover the full value chain for CRMs, some focussing on economic aspects, such as international trade, while others illustrate how good environmental, social and governance performance can be achieved whilst maintaining adequate levels of supply. The role of internationally-accepted tools and guidance developed by the United Nations Economic Commission for Europe (UNECE) in providing solutions to problems with CRM resource data is emphasised. This work aims to demonstrate how these tools can act as a platform for an international accepted effective and holistic framework for the sustainable resource management of CRMs alongside national initiatives.

The research aims to identify the most significant barriers to achieving sustainable supply of CRMs and to provide recommendations for appropriate mitigation. The focus is on generic, high-level issues that influence the supply of many CRMs. Given the diversity of the CRMs and the complexity of their supply chains it is not possible to provide an exhaustive review in this study.

This report also assesses the possibility of establishing a UNECE International Centre of Excellence on Resource Management in the UK. Those areas in which the UK has an international reputation for excellence in research and innovation are identified and opportunities for building on this track record through such a centre are listed.

1.2 SUMMARY OF CRITICAL RAW MATERIAL 'OVERVIEW OF ACTIVITIES AND POLICY REPORT'

This report builds on a landscape mapping exercise which reviewed the issues and policies associated with resource management and sustainable supply of CRMs[1]. This review, here referred to as the *Overview of activities and policy* report, highlighted the resource management tools developed by the UNECE, namely the UNFC and UNRMS. It summarised relevant projects, current policies related to CRMs, data standards, key stakeholders and their linkages.

The focus on the UNECE tools and frameworks was driven by the need for harmonised classification of mineral resources and for effective and sustainable resource management, which are widely recognised as key elements of strategies for the sourcing and use of raw materials. As a result, there is now considerable global interest in the use of UNFC and development of the UNRMS. In addition, the growing requirement for greater knowledge and improved management of CRM resources has led to a need to map CRM supply chains. This aligns well with the goals of the UNRMS with potential for it to become an accepted international standard.

The *Overview of activities and policy* report summarises recent and ongoing activity related to the sustainable supply of CRMs. It outlines the causes of recent burgeoning demand for CRMs and highlights two major challenges for the future provision of secure CRM supply to the UK:

- the need to rapidly increase supply of metals that were previously used in small amounts, but which are now required in much larger quantities for low carbon technologies such as batteries and clean energy generation.
- the need to ensure supply is low-carbon, causes minimal environmental harm and provides long-term social and economic benefits to affected communities.

A wide range of policy related to mineral resources has been developed in response to these challenges. These include the Paris Agreement[2], the EU Batteries Directive[3], the EU Green Deal[4], the EU 'conflict minerals' legislation[5], the US Dodd-Frank Act[6], the Net

Zero Strategy[7], and the UK Environment Act[8]. These aim to:

- improve security of raw material supply;
- reduce carbon emissions associated with the life cycle of raw materials;
- reduce environmental and societal harm related to raw material production and consumption;
- promote the development of a circular economy.

A long-term strategy for the sustainable management of all mineral resources will contribute to the attainment of these goals. The development of such a strategy is fundamentally dependent on improving our understanding of how raw materials are produced, the impacts of their production and use, and how they flow through society. To fulfil these requirements, we need a broad range of metrics covering the complete material life cycle, including data on numerous geological, economic, metallurgical, social and environmental factors. A simplified representation of these flows and processes showing the linkages between different points in the lifecycle of CRMs is shown in Figure 5. Decarbonisation of resource consumption and transition to a circular economy requires this data and understanding and, together with the UK's ambitions for economic growth, gives a new level of urgency to resolving these matters.

2 Background information

2.1 WHAT ARE CRITICAL RAW MATERIALS?

Global concerns are growing over the long-term availability of sustainable supplies of the minerals and metals needed by society. Of particular concern are so-called 'critical raw materials' (CRMs), which are of increasing economic importance but have a relatively high risk of supply disruption. The escalating demand for CRMs is being driven by the rapid uptake of novel technologies that are being deployed to support global decarbonisation. These technologies utilise a wide range of minerals and metals which are sourced through complex and dynamic global supply chains. Consequently resource-consuming economies, which are highly reliant on imports of these materials, are potentially vulnerable to supply disruption. Such supply restriction is seldom due to limited geological availability, instead it most commonly arises from other causes of a geopolitical, economic, environmental or social nature. It is, therefore, important to assess what materials are at risk of supply disruption and the severity of consequent impacts. This, in turn, assists in the development of appropriate mitigation strategies for sustainable resource management.

While there is no single or fixed list of CRMs, criticality assessment is generally undertaken by evaluating two key dimensions:

- the likelihood of supply disruption, commonly referred to as supply risk; and
- the impact of, or vulnerability to, supply disruption. This is generally estimated by measuring the economic importance of the industrial sectors that depend on supply.

In the past decade numerous criticality assessments have been published by governments, NGOs, academics and commercial companies. All assessments rely on the availability of reliable data to allow quantification of the two key dimensions of criticality. An overview of the methods, indicators and metrics used in criticality assessments was published by Schrijvers et al. (2020)[9] .

Criticality assessments can have an important role to play in the development of policy and research aimed at underpinning security of supply, encompassing entire mineral supply chains from deposit formation to exploration, mining, processing, manufacturing and recycling. They also elucidate other possible supply barriers such as trade restrictions, social licence to operate and environmental constraints related to land, water and energy use. They highlight those materials where further in-depth analysis is required, where data availability and quality are inadequate and where insight into future supply and demand is lacking.

In contrast to most major industrial metals, such as aluminium, copper and iron, the knowledge base for many CRMs is seriously deficient because, until recently, demand for them has been limited. CRMs are typically produced in small amounts, hundreds or thousands of tonnes per year, from a few sources worldwide. Many lack their own production infrastructure and are recovered only as by-products of the extraction of another, parent metal. For example, almost all cobalt is a by-product of the mining of copper or nickel, while most rhenium, tellurium and selenium are recovered only as by-products of copper extraction[10,11]. Another serious issue for resource management is that national and global reserve and resource data for many CRMs are poorly known or entirely lacking.

On account of the concentration of production in a small number of countries, together with their small and opaque markets, many CRMs are characterised by high levels of price volatility. This is a significant barrier to investment in new projects and also a serious concern to consuming industries that require secure and stable supplies of these materials. Furthermore, recycling rates for most CRMs are very low, such that supply from secondary resources is currently limited.

2.2 DEFINITION OF RESOURCES AND RESERVES

The concepts of mineral ‘resources’ and ‘reserves’ are fundamental to the operation of the mining industry because they are used to define how much material is currently feasible to extract or which might become feasible if circumstances change in the future. These concepts are commonly misused or conflated, with potentially serious consequences for decision making by government and industry.

While various definitions of resources and reserves have been published, one of the most widely accepted was published by CRIRSCO (2019)[12]:

- a ‘resource’ is a concentration or occurrence of material of economic interest in or on the Earth’s crust in such form, quality and quantity that there are reasonable prospects for eventual economic extraction. The location, quantity, grade, continuity and other geological characteristics of a mineral resource are known, estimated or interpreted from specific geological evidence and knowledge. Mineral resources are subdivided, in order of increasing geological confidence, into inferred, indicated and measured categories.
- a ‘reserve’ is the economically mineable part of a mineral resource. Studies to at least pre-feasibility level will have been carried out, including consideration of and modification by realistically assumed mining, metallurgical, economic, marketing, legal, environmental, social and governmental factors. The results of the studies demonstrate at the time of reporting that extraction could reasonably be justified

In simple terms, reserves are that part of an identified resource that could be economically extracted at the time of the assessment. The determination of mineral resources and reserves is the means by which deposits that are currently economically extractable (reserves) are distinguished from those where economic extraction of a commodity is potentially feasible (resources).

It is important to note that reported resources for any particular commodity represent only what has been found to date and do not in any way reflect the total amount present in the Earth’s crust, commonly referred to as the ‘resource base’. A portion of the resource base will be sufficiently concentrated to form a resource that is potentially economically extractable. Known resources are but a small part of these resources, while the majority is currently ‘undiscovered’. The quantity of undiscovered resources, which could ultimately contribute to supply, cannot, therefore, be neglected. However, the quantitative estimation of undiscovered resources is a complex technical process associated with high levels of uncertainty. It can only be undertaken through detailed geological assessments underpinned by a sound understanding of the processes that lead to the concentration of metal in the Earth’s crust. To date, there are few published estimates of undiscovered resources: these are restricted to certain metals, such as copper, where the processes of mineral deposit formation are well understood, and to certain areas where the geology is particularly well known[13-15].

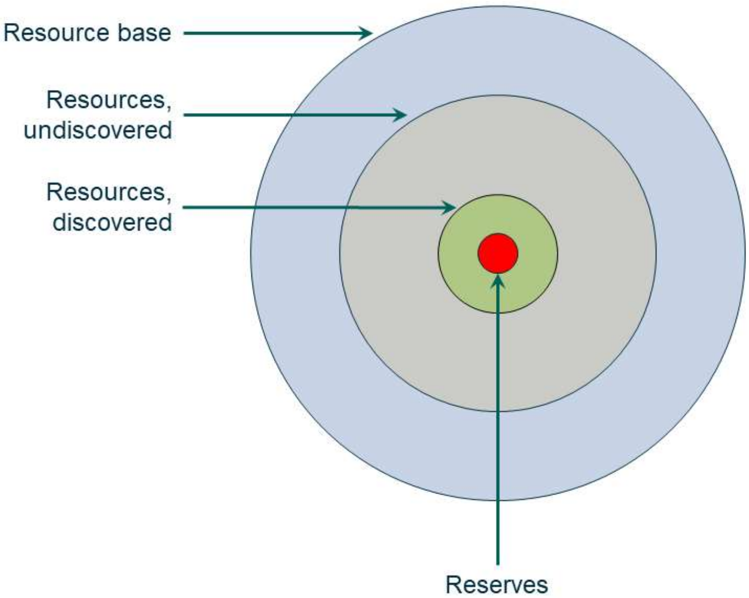
The first stage in the identification of a mineral resource is the conversion of exploration results from a prospective area into a quantitative estimate of the amount, quality and distribution of the target metal in bedrock. This typically involves drilling, assaying and preliminary metallurgical testing to determine if the metal can be effectively separated from its host rock. To further increase confidence in the economic viability of the resource a considerable amount of additional investigation is undertaken. This involves detailed evaluation of all aspects of project development (geological confidence, technical feasibility, ESG factors, etc.) and may take several years to complete. On account of the time and cost of these activities they are focussed on those areas considered to be the most promising. Consequently, discovered resources are very much smaller than the undiscovered resources from which they have been defined. The vast majority of reconnaissance exploration projects are abandoned without ever verifying the presence of a discovered resource.

The next phase of resource evaluation involves comprehensive technical investigations to confirm the size and grade of the deposit, to determine how the ore can be mined and processed, and how the target metal can be extracted. A mineral reserve is then defined, given favourable economic, political and social conditions, in conjunction with a full financial analysis to confirm economic viability. However, this reserve is valid only at a particular point in time and is best regarded as a working inventory of the amount of mineral available to extract at the time the assessment was made. As a result of the way in which resources and reserves are estimated the quantity of undiscovered resources is very much larger than that of discovered resources which, in turn, is much larger than that of reserves, often by many orders of magnitude (

Figure 1). Each successive class is associated with an increasing level of confidence, corresponding to the increasing amount of data required for its classification.

2.3 REPORTING OF RESOURCES AND RESERVES

Different jurisdictions have different ways of measuring and reporting mineral resources and reserves. Various reporting systems or codes set out minimum standards, recommendations and guidelines for the public reporting of exploration results, mineral



resources and ore reserves. These may be divided into: those commonly used by the minerals industry, defined by the CRIRSCO template; and the United Nations Framework Classification (UNFC), developed by the UNECE, which is focussed on national-level strategic resource management.

2.3.1 CRIRSCO-type reporting

There are several internationally recognised systems of reporting resource and reserve data (also known as reporting codes or standards). These include: the Australian Joint Ore Reserves Committee (JORC) Code; the Canadian National Instrument (NI 43–101); and the Pan-European Reserves and Resources Reporting Committee (PERC). Exploration and mining companies will typically use the reporting code of the stock exchange on which they are listed. For example, companies operating in the UK may employ both the Canadian and Australian codes because they are registered on stock exchanges in both countries. These codes and standards have been aligned and standardised to some degree by the Committee for Mineral Reserves International Reporting Standards (CRIRSCO). In addition to these internationally-recognised codes, many other national codes exist but their usage is normally restricted to a specific country.

Figure 1. Schematic representation of the relative size of the quantities represented by the terms resources and reserves (not to scale). Modified from Graedel et al. (2014)[10]

The CRIRISCO template splits resources and reserves into additional categories based on the likelihood of development as shown in Figure 2. This subdivision is a feature of all codes, standards and classifications, and is based on levels of confidence in the various factors that influence project development (these are known as the 'modifying factors'). It is important to note that the CRIRSCO family of codes has been designed specifically for the reporting of results to stock exchanges to ensure a consistent standard is applied for the protection of investors. As a result, any 'reserves' reported should not be considered as physical stocks, but as economic entities that have a realistic chance of being extracted in the future (typically within 5 years).

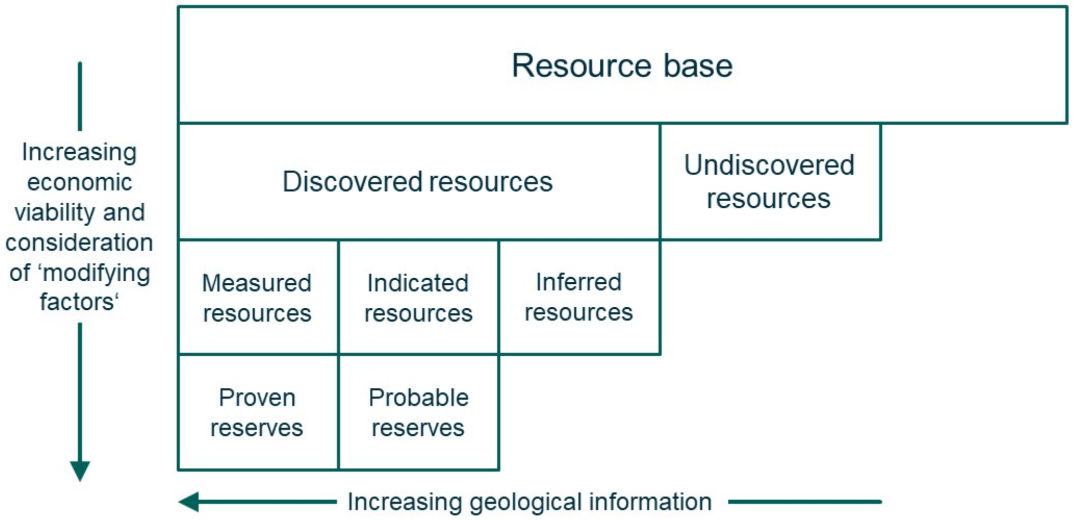


Figure 2. The relationships between reserve and resource categories contained in the CRIRSCO template and the resource base. Modified after Lusty & Gunn (2015)[16].

2.3.2 United Nations Framework Classification (UNFC)

The UNFC is a resource classification system developed by the UNECE to provide a harmonised and consistent way of reporting estimates for a variety of resources (fossil fuels, mineral resources, renewable energy, etc.)[17]. Detailed discussion of UNFC can be found in Bide et al.,2022[18], Bide et al., 2019[19] and Simoni et al., 2021[20].

Resource development projects are evaluated in the UNFC on the basis of their economic, technical, social and environmental feasibility for resource production in the future[17]. Various criteria are used to classify the resource into different categories based on:

1. environmental-socio-economic viability (E-category);
2. field project status and feasibility (F-category); and
3. degree of confidence in the estimate (G-category) (Figure 3).

A notable advantage of the UNFC system over those that follow the CRIRSCO template is that it is better suited to resource reporting and aggregation of resource quantities at national and regional scales thereby facilitating decision-making on large-scale, long-term, resource management.

Although conversion of CRIRSCO-compliant resource estimates into the UNFC classifications can be readily accomplished[21] (Figure 4), UNFC enables a more detailed assessment of the resource quantities according to the E, F and G categories. The UNFC system offers greater flexibility as it can accommodate resources that do not comply with CRIRSCO reporting codes, such as historic estimates or national reporting codes. Resources that are uneconomic at the time of reporting can also be included, thus allowing the creation of a comprehensive mineral inventory and a longer-term outlook for mineral supply.

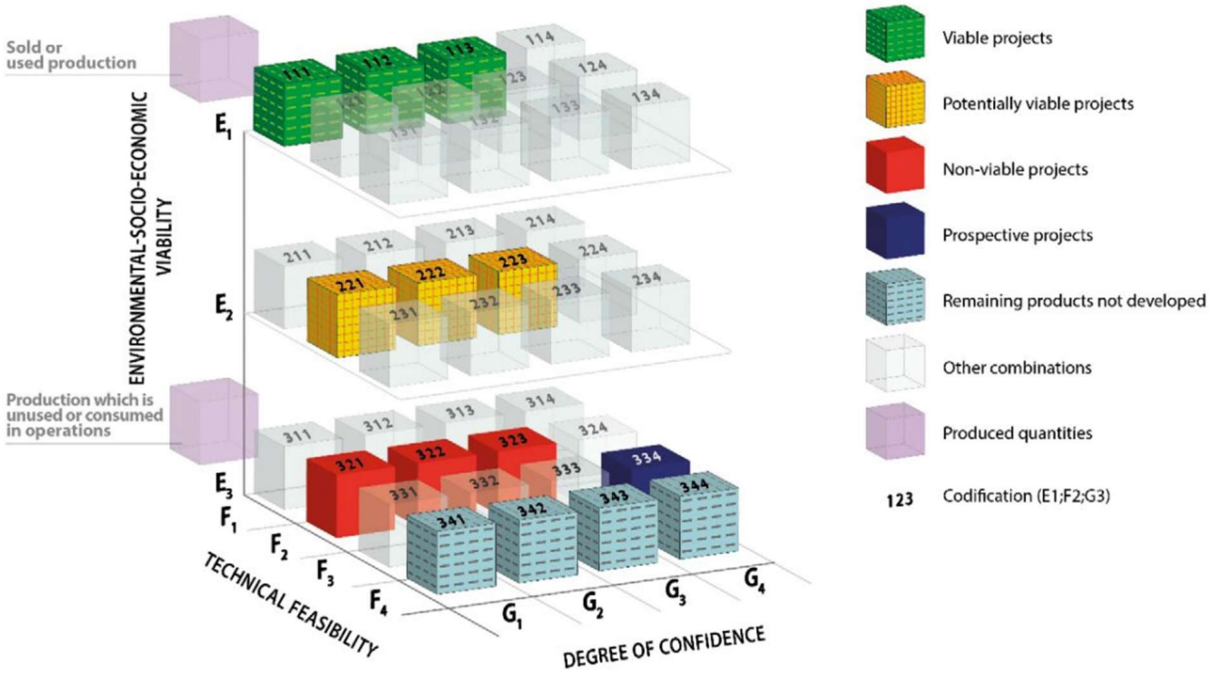


Figure 3. The UNFC classification system. From United Nations Framework Classification for Resources Updated 2019, UNECE, © (2022) United Nations. Reprinted with the permission of the United Nations[17].

CRIRSCO Template		UNFC-2009 minimum categories			UNFC-2009 Class
Mineral reserve	Proved	E1	F1	G1	Commercial projects
	Probable			G2	
Mineral resource	Measured	E2	F2	G1	Potentially commercial projects
	Indicated			G2	
	Inferred			G3	
Exploration target		E3	F3	G4	Exploration projects

Figure 4. Comparison of UNFC classes to the CRIRSCO template. UNECE, © (2022) United Nations. Reprinted with the permission of the United Nations[21].

It should also be noted that the UNFC system aims to classify directly the tonnage of a certain commodity or product, while CRIRSCO-compliant resources identify an ore tonnage and the associated grade of each contained metal or mineral. A CRIRSCO-compliant resource classification (e.g. measured resource or proven reserve) applies to the whole ore body, while the UNFC classification applies only to one commodity. This has the advantage that each commodity can be classified separately in regards to uncertainty and development status. This is particularly important for by-product CRMs that may not have been considered for future extraction.

2.4 INTRODUCTION TO THE UNITED NATIONS RESOURCE MANAGEMENT SYSTEM (UNRMS)

The UNRMS is a new concept developed by the UNECE that is planned to be used as a toolkit for managing resources[22]. The main goal of the UNRMS is to develop tools for the sustainable management of resources aligned with the UN Sustainable Development Goals, unlike other more established and mature resource management systems, such as the Petroleum Resource Management system (PRMS), where the focus lies on the commercial status of projects[23]. The UNFC lies at the heart of the UNRMS by providing a system for a harmonised quantification and aggregation of different resource types based on project maturity. The UNRMS can use this information to build a holistic system that integrates all parts of the supply chain (i.e. production, processing, manufacturing, use, end-of-life treatment). In addition, it considers resources not as isolated and independent elements, but integrates different resource types from all sectors and their relationships and effects on each other (e.g. mineral resources and groundwater resources). Environmental, social and governance aspects are at the core of this system and should be considered at each stage of development. This is represented, alongside UNRMS's relationship to UNFC and various stages in the minerals value chain, in Figure 5.

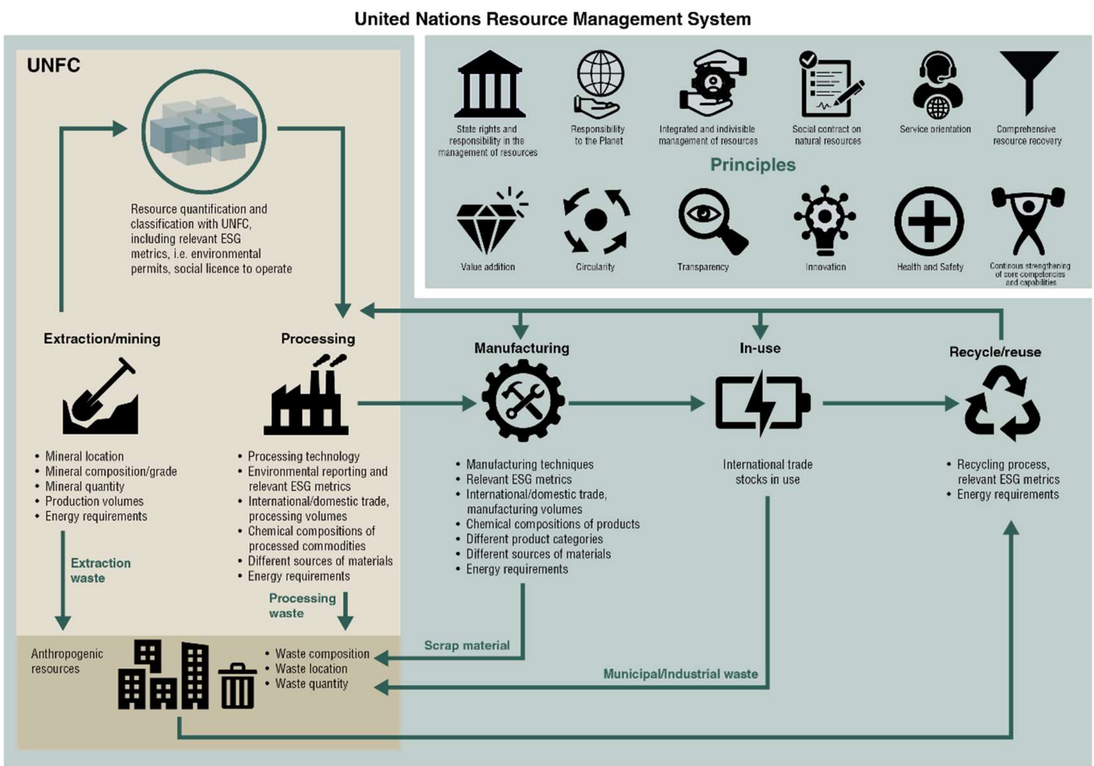


Figure 5. Schematic representation of the UNRMS, showing the value chain and associated data requirements and the linkage to the UNFC. While UNFC assesses data for the exploration and extraction phases, the UNRMS is based on twelve principles, which require data for the whole value chain (Figure 6).

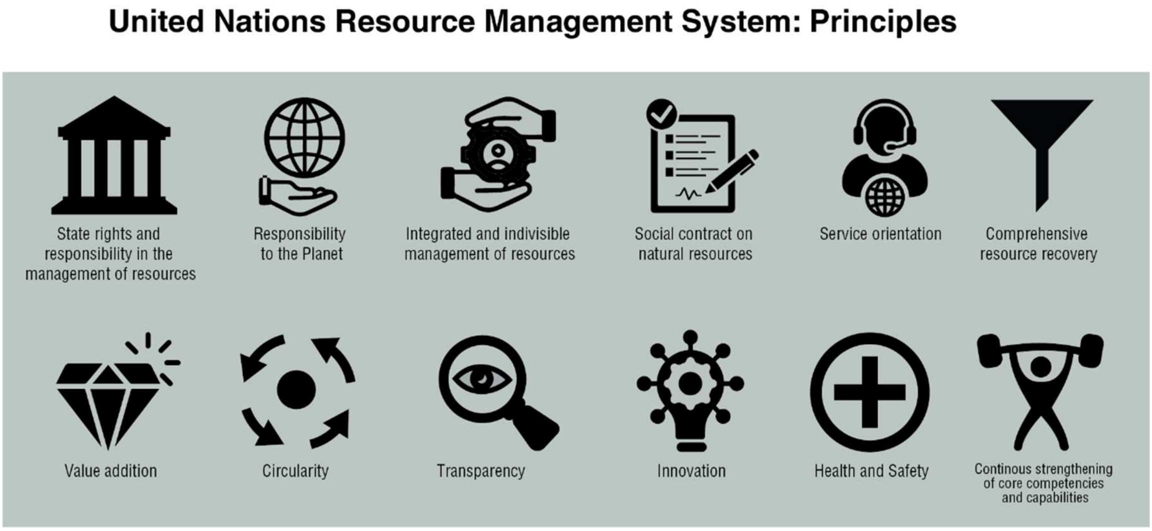


Figure 6 The UNRMS principles.

Twelve fundamental principles have been formulated that define all aspects that should be considered in sustainable resource management (Figure 6). The UNRMS has had limited practical application to date. Its implementation commenced with the establishment of a number of UNECE International Centres of Excellence which will continue to develop and apply the system to many resources in different parts of the world.

2.5 UNECE INTERNATIONAL CENTRES ON SUSTAINABLE RESOURCE MANAGEMENT

The UNECE has begun to establish International Centres of Excellence on Sustainable Resource Management (ICE-SRM). Their function will be to build regional centres and networks of collaboration in sustainable management of resources that are needed to reach the goals of the 2030 Agenda for Sustainable Development. The aim is to promote the use and further development of the UNFC and the UNRMS on a regional scale and to build national and regional capacities to apply these systems. The ICE-SRMs will operate under the guidance of the Expert Group on Resource Management (EGRM). The UNECE has published criteria for ICE-SRM designation and terms of reference[24]. The key criteria that are required for the establishing an ICE-SRM are:

1. Commitment to attaining the objectives of the UN to deploy UNFC and UNRMS.
2. Commitment to active engagement between all ICE-SRMs to ensure consistency in the application.
3. Establishment as a going concern and as a legal entity with strong relationships into the regional resource development community.
4. Political support in the region for the ICE-SRM.
5. Commitment to the objectives of UNFC, UNRMS as well as the UN 2030 Agenda and the Paris agreement, in particular those that are relevant for the regional, national and local needs.
6. Commitment to innovation and continuous development of sustainable resource management in alignment with UNFC and UNRMS policies and objectives.
7. Full transparency and compliance with norms and requirements regarding potential conflicts of interest.
8. Competence and capacity in sustainable resource management.
9. The ICE-SRM is responsible of its own resourcing (financial, human, physical) and must be able to support a central UNECE resource management hub both in-kind and financially.

10. It must have a physical infrastructure or access to it, including organisational infrastructure and regional ecosystem and demonstrated delivery mechanism.

When these criteria are fulfilled, the centre can identify opportunities and barriers to the adoption of UNFC and UNRMS specifically within their field of research interest and expertise. It should also support any stakeholders in their activity footprint to achieve the 2030 Agenda of Sustainable Development. Projects of the ICE-SRM should include some or all of the following activities:

1. Capacity building: Conduct training on appropriate procedures and certification of UNFC and UNRMS; research in the field of sustainable resource management; case studies; consultation for government and industry; preparation of training materials.
2. Contribution to further development and maintenance of UNFC and UNRMS: Engage in the network of ICE-SRM; develop application of UNFC and UNRMS; develop principles for public private partnership; develop technology innovation platforms; develop and implement financial reporting guidelines; develop quality assurance procedures.
3. Advocacy: gather and disseminate knowledge through partners; catalyse industry tools and training development; identify and address region-specific potential barriers to implementation; foster public engagement through e.g. public events; support resource management improvements.
4. Outreach: conduct workshops; institute a website; prepare publications and documentation; present at key venues; promote and disseminate transparently; support dialogue between international practitioners; promote global recognition of UNFC and UNRMS; provide strategic consultancy service to governments, industry and the financial sector.
5. Reporting: report to EGRM; annual reporting on activities and achievements, prepare work plan for the coming period and plan sources and uses of funds.

The full terms of reference for the ICE-SRM can be found online at: https://unece.org/node/349267

2.5.1 Current and planned International Centres on Sustainable Resource Management

At present there are five different ICE-SRMs at the planning stage.

Table 1 gives an overview of these centres, their activity footprint and objectives. The ICE-SRM in Moscow is currently the most advanced. It is supported by academia (State University of Moscow), the resource industry Gazprom, Rosneft) and financial institutions (BRICS Bank and others)[25].

Table 1 Overview of current ICE-SRMs in development by the UNECE.

Location/ Association	Activity footprint	Objectives and scope	References
China	China	No definite plans; continuous development of bridging UNFC and the Chinese national standards on mineral resources and petroleum	https://unece.org/climate-change/news/countries-are-committing-implementation-united-nations-resource-management[26]
Coordinating Committee for Geoscience Programmes	East and Southeast Asia	Establish harmonised standards for sustainable	https://ccop.asia/e-library, CCOP Strategic Plan 2021-2025[27]

in East and Southeast Asia (CCOP)		resource management in the region	
Mexico	Latin America	No definite plans; potential further development of case studies in petroleum and minerals sector with focus on environmental and social issues	https://unece.org/DAM/energy/se/pdfs/egrm/egrm10_apr2019/ECE.ENERGY.GE.3.2019.5_e.pdf[28]
Russia, Moscow	Commonwealth of Independent States	Develop financial reporting standards based on UNFC for industry-wide application; focus on new clean technologies for energy and mining industry and carbon footprint comparison of all energy sources	https://unece.org/sites/default/files/2021-04/02%20Igor%20Shpurov_Presentation%20%28EN%29.pdf[25]
Geological Service for Europe, Slovenia	Europe	Sustainable resource management in Europe, focussed on CRMs in primary and secondary resources	https://www.eurogeosurveys.org/wp-content/uploads/2019/03/Geological-Service-for-Europe-_12.2018.pdf[29]

3 Stakeholder engagement

3.1 PURPOSE AND SCOPE

A range of industry and academic experts was consulted to ascertain their views on the most important issues facing the sustainable supply of CRMs to the UK and to identify appropriate mitigation. The stakeholders consulted were identified largely on the basis of the recent landscape mapping exercise (listed in Table 2). An effort was made to ensure that all aspects of the CRM supply chain were represented, although time constraints prevented a comprehensive industry-wide consultation.

The stakeholder interviews were centred around a core set of questions (Appendix 3). However, given the broad range of interests represented, the interviews were focussed on those issues of greatest concern to individual consultees. The results of the stakeholder interviews have been used to inform the recommendations made in this report.

3.2 RESULTS OF STAKEHOLDER CONSULTATION

The most important, and commonly encountered, issues that emerged from the interviews are:

1. Resources of CRMs are in many cases more complex and more difficult to define than for other raw materials. Some are by-products of other commodities (e.g. cobalt in copper or nickel mines) and others are hosted in unusual resource types that are not currently well understood (e.g. Li-brines). More research is needed to understand the geology and abundance of CRMs. The UK has the necessary expertise to be a leader in this aspect of CRM research.
2. The most significant barrier to development of new CRM projects is the difficulty of obtaining a Social Licence to Operate (SLO) for new sites. This is due to the negative perception of resource extraction by the public, the lack of understanding regarding where raw materials are sourced and the lack of due consideration of SLO from the earliest stages of project development.
3. Current exploration activity for CRMs in Great Britain is at a low level despite the potential benefits of domestic production to increase supply chain security. There is currently no centralised system that manages the collection of exploration data in Great Britain. This results in the loss of valuable information that could be used to guide future exploration. In order to promote indigenous exploration for mineral resources, a more centralised approach to data collection from exploration projects could be a relatively inexpensive way to attract indigenous exploration and development.
4. Despite potential for some CRM supply from indigenous sources in the future, the UK will remain heavily reliant on overseas trade for CRMs in the foreseeable future. As a result, understanding of overseas sources of CRMs and international cooperation is of great importance.
5. The large number of internationally-accepted sustainability standards and frameworks currently in place make reporting and certification confusing for companies, consumers and investors who want to support sustainable mining. Convergence, alignment and harmonisation of these standards is needed to boost sustainability in mining and along the whole supply chain.
6. There is a need for consistency and alignment of standards for data and management to support transparency in the mining sector. The various relevant datasets for minerals (i.e. economic, environmental etc.) should be linked and available in one place to facilitate easy access and to allow a better understanding of how different aspects of the CRM supply chain are linked. However, the extractive industry has serious concerns about publishing sensitive and confidential

data at the required resolution that may affect their market competitiveness. More support for the acquisition and publication of pre-competitive data by government institutions and academia could help resolve this issue.

7. There is a need to understand the whole value chain of CRM production, including all stocks and flows in different stages, various intermediate products that are produced for different end-uses and what happens at the end-of-life (e.g. recycling). In addition, all processes that are involved in material transformation between the different stages should be assessed in detail and quantified. This requires industry to be open and transparent about raw material flows, material handling and processing. This will help to ensure that materials are used efficiently and with minimal losses through their lifecycle. This requires better data collection throughout the lifecycle of a project, with greater detail and more transparency from industry at the resolution required for mapping of raw material lifecycles.
8. The need for more collaboration between policy makers, academic researchers and industry was stressed by all consultees. Collaboration should also be supported across all disciplines linked to the supply chain of CRMs, from geologists and social scientists to recycling engineers and many more.

3.3 STAKEHOLDERS CONSULTED

Table 2 List of stakeholders consulted.

Name	Organisation	Principle role/area of interest/project involvement
Andrew Bloodworth	British Geological Survey	Policy Director and resources and decarbonisation lead
Aidan Davey	International Council on Mining and Metals (ICMM)	COO and Director of the environment programme for one of the largest trade bodies representing global mining
Charlotte Griffiths (CG); Harikrishnan Tulsidas (HT)	UNECE	Chief of Section, Sustainable Energy Division (CG); Economic Affairs Officer (HT)
Dr Karen Hanghøj	British Geological Survey	BGS Executive Director, CMEC member, UNECE ERGM member
Professor Richard Herrington	Natural History Museum	CMEC member, CRM resource expert
Veera Johnson	Circulor	Co-founder of a consultancy developing systems for material passports and traceability. CMA member
Susannah McLaren (SM) and Tom Fairlie (TF)	The Cobalt Institute	Head of Responsible Sourcing and Sustainability (SM) and Sustainability Manager (TF) at the trade body representing the cobalt industry
Professor Daniel Müller	Norwegian University of Science and Technology	Expert in industrial ecology and chair of the International Society of Industrial Ecology's section on Material Flow Analysis
Evi Petavratzi, Andrew Hughes, Jon Ford, Richard Shaw	British Geological Survey	BGS experts in the global lithium supply chain, including exploration, mining, environmental impacts and manufacturing

Jon Russill	SRK Consulting	Senior consultant dealing with early stage mineral projects, both in the UK and overseas
Dr Long Seng To	Loughborough University	Director of the Centre for Sustainable Transitions at Loughborough University and chair of the solar energy subgroup of the UN ERGM
Professor Frances Wall	Camborne School of Mines, University of Exeter	Deputy Associate Dean for Research and Impact. Lead on the Met4Tech project. Expert in CRM development and resources in the UK

4 Case studies demonstrating current supply issues and good practice

The following case studies illustrate examples of existing barriers to the sustainable supply of CRMs and also highlight good practice in dealing with these. These examples cover the full value chain for CRMs, some focussing on economic aspects, such as international trade, while others illustrate how good environmental, social and governance performance can be achieved whilst maintaining adequate levels of supply. Five case studies are presented: three deal with the supply of graphite, lithium and cobalt, while the other two focus on the management of mineral exploration data and on the development of traceability tools for CRM supply chains respectively.

4.1 SECURING SUSTAINABLE SUPPLIES OF GRAPHITE, WITH A FOCUS ON AFRICA

4.1.1 Introduction

Graphite is a crystalline form of carbon (C) and one of only a handful of naturally-occurring native elements (i.e. uncombined with any other elements). It is one of the softest known minerals, in stark contrast to the other main form of carbon, diamond, which is the hardest naturally-occurring mineral.

Graphite has physical and chemical properties that are valuable for many industrial and advanced technology applications, such as a high melting point in non-oxidising conditions, and thermal conductivity and electrical resistivity that make it ideal as a conductor of heat and electricity. It is an industrial mineral which has, for many years, been used as a raw material for refractory products particularly in steel manufacture, as well as in metal bearings, brake linings, lubricants, paint and pencil lead[30]. However, in recent years, its use in lithium-ion rechargeable batteries, where it is the preferred anode material, has significantly increased the demand for graphite. This has put pressure on the established supply chain especially because the global trade and production of graphite anode materials is dominated by China. This supply risk is driving a surge in exploration activity in many parts of the world including east Africa.

4.1.2 Graphite occurrence

The economic value of some industrial minerals such as graphite relies not just on their mineralogical and chemical characteristics but also on their physical properties. Those properties considered important for the industrial use of graphite include graphite purity, particle size, electrical and thermal conductivity, degree of crystallinity, expandability, lubricity and bulk density. The specifications drawn up between mineral producers and consumers have considerable significance for mineral exploration companies as they are a clear guide to the types of graphite that are suitable for different applications.

Graphite occurs in three natural forms, each with different commercial applications[31]:

- Amorphous graphite: finely crystalline graphite that is mostly formed by the metamorphism of carbonaceous rocks such as coal. It is typically used in low-value applications, such as foundry sand mould coatings, pencils and paint, and in lubricants and some refractory products. The main global suppliers are China, Mexico, Russia and Austria.
- Flake graphite: crystalline flakes of graphite that have a maximum dimension between 75 microns and 4 cm. They were formed by the recrystallisation of carbon in sedimentary rocks and are found in Archean to late Proterozoic age metamorphic rocks such as gneiss, marble and schist. Flake graphite is the main commercially traded form of graphite. Flake graphite is preferred for use in clay-graphite crucibles and magnesia-carbon refractories, for the production of High Purity Spherical Graphite (HPSG) used to manufacture Active Anode Material (AAM) for lithium-ion batteries, high purity

refractory bricks used to line steel kilns, vehicle brake and clutch linings and high purity lubricants. The fine-grained (<75μm) product of flake graphite mining is also used as a substitute for amorphous graphite. The main global suppliers are China, Brazil, India, Canada, Madagascar, Mozambique and Ukraine.

- Vein (lump) graphite: highly crystalline, massive form of graphite that is deposited in veins by fluids during metamorphism. It is often closely associated with flake graphite and occurs in similar geological settings. It is mostly used for lubricant and refractory applications. It is also used in high-quality electrical motor brushes and other current-carrying carbon products, which benefit from the high purity and crystallinity of vein graphite. The main global supplier is Sri Lanka.

In the UK, minor amounts of graphite are widespread in metamorphosed carbon-rich sedimentary rocks, particularly in the Lower Palaeozoic sedimentary rocks of Wales, and in the Cambrian and Precambrian rocks of the Northern Highland and Grampian terranes of Scotland. The Seathwaite deposit in the Lake District, hosted by andesitic volcanic rocks, is well known as it provided graphite for the pencil industry in Keswick. There are no graphite occurrences in the UK that are considered to be potentially economically significant. There has been no systematic or modern exploration for graphite and there are no deposits for which graphite resources or reserves have been reported[32].

Currently there is no production of graphite in the UK. It was produced on a small scale in the 19th century but it is unlikely to be mined in the future on a commercial scale in the UK due to the small size and restricted accessibility of the remaining graphite resources[32,33].

4.1.3 UK graphite use and trade

In the UK graphite has a long history of use in established industries including aerospace, nuclear power generation, the petrochemical and automotive sectors, and glass and steel manufacturing. The UK Net Zero Strategy sets out aspirations to establish electric vehicle (EV) battery gigafactories will increase the UK demand for HPSG used in lithium-ion battery AAM.

Natural graphite imported into the UK comes from the following countries[34]:

- EU countries: mostly from Austria and Germany with a small amount from the Netherlands. In 2020, European Union (EU) graphite imports into the UK were 879 tonnes (value £1.1 million).
- Non-EU countries: mostly from China with small amounts from Madagascar, Mozambique, Russia, Sri Lanka and Turkey. In 2020, non-EU graphite imports into the UK were 6364 tonnes (value £4.3 million).

UK trade in natural graphite for the period 2015 to 2020 is shown in Figure 7.

Published trade data groups together all forms of graphite as 'natural graphite'. This means that it is not possible to evaluate the proportion of each used in different applications and makes it difficult to determine the trade flows of different forms of graphite used in the battery supply chain (or any other industry).

4.1.4 Supply chain for battery-grade graphite

The global supply of graphite is dominated by China. In 2020, China produced an estimated 650 000 tonnes, representing 65% of global production of graphite (1 million tonnes)[35]. The other main graphite producers, in descending order of production in 2020, were: Brazil, Madagascar, North Korea, India, Mozambique, Russia, Austria, Turkey, Ukraine, Norway and Canada[35]. The global demand for graphite is set to rise dramatically to 4 million tonnes per year by 2030 and demand will outstrip supply before 2030[36]. New sources and supply chains will be needed to bridge the gap between supply and demand caused chiefly by the increasing need for battery raw materials.

The processing and manufacturing of battery materials and components take place in very few countries. China is currently the only country in the world to produce HPSG and one of a handful producing AAM, alongside Japan and South Korea[37]. This concentration of key stages in the supply chain in a small number of countries is a potential risk to the security of global graphite supply. In addition, the lack of information on, and opportunities to scrutinise, the processing operations in China makes it difficult to guarantee that global environmental, social and governance (ESG) standards are met.

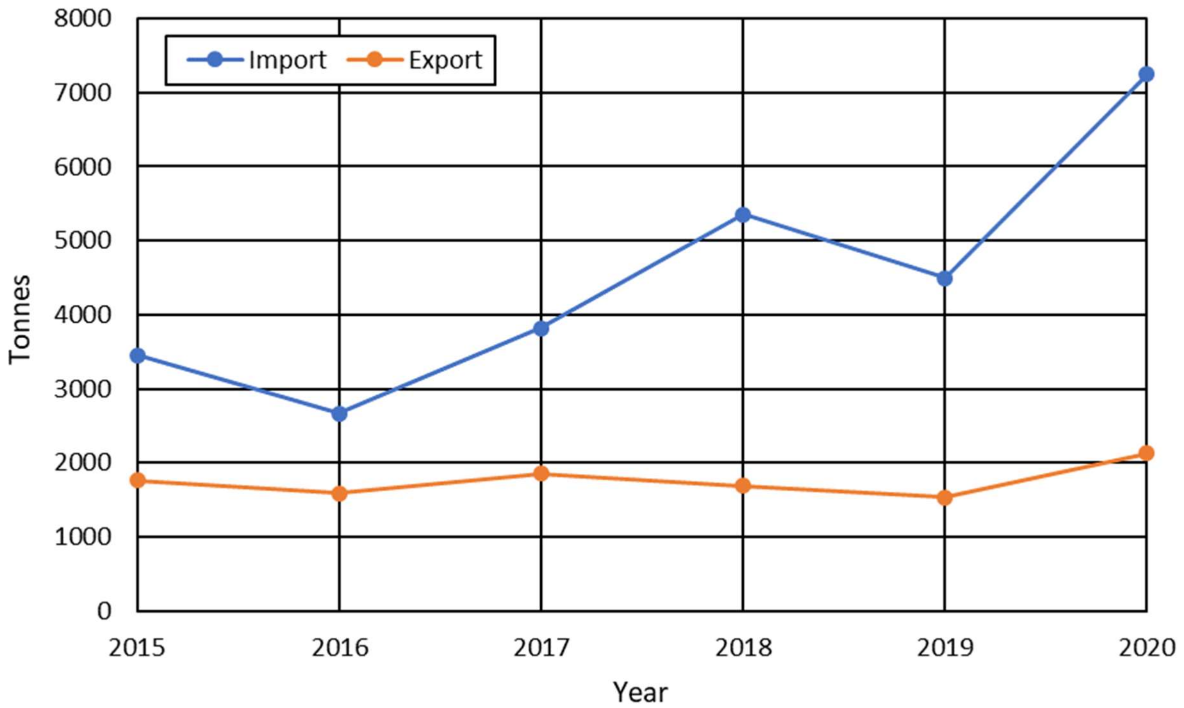


Figure 7. UK trade flows of natural graphite, 2015 to 2020. Source: Trade data for natural graphite (Harmonised System commodity code, HS 2504) from UK Trade Info[38].

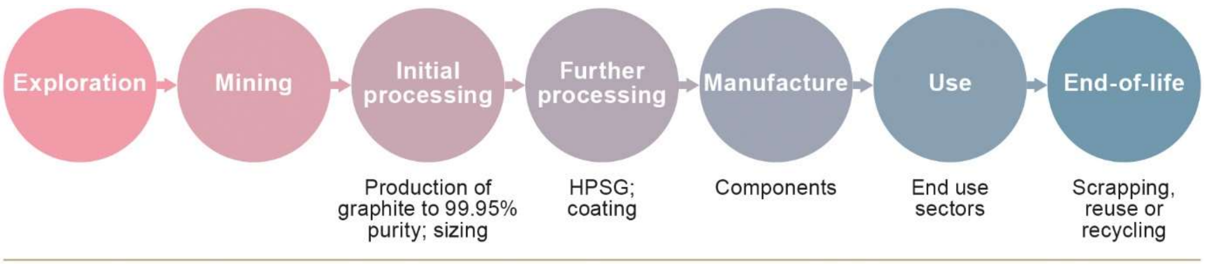


Figure 8. The stages in the graphite supply chain.

Given the large scale of the deposits and advanced development of some mining projects, Africa has the potential to become a leading producer of responsibly sourced and sustainable graphite. However, such opportunities will need to be carefully planned and managed in consultation with all stakeholder groups, especially in regions and with communities with little prior experience of mining and processing operations.

The graphite supply chain for batteries comprises the following stages (Figure 8).

1. Exploration stage: discovery, resource assessment, planning and commissioning of the mine.
2. Mining stage: mining and initial processing to produce graphite concentrates.
3. Processing stage: processing to make specialised graphite products such as spheroidisation to make HPSG and coating.
4. Manufacturing stage: manufacturing of AAM for lithium-ion batteries.

5. Use stage: production and use of the consumer product.
6. End-of-life stage: scrapping, reuse or recycling of graphite, for example to produce graphene.

4.1.5 Focus on Africa

4.1.5.1 Graphite resources and production

Graphite resources in Africa occur in ancient geological terranes that form the Precambrian 'basement' of the continent. These consist of large, tectonically stable blocks of continental crust ('cratons') surrounded by mobile orogenic 'belts' that were deformed by intense tectonic stresses. Graphite is typically hosted in high-grade metamorphic rocks such as schist, gneiss and marble. Across the continent, particularly in the Mozambique belt in eastern Africa, significant graphite deposits have been identified many of which have delineated reserves and resources.

Graphite production in Africa mainly takes place in Madagascar and Mozambique. In Madagascar there are three graphite mines, Gallois, Graphmada and Sahamamy Sahasoa, with a combined production in 2020 of 48 500 tonnes. In Mozambique there are two mines, Ancuabe and Balama, with a combined production in 2020 of 18 159 tonnes[35]. Graphite production is due to restart in Namibia in 2022[39]. Small amounts of graphite are produced in Tanzania and Zimbabwe.

Exploration has identified significant deposits of graphite in Botswana, Ghana, Guinea, Madagascar, Malawi, Mozambique, Namibia, Tanzania (Figure 9) and Uganda. Minor occurrences have also been reported in several other countries in Africa.

Examples of advanced exploration projects and mining operations for graphite in eastern Africa include:

- Balama flake graphite mine in Cabo Delgado Province, northern Mozambique, has a JORC-compliant resource of 1.4 billion tonnes at 10% graphite. The graphite operation has a production capacity of 350 000 tonnes per year (tpy) and a projected life span of 50 years. It is planned to export small flake graphite (75-150 μm) to Syrah Resources' battery anode plant currently under construction in Vidalia, Louisiana, USA. This will be the first major integrated producer of natural graphite HPSG and AAM outside China for electric vehicle batteries[40,41].
- Gallois flake graphite mine in Madagascar has a JORC-compliant indicated resource of 174.5 million tonnes at 6.7% graphite and plans to increase current production capacity to 140,000 tpy[42].
- Nachu flake graphite exploration project in Tanzania has a JORC compliant resource of 174 million tonnes at 5.4% graphite[43].
- Malingunde flake graphite exploration project in Malawi has a JORC compliant resource of 65 million tonnes at 7.1% graphite[44].

Figure 9. Graphite exploration, Epanko graphite project, Tanzania (© EcoGraf Limited).

Other parts of Africa with geology favourable for the occurrence of graphite have similar Precambrian basement terranes to those in eastern Africa. The following are currently the focus of active graphite mineral exploration and/ or development of mining operations:

- Pencil Hill flake graphite exploration project in the Archean Motloutse Complex near Francistown in Botswana has a JORC compliant resource of 6.9 million tonnes at 8.82% graphite [45].
- Kambale flake graphite exploration project in the Precambrian West African craton in northern Ghana has a JORC-compliant resource of 14.4 million tonnes at 7.2% graphite[46].
- Lola flake graphite exploration project in the Precambrian West African craton in south-east Guinea has a NI 43-101-compliant resource of 19.14 million tonnes at 4.37% graphite[47].
- Okanjande flake graphite exploration project in the Namaqualand Metamorphic Complex in northern Namibia has a NI 43-101 -compliant measured resource of 9.56 million tonnes at 6.25% graphite[48].
- Orom cross flake graphite exploration project in the Neoproterozoic gneisses and schists in northern Uganda has a JORC-compliant resource of 16.35 million tonnes at 6.01% graphite[49].

Other prospective areas in Africa with no current mineral exploration projects include the Neoproterozoic Arabian Nubian Shield in Egypt, the Mozambique belt in Ethiopia, Kenya, Zambia and Zimbabwe, the West African Craton in Nigeria, the Paleoproterozoic Beit Bridge Complex in South Africa and ultramafic rocks (igneous rocks rich in Mg and Fe) in Morocco. Figure 10 shows the distribution of current graphite exploration projects and operations in Africa.

4.1.5.2 Constraints on graphite resource development in Africa

Graphite production is ongoing in Madagascar, Mozambique and Tanzania[50]. Given the high level of exploration, production in these countries is likely to increase in the future.

Currently graphite mining in Africa produces only graphite concentrates which are exported to China. There is no production in Africa of HPSG or AAM, although the scale of the known graphite resources would appear adequate to support such local value addition. This is in accord with one of the principles of the United Nations Resource Management system (UNRMS) and is essential to the attainment of Sustainable Development Goals across the globe.

Factors that may contribute to the successful development of graphite mining operations in Africa include:

1. **High quality mineral deposits and geological information:** good quality, detailed, accessible geological information for mineral resources is a key requirement for mineral-rich countries looking to attract investment, particularly Foreign Direct Investment (FDI). Such data is often non-existent or hard to access.
2. **High standards of governance, legal framework and regulatory stability:** good governance of the mining industry is essential to attract investors and to ensure positive impacts for communities. A transparent, equitable and consistent legal context, and effective support and monitoring by well-organised government institutions are needed. There is a variety of different governance mechanisms across the relevant jurisdictions, which do not always meet good practice standards. The implementation of AMREC (African Mineral and Energy Resources Classification and Management System) may help to improve and standardise the governance of mineral resources in Africa.
3. **Good infrastructure, mining services and supply chain:** mining investments require reliable infrastructure (roads, rail networks, ports, water supply and power generation). Mining services and a clear understanding of the supply chain are also needed. Graphite mineral processing is highly energy intensive and requires a reliable source of energy.
4. **Environmental regulations:** high standards of environmental regulation, and their continual monitoring and enforcement, are required in the vicinity of mine sites and processing plants. This is especially the case in areas where mining has not previously been carried out.
5. **Equitable taxation and use of revenues:** a competitive and well-structured fiscal regime and access to foreign exchange are important. Foreign Direct Investment (FDI) is an opportunity for governments to finance infrastructure development, sustainable economic growth to generate job creation, and involvement in exploration, extraction and processing.
6. **Skills and human resources:** a cadre of well-trained, highly skilled local staff will be essential for the development of a graphite mining industry in any African country. There is commonly a shortage of skills across the whole project lifecycle, from mineral exploration, to environmental mitigation and downstream processing and manufacture. Capacity building and the use of standard international frameworks (such as AMREC, UNFC or UNRMS) may help to fill this gap.

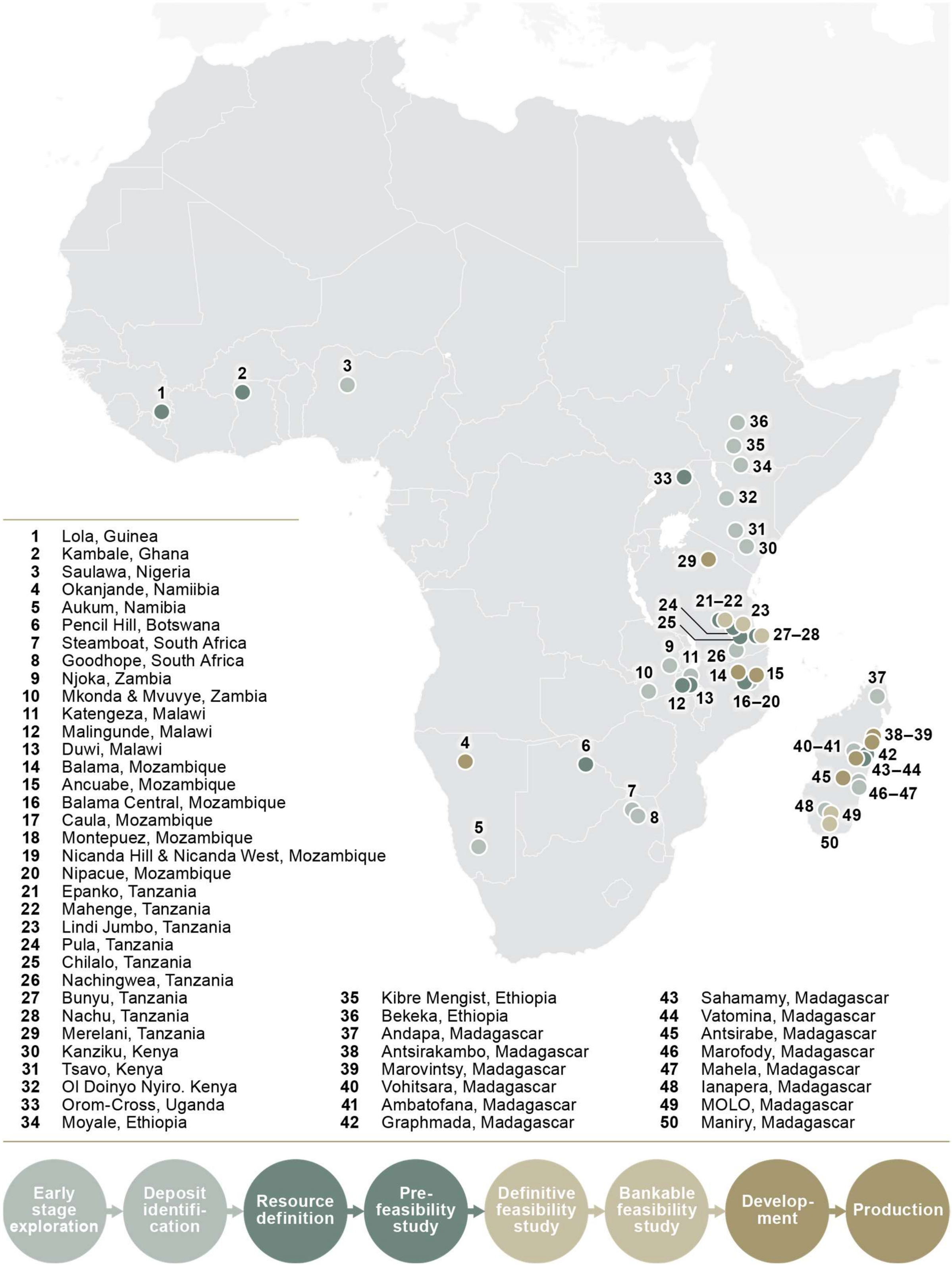


Figure 10. The distribution of graphite exploration projects and operations in Africa. Source: Mitchell & Deady (2021)[50]

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4.1.6 Conclusions

The global graphite industry faces significant challenges in maintaining supply to meet the increasing demand for battery raw materials. Global graphite resources are abundant, particularly in eastern Africa, and could make a significant additional contribution to supply. However, maintaining a sustainable, transparent and diversified global graphite supply chain will be a considerable challenge. Meeting the conditions required to establish successful graphite mining operations in Africa will take many years. This will depend on long term commitments by governments and industry, underpinned by the support and trust of all stakeholder groups, especially local communities. The ability of UNFC, through its incorporation into AMREC, to compare and contrast the impacts of multiple projects, with a clear focus on ESG, could help to ensure effective environmental management of new developments. The establishment of the capacity to produce HPSG and AAM is arguably the key challenge in ensuring the benefits of graphite resource development are retained in Africa.

4.2 LITHIUM: THE COST OF A GLOBAL RUSH FOR 'WHITE GOLD'

4.2.1 Introduction

Lithium is a soft, silvery-white alkali metal with a unique set of chemical and physical properties that makes it a valuable component of many commercial applications. Lithium has high conductivity and is the most electronegative metal, making it ideal for use in battery cathodes. Its high mechanical strength and thermal shock resistance are well-suited for the manufacture of high-temperature lubricants and heat-resistant glass and ceramics.

Lithium can be processed into a variety of chemicals and is traded globally in many forms, including concentrates, carbonates, oxides and hydroxides, chloride, bromide and metal. Lithium carbonate is the precursor chemical for all other chemicals with the exception of metal and metal derivatives, which are derived from lithium chloride.

Lithium carbonate and lithium hydroxide are the two lithium compounds used for battery cathode production. This market has witnessed rapid expansion over the past 10 years owing to rising demand from three industry sectors: electric vehicles (EVs), consumer electronics and energy storage.

The type of lithium battery used in these industries is known as a lithium-ion (Li-ion) battery. It is rechargeable and has a higher energy density than lead-acid or nickel-cadmium rechargeable batteries, which means it is well-suited to applications where space is at a premium. Lithium carbonate is the most widely used lithium compound in Li-ion batteries, but several market participants anticipate lithium hydroxide taking over as the primary product as adoption of nickel-rich cathodes, which typically use hydroxide, increases over the coming years[51]. Flexibility of production will be essential to keep pace with a range of industrial and technological advances.

Global lithium production has increased three-fold between 2009-2019[52,53] (from existing producers), driven largely by the rapid expansion of the EV market and demand for Li-ion batteries. Looking ahead, there is further substantial growth forecast in low-carbon technologies as part of the global energy transition away from fossil fuels. This could see lithium demand increase by 42 times relative to 2020 demand by 2040[54].

4.2.2 Geological occurrence

Lithium can be concentrated in four types of mineral deposit: continental brines; geothermal and oilfield brines; volcano-sedimentary deposits; and pegmatite and granite deposits. Current global lithium production is split between pegmatites (particularly in Australia), with a share of about 60%, and continental brines (particularly in Chile and Argentina), with a share of about 40%. Lithium-bearing pegmatites are also important sources of other valuable co-product metals such as tantalum, caesium and tin.

Lithium does not occur as a native element, and instead is found in a range of minerals[55]. The most abundant lithium-bearing mineral found in economic deposits is spodumene, which occurs in pegmatites and granites. The largest lithium-bearing pegmatite deposits occur in North Carolina, USA, at Manono in the DRC and at Greenbushes in Australia. Other well-known pegmatite deposits include those at Bikita in Zimbabwe and Tanco in Canada. Future sources of lithium could include deposits of the lithium-enriched minerals hectorite and jadarite[55]. The Jadar deposit in Serbia is one of the largest greenfield lithium projects in the world[56], with planned production of 58,000 tonnes of lithium carbonate (55,000 tonnes of which is battery-grade) annually at steady state. Rio Tinto has committed US$450 million in pre-feasibility, feasibility and other studies in Jadar to understand the nature of the deposit, with a further US$2.4 billion earmarked for mine construction, subject to necessary approvals, permits and licenses. However, the project is currently facing strong opposition from stakeholders over the potential environmental impact of a mine, and in January 2022, the Serbian government withdrew the spatial plan and revoked Rio Tinto's licence to operate.

Extraction from brines is mostly from continental deposits, such as the salt lakes and salt pans of the central Andes in South America, which are known locally as salars. The salars are situated in basin and range settings surrounded by volcanic deposits (e.g. ignimbrites, tuffs) that are the main source of mineralised lithium, which is leached into the salars. Rainfall is typically very low on the salars, but rising as the elevation increases away from the salar itself[57]. Rainfall recharge is very limited, if it occurs at all in the centre of the salar (nucleus). Outflows are primarily from evaporation, which is orders of magnitude higher than the rainfall and abstraction. The brine is pumped from the nucleus of the salars and then concentrated using a series of evaporation ponds, although alternative methods of extraction, for example 'direct lithium extraction' (DLE) are also available. One of the largest brine deposits in South America is the Salar de Atacama in northern Chile, which, covering an area of approximately 3000 km^2, currently accounts for about one third of global lithium output[58]. Extraction from geothermal and oilfield brines has also been demonstrated, albeit not on a commercial scale.

Historically pegmatites have been the predominant source of lithium and it is only the development of brine operations in South America that has in recent years reduced the share of lithium supply sourced from pegmatites. Although brine operations' cash costs are almost twice that of hard-rock assets owing to processing costs and high royalties[59], the value of the concentrate produced is generally higher. However, owing to the growing importance of lithium hydroxide in new battery technologies, hard rock projects are looking increasingly attractive. The lithium hosted in spodumene (hard rock) can be processed into either lithium hydroxide or lithium carbonate, while brines are first processed into carbonate, then into hydroxide at an additional cost.

4.2.3 Global lithium resources

Lithium resources encompass a variety of deposits and minerals, all with very different characteristics, which can make it difficult to determine suitability for end-use applications i.e. not all lithium resources are suitable for battery-grade lithium carbonate or hydroxide. In addition, the rapid rise in demand for lithium over the past few years has also reduced the lead-in time for quantifying global resources, which means that there is still a relatively high level of uncertainty in the published data.

Global lithium reserves currently stand at approximately 22 million tonnes, led by Chile, Australia, Argentina and China[60]. Global lithium resources have been estimated at approximately 89 million tonnes, with the largest resources held by Bolivia, Argentina, Chile and USA. In 2021, there were nine countries known to be producing lithium (Figure 11). Of these, five were extracting lithium from brine and five were producing lithium minerals from pegmatites[61](China has both).

Resource estimation for hard rock lithium deposits is relatively straightforward given the available industry standards (e.g. JORC, PERC etc.) which have long been applied to deposits of solid mineral raw materials. However, the quantification of liquid resources such as brines is much more complicated. In these deposits the mineralisation is mobile and can change over time as brines migrate and interact with their surrounding environment, which, until recently, precluded the application of standard methods to these resources[62]. Uncertainties in the amount, grade and distribution of the brine resource presented serious obstacles for planning and management at both operational and strategic levels and were a serious disincentive to investment. As a result, in 2019 the Joint Ore Reserve Committee (JORC) adopted *Guidelines for the Resources and Reserve Estimates for Brines*[63] that was jointly developed by the Australian brine industry and its hydrogeologists in conjunction with the Association of Mining and Exploration Companies (AMEC). The guidelines draw on the Canadian Institute of Mining's (CIM) existing '*Best Practice Guidelines for Resource and Reserve Estimation of Brines'*[64]. The brine reporting under the JORC guidelines applies to all minerals contained in brine (lithium, uranium, potassium etc.) and was introduced to improve consistency and transparency of the information provided to the market. It provides a standardised reporting model which requires participation by a team of qualified persons, including geologists, hydrogeologists, geochemists and chemical engineers, although this is not used extensively by the industry.

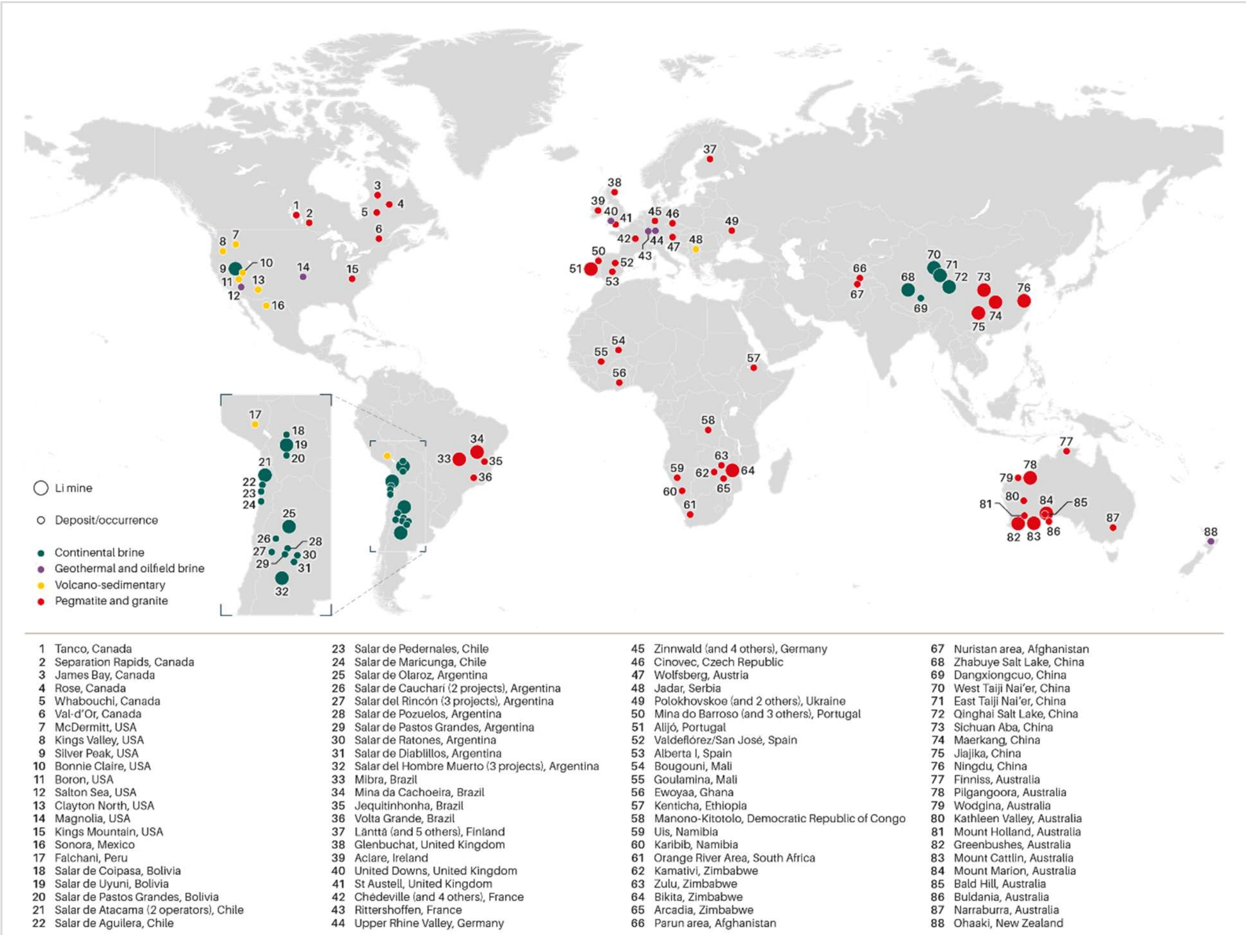

Figure 11. Global lithium mines, deposits and occurrences. Source: Shaw (2021)[61].

4.2.4 **The lithium supply chain**

Due to the significant rise in demand for lithium for use in batteries there has been considerable interest in all aspects of the supply chain in order to secure future sustainable supplies. Global mineral supply is currently dominated by South America, Australia and China, while processing and battery manufacturing is well-established and concentrated in China, accounting for 80% of global refining capacity, 77% of global cell manufacturing capacity and 60% of global battery component manufacturing capacity[65]. This geographic concentration of key steps in the supply chain makes it difficult for new players to enter the market and raises potential supply security risks. There are six main stages in the lithium supply for batteries (Figure 12):

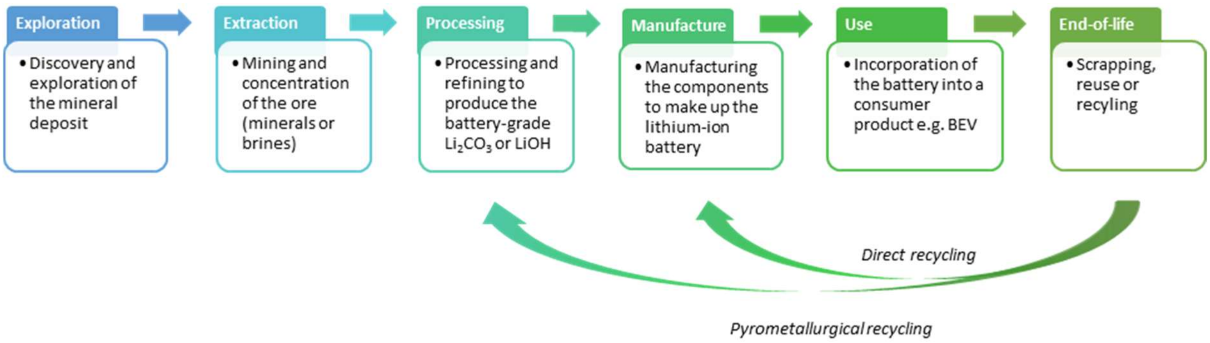

Figure 12. The lithium supply chain. Adapted from Goodenough et al. (2021) [66] and Zhou et al. (2020)[67].

4.2.5 UK occurrences

In the UK lithium primarily occurs as a minor element in the mica found in granite and granite pegmatites, especially in south-west England. During the 19th century a small amount of lithium-bearing mica was extracted from the Trelavour Downs pegmatite in the St Austell Granite[68], which was the only known site of lithium extraction in the UK until very recently.

Since 2017 two exploration companies, Cornish Lithium and British Lithium, have been exploring for lithium in England. Cornish Lithium is focussed mainly on lithium extraction from geothermal brines[69], while British Lithium is investigating lithium-bearing mica in the St Austell area[70]. In January 2022, British Lithium produced lithium from mica at pilot scale for the first time at its new pilot plant in Cornwall[71]. The pilot plant incorporates the entire processing cycle, from quarrying through to the production of battery-grade lithium carbonate.

All of the major granite bodies in south-west England contain lithium-bearing micas, although the amount of lithium contained in the micas is highly variable. There are three granite bodies in south-west England that are known to contain appreciable amounts of the Li-rich minerals zinnwaldite and lepidolite, namely the Tregonning-Godolphin and St Austell Granites, and the Meldon Aplite[68].

There are also two lithium-bearing deposits in north-east Scotland. In Glenbuchat, an occurrence of elbaite-bearing (lithium tourmaline) boulders led to the suggestion of an LCT (lithium-caesium-tantalum) pegmatite at depth[72], though this has never been explored. Approximately 30 km south-west of Glenbuchat is the Glen Gairn Granite in which lithium-bearing mica is also known to occur[73].

4.2.6 UK use and trade

The UK's commitment to a net zero economy by 2050 has been a catalyst for the transition to EVs. In November 2021, it was announced that the sale of new petrol and diesel cars would be phased out by 2030 and that all new cars and vans would be zero emission by 2035. This is expected to lead to significant demand for Li-ion batteries for EVs in the UK.

According to UN Comtrade data the UK recorded net imports of 1173 tonnes of lithium (combined carbonate, oxide and hydroxide form) in 2019[74] (Figure 13). The majority of imports were from two main countries, Belgium (39%) and Germany (34%). This is considered to reflect the location of major seaports in Europe rather than the original source of the lithium. Chile and China contributed smaller volumes, 8% and 7% respectively, to UK imports of lithium. Unfortunately, with the published trade data for lithium grouping oxides and hydroxides together, it is difficult to evaluate how the different forms of lithium are actually used in the UK.

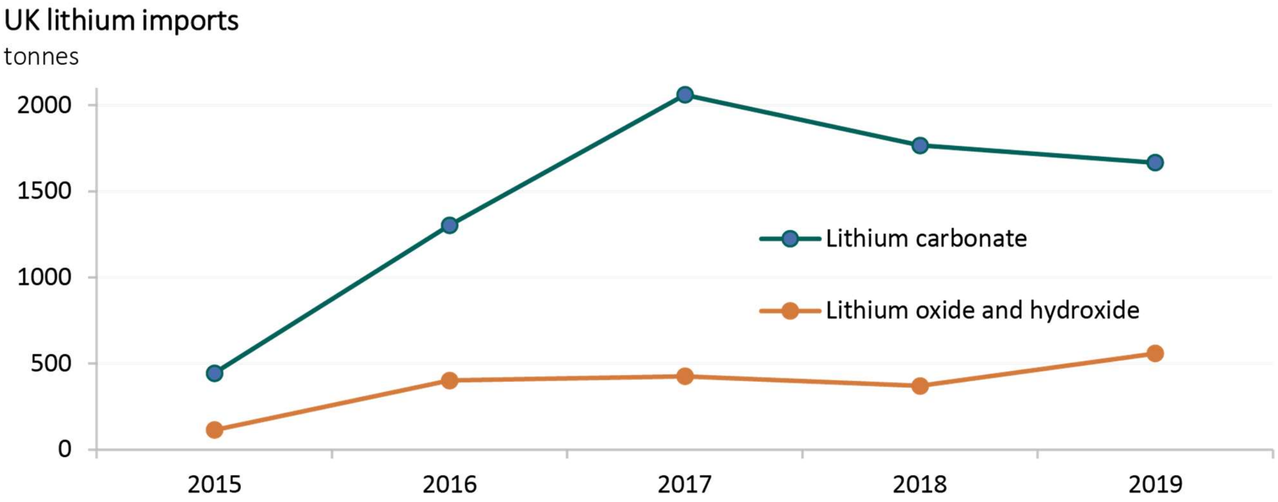

Figure 13. UK lithium imports. Source: DESA/UNSD UN Comtrade [74] database.

With no established domestic supply of lithium, the UK is dependent on imported material, which has a high carbon footprint. There are seven key challenges that require resolution to ensure the development of a Li-ion battery ecosystem in the UK[75]:

1. Understanding supply chain timescales
2. Sustainable and secure supply
3. Scaling up Li-ion battery production
4. Fostering global interactions
5. Alignment in pace of change in technology and regulations
6. Developing a multi-disciplinary response to challenges
7. Moving towards a circular economy

To address these issues, the UK is working to establish an internationally competitive supply chain for EVs[76], which includes support for sustainable lithium extraction in south-west England, as well as recycling opportunities for secondary supply. Government support also extends downstream, through investment in battery production and technology. Battery manufacturer, Britishvolt, has recently received an in-principle offer of government funding through the Automotive Transformation Fund for its planned gigafactory in Blyth, Northumberland. The project is set to create several thousand new jobs and produce enough batteries for over 300,000 electric vehicles each year[77]. The recent funding announcement is considered a major step in creating a commercialised battery ecosystem in the UK, and follows earlier boosts to the sector, including the announcement by Ford investing in its Merseyside transmission plant to make EV components[78] and the expansion of Nissan's facility in Sunderland working with Envision AESC to create a gigafactory[79].

4.2.7 The implications of rapidly expanding supply: a focus on Salar de Atacama, Chile

The expansion of lithium mining over the past 20 years, with large scale extraction in new deposit types and previously unexplored regions with limited historical data, has highlighted several environmental, social and governance (ESG) challenges that need to be addressed to ensure the role of lithium in the transition to a low carbon economy is sustainable. For producers operating in the Salar de Atacama, which currently accounts for approximately one third of global lithium supply[58], the rapid expansion of the industry and lack of knowledge around the natural systems involved has caused several significant issues:

1. **Water scarcity:** Salar de Atacama is situated in one of the driest regions in the world, the Atacama Desert (hyper-arid). It is a basin of internal drainage, with the incoming surface and groundwaters leaving the basin via evaporation. The groundwater system that underlies the salar is extremely complex, featuring high salinity brines in contact with fresh water as well as a spatial distribution of lithium concentration within the brines. Brines

are pumped and the lithium concentrated via a number of evaporation ponds. There is a complex relationship between the brine and surrounding fresh water which is used for potable water supply as well as supplying lagunas (surface water ponds) that support flamingos. A further complication is that the inflow that supports the natural evaporation may have been recharged in climatically wetter periods, many hundreds of years before present day.

2. **Biodiversity loss:** the flagship species within the region are flamingos, which rely on the surface water ponds or lagunas for their food and breeding grounds. The factors that control the occurrence of these ponds are not well understood and they are influenced by climatic variation and potentially may change in response to brine abstraction. There is a perception of habitat loss due to human activities in the region. However, climate change may already be increasing temperatures and could change the already low rainfall in the area. These have the potential to negatively impact the lagunas and hence the flamingos. Disentangling the various impacts on the lagunas and hence the flamingos, by direct human changes or global climate change and historically wetter periods is problematic.
3. **Social licence to operate:** the Salar de Atacama is the ancestral territory and home of the indigenous Lickanantay people, who consider the water and brine of the region as sacred. As a result, lithium mining in the region has led to cycles of conflict, social activism and negation for many years, demonstrating the delicate balance between mineral governance and social participation[80,81]. During the 1970s the government designated lithium as a 'strategic resource' owing to its use in nuclear power generation systems, which gave indigenous peoples very little control over how the resources in their community are managed. The regulatory framework in Chile has improved in recent years and there has been some progress with regards to positive community relations, such as Albemarle's agreement with the Council of Atacameñan Peoples (CPA)[82]. However, there is still scope for improvement, particularly for capacity building and technical knowledge in local communities.

4.2.8 Conclusions

Ongoing expansion of the EV market and associated demand for Li-ion batteries is expected to drive significant growth in global lithium supply. Current production levels are sufficient to meet demand for the next few years, and current estimates of global resources are able to meet projected requirements over the longer term (providing they move into production), with several expansions and projects in the pipeline. However, lithium resources remain poorly understood, particularly those in brine deposits: the processes of salar formation are relatively unknown; the extraction chemistry is complex; and existing reporting standards, which are tailored towards assessment of solid mineral deposits, are not fit for purpose.

The application of UNFC to salar deposits may provide a better way of representing brine deposits and for comparing different deposit types. However, specific guidelines and frameworks will need to be developed to accommodate for the particularities of brine deposits. There is an important data gap to be filled prior to developing UNFC standards for brines, not least UNFC standards that are applicable to all Li deposits.

There are also numerous case-specific ESG issues that need to be addressed before the industry can unlock the investment required for significant expansion of lithium production, particularly in new areas, although it is important that they are approached in a holistic way, rather than referring to them as a component of individual projects. In addition, the market cannot rely on major contributions from battery recycling as the size of the secondary resource in end-of-life products is small and the global capacity for recovering lithium from batteries is currently restricted to a few locations. The UNRMS has potential application to both these issues: by developing an internationally-accepted streamlined framework for capturing and comparing ESG issues; and by providing a better understanding of the entire supply chain (via the use of tools such as material flow analysis) to quantify materials available in waste streams.

There is development potential for lithium in the UK and exploration activity in south-west England has increased in recent years. However, these projects are still in their early stages and are a long way from becoming commercial sources of supply. The UK also has little downstream capacity in other key stages of the lithium supply chain, notably mineral processing and refining.

Ultimately, supply of lithium is not a question of resources or availability, but rather whether the combined effects of improved ESG performance, clear policy frameworks and international collaboration can facilitate sustainable investment to drive the expansion required to meet a rapid growth in demand.

4.3 THE UNFC CLASSIFICATION OF COBALT-BEARING DEPOSITS IN EUROPE

4.3.1 Background on cobalt

Cobalt has many industrial uses on account of its high strength at elevated temperatures, its wear and corrosion-resistance and its magnetic properties. Until recently it was mainly used in a wide range of alloys with diverse applications from superalloys in jet turbines to cobalt-chrome alloys in dental and medical devices. However, its main use at present is in cathodes for rechargeable lithium-ion batteries, used in electric vehicles (EVs) and portable consumer devices. This accounts for about 57% of global demand, with alloys now amounting to 13%[83]. The third largest use (8%) is in hard metals which are used in cutting, grinding and boring tools for the automotive, aerospace, energy, mining and construction industries. Other important uses include pigments, catalysts and magnets.

Figure 14 Nickel-copper-cobalt ore and its end-products nickel (blue) and cobalt sulfates (orange) produced at the Sotkamo mine in Finland operated by Terrafame. The mine produces these chemicals used for battery technologies on-site. The Sotkamo mine has the largest cobalt resources and reserves in Europe, that are currently in production (© Terrafame Ltd. 2020[84]).

Global mine production of cobalt is approximately 139 000 tonnes (average 2015-2019), while refined metal production averaged 117 000 tonnes over the same period[52]. Since then global demand for cobalt has escalated, with refined metal production increasing from 80 000 tonnes in 2010 to 135 000 tonnes in 2019[52]. At the same time,

mine production is dominated by the Democratic Republic of Congo (DRC) which accounts for 61% of the global total. Production of refined metal is dominated by China (56% of world total) with Finland, the second largest producer, accounting for 11% [52]. Almost all cobalt is recovered as a by-product of the extraction of either copper (c. 60%) or nickel (c. 38%), hence its availability is closely linked to the supply of these metals[85] (e.g. the main product at the Sotkamo mine in Finland is nickel; Figure 14). About 2% of global production is from mines that produce cobalt as the main product[86]. Cobalt has been classified as a critical metal by the EU since publication of its first criticality assessment[87]. Mine and refinery production have remained highly geographically concentrated, thus contributing to concerns about the vulnerability of European industry to supply disruption. In particular, a significant amount of cobalt production in the DRC is derived from unregulated and illegal mining operations, which may be associated with unsafe working practices and the use of child labour. The growing requirement for sustainable and responsibly sourced cobalt has, therefore, provided new impetus to ensure that the supply chains are ethical and transparent and to diversify the supply base by finding additional resources in other countries and by increasing recycling. The end-of-life recycling input rate for cobalt is currently estimated to be 22%, mostly from alloys in new and old scrap[86,88]. The processing and refining of copper and nickel ores are not generally optimised for cobalt recovery, so there is also significant potential to extract cobalt from mine tailings and slags from past operations[86].

Given the rapid transition to low carbon transport, cobalt demand is likely to continue to grow rapidly. Furthermore, the EU and UK both aspire to become major suppliers of EVs and EV batteries to the international marketplace. Consequently, there is considerable interest in building responsible and resilient global cobalt supply chains.

4.3.2 Aim of the study

The United Nations Framework classification (UNFC) is a resource classification system to harmonise different resource data and can be used to aggregate resources based on their classification (see section 2.3.2 for a detailed description of the methodology). In 2021 a study led by BGS used the UNFC system to harmonise and combine all available data on cobalt resources in Europe[89]. On the basis of this compilation of known resources, combined with detailed knowledge of the geology of Europe, the potential for the discovery of additional cobalt resources was evaluated. This work is summarised here to highlight the potential benefits and challenges in using the UNFC system for CRMs like cobalt as well as the benefits of improved understanding of mineral resources on a continental scale.

4.3.3 Data collection and methods

This study was undertaken by BGS in collaboration with the geological survey organisations of Finland (GTK), Norway (NGU) and Sweden (SGU) and LARCO, a mining and metallurgical company based in Greece. Information on cobalt-rich deposits was acquired from diverse sources including: published research; company websites and reports; and databases hosted by geological surveys and research institutions. This permitted construction of a cobalt resource database for 25 European countries including information on the current operational status of individual deposits, previous activities (such as past exploration, mining or metallurgical processing), resource estimates and the geological classification of the deposit type.

A total of 509 cobalt-bearing deposits and occurrences was identified, although cobalt resource data were available for only 151 deposits in 12 countries. No cobalt resources were reported using the UNFC classification. Instead resource estimates utilised a variety of reporting codes, some CRIRSCO compliant and others not. In order to convert these to UNFC, decision-flow tools developed by Bide, et al. [18] were used to guide the initial allocation of each deposits to a particular UNFC category. Where CRIRSCO-compliant resource data was available, conversion to UNFC was carried out in accordance with the 'bridging' procedures described in UNECE [21] (111 and 112 for reserves; 221, 222, and 223 for resources). Compliant resources that were reported in the past, but were subsequently abandoned and never updated, were downgraded in this study to E and F categories 3 because they do not relate to current circumstances (331, 332 and 333). For many other deposits the reporting code was either not specified or was not CRIRSCO-compliant. In these cases, class 334 was used for current exploration projects for cobalt and class 344 for any other resource estimate with known cobalt grades.

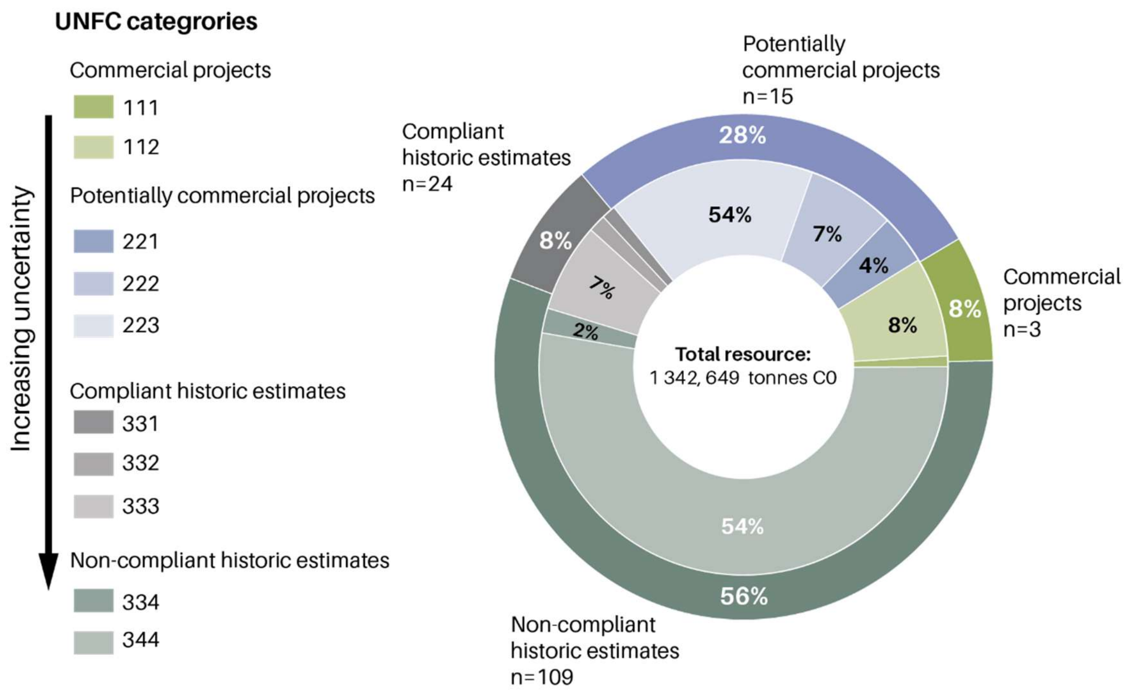

Figure 15 Cobalt resources in Europe classified using the UNFC classification system (n = number of deposits). Segments with no label have a share of one percent or less (Source Horn et al. (2021) [89], CC BY 4.0).

In some deposits published compliant resources relate only to the potential main products, generally copper or nickel, and no cobalt grades in the ore were reported because it was not considered for future extraction. In these cases the cobalt tonnage in the ore was estimated in this study by using non-compliant data (e.g. historic resource estimates, governmental or academic research). The UNFC classification of the cobalt resource is, therefore, allocated to a lower G-class than the main product on which the compliant resource is based. The E and F categories for the cobalt resource were also lowered because cobalt extraction had not been considered when environmental-socio-economic and technical feasibility were assessed for extraction of the main products.

4.3.4 Results

Following classification of all the individual cobalt resources into the UNFC system, the total resource in each class was calculated. The overall total of 1,342 649 tonnes of contained cobalt includes only 8% (114 638 tonnes) in currently commercial projects (classes 111 and 112) (Figure 15). These are found in just three deposits, where cobalt is currently produced. The largest proportion is in the Sotkamo mine in Finland[90] (99 788 tonnes) (Figure 14). Cobalt resources that are potentially commercial represent 28% of the total resources in the UNFC classes 221, 222 and 223 (370 409 tonnes contained cobalt). Most of these quantities are either reported in current exploration projects or belong to operating mines and would need further evaluation before they can be deemed viable for cobalt production. Another eight percent (111 107 tonnes contained cobalt) lie in UNFC classes 331, 332 and 333 with the majority in class 333. Most identified cobalt resource estimates are classified in non-compliant historic resource estimates related to 109 different deposits (746 495 tonnes). Of these historic estimates, a small fraction (29 674 tonnes contained cobalt) is located in areas of current exploration, while the majority (716 821 tonnes) are additional quantities found in areas where there is no current exploration for cobalt.

While the total cobalt resource (>1.3 million tonnes Co metal) is very large it is important to stress that only a small proportion is currently commercial to extract, as demonstrated by UNFC classification. More than half of the total is found in non-compliant historic estimates associated with high levels of uncertainty on all three UNFC axes (E, F and G). A considerable amount of work is required to move projects into the potentially commercial and commercial categories. Furthermore, the resources that may be extracted in the future will still not be fully available to the market as material losses during processing, refining and manufacturing are inevitable, especially for by-products. It is therefore also important to consider material flows and stocks along the whole supply chain when using such resource data to predict future supply. This can for example help to identify inefficiencies in material recovery and potential resources in secondary materials such as mine tailings.

4.3.5 Recommendations for better understanding of cobalt resources through UNFC application

The study of cobalt resources in European deposits showed that the UNFC system can be a powerful tool for accommodating various types of data with differing levels of confidence. It can be used not only to evaluate and classify a resource on a deposit scale, but also to aggregate and compare resources on national, regional and global scales. The versatility of the UNFC system is inevitably associated with a degree of subjectivity in the data interpretation, in particular when data uncertainty is high. The resource classification can also vary greatly between different types of mineral commodity. For by-products like cobalt, which commonly make only a small contribution to the revenues of a mining project, data is often sparse, outdated or is insufficiently detailed to provide a reliable resource estimate. This contrasts markedly with the main extractable commodity of the deposit, commonly copper or nickel, for which the availability of high-quality data allows reporting of compliant resources in terms of ore tonnage and metal grade. If data on potential by-products were routinely collected and reported by companies then more reliable resource estimates could be made and the options for future supply better assessed. This would inevitably mean extra work on the part of the mining company for a commodity that it is not currently considering for extraction. On the other hand, given the likelihood of sustained high levels of demand for cobalt, it is expected that industry will pay increasing attention to potential by-products in the future. Similar considerations apply to several other by-product critical raw materials such as indium, germanium, selenium and gallium.

When using the UNFC system it is important to review resource estimates that have been bridged from a CRIRSCO-compliant resource estimate. While this conversion is a straightforward process, the current development status of each deposit should be compared with the situation when the compliant resource estimate was published. For example, CRIRSCO-compliant resources that are several years old are unlikely to reflect the current economic, environmental and social situation of the project and should therefore have lower E and F classifications.

A case study on the cobalt resources of Finland, conducted in the EU-funded Mineral Intelligence for Europe (MINTELL4EU) project by the Geological Survey of Finland[20,91], took a similar approach to the application of UNFC, although some resources were classified differently and others were added:

1. They included UNFC classes 342 and 343 in certain cases where there is a

compliant resource estimate with cobalt grades, but where there is no information on cobalt extraction (F4) and cobalt was not included in the permitting licence (E3). These classes do not appear in the BGS-led study, but contribute additional useful information to the resource data.

2. They added undiscovered resources, categorised as 344. This was based on GTK's geological assessments which calculated the probability of identifying certain resource quantities in deposits of specific types in geologically favourable areas[14,15]. Such undiscovered resources do not refer to a specific deposit and are not, therefore, comparable with resources allocated to class 344 in the BGS study, which comprised non-compliant resources aggregated from individual deposits.

Comparing these UNFC case studies on cobalt demonstrates that application of the system can be undertaken in different ways and that more guidance is needed to ensure a consistent approach such that substantially different resources are not aggregated in the same class. As the UNFC system has potential global application to identify supply risks and to prioritise areas for future exploration, it is important to ensure that data is interpreted in the same way in all countries ensuring a reliable classification of resources using the UNFC system.

It is important to stress that reported cobalt resources represent only what has been found to date and do not equate to all the cobalt present in the Earth's crust[10]. Known resources are a small part of the total resource base, which is estimated to include a large quantity of 'undiscovered' resources on the basis of what we can expect to find around known deposits and in geological settings elsewhere which are considered favourable for the occurrence of cobalt-bearing deposits. Our knowledge base of cobalt, like many other critical raw materials, is limited because until recently we have not needed it in large quantities. However, the growth in future demand will stimulate high levels of exploration for cobalt and underpinning research, thus enabling us to determine where and how to find additional resources.

4.3.6 How can we ensure secure and sustainable supplies of cobalt in the future?

The study by Horn et al. (2021)[89] has demonstrated that undertaking a detailed review of all aspects of known cobalt deposits in Europe in conjunction with a wide variety of experts from different organisations and harmonising that data using UNFC can provide a good idea of the location, nature and status of these deposits. Despite the issues related to data availability and quality, this can allow a harmonised estimation of cobalt resources using UNFC. A similar approach could be applied elsewhere in the world, providing valuable information on the quantity, distribution and nature of resources and thus the potential future availability of cobalt on a global scale.

The majority of known cobalt resources in Europe are in historic projects that have high levels of uncertainty in their E, F and G categories and cannot currently be classified as either commercial or potentially commercial. A considerable effort is required to 'upgrade' these and effectively shift them into those UNFC classes that indicate a greater likelihood of extraction. This will require detailed assessment of the numerous factors that contribute to the ranking on each of the three axes in the UNFC system. The additional detail of the UNFC system compared to other resource classification systems can help to identify and tackle the factors that may hinder project development, whether these are environmental, social or governance factors, issues with technical or economic feasibility, or simply a lack of data.

The degree of confidence in the reported UNFC estimate of G relates essentially to the level of geological understanding of a deposit. In order to increase this confidence a considerable amount of data is required on the abundance, mineralogy and distribution of cobalt within a particular deposit. This may require a considerable amount of additional exploration, both at and below the ground surface, as well as intensive laboratory investigations. In this way a three-dimensional model of the orebody can be developed which will serve as a basis for mine planning, for the beneficiation and processing of the ore and for handling the waste streams at all stages.

In the European study[89] the technical feasibility (F) of cobalt extraction was not assessed in most cases because cobalt was not considered as a potential product in these deposits. This aspect will, therefore, require an in-depth study to ensure it is technically, economically and environmentally feasible to extract cobalt from the ore in a suitable form for subsequent processing. As cobalt is a by-product of nickel or copper production in most deposits, the metallurgical processing is set up to optimise recovery of the main product metals. The amount of cobalt recoverable from that deposit may be much less than is indicated by the resource estimates. Where the abundance and distribution of cobalt in the ore are similar to other well-known deposits in a particular area and where appropriate beneficiation and metallurgical processing capacity is already in place then upgrading the F category might be relatively straightforward. However, extensive detailed testing is essential to ensure efficient cobalt recovery is feasible because no two ore deposits are the same and small differences in physical and chemical composition can have major implications for technical performance and recovery of cobalt.

Those deposits in Europe which have historic and outdated estimates of cobalt resources will need reassessment to ensure they meet current environmental, social and governance requirements that would allow them to be classified as commercial or potentially commercial projects according to UNFC. Some projects may be regarded as 'non-starters' from an early stage in their exploration on account of serious barriers to development. For example, this may be because of potential negative impacts on the local environment, proximity to settlement or to areas of designated landscape or cultural significance. In other cases extensive detailed investigations will be necessary to justify their reclassification to commercial or potentially commercial projects. This might entail a great variety of activities, outside the scope of the UNFC itself but relevant to the aims of the UNRMS. Apart from technical assessment of numerous environmental parameters, extensive dialogue with all stakeholder groups, from local communities to national governments, will be essential to ensure negative impacts are minimised and benefits are shared equably, both during operations and following closure. Given the broad scope of these considerations and the time and expense incurred, some form of project evaluation based on ESG requirements would seem to be helpful in order to identify those potentially most appropriate for development and to identify the main challenges in cobalt supply. Such a study is currently in preparation by the BGS.

4.4 UK MINERAL EXPLORATION DATA: AN EXAMPLE FROM NORTHERN IRELAND

Data from mineral exploration activity is of considerable value to a nation as it can give significant insight into the mineral endowment of a particular area or geological terrane. Such information assists strategic planning in terms of understanding the capacity for indigenous mineral production and also encourages further exploration investment. The legal issues concerning mineral exploration in the UK are very complex due to the combination of a very long history of mineral exploitation, private minerals ownership and a local planning system which is devolved to the regions. An explanation of the various systems in place in different parts of the UK can be found in Colman et al. (2000)[92]. In Great Britain most minerals, apart from precious metals and oil and gas, are owned privately. There are no centralised systems for managing or recording exploration activity and data in Great Britain. This results in valuable data collected by the minerals industry being effectively lost. The absence of records of past exploration activity is often stated by the industry to be a barrier to new investment.

Most countries and jurisdictions that host an active exploration and mining industry operate a centralised approach to licensing. For example, Finland[93] and Norway[94] have requirements for exploration data to be collected by a central body and held for the benefit of the nation, both to further scientific research and to promote investment. Northern Ireland takes a significantly different approach compared to other parts of the UK. Here exploration activities are licensed by the local Department for the Economy with technical (geological) oversight provided by the Geological Survey of Northern Ireland. Examination of the procedures in place in Northern Ireland can provide useful insight into how such a system operates and the lessons that might be applied in other parts of the UK or elsewhere. CRMs are not specifically singled out in this discussion, although the issues for CRMs are essentially the same as for any other mineral.

4.4.1 Northern Ireland mineral exploration and development

Northern Ireland legislation governing the development of high value minerals (i.e. metals, industrial minerals and coal) dates from 1969. The Mineral Development Act (Northern Ireland)[95] vested ownership of all minerals in the local government department responsible for economic development, currently the Department for the Economy (DfE). Under this legislation DfE has the power to grant licences to anyone wishing to explore for minerals in Northern Ireland.

There are a number of exceptions to the vesting, the most notable being that precious metals (gold and silver) remain the property of the Crown and fall outside the local legislative remit. Development of construction materials (hard rock aggregates and sand and gravel), which might be referred to as minerals under planning legislation, is managed at a local council level.

4.4.2 Licensing

Mineral Prospecting Licences (MPL) may be awarded for a six-year term for a single area up to a maximum of 250 km^2 on a first-come first-served basis. Multiple licences may be held by a single company or group of companies. Under the terms of the legislation a licence application must be made in the form prescribed in Schedule 1 to the Mineral Development (Applications, Fees and Model Clauses) Regulations (Northern Ireland) 1970 and accompanied by the application fee, currently set at £450. In addition to the completed form, an application should also contain:

- Two ordnance survey maps showing the area applied for, usually at a scale of 1:50 000;
- Audited accounts and any additional information to enable a Financial Viability Assessment to be conducted, (including audited accounts for any parent company, if applicable);
- Any additional supporting information which the Department requests (for example, interim balance sheets, corporate structure, etc.).

As well as the financial evidence requirements applicants must also provide evidence of their technical capability to carry out exploration activities proposed for the licence and an understanding of the mineral potential of the application area. This understanding should be demonstrated in an initial two-year work programme which must be submitted as part of the application.

As part of the environmental, social and governance (ESG) responsibilities of DfE, and in addition to the safeguards inherent in the application itself, further assessment of applications is carried out by the Geological Survey of Northern Ireland (GSNI). Financial viability of the applicant (or parent company), geological relevance of the proposal and potential environmental impact on environmentally designated sites are considered at the time of application. A public consultation process considers representations from local government departments, district councils and members of the public.

4.4.3 Governance

The geological rationale for the application must be evident in the application form. Specifically, this means that there must be a reasonable and considered basis for making the application and targeting the minerals identified. Similarly, the geological model that is being used as a starting point for exploration should be indicated. The proposed model should fit with and be supported by the geological history of Northern Ireland. These questions are considered by technical staff in GSNI who have experience in the local geology, historic data and academic study archives and exploration practices in the region. It is expected that industry best-practice techniques will be employed in addition to adherence of any additional local legislation requirements (e.g. legislation for drilling and trenching and environmental restrictions resulting from site designations). Each application is assessed on its own merits on a case-by-case basis. This is also the situation where the licence has run its 6-year term and the incumbent company wishes to continue evaluation of the area. In this case, current policy is for the licence holder to apply for the same area and, although there is no guarantee of security of tenure, it is usual for a seamless transition to take place.

The proposed work programme submitted at the time of application must support the exploration process for the target minerals. Exploration covers desktop studies, any geochemical or geophysical prospecting method and includes trenching and drilling. The anticipated techniques that will be employed to carry out the exploration are outlined in documentation on the DfE website[96] along with guidance for the applicant[97]. At advanced project stages the MPL also permits the extraction of bulk samples which may be required for laboratory-scale processing as part of a pre- or full feasibility study. The work programme should demonstrate a systematic approach to target identification, ranking and investigation and additionally include indicative costings of the proposed activities. Annual reporting of the exploration results and findings of the work carried out is appraised by GSNI on behalf of DfE. The reported activity and licence expenditure are assessed against the agreed work programme and minimum spend commitment that are submitted at time of application. Lab assays, raw geophysical data and interpretation reports must be submitted to the GSNI for archive under the 1969 Mineral Development Act[95]. Currently there are no exploration projects licensed by DfE at a stage where a resource has been identified.

4.4.4 Environmental

As the licensing body for minerals in Northern Ireland, DfE is considered the competent authority under the terms of the EU Habitats Directive and, despite any changes to regulations following EU exit, DfE maintains the level of environmental protection that was required under EU law. Environmental screening of licence exploration activity remains as a matter of course. Possible impacts on Natura 2000 sites, Areas of Special Scientific Interest and Ramsar sites are all considered as part of the ESG process.

Some of the most prospective areas in Northern Ireland coincide with areas of relatively high density of protected sites. Fresh water pearl mussels (a UK priority species) are found in some rivers in the Sperrin Mountains, as are Atlantic Salmon which contribute to the pearl mussel breeding cycle. Both of these species can be impacted by sediment sampling carried out for exploration. Lowland raised bogs and blanket bogs can be disturbed by footfall during soil sampling and geophysical surveys. Large expanses of upland area in the east of Northern Ireland are protected as breeding sites for ground-nesting birds of prey. Any proposed activity within these areas, or close to the boundary, has to be screened for potential negative impact.

Licence-level screening is carried out at time of application in order to identify potential areas where exploration activity might require additional constraints or potential refusal of permission. Should the licence be awarded, GSNI operates in consultation with the Northern Ireland Environment Agency to assess work proposals. In order for this to be achieved, all activity specified in detail to be carried out under the terms of the licence must be notified to DfE prior to field deployment. Once the specific location for exploration and method of sample collection have been notified the activity is screened against any designated site that may be impacted. This is carried out on a case by case basis and dependant on the type of exploration activity and the reason for the environmental designation. Where a Natura 2000 network site is involved, the Conservation, Designations and Protection branch of the Department for Agriculture, Environment and Rural Affairs is consulted directly for input and guidance.

4.4.5 Social

If all application requirements are in order and the application is deemed valid DfE will consult with a range of statutory and regulatory organisations. The consultation will be publicised by placing a Public Notice in all relevant local and regional press and on the DfE website. Public access will be provided for people to view all the relevant documentation.

DfE will consider any issues or concerns raised and, where necessary, seek expert advice from other government and non-government bodies. Once the consultation period has ended and all the points have been identified and considered, the DfE will produce a consultation response document which will be sent to relevant people/organisations and placed on the Departmental website. DfE will then determine whether or not an MPL should be granted and what specific conditions may be required.

The profile of mineral exploration and development in Northern Ireland has been elevated in recent years following the submission of a planning application by Canadian company Dalradian Gold[98] for an underground narrow-vein gold mine at the Curraghinalt townland in the Sperrin Mountains. The mine location is situated in a rural community, within the boundary of an Area of Outstanding Natural Beauty. There is significant local opposition to the development including from the local government district council.[99]. Whereas mineral exploration licence application consultations may previously have received single digit representations prior to the planning application, in the years immediately following the application hundreds of comments were received in opposition to base metal prospecting licence applications. The opposition remains, albeit at a lower level, and is voiced regardless of the target mineral. Most of the objections are to the process of mineral development, frequently confusing and conflating exploration with mining operations. Mining is, in fact, a much later stage of project development and is subject to additional rigorous licensing procedures.

The Institute of Geologist of Ireland (IGI) has recently established a working group on minerals '*to provide factual, science-led information on mineral exploration and mining in Ireland* '. The working group has produced a series of factsheets as an educational resource, available for download at https://igi.ie/committees/minerals-information-working-group/[100].

Despite the opposition to mineral development from concerned groups, the industry perception of the licencing process has been positive. In the annual survey of mining companies, carried out by the Fraser Institute, a Canadian independent public policy think tank, Northern Ireland ranked in the top 10 in Europe in the Policy Perception Index for the three consecutive years[101]. Ranking has not been possible since 2018 due to the minimum number of respondents required not being present in Northern Ireland.

4.4.6 **Data**

Reporting on mineral exploration activity in Northern Ireland is required annually. The report archive of geological investigations carried out by licenced companies is held by the GSNI and forms a comprehensive record of activity spanning the 50 years that the current legislation has been in place. In excess of 200 prospecting licences have been held for a variety of metallic and industrial minerals over the 50-year period and interest in Northern Ireland as a focus of exploration still remains. Any company that wishes to apply for a licence may request information for areas of interest and historic reports can be released after a maximum confidentiality period of 10 years.

In addition to data collected by industry, a government-funded regional survey in support of economic mineral development in Northern Ireland collected data from the whole of the country between 2004 and 2007 (https://www.economy-ni.gov.uk/articles/introduction-tellus-project)[102]. Regional multielement geochemistry and high-resolution airborne geophysics are now available as modern supplements to the exploration archive. These datasets have been made freely accessible under the UK INSPIRE legislation. This state-funded mineral exploration programme significantly increased licence applications after its release and has greatly enhanced knowledge of the mineral endowment of Northern Ireland (Figure 16) The results of the Tellus programme have also been analysed with respect to the potential for CRMs in Northern Ireland by Lusty (2016)[103]. This study concluded that there may be potential for CRMs as by-products of major metal extraction in Northern Ireland, although significant further investment in exploration was required to understand the location and potential of deposits.

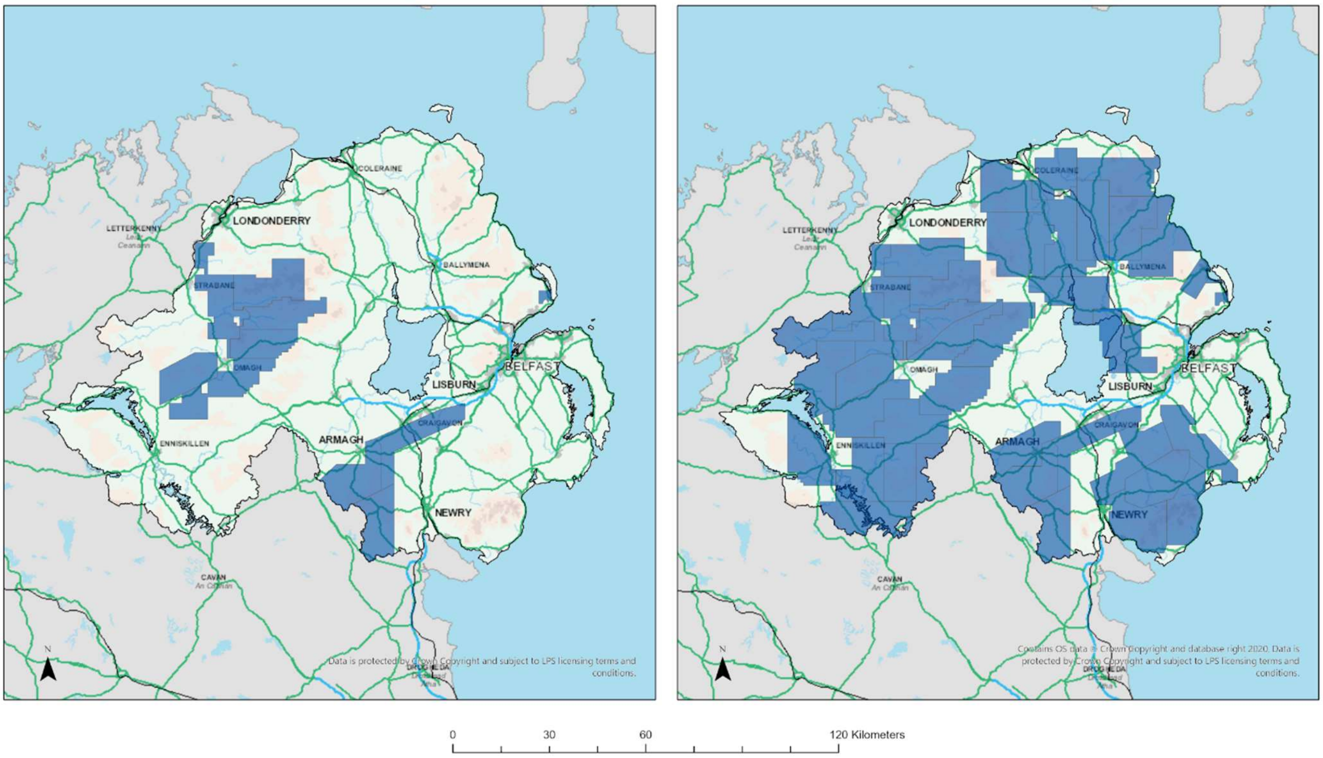

Figure 16. Northern Ireland mineral prospecting licences before the Tellus project (2006) (left) and maximum coverage following release of Tellus geochemical and geophysical data (2009) (right). *Contains Ordnance Survey data © Crown copyright and database right 22. Ordnance Survey Licence No. 100021290 EUL*

4.4.7 The future

The Tellus project not only stimulated industry investment but also created a wealth of data for academic research. Some of this work has been published in Young, (2016)[102] and the dataset continues to act as a resource for PhD and MSc studies in Ireland. Research into the licensing and legislation regime was carried out by the Geological Survey of Northern Ireland[104]. A review of international mineral legislation, targeting high-ranking Fraser Institute countries, resulted in a number of recommendations for improvements to the current Northern Ireland system.

As part of an update to the legislation it was proposed that:

- Mineral resources should be recognised as a national resource and

fall under a central management structure
- Royalty payments should be used to compensate the communities that bear the brunt of mineral development
- Local government should have an active role in environmental stewardship of economic metallic mineral development
- Management of minerals should be carried out sustainably, balancing the economic, social and environmental considerations
- The release of timely, accurate and contextual public information concerning natural resource development should form part of the remit of the single point, central management approach to ensure the effective management of natural resource development.

Following the submission of this thesis, the parent Department of the GSNI issued a call to tender[105] in 2020 for a study to consider the potential economic, social and environmental impacts of mineral development in Northern Ireland, with specific reference to the EU critical minerals list as published in 2017[106]. The results of the study will be used by DfE to inform how mineral development might be managed in the future to support the circular economy and the transition to net zero.

4.4.8 Conclusions

The unique governance model for Northern Ireland has resulted in significant divergence in terms of how mineral exploration and related data are managed compared to the rest of the UK. The centralised system provides a single repository of information relating the national mineral endowment. It also allows the minerals industry to access previous exploration results, thereby encouraging further investment and avoiding duplicated effort. Significant state investment in regional geological datasets through the Tellus project has also helped to stimulate industry activity. Since 2005 over £90 million has been invested in exploration by industry and a quarter of Northern Ireland is currently under licence for high value minerals, making it the most explored region in the UK for gold[107].

As well as improving and disseminating geological knowledge a centralised approach also helped highlight the main causes of concern and what actions exploration companies will need to take to ensure local community support for their activities.

4.5 APPLICATION OF BLOCKCHAIN FOR TRACEABILITY IN CRITICAL MINERAL SUPPLY CHAINS

4.5.1 Introduction

End-users of metals and minerals are coming under increasing pressure to prove that the materials they use are responsibly soured and sustainably produced. Certain critical raw materials have been subject to particular scrutiny in recent years as rapid growth in demand raised concerns over the security of supply. Cobalt and lithium, both key components of the lithium-ion batteries used in electric vehicles (EVs) and consumer electronics, are two raw materials that have attracted significant media attention owing to the growing social and environmental impacts in the countries where they are mined, including biodiversity loss, water scarcity and child labour[108].

According to the UN, traceability is defined as 'the ability to identify and trace the history, distribution, location and application of products, part and materials to ensure the reliability of their sustainability claims[109]. In a minerals context, greater supply chain traceability will help companies contribute to sustainable development goals and responsible sourcing, particularly from conflict-affected or high-risk areas, while also creating enabling conditions for trust and constructive engagement throughout the supply chain.

Responsible sourcing issues present significant reputational, legal, compliance and commercial concerns for companies spanning the entire battery supply chain[110]. In addition to mounting legislative pressure, the media, NGOs and international organisations are also raising the public's awareness, which, in turn, is driving the need for greater supply chain transparency. In addition, traceability is now a requirement in both national and international policy landscapes: for example, the EU 'conflict minerals' legislation[5], enacted in 2017 the US-specific Dodd-Frank Wall Street Reform and Consumer Protection Act (2002)[6]; and the EU Batteries Regulation[111], along with specific requirements in the UK Environment Act[8].

However, there are various technical, political and economic barriers to supply chain traceability[112]:

- **Confidentiality** – many companies will want to hide information to gain competitive advantage, so there may be a reluctance to share certain information or identities, particularly with regards to supply.
- **Points of aggregation** – the minerals supply chain includes aggregation points where material from different sources, including potentially from artisanal and small-scale mining (ASM), are combined.
- **Points of transformation** – most minerals undergo several processing stages, such as crushing, separation and refining, during which time the product characteristics (size, weight, grade) change. This makes the physical tracking of minerals difficult.
- **A lack of technical capacity** – language, lack of skills, availability of suitable personnel and non-centralised record keeping can all be obstacles, particularly in smaller and fragmented supply chains.
- **A lack of standardised documentation** – chain of custody information varies between supply chains. Furthermore, many systems are still paper-based, which are susceptible to fraud or mistakes in data entry.
- **Access to information and/or education** – many organisations are not aware of the benefits of traceability or the technologies that exist to help them solve supply chain issues.

4.5.2 Blockchain as a tool for traceability

Blockchain was popularised in 2008 as the technology underlying the digital cryptocurrency Bitcoin. In recent years, however, it has emerged as a tool for resource governance[113] and mineral supply chain traceability[114]. Blockchain is a technology that allows real-world data to be validated and subsequently stored as an immutable 'block' on a collectively owned or private permission database. Every block is validated on previous blocks, and the resulting blockchain is therefore immutable.

In a mining and minerals context, blockchain provides a platform onto which supply chain transactions can be recorded from mine to smelter and beyond. Data including weight, quantity, grade, in addition to information on provenance and responsible production, can be uploaded to the system and validated at appropriate points along the supply chain. It is then linked to the physical material using bar codes, tags or other Internet of Things (IoT) applications. This information can then be shared with downstream buyers, consumers and other third parties. Blockchain has various features[112,115] that differentiate it from existing traceability tools, like traditional chain of custody systems:

- **Need for consensus** – blockchain requires that all participants come to consensus over the type of information recorded on the database, encouraging responsible production standards between all actors in the supply chain.
- **Immutable records** – once a transaction, or block, has been successfully added to the blockchain, it is time-stamped, validated and linked to the block before and after it, thus generating an immutable record.
- **Decentralised control** – the decentralised control in a blockchain network minimizes the risk of corruption and reduces points of weakness.
- **Accessible, encrypted information** – depending on the privacy level, defined datasets can be made accessible in real time to any third party, including downstream buyers, auditors, investors, etc. while remaining encrypted to protect confidential information
  - **Scalability** – a blockchain network can be scaled to include other producers and supply chains beyond those initially involved.

- **Cost reduction** – the potential reduction of audits, personnel and transaction costs associated with a traditional CoC system.

Several companies are already exploring the use of blockchain in the context of critical mineral supply chains. This case study uses the real-world experience of UK-based global technology company, Circulor, who offer proven solutions to tracing some of the world's most complex supply chains.

Circulor uses a combination of technologies – traditional databases, blockchain and business logic – to create a digital twin of materials and track the physical flow from its origin through the various industrial processes to provide an immutable record of provenance, activity and compliance (**Error! Reference source not found.**). A private, permission-based blockchain network is used so sensitive data can be uploaded onto the blockchain without upstream supply chain participants gaining visibility, as this is commercially sensitive data. In addition, rather than following the paperwork as a proxy, tagging and tracking the material itself provides far greater accuracy.

Circulor is currently working with EV company, Polestar, to ensure transparency and greenhouse gas (GHG) reductions throughout their supply chain. The ability to dynamically track and attribute carbon dioxide (CO_2) emissions throughout their supply chain is expected to help Polestar reach its goal of producing a climate-neutral car by 2030[116]. The initial focus of Circulor's work will track minerals and materials used in Polestar batteries and the related CO_2 emissions, with plans to expand to the rest of the car. The CO_2 tracking will establish the emissions that have been created during the manufacturing process, as well as those inherited from suppliers further upstream. Circulor's blockchain solution is already used at scale in the Polestar 2 EV for the traceability of cobalt used in its Li-ion batteries.

Circulor is also working with Li-ion battery producer, Britishvolt, to track its battery material supply chains, as well as the supply chains and GHG emissions associated with construction and maintenance of its gigafactory in Northumberland[117].

Circulor's approach to provenance tracking, coupled with GHG and ESG reporting, provides customers with the information to make decisions and ensure responsible and sustainable sourcing, while real-time transparency ensures local communities are protected, labour laws and safety protocols are adhered to and workers are fairly compensated.

Similar approaches have also been adopted by the Global Battery Alliance (GBA) in their battery passport initiative, where the concept of a 'digital twin' for products and components is seen as essential for ensuring traceability. Their version of this system is under development and due to launch at the end of 2022[118].

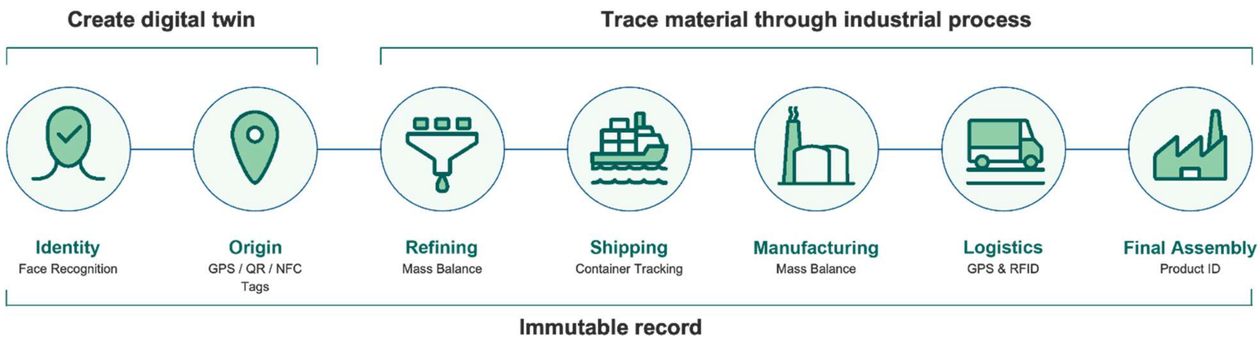

Figure 17. Circulor's system of supply chain traceability. © Circulor.

While the results of blockchain are promising, many of the existing challenges of traceability still prevail[112], particularly for artisanal and small-scale miners[119]. The issues are, however, now more nuanced:

- **Need for consensus** – reaching a consensus around types of data and responsible production standards is a requirement for blockchain to work, but amongst companies. with different risk exposure and supply chain positions this can be difficult.
- **Digitisation** – transforming paper-based, non-standardized CoC systems into a digital system like blockchain will be a lengthy and expensive undertaking.
- **Cost** – large amounts of required computing power and operational overheads are likely make blockchain unaffordable for many small companies, particularly in developing nations.
- **Technical challenges around data input** – if users are not trained and poor-quality information enters the blockchain system this will be replicated in the output, also known as 'garbage in, garbage out'.
- **Third party auditing** – blockchain does not replace on-site due diligence or third-party assurance of data and responsible production, so audits will still need to take place.
- **Risk** – blockchain is still a relatively new technology, and there is a risk that data issues and security vulnerabilities may still arise.

In addition to the challenges above, blockchain is often seen as going against mainstream business models by risking competitive advantage through increased transparency[120]. This has resulted in the growing prominence of private blockchains, which has now largely replaced the original aspirations of public blockchain technology, and claims of openness, democratisation and accessibility are much more nuanced[114].

The Responsible Minerals Initiative is one of the bodies who sought to address some of the challenges related to integrating different systems for measuring and tracking material flows and datasets in its *Blockchain Guidelines*[121] by promoting the following:

1. The adoption of shared definitions of terms and concepts related to mineral supply chains.
2. The development and adoptions of a unique identification system for mineral supply chain actors.
3. Consensus on fundamental data attributes for:
   a. The identification of supply chain actors.
   b. The provenance of minerals or metals transactions.
   c. The context on the origin and production of the minerals or metals.
4. The adoption of emerging technical standards on interoperability for blockchain and distributed ledger technology.

4.5.3 Future data requirements

As regulators and policy makers continue to strive towards a fully functioning circular economy, the data requirements for traceability in mineral supply chains are expected to become increasingly granular. It is likely to extend to the sourcing of all materials used in products (not just conflict minerals), in addition to second-life and recycling processes, and all the emissions created across the entire supply chain. While the collection and reporting of additional data will be the responsibility of suppliers and manufacturers, the derived benefits of open and transparent supply chain reporting will far outweigh this burden.

4.5.4 Conclusion

Ensuring traceability of supply chains is now a requirement of many international standards and included in legislation in some jurisdictions, whilst also mandated by investors and shareholders, and increasingly demanded by the public. The increasing complexity of this undertaking has seen new technologies and systems, such as blockchain, gain traction.

There are many potential benefits of using blockchain for greater transparency and traceability in mineral supply chains. Not only can it reward and incentivise responsible production to help alleviate growing public concerns, but it can also build trust between upstream and downstream partners and reduce transaction time and costs[112]. Traceability can also maximise the global energy transition to net-zero by supporting organisations to understand their carbon emissions and develop a fully functioning circular economy.

While existing tools such as Material Flow Analysis are useful for improving efficiency and sustainability, they do not provide a holistic and dynamic view across mineral supply chains in real time. Ensuring traceability should be an important part of any future resource management system such as UNRMS, alongside continued investment into emerging technologies and capacity building.

5 Issues and recommendations for improving supply of critical raw materials

The results of the authors' research and the consultation with industry experts have been used to identify some of the key challenges to maintaining sustainable CRM supply. This, in turn, has allowed a series of recommendations for the mitigation of these challenges to be developed. Those topics in which the UK has an established capacity and track record relevant to such mitigation are identified. Given the diversity of CRM applications and sourcing it is not possible to provide an exhaustive review of all issues related to the sustainable supply of all CRMs. However, emphasis is given to those aspects where the use of UNFC or UNRMS may be of particular benefit.

5.1 MINERAL RESOURCES

5.1.1 Resource characteristics

CRMs are valued for the specific properties they impart to a wide variety of specialised materials, components and products. The function and performance they provide depend fundamentally on the physical and chemical properties of the particular material in question, either when used alone or in combination with others. However, it is important to note that, whereas many metals have established processing routes that result in the production of pure metal suitable for almost any end-use, this is not the case for all CRMs, such as graphite, lithium and the rare earth elements (REE). For example, the physical mode of occurrence (grain size, shape, crystallinity, etc.) of graphite within a deposit is a significant factor in determining its preferred end-use (see graphite case study, section 4.1). Similarly, REE are seldom utilised as high-purity single elements. Instead, they are used in a variety of materials, comprising mixtures of REE, sometimes alloyed with other metals, for particular purposes. For example, the principal use of REE is in neodymium-iron-boron high-strength magnets which are essential to many green technologies such as wind power and electric vehicles. The main rare earths used in these magnets are neodymium and praseodymium, which are relatively abundant, light REE, together with dysprosium and terbium, which are scarce, heavy REE. It is, therefore, essential to understand both the abundance and distribution of individual REE within a deposit in order to determine its suitability as an economic source of REE and to identify a cost-effective route for processing and extraction. This is particularly important given that more than 200 REE minerals are known to occur in nature but most have low contents of the sought-after heavy REE. Similar issues apply to many other CRMs such as lithium. Although a deposit may contain a known amount of lithium, it is essential also to understand the mineralogy and mode of occurrence of lithium within the deposit in order to determine the optimum processing route for the ore that will yield a product of appropriate composition and purity for a specific end use (see lithium case study, section 4.2).

5.1.2 Lack of research and exploration

Many (but not all) CRMs occur in nature as minor constituents of the ores of major industrial metals such as aluminium, copper and nickel. Until recently demand for many of these CRMs was limited and little consideration was given to their recovery. Today, however, with rapidly growing demand from low carbon technology, there is considerable interest in identifying new, sustainable sources of these raw materials. It is, therefore, essential to understand the abundance and distribution of potential by-products, such as cobalt, tellurium, indium and gallium, within the ores of the host metal. Only with this detailed knowledge can CRM resources be properly evaluated and appropriate processing technology developed. Such knowledge is crucial to establishing the feasibility of a new project, in terms of both economic and environmental performance, and thus in raising investor confidence and gaining the support of governments and local communities.

Another challenge associated with maintaining adequate supply of CRMs is that in the past most were not studied in commercial or government programmes of research and exploration. Even now the majority of global exploration expenditure is focussed on gold, iron, aluminium and other base metals, such as copper, zinc and nickel, which benefit from long-established, diversified and stable markets. Consequently, the knowledge base for many CRMs is limited and detailed understanding of the processes responsible for their concentration in the Earth's crust is lacking. As a result, global expertise on where and how to find new CRM resources and to evaluate the economic prospects for extraction is in short supply. However, in the past decade, there has been a notable global increase in research aimed at identifying new CRM resources and extracting them in a safe and sustainable manner. While a considerable amount of research has been initiated in the EU, China, the USA, Australia and Canada (see for example the joint USA, Canada and Australia Critical Minerals Mapping initiative[122] or the EU's Raw materials information system[123]) the UK is also a leader in this field and has a strong, internationally-respected track record in the area. UK research expanded significantly in 2013 with a major five-year Natural Environment Research Council (NERC) led programme, SoS MinErals, which focussed on the genesis, metallogeny and novel extraction technologies of cobalt, tellurium, selenium, indium, gallium and REE, in land-based and sea-floor mineral resources. The programme funded 24 postdoctoral research associates and 17 PhD researchers and resulted in more than 100 publications[124]. SoS MinErals, together with many collaborations involving overseas government agencies and commercial companies, has led to a growing cohort of UK-based researchers in this field. This knowledge base has also been significantly augmented in recent years via European funded projects such as HiTech AlkCarb[125] and EURARE[126], which have developed new geological models to better understand REE deposits. Other ongoing UK-funded projects include LiFT[127] and Met4tech[128], which seek to better understand the formation of lithium deposits and the potential for circular economy in technology metals respectively.

BGS has also undertaken research into the formation of CRM deposits for well over a decade. This has included many MSc and PhD projects, both in the UK and overseas, leading to numerous publications in the peer-reviewed literature (for example, Goodenough et al. 2017[129], Walters et al. 2013[130], Shaw et al. 2016[131], Broom-Fendley et al. 2017[132], Shaw et al. 2022[133]). The BGS critical metals team continues to work with academia, industry and governments to advance the understanding of the Earth processes that produce deposits of critical raw materials in terrestrial and submarine environments[134], the latter being the focus of the Blue Mining[135] and MarineE-tech[136] projects, which have significantly expanded our understanding of deep sea CRM deposits. Several other universities and academic institutions in the UK also have long established expertise in the formation of CRM deposits. These include the universities of Exeter, Leicester, Southampton, Imperial College and the Natural History Museum.

It is important to stress that each deposit containing CRMs is unique and will require extraction and processing tailored to the characteristics of its ore. Researchers in this field are currently in the early stages of building a comprehensive knowledge base to underpin CRM exploration and extraction. It is likely to take several decades to produce reliable deposit models for some CRMs that will enable us to locate and extract new primary resources efficiently and sustainably.

5.1.3 CRM resource estimation

While the geological understanding of many CRMs is inadequate, there are also significant knowledge gaps concerning the amount and quality of CRM resources. Data to quantify CRM resources is commonly absent, either due to a lack of historical exploration or because the CRMs have not been considered by the extractive industry as potentially valuable by-products or co-products. Such data gaps are common where a number of commodities are present in a single deposit. In such cases, data is commonly only available for the main economic product, generally major industrial metals. Additional commodities, such as CRMs, may be present at grades below those that are currently economically workable or may be ignored because they are not considered necessary for the overall economic viability of the project.

5.1.4 Lack of harmonised resource standards

Another significant issue concerns the myriad of commonly-incompatible standards and reporting systems used for the presentation of mineral resource data in different jurisdictions. The application of UNFC can provide significant benefits in this respect because it is designed as a tool for harmonised resource reporting, thus enabling the aggregation of resource data from individual deposits and the compilation of national mineral inventories. This, in turn, facilitates a better understanding of the possibilities for new domestic supply and highlights the degree of international concentration of resources and production of a particular CRM. The cobalt case study (see section 4.3) illustrates the application and benefits of UNFC for a particular CRM.

Box 1 gives an example of how UNFC can enhance national-level understanding of minerals development and assist in delivering policy objectives.

A recent study by Bide et al. (2022)[18] presented a UK resource inventory using UNFC classes. It highlighted the existing data availability, the current status of the known resources and identified how the resources might be developed.

This analysis is particularly pertinent to CRM resources. For example, all current data on lithium in the UK are reported in the lowest classes of the UNFC ('E3', 'F3' and 'G3 or 'G4'). This suggests that any indigenous production would be many years away considering the typical length of exploration programmes and the planning and permitting requirements in the UK. Nevertheless, exploration for lithium in parts of the UK is ongoing[137,138] and this will move the position of some resources along the G axis as geological confidence improves. Additionally, research is underway into the technologies required to convert UK-sourced lithium into the lithium carbonate required for batteries[139] . If this research is successful, it will move some UK resources along the F axis in UNFC. However, neither of these actions in themselves will lead to the opening of a new mine. For this to happen there also needs to be movement along the UNFC's E axis with regards to the economic, social and environmental aspects. This demonstrates the usefulness of the UNFC system for identifying all areas that need attention in the development of potential mining projects.

Most of the data presented by Bide et al. have low confidence levels on all three UNFC axes. They should, therefore, be considered to represent stocks of geological material in the ground that may be available to work at some point in the future depending on economics, technical, environmental and social feasibility and further geological investigation. They do not represent stocks of material that are available for extraction in the short term. Nevertheless, consideration of low-confidence resource estimates of this type is important to demonstrate that in many cases geological availability is not the primary barrier to resource development.

In contrast, where confidence is high on all UNFC axes, for example 'E1', 'F1' and 'G1', the data represent reserves that are currently available for extraction. However, such data represent dynamic entities that may change in response to fluctuating economic or other circumstances, leading to a change in the project classification. The Drakelands tungsten-tin mine (now renamed Hemerdon) in Devon, which was in production between 2015 and 2018, provides a good example of such variation over time. As a result of inefficient mineral processing, low metal prices and a lack of financial liquidity, the E and F axis classification changed to lower classes overnight when the owner's bankruptcy was declared in 2018[140]. However, the stocks of material in the ground did not actually change and the classification will revert to UNFC 111 if the technical issues can be overcome and market conditions are favourable. This would allow the mine to be brought back into production. Consequently, any mineral resource data is only a 'snapshot' of circumstances prevailing at the time of reporting. It is, therefore, important to review mineral resource data regularly to ensure it reflects current circumstances.

Box 1. The application of UNFC to CRM resources in the UK.

Recommendations:

The UK is internationally respected for the strength and depth of its research into the formation of CRM deposits. This expertise should be further developed to address the lack of geological understanding of many CRM resources, both in the UK and overseas. Collaborative partnerships with researchers and governments in Africa and Latin America, which BGS already has in place, should be significantly expanded.

UNFC can be used as a tool to compare CRM resources, where data are available, to ensure consistency across different deposit types. This can also enable good practice to be disseminated and shared. Given UK experience in this field and the high level of interest in the application of UNFC in Europe, there is considerable potential for mutually beneficial collaboration with overseas geological survey organisations in implementing and developing the use of UNFC.

UNFC can be used as a tool to holistically capture data for all commodity types (including by-products, and those previously considered as waste) to ensure the full value of extraction is captured. UNFC should, therefore, be considered to be the most appropriate standard for national reporting. This will require industry to report data using UNFC and those responsible for regional/national-level, strategic planning for minerals to adopt UNFC. This can be achieved by regulation to mandate standards for resource data when collected by national agencies, as the EU has done, or by private companies, as done by the African Union using AMREC. Education of all stakeholders on the benefits of using UNFC would also promote its adoption as a global resource management tool. The establishment of an ICE-SRM could be a vehicle for long-term development of UNFC. This would involve training in UNFC application as well as the use of case studies that demonstrate its benefits.

5.2 EXPLORATION AND ECONOMIC DEVELOPMENT

5.2.1 Indigenous supply

Exploration is the first stage in determining the existence and economic potential of any mineral resource. Without mineral exploration resources will remain unidentified and there will be no reserves and, consequently, no mineral production. Therefore, the knowledge acquired through exploration has considerable long-term value, acting to promote further detailed assessment that might ultimately lead to the opening of a new mine. In Great Britain mineral exploration data for most commodities, apart from gold and silver which are owned by the Crown, is not captured systematically. Most of it remains in the hands of individual companies and is not available for the long-term benefit of the nation. In contrast, many countries with established mineral extraction industries and who are seeking further investment have robust, centralised systems where legacy data and physical materials can be readily accessed. In Europe, Finland and Norway provide examples of good practice in mineral exploration and development legislation[141,142], with easy access to data via an online database[94,143]. The case study for Northern Ireland (section 4.4) demonstrates the benefits of a centralised system for capturing exploration data.

In some overseas jurisdictions, notably where mining is already a major industry, such as in parts of Canada and Australia, governments are actively promoting commercial investment related to CRMs[144,145]. This involves the provision of regional scale geological surveys/ maps, preliminary exploration data and financial incentives to encourage companies to carry out more targeted exploration for CRM deposits. As a result, an increasing number of 'junior' companies are becoming involved in exploration for CRMs. Furthermore, the 'major' mining companies, whose business is traditionally focussed on iron ore, bauxite and base metals, have also begun to take a serious interest in CRMs. The Jadar lithium deposit in Serbia, where Rio Tinto had committed to spend more than US$ 2 billion exemplifies this trend[56].

The UK currently has no supply of CRMs from indigenous primary sources although there is some potential for development. For example, two companies are currently exploring for lithium in Cornwall[146,147]. In Devon, Tungsten West is planning to re-open the Hemerdon tungsten-tin mine which comprises a world-class resource of tungsten[148]. This deposit may assume considerable strategic importance if tungsten supply from Russia, traditionally an important supplier to Europe, is curtailed as a result of events in Ukraine. Russia is also a major global producer of nickel and palladium. The price of these metals has risen sharply in recent weeks and future supply to the global market is uncertain. This highlights the need to diversify primary supplies to alleviate risks to nickel and palladium supply. There is some resource potential in north-east Scotland[149] although it has not been systematically evaluated using modern technology.

5.2.2 **Overseas supply**

It is very likely that the UK will remain heavily reliant on imported supplies of most CRMs for the foreseeable future. The UK has an advantageous position with respect to overseas exploration and mining with many mining multinational companies based in London[150] and a dynamic 'junior' sector, funded in part by the London Stock Exchange's AIM market.

Strong and stable trading and diplomatic relationships with partner countries are essential to secure CRM supply chains. Such relationships can be established in many ways, including, for example, through programmes of long-term technical assistance or by capacity-building projects with foreign government institutions. For example, in the past 15 years, BGS has undertaken short-term capacity building projects in collaboration with national geological survey organisations, in many countries including Kenya, Ethiopia, Liberia, Nigeria, Sierra Leone, Ghana, Kyrgyzstan and Tajikistan. These projects establish contact with government officials at the highest level and build a long-lasting legacy of strong relationships with the local professional community. They may also allow BGS to undertake collaborative research with, and provide advice to, the private exploration sector operating in those countries. A similar approach has been taken by other countries. For example, the EU, in conjunction with 12 European geological surveys, carried out the PanAfGeo project[151] between 2016-2021. This provided geoscientific training to increase geological knowledge and skills within several African geological surveys. A second 5-year programme, PanAfGeo-2[152], has recently commenced.

In addition to short-term capacity building, the conduct of major regional geological surveys, including geochemistry and geophysics, provides invaluable baseline data and helps to build strong relationships with partner countries. Such surveys provide new information on mineral potential and stimulate exploration by the private sector. The Tellus regional geophysical and geochemical survey, conducted in Northern Ireland between 2004 and 2006, provides a good example of the benefits of this approach (see Northern Ireland case study). With funding from the UK and various international agencies, such as the World Bank, BGS has undertaken similar major regional surveys in several other countries, including Zambia, Bolivia, Indonesia, Nigeria and Morocco. Although some of these investigations are several decades old the results remain potentially useful to the minerals industry. In particular, they may provide valuable insight into the potential occurrence of CRM resources, which, at the time of the original work, were of no commercial interest.

Some countries with established mining industries and significant CRM resources are potential sources of supply to the UK (see graphite & lithium case studies, sections 4.1 & 4.2). Geological potential is also good in many other countries although few modern evaluations of CRMs have been undertaken especially for by-product metals which may have been ignored in the past. For example, potential sources of nickel and the platinum-group minerals, including palladium, are present in southern Africa, notably in South Africa, Zimbabwe and Botswana.

Recommendations:

UK exploration data for CRMs should be systematically captured and made publicly accessible. There is currently no vehicle for this in Great Britain, although the systems operated in Northern Ireland and elsewhere in Europe demonstrate the merits of such an approach. The availability of new exploration data, either from commercial activity or state-sponsored investment, would help to promote exploration for CRMs in the UK.

Due to the low volume of global CRM production and the concentration of production and processing overseas, steps need to be taken to ensure that the UK's CRM supply chains are robust, diversified and sustainable. The application of tools like UNFC and UNRMS can contribute to a thorough evaluation of all aspects of projects based on indigenous resources

Given the limited geological potential for CRMs in the UK, the UK should foster relationships with other countries that have established mining industries and good geological potential for the occurrence of CRMs. This should involve capacity building, training provision (especially in the facilitation of regional mineral exploration) and economic/geoscience research collaboration to build relationships with overseas governments in developing countries. In addition, the UK should ensure strong links are maintained and expanded in countries such as the USA, Canada, Australia and EU member states, that share the UK's aspirations for secure and sustainable CRM supply.

The UK government should work with UK-based mining and exploration companies to explore options for CRM supply from overseas. The UNFC and UNRMS can also help with evaluating overseas projects based on their performance in sustainable and responsible sourcing.

5.3 SECONDARY RESOURCES

5.3.1 Barriers to recycling

In the future there will be considerable scope for recovering CRMs from end-of-life consumer products to complement that derived from primary resources. However, given the relatively small volume of most CRMs used in most applications, there is a clear need for international collaboration in terms of facilitating industrial partnerships and facilitating the flow of waste materials over international boundaries to ensure adequate supplies of appropriate feed material to underpin investment in domestic processing technology.

Recovery of CRMs from end-of-life consumer products is expensive and technically complex. It is not, therefore, widely undertaken in the UK. Currently only the highest value metals are recycled at any significant level, e.g. the extraction of platinum group metals from autocatalysts by Johnson Matthey. This has been successful due to a combination of the specialist recycling technology developed over many years by Johnson Matthey, the high value of PGMs and the well-established procedures for the disposal of used vehicles. However, the UK has considerable expertise in developing technological solutions for CRM recovery from waste, for example research by the Faraday Institution and University of Birmingham into recovery of lithium from batteries[153] (the ReLiB project) or the Met4Tech projects work on recycling technologies for CRMs.

5.3.2 Secondary resources from mine waste

The recovery of CRMs from waste from historic mines has considerable potential to augment supply. There are many abandoned mines where CRMs were not previously recovered and CRMs ended up in waste streams such as tailings or slags. There are also many current operating mines that do not recover certain metals such as cobalt because the extraction technology is either absent or not optimised for by-product recovery.

Reprocessing of historic mine waste can be economically feasible under the right circumstances. For example, the Metalkol Roan Tailings reclamation operation in the DRC is producing cobalt and copper from mine tailings that accumulated since the 1950s from primary ore production in the area[86,154]. In the UK and Europe there are also many locations where the recovery of CRMs from mine waste might be feasible e.g. REE from bauxite processing in Greece and Turkey[155] and from kaolin waste in Cornwall[156].

5.3.3 Lack of data for waste materials

Holistic resource management systems as proposed by UNRMS and the use of specific tools such as material flow analysis can help to quantify CRM stocks and flows and identify in what waste materials (mine waste, scrap, etc.) they accumulate during their lifecycle. The UK is well regarded in this field, for example work by BGS to quantify the flow of lithium in global battery markets[157] or work undertaken by the NICER programme[128]. However, there are currently fundamental data gaps regarding the volumes and properties of CRMs contained in waste materials. For some waste streams there are no available data, while in other cases the data are aggregated to such an extent that it has little or no value. Until the flows and compositions of these materials are adequately quantified it is impossible to understand how they can contribute to supply. In addition regulation surrounding the disposal of waste products is commonly considered to be a major barrier for re-using material that has been categorised as 'waste'. In particular, the ‘waste law’ inherited from the European Union includes the definition of what constitutes waste and what can be done with it, how and where it can be transported, etc.[158].

Recommendations:

Further research is required into how waste data and data for recycled materials is categorised and quantified.

Detailed mapping of complete supply chains is required in order to understand what contribution recycling may make to CRM supply to the UK. This should build on existing UK expertise in this field and ongoing research being conducted.

Further research is required to improve waste characterisation and CRM recovery potential from disused mine sites both in the UK and abroad. Such data may stimulate the extractive industry to evaluate the potential for CRM recovery from such locations and also to develop new processing technology optimised for CRMs. International collaboration aimed at the recovery of CRMs from various waste streams at different locations should be encouraged.

Consideration of the regulatorily barriers in waste management law to that prevents the re-use of materials classified as waste and to ensure the re-use and recycling of CRMs from waste materials is prioritised.

There is a need for the development of improved recycling technologies for the recovery of CRMs from consumer products and from mining and processing waste. The collection and sorting of end-of-life products also require significant improvement if they are to make a significant contribution to CRM supply in the UK. Incentives and policy drivers for recycling of CRMs and financial benefits for reductions in the environmental footprint of materials are required (for example as initiated by the reporting requirements for traceability and recycled contents contained within the UK Environment Act and EU Batteries Directive). Requirements for manufactures to design products for re-use and recycling will likely play an important role here.

5.4 INCREASING THE SUSTAINABILITY OF SUPPLY

5.4.1 Harmonisation of sustainability standards and guidelines

Governments, investors and consumers are increasingly paying attention to how raw materials are produced and handled to ensure supply is responsible and sustainable. As a result, in many countries the extractive industry is changing its operational practices to align resource exploration and production with the UN sustainable development goals. Critical raw materials are often at the forefront of this issue as the materials needed for the green transition, such as graphite, cobalt and lithium, are required in ever-increasing quantities and are commonly extracted from previously unexploited deposits using new processing technologies. Given these new imperatives sustainable resource management faces many challenges that need to be addressed to ensure that raw material supply is truly sustainable.

Currently a broad array of guidelines and standards for ESG adherence is in use in different parts of the world and in different industrial sectors covering both sustainability reporting and responsible sourcing. These include schemes developed by the OECD (i.e. the Due Diligence Guidance for Responsible Supply Chains of Minerals from Conflict-Affected and High-Risk Areas[159]), the International Finance Corporation[160] (IFC), the Global Reporting Initative[161] (GRI), the Initiative for Responsible Mining Assurance[162] (IRMA) and many others. The reader is referred to the report 'Overview of activities and policy' for a more detailed review of current sustainability schemes[163] as well as recent work undertaken by the Parliamentary Office of Science and Technology (POST)[164]. The proliferation of guidelines and standards may have serious consequences: on the one hand, producers and consumers might be burdened with extra work as they are required to follow different schemes from individual jurisdictions; while, on the other hand, it may cause confusion among investors and end-users who do not know which schemes are reliable and trustworthy. There is also the risk that companies following best practice are placed at a competitive disadvantage compared to those who do not and yet still manage to achieve some form of sustainability certification. Sustainable investment is an important part of the UK's net-zero commitment[165] and the EU's European Green Deal[4], but, without a harmonised system of definitions, standards and guidelines, investors may struggle to find reliable information and there is a real risk of greenwashing and misunderstanding of how CRMs from different sources actually compare with respect to sustainability. Initiatives such as the commitment to create an International Sustainability Standards Board for ESG reporting[166], announced by the International Financial Reporting Standards (IFRS) Foundation at COP 27, held in Glasgow, 2021, show how this issue is being recognised but further work is required to ensure harmonisation for mining and CRM-specific projects.

5.4.2 Gaps in sustainability reporting

Some specific aspects of ESG are better regulated through standards and guidelines than others. This may be due to high levels of public interest and media coverage of certain issues, while others are largely overlooked. A notable example is the concern about human rights, dominantly child labour, related to artisanal cobalt mining in the Democratic Republic of Congo (DRC). Several schemes aimed at improving the working conditions and practices in the region are now in operation[167,168]. Although this focus is welcome, other sustainability aspects, such as the impact of cobalt mining on the environment and on biodiversity, are relatively neglected. It is important that all factors that might affect the feasibility and sustainability of a mining project are given full and appropriate consideration so that different projects can be compared and informed decisions made by governments and investors.

5.4.3 Sustainability issues for CRM deposits in previously unexploited terranes

For some critical raw materials novel resource types are increasingly being considered as potential sources of supply. However, in such cases experience in their mining and processing is inevitably limited and the potential long-term impacts have not been fully evaluated. Lithium-bearing brines which occur in the salar systems of the high Andes provide a good example. Here the effects of rapidly increasing lithium production from salars, which are part of large and complex hydrological systems, are not well understood. Water scarcity, biodiversity loss and the social and cultural impacts on the indigenous people cast serious doubt over the sustainability of lithium production in the so-called lithium triangle in Argentina, Chile and Bolivia (see lithium case study, section 4.2). There are also concerns about the potential extraction of CRMs from sea-floor resources where large endowments of cobalt and other critical metals are known[169-171].

Deep-ocean mining may have little or no effect on human populations and sites of cultural or natural significance and will generally have a smaller infrastructural footprint (roads, building complexes, etc.) than land-based mining operations. On the other hand, there is considerable uncertainty about the effects of mineral extraction on the ecosystems of the deep sea, which themselves are not well known. These examples highlight just some of the problems that may arise from the rapid growth in CRM production. They serve to illustrate the importance of having a full understanding of any deposit or resource and its relationship with its surroundings before commercial extraction is considered.

5.4.4 Sustainability skills gaps

It is also important that sustainability aspects of exploration and mining are considered at the earliest stages of project development. In many cases geologists are the first people on the ground when a new resource is being investigated. mineral exploration, commonly involving collection of samples from and below the ground surface, means that geologists are the first to come into contact with local stakeholders. However, they seldom have the knowledge and skillset to assess the wide variety of ESG considerations, leading to a lack of effective early public engagement, which may seriously affect the feasibility of an exploration project. Internationally recognised resource reporting codes and standards (PERC, JORC, etc.) are now beginning to incorporate ESG aspects into the modifying factors that distinguish a reserve from a resource[172,173]. This will require exploration companies to introduce new skillsets to their staff in order to assess ESG issues early in project development. The skills and resources required to ensure other aspects related to sustainability, such as the transition to a circular economy and increased use of secondary and recycled sources, are also important to consider for sustainable supply (see section 0 and section 0).

Recommendations:

High priority should be given to harmonisation and standardisation of reporting sustainability issues in the extraction of CRMs. A system that provides comprehensive practical guidelines that can be used as a template to standardise the various schemes would be of great value. The UNRMS could serve as an overarching vehicle for the harmonisation of data collection and the implementation of sustainability principles. If all schemes were to follow guidelines developed by a trusted entity such as the United Nations, then projects from all over the world could be reliably compared and the confidence of investors and end-users assured. The availability of guidance developed by the UN would facilitate and help to promote the process of integrating harmonised standards into national and regional legislation and policy.

With appropriate standards in place tools to ensure good industry practice could be developed, providing benefits to both producers and consumers. For example, the use of labels to identify products that use sustainably-sourced raw materials, similar to ‘Fairtrade’ or ‘Red Tractor’, would help consumers to make informed choices. Similarly, sustainability certificates and labels are also required for green investments. In order to gain this certification companies would be incentivised to follow sustainability guidelines and to publish all supporting data. As the broad acceptance and implementation among all stakeholders of such schemes can take many years, it is important to introduce such schemes as soon as possible. International centres of excellence for sustainable resource management would be ideally placed to conduct case studies on such schemes, to facilitate revisions and updates and to promote their widespread uptake.

Introducing a standardised taxonomy for terms in the field of sustainability and ESG will also help investors to make informed decisions and avoid greenwashing. Such a ‘green taxonomy’ is currently part of the UK’s green finance strategy[165], while the EU is also developing a taxonomy classification system to strengthen sustainable investment in Europe[174]. These systems should include specific terms and definitions that are associated with the extractive industry. The UK has a strong and robust legal system and is, therefore, in a good position to incorporate such sustainability aspects into financial legislation and to demonstrate good practice in this field.

A harmonised resource management system should also be comprehensive in its scope, ensuring that all relevant issues are fully considered. Although some aspects may be of greater importance than others in the case of a particular project, none should be ignored.

ESG aspects should be incorporated into the evaluation of a project from the outset to ensure the sustainability of production and to minimise risks during project development. New skillsets in ESG evaluation and assessment are required for exploration companies to ensure that all factors that might affect project development are properly assessed. More education in ESG performance and sustainability aspects in the exploration and mining sector is required in universities and at other educational levels. All professions involved in the extractives sector, including exploration, mining and extractive metallurgy, should widen their skillset in this field.

5.5 INDUSTRY PROVISION OF DATA AND DATA AVAILABILITY

5.5.1 Data gaps and barriers to data access

All the tools, classifications and standards described in this report rely on the availability of a large amount of detailed data. This requirement will continue to increase as more analysis of CRM value chains and related ESG metrics is undertaken. Such data can only be supplied by the minerals and manufacturing industries themselves, although state agencies can play an important role in collating and managing that data. Filling existing data gaps and adding any new reporting requirements depends, therefore, on collaboration with industry, either through legal obligations or voluntary initiatives, both of which have yet to be developed in the UK. The lack of data presents a fundamental problem for understanding raw material supply chains, especially with regard to resources as well as material stocks and flows. This is difficult to resolve as in many cases the required data is never generated because there is no incentive to do so or because the data may be held in confidence for commercial reasons and is not publicly available.

These challenges are not insurmountable. The extractive and manufacturing industries are accustomed to collecting and reporting large quantities of various types of data. For example, various ESG certification schemes and rating agencies (in order to understand the risks related to individual projects) are provided with a considerable amount of environmental data (section 0) by the minerals industry. If industry were convinced of its benefits, similar provision of data could be established for collecting and reporting stocks and flows for CRMs. Such benefits may include new policies which requires improved resource management practices, such as the requirement to maximise the value of, currently unquantified, co- and by-product materials at particular stages of the supply chain. Another driver may come from investor and consumer requirements to ensure sustainable consumption. For example, traceability and increased supply chain transparency.

Due consideration also needs to be given to issues related to competition, commerciality and confidentiality of data, which may be a serious barrier to improving data availability. It is possible that these issues may be overcome or alleviated by suitable aggregation of data, or by demonstrating that the release of such data actually benefits industry by promoting consumer confidence. Centralised reporting of industry data and national management and dissemination can also provide benefits to industry through the promotion of investment. As discussed in the Northern Ireland case study (see section 4.4), if exploration data is made available when it is no longer commercially sensitive, then this may help to promote future investment in exploration.

Given appropriate incentives and policy drivers, data provision may be improved in many countries, but it is likely to remain problematic where governance is weak. For example, in the Democratic Republic of Congo (DRC), the world's largest producer of mined cobalt, there is a large informal artisanal mining industry which makes a significant contribution to supply but is largely unregulated by government. Consequently, it is difficult to ascertain the scale and nature of issues related to cobalt supply from the DRC as detailed in a recent BGS contribution to a report on the international artisanal mining sector[175]. Furthermore, illegal transportation of cobalt ore from the DRC to neighbouring countries may result in erroneous national trade statistics and consequent uncertainties in the quantitative modelling of global cobalt supply chains. Another issue arises where countries do not disclose data relating to CRMs. For example, China has a significant share of global production and manufacturing of many CRMs but very little data is published on the industry in China.

5.5.2 Fragmentation of resource data

As well as the need for increased sharing of data, the systems for collating and managing this data must be established by national governments. Such systems are commonly fragmented between different departments, each managing datasets for different areas of interest. For example, emissions data may be separated from material production or trade data, when in fact all are intrinsically linked, or need to be linked for the purpose of effective resource management. Given the complex and highly technical nature of much of this data it requires an in-depth understanding to ensure its meaningful and effective use. For example, misunderstanding of mineral resource data has led some authors to erroneously conclude that the world is running out of mineral resources[176]. This has potentially serious implications for research and policy related to raw material supply.

By considering raw materials data in a holistic manner it becomes possible to evaluate geological and resource aspects alongside environmental and social considerations. This is the approach advocated in the UNRMS that will be implemented through the UN centres of excellence.

5.5.3 Data gaps and issues with data standards and classifications

In addition to issues related to all data types there are various concerns over particular types of data. Reviews of such data relating to CRMs are given in Bide et al. (2019)[177] and Brown et al. (2015)[178]. Notable issues include: the lack of compatibility between different classifications and standards for reporting mineral resources; and the lack of trade data at a suitable resolution for understanding CRM flows[179]. Large databases for imports and exports are available from the UN and some individual nations, but the level of detail is rarely sufficient to resolve CRM trade flows. Individual trade codes may include several CRMs, while others may aggregate multiple forms of a single CRM. For example, various cobalt chemicals are reported under a single commodity code. However, the cobalt content of each chemical is different so it is not possible to determine the actual traded volume of cobalt. The same is true for many lithium products (see lithium case study, section 4.2) and other CRMs. This issue extends across the entire value chain with the classification of recycled materials similarly lacking the appropriate level of detail.

International standards organisations, such as ISO, have established technical committees, on which the UK is represented, to attempt to harmonise standards related to material properties for CRMs and derived products[180]. Such international cooperation is essential to build understanding of the wide variety of CRM-based materials and products (battery types, etc.). However, outputs from such work are often very technical in nature, relating to very detailed product and material chemical compositions. This is very different to the level of information available from statistical data for national level trade and production. Expertise in specific commodities is required to translate from such standards to the resolution available from statistical data.

Recommendations

Data gaps need to be clearly understood and steps need to be taken to fill them or adopt suitable proxies. These data gaps may be filled by:

Policy intervention requiring industry to disclose more data, for example the need to report recycled contents or sourcing as set out by the EU eco-design regulations[181] and UK

Environment Act[8]. Such polices instigate development of new strategies for reducing material consumption and increasing supply chain transparency.

Industry acceptance of the value of collecting and disseminating data (as is already taking place for a wide variety of ESG data).

Consumer pressure on industry to disclose data relating to traceability and the environmental impact of products.

To address the skills shortage and lack of understanding of raw materials data a UK critical minerals intelligence centre should be established, as stated in the UK's net zero strategy[182]. Collaboration with other UK stakeholders, such as the Office for National Statistics, should be encouraged.

In parallel with existing initiatives (e.g. National Materials Datahub[183]; Interdisciplinary Circular Economy Centre for Technology Metals – Met4Tech Virtual Data Observatory[128]), improving data quality, harmonisation, timeliness and accessibility on stocks and flows of CRMs throughout their value chains should be considered as part of the National Data Strategy and UK CRM strategy (aimed at securing technology critical minerals and metals, as planned in the UK net zero strategy[182]). Ideally such data should be handled by a single body. Alternatively, data sharing among different data holders needs to be improved.

UK should also work with international organisations dealing with trade statistics and codes (e.g. the UN, EU, World Customs Organisation). The data requirements for effectively mapping CRM supply chains needs to be agreed and appropriate changes implemented.

5.6 STAKEHOLDER ENGAGEMENT AND COMMUNICATION

5.6.1 Improving communication among stakeholders

The need for improved communication of issues related to the sustainable supply of CRMs was highlighted several times in the stakeholder consultation carried out in this study. Experts in different sectors, across academia, industry and government, need a better appreciation of the issues involved at each stage of the supply chain. Improved communication and engagement with all sectors of society is also essential. The UNFC is helpful for promoting dialogue between different stakeholders as it is designed to enable comparison between a wide variety of resource types. An example of this is provided by the Solar Subgroup of the UN Expert Group on Resource Management (
The Solar Subgroup of the UNECE Expert Group on Resource Management (EGRM) (chaired by representatives from the UK) developed the 'Specifications for the Application of the UNFC to Solar Energy' (2019)[184] and contributed to the 'Application of the UNFC for Resources to Renewable Energy' (2021)[185] which identified the following areas that could benefit from classifying renewable energy projects using the UNFC:

- Project development
- Banking and investment
- Energy and utilities
- Regulation and accounting
- Government policy and accounting

This highlights the diversity of stakeholders, with different needs and ways of working, who benefit from a better knowledge of the development status of resources and might usefully apply the UNFC. The Solar Subgroup is directly engaging with key stakeholders from these sectors to enable communication across different parts of the industries involved and demonstrate the value of adopting the UNFC Solar Specifications. The Subgroup is focusing on engagement with integrated energy companies, solar project developers, financial institutions, and regulators. This work includes interviews to a develop a deeper understanding of the potential benefits of adopting the UNFC and developing case studies applying the UNFC to specific projects that demonstrate the benefits for each stakeholder group. This approach could inform future engagement of the UNECE EGRM with stakeholders and encourage the adoption of the UNFC in different sectors. This approach also ensures data is harmonised across different stakeholders allowing for a better understanding of the overall system.

Box 2), a working group to develop the specifications for solar energy resource classification using UNFC.

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Box 2. Stakeholder engagement and outreach by the Solar Subgroup[186].

5.6.2 Public perception of CRMs

The poor perception of the extractive sector amongst the general public is a serious concern for the development of new CRM projects. There are numerous examples of this in many countries, including the UK and the EU e.g. the Curraghinalt project in Northern Ireland (see Northern Ireland case study, section 4.4); the Norra Kärr REE project in Sweden[187]. The linkages between consumer products, essential for modern living, and the extraction of raw materials are not widely understood. This has led to the perception that the extractive industry is unnecessary and excessively harmful. Given wider public engagement on minerals issues, consumers are likely to take greater interest in the source of the materials in a product and the environmental impact of their production. This may lead to significantly increased support for sustainable extraction. Such a shift has occurred in other industrial sectors such as agriculture and fashion, where sustainability is now a major market driver and companies adhering to sustainability standards are held in high regard.

The wide societal distrust of the extractive sector and the lack of appreciation of its growing importance in everyday life has contributed to a shortage of skills in mineral exploration and the environmental and social assessment of mineral-related projects. Numerous research projects have attempted to address these issues and advance understanding of the benefits of the extractive industry. Recent examples include the EU-funded INFACT and MIREU projects[188,189]. These studies have highlighted how the failure of community engagement is the biggest risk to mining projects in European countries. They also provide recommendations for improving community engagement, which may be applicable in the UK if the indigenous mining sector were to be expanded. The INFACT project describes the major barriers to mineral development in Europe. A Europe-wide survey on mineral exploration showed that ideological opposition to minerals development was one of the greatest issues facing minerals development[190]. Increased collaboration with social scientists, who previously have had little involvement in the extractive sector[191], is likely to be beneficial.

Recommendations:

Consideration needs to be given to how negative perceptions of poor environmental performance for all extractive activities can be challenged via social inclusion and participation in the responsible sourcing of raw materials. This can be achieved by providing industry with good practice guidance for early stage project development. A multi-disciplinary approach involving social and environmental scientists in roles that have been traditionally undertaken by geologists should be encouraged.

There needs to be greater awareness among the general public of the value of raw materials and their importance to consumer products as well as their role in decarbonisation technologies. Educational projects that highlight the importance of minerals should be developed and disseminated to all stakeholders. If more transparent supply chains are developed this will act to demonstrate the environmental credentials of CRM sources that follow best practice for ESG (see section 0).

New research and initiatives, such as the planned Critical Minerals Intelligence Centre, should be undertaken to include input from a range of stakeholders who have in-depth knowledge of the value chains of individual CRMs and of potential issues for the UK economy. Future projects should include extensive stakeholder consultation and multidisciplinary expert input to augment data-driven studies.

5.7 CONSIDERATION OF THE WHOLE VALUE CHAIN

5.7.1 The need for a 'systems thinking' approach

The material needs of society are met by dynamic international supply chains. However, their complexity is such that we do not fully understand how materials are produced, used and discarded, in what quantities and with what consequences. A holistic, systems-based approach is required in order to examine the way resources are used in the economy and their impacts on the environment and on society. We need to analyse the net effects of material demand and supply, understanding the resource benefits, impacts and trade-offs across the globe. Existing monitoring is driven by the monetary value of the supply chains and does not address their physical dimension, namely resource and material flows. Existing physical data tends to focus on single stages, such as mine production, and does not provide the evidence base for holistic assessment of the supply chain, including impacts on climate change, progress towards the circular economy, attaining the SDGs and securing long-term CRM supply.

These deficiencies may be addressed through quantified mapping of CRM supply chains. This is generally carried out using methods such as Materials Flow Analysis (MFA), Input – Output analysis, Life Cycle Assessment (LCA) or similar frameworks that use the concepts of mass of balance or by mathematical modelling of the physical economy. This mapping may allow identification of resource management issues, such as material imbalances and losses from the system, and underpin the development of appropriate interventions for their mitigation. The emphasis of such mapping is to clarify the linkages between sources, pathways and sinks of materials, based on the principle of the conservation of matter[192]. These methods can address resources defined in the wider content including materials, energy, environment and waste. The UK has a track record in this field. For example, the UKFires project measured flows of stocks and energy to consider how society can achieve net-zero[193]; and the Faraday institute has quantified carbon emissions from electric vehicles and their batteries[194] using Life Cycle Assessment tools.

An example of good practice for mapping of stocks and flows of raw materials has been developed by the EU-funded MinFuture project[195] (2016-2018) focussed on the development of a framework for monitoring the physical economy, using MFA and focusing on CRMs (see Box 3).

The MinFuture project examined the growing complexity of global material supply chains linking the extraction, transport and processing stages of raw materials. It aimed to identify, integrate and develop expertise for global material flow analysis and scenario modelling. This led to the production of a roadmap for moving towards the monitoring of the physical economy with specific urgent actions that should be followed to achieve this[195]. The roadmap distinguished seven components:

Figure 18. The seven components and hierarchical structure of the MinFuture project Framework

Systems
Key messages: Monitoring the system of the physical economy on various scales (site, company, region, country, global) is indispensable for effective resource management and emissions control.

Data
Reporting data with their system context ("coordinates") adds clarity and robustness and facilitates data harmonisation. Government authorities should consider describing their data with metadata about the system location of the measurements. Monitor systems, not isolated flows

Models & scenarios
The robustness of models is usually limited by a lack of robust data and system understanding. Adding mass and energy balance constraints to resource and emission models enhances the robustness of forecasts. Improving system understanding and data quality is the most effective way to improve the quality of forecasts.

Uncertainty
Uncertainty analysis makes uncertainties transparent and enables users to identify the strengths and weaknesses of the model. Systematically evaluating uncertainty enhances the robustness of results and interpretations.

Indicators
Strategies to enhance the indicator performance often cause in problem shifts. The definition of indicators (or indicator sets) can be enhanced through an explicit system definition. This adds clarity to the definition and facilitates a robust selection of indicators that capture potential problem shifts.

Visualisations
Visualisations can capture multiple dimensions, which adds clarity and transparency, and provide interpretations of complex systems. Visualisations can be strengthened by integrating different modes of communication (images, words, and numbers).

Strategy & decision support
Improving the robustness of the system understanding and the data is the most critical aspect for improving resource strategies. MFAs can inform strategies for monitoring the physical economy by providing a language for integrating data and for identifying key points for measurements.

Box 3. The MinFuture Framework to improve monitoring of the physical economy.

It is important to ensure that this kind of analysis covers the full range of the lifecycle of raw materials, incorporating the in-use and end-of-use stages with due consideration to the barriers discussed in section 5.5.1. Currently much research in this area only considers the lifecycle up to the manufacturing stage which is not sufficient for development of the circular economy.

Understanding how to map supply chain linkages is likely to come from the compilation of numerous small-scale case studies rather than by a 'top down' implementation. Such studies will feed into the development of a new set of tools, frameworks and good practice. This is consistent with the approach set out by UNRMS[22]. Industrial and raw materials sourcing strategies need to balance benefits to society with economic growth. As more advanced tools for resource management are developed care needs to be taken that the two get equal consideration. A whole-system approach should be able to identify where real benefits to raw material supply can be achieved without compromising environmental performance or social acceptability.

5.7.2 The need for interdisciplinary research

The broad technical requirements of advanced resource management systems, as proposed by UNRMS, and as required by policy initiatives such as battery passports[3], or initiatives such as the OECD due diligence guidance[159] requires expert input from industry and from social and environmental science. This would promote greater sustainable resource management to facilitate our technology needs at present and in the future. The UK has an excellent track record of research regarding material uses, properties and applications. This includes centres such as the Royce institute[196], the Centre for Industrial Energy, Materials and Products[197], the UKFires network[198] and the Met4Tech Circular Economy Centre[128], which is part of the UKRI National Interdisciplinary Circular Economy Research Hub, and the UKRI-funded TransFire project[199] looking at efficiencies for the UK mining and manufacturing sectors. Linking these areas of research with geoscience and environmental experts will be required to integrate CRM supply chains into the circular economy.

5.7.3 The use of 'digital twins' and blockchain technologies

Such detailed mapping of supply chains closely aligns with the 'digital twin' concept, a virtual representation of a system that spans its lifecycle, that is used in many industrial processes and systems and is proposed as a solution for battery/raw material passports[118]. Such a system is important to ensure traceability along the supply chain and requires new technologies such as blockchain as it is shown in the case study on blockchain and traceability (see section 4.5) The use of MFA and digital twins is now the focus of considerable research into CRM supply chains and it is likely that these will underpin resource management systems such as the UNRMS.

5.7.4 Resource as a service

Although at the early stage of development, one advantage of a better understanding of the whole value chain is that concepts such as 'resource as service' can be implemented[200]. The 'service' concept can be used to promote a circular economy approach to many consumer goods. Regarding raw materials it envisages that materials do not change ownership through their life cycle, but are seen as a service to a subscriber at the centre of the business model. The concept aims to improve traceability of materials and to retain the highest value in a circular economy but requires understanding of where in-use materials actually are with regard their stage of use.

Recommendations:

Detailed mapping and quantification of complete CRM supply chains and physical stocks of CRMs needs to be undertaken. Existing models need improved resolution which might be achieved using tools such as MFA looking at individual CRMs across their lifecycle. Such mapping will enable tools such as digital twins of CRM-derived products to be created. This analysis should focus on the UK-specific demand for CRMs, with an emphasis on the strategic technologies and sectors that underpin the policy objectives of the government. This should be informed by close engagement with major sectors of UK manufacturing (e.g. electric mobility, aerospace and defence, renewable energy).

Analysis of value chains covering only part of the lifecycle should be replaced with models that cover all stages, including use and end of life, to allow a better understanding of how circular economy can be improved. This will increase knowledge on where data gaps currently exist, via the development of case studies for individual metals and components.

New ways to improve existing supply chain mapping methodologies need to be considered, to address data gaps and understand uncertainty including the development of mathematical modelling techniques such as those being developed by the UKRI Circular Economy Hub[201].

There needs to be coordination between different national authorities, for example statistic offices, geological surveys and environment agencies, to ensure all relevant datasets are accurately and consistently used in new models. This will maximise the benefits of material flow analysis for natural resource management and environmental protection.

Development of MFA for CRMs needs to be linked with parallel, similar systems, that are currently being developed such as raw material digital twins, battery passports and any new frameworks developed by UNRMS to ensure alignment. Such initiatives may be implemented and coordinated through a UNECE ICE-SRM.

6 The benefits and potential function of a UK-based International Centre on Sustainable Resource Management

One objective of this research was to consider how a UK-based ICE-SRM could help to improve practices relating to managing supply risks and the sourcing of sustainable CRMs. Such a centre would focus on furthering the development of the UNRMS and UNFC and on promoting their application. It would also be beneficial to UK in terms of overcoming barriers to sustainable supply and enhancing UK-based research and innovation in this broad field. A UK-based ICE would also act as a forum for developing multidisciplinary collaboration among researchers worldwide.

Whilst many of the recommendations given in section 5 highlight research and policy designed to overcome barriers to CRM supply many are outside the scope of an ICE, for example those that relate specifically to the UK policy landscape, or public perception of the extractive sector. To ensure maximum effectiveness any new ICE should to build on and not duplicate work already being undertaken and planned by the existing ICEs (see section 2.5) by utilising the strengths of the UK research community and the extractive and manufacturing sectors. The following are considered to be the most appropriate thematic areas.

6.1 BETTER UNDERSTANDING OF CRM RESOURCES AND INTERNATIONAL RELATIONSHIPS

Better understanding of the locations and properties of primary CRM resources are crucial in planning for secure and sustainable supply. This requires basic geological research to understand the genesis, global distribution and chemical properties of CRM-bearing deposits. This enhanced knowledge base will underpin future exploration for new deposits, both in the UK and overseas. It will improve the effectiveness of exploration and facilitate the development of more efficient metallurgical processing to ensure that valuable by-product CRMs are recovered. Application of the UNFC from the start of project evaluation will ensure that economic and ESG considerations are also taken into account and potential barriers to project success are identified at each stage. Such work should also consider secondary resources contained within mine waste.

The essential research, which the UK is well placed to lead, may in part focus on indigenous resources in the UK, but it is envisaged that new sources of CRM supply from overseas will need to be investigated. For example, as outlined in the case studies presented here, there is considerable potential for additional supply of graphite from several countries in east Africa and of lithium from South America. This will require collaborative research partnerships to be developed with countries that have established mining industries and potential for economic CRM deposits. It will also help to promote of the aims of the UNECE and will enhance UK expertise in this area. Activities such as capacity building, training provision and research collaboration aimed at improving the UNFC and UNRMS will help to strengthen relationships with overseas governments in developing countries. Research links with other countries, such as the EU, USA, Canada and Australia, that share the UK's aim of securing sustainable CRM supplies, should also be expanded to assist in diversifying the supply base.

6.2 ALIGNMENT OF ESG STANDARDS

The sustainability of CRM supply and the need for robust, internationally accepted, indicators and reporting standards for ESG are of growing importance. This is dictated by the need for environmental protection, improved governance in mineral resource development and for public engagement throughout project development. As a result, a wide variety of standards, guidelines and certification schemes now exist. This has led to confusion and uncertainty amongst industry and consumers as to what is actually required and which standards are the most appropriate for a particular project or product. The alignment and standardisation for reporting sustainability issues in the extraction of CRMs will help to allay this loss of confidence and reduce the risk of ‘greenwashing’. A focus on ESG issues using the UNRMS within an ICE could serve to promote the harmonisation of data collection and the implementation of sustainability principles. This would require an evaluation of existing standards to identify differences and similarities and to elucidate current gaps and weakness in ESG reporting. This could be developed into a single system, using resource management principles, that provides comprehensive practical guidelines to facilitate standardisation of the various schemes. The availability of guidance for the alignment of disparate ESG standards under the UNRMS would help to promote the integration of harmonised standards into national and regional policy and legislation.

Several international organisations and corporations based in the UK would be well placed to play leading roles in the development of harmonised ESG guidance through a UK-based ICE. These include: the London Metal Exchange (LME), which has established requirements for responsible sourcing for traded commodities[202]; the International Council on Mining and Metals (ICMM), which has introduced principles to strengthen social and environmental requirements[203]; and the Cobalt Institute which promoting sustainable and responsible production in the cobalt industry[204]. Furthermore, several major international mining companies with offices in the UK, including Rio Tinto, Anglo American and Glencore, are working on improving their ESG and sustainability performance and could contribute to the development of ESG guidance as part of the UNRMS.

Another complementary task that needs to be undertaken to allow alignment of ESG standards is the development of standardised taxonomies for terms in the field of sustainability and ESG. Such a ‘green taxonomy’ is currently part of the UK’s green finance strategy, while the EU is also developing a taxonomy classification system to strengthen sustainable investment in Europe. These systems should include specific terms and definitions that are associated with the extractive industry. The UK has a strong and robust legal system and is, therefore, in a good position to incorporate such sustainability aspects into financial legislation and to demonstrate good practice in this field and across the network of UNECE ICE’s.

6.3 DEVELOPING TOOLS TO QUANTIFY AND MAP THE WHOLE VALUE CHAIN

A holistic, systemic approach is required to fully understand material supply chains and thus allow development of strategies for the sustainable management of CRM resources.

The application of MFA and other modelling tools to CRM supply chains has not yet been widely undertaken. An important activity to be carried out under the auspices of the ICE should include detailed mapping of complete supply chains for selected individual CRMs, such as those required for Li-ion batteries. This would involve analysis of the material stocks and flows throughout the value chain, from raw material extraction, through processing and manufacture to end-of-life treatment. Such analysis can be undertaken using the UNRMS principles to provide examples of frameworks for development of practical applications of UNRMS. Such incorporation of the UNRMS principles will also ensure that environmental and social considerations are integrated with the physical monitoring of CRM stocks and flows. Such work will increase understating of the issues with data availability, quality and gaps for the information vital for the application of MFA. Development of expertise here, combined with better provision of data by industry, will allow more robust estimates of stocks and flows and thus identify where losses are greatest and where intervention is needed.

This analysis should focus on those CRMs most critical to the UK, with emphasis on the strategic technologies and sectors that underpin the policy objectives of the government. This needs to be informed through close engagement with industry experts in major UK manufacturing sectors (e.g. electric mobility, aerospace and defence, renewable energy). This in turn will facilitate better communication and data sharing between industry and the research community.

The development of case studies for individual metals and components in the framework of an ICE will also build on the UK's existing strengths in this area, as is currently being undertaken by the National Interdisciplinary Circular Economy Research Programme, to improve the UK's expertise and understanding of CRM supply chains. This will allow identification of issues with current levels of available data (from data types such as trade or reported production) and enable elimination of these issues.

Appendix 1 Acronyms

RESOURCE CODES, CLASSIFICATIONS AND STANDARDS

AMREC	The African Mineral Resource Classification is an Africa-specific resource classification based on UNFC.
CIM	Canadian Institute of Mining Metallurgy and Petroleum, which develops the NI 43-101 reporting code.
CRIRSCO	Committee for Mineral Reserves International Reporting Standards. Body responsible for publishing and maintaining the CRIRSCO International Reporting Template ('CRIRSCO Template'). Member organisations of CRIRSCO are known as National Reporting Organisations (NROs) from 7 countries and regions (including Europe). Each is responsible for developing and maintaining a code or standard incorporating CRIRSCO definitions and principles alongside national or regional regulatory requirements.
ESG	Environmental, Social and Governance; this represents a set of standards and metrics to ensure development takes place with a social licence to operate, minimising environmental harm and benefiting local communities. It can relate to specific projects or companies and often used by investors/ financiers to assess risk.
INFACT	Innovative, Non-Invasive and Fully Acceptable Exploration Technologies, EU-funded project.
INSPIRE	Infrastructure for Spatial Information in the European Community. The INSPIRE Directive in Europe establishes an infrastructure for spatial information to support community environmental policies and policies or activities that may impact on the environment. The purpose of the INSPIRE Directive is to ensure that the spatial data infrastructures of the Member States are compatible and usable in a community and trans-boundary context.
IFRS	International Financial Reporting Standards Foundation, a not-for-profit, public interest organisation established to develop a single set of high-quality, understandable, enforceable and globally accepted accounting and sustainability disclosure standards.
JORC	Joint Ore Reserves Committee. A body managing the JORC Code which is the Australasian Code for Reporting of Exploration Results, Mineral Resources and Ore Reserves. JORC is a member of CRIRSCO, being the National Reporting Organisation for Australasia. Reports prepared in accordance with the JORC Code and issued with a certificate of consent from the Competent Persons who prepared them are accepted by all major international stock exchanges including those regulated by the European Securities and Market Authority (ESMA) in Europe.
NI 43-101	National Instrument for Standards of Disclosure for Mineral Projects within Canada. The reporting code is developed by the Canadian Institute of Mining Metallurgy and Petroleum (CIM). The code is used by companies listed on the Toronto Stock Exchange.

PERC	Pan-European Reserves and Resources Reporting Committee. A not-for-profit organisation responsible for the PERC Reporting Standard, which incorporates all definitions and principles set out in the CRIRSCO International Reporting Template. PERC is a member of CRIRSCO being the National Reporting Organisation for Europe. Reports prepared in accordance with the PERC Standard and issued with a certificate of consent from the Competent Persons who prepared them are accepted by all major international stock exchanges including those regulated by ESMA in Europe.
PRMS	Petroleum Resources Management System. A petroleum resources classifications framework sponsored by a range of industry bodies and published by the Society of Petroleum Engineers (SPE).
SDG	Sustainable Development Goals. These are 17 integrated goals, developed by the UN, and set out in the 2030 Agenda, and are designed as a call to action to end poverty, protect the planet and ensure that by 2030 all people enjoy peace and prosperity.
UNFC	United Nations Framework Classification for Resources.
UNRMS	United Nations Resource Management System (incorporates the UNFC).

ORGANISATIONS AND GROUPS

AIM	The Alternative Investment Market. a submarket of the London Stock Exchange
AMEC	Association of Mining and Exploration Companies
BGS	British Geological Survey
BRIC	Group acronym for Brazil, Russia, India and China
CCOP	Coordinating Committee for Geoscience Programmes in East and Southeast Asia
CMA	Critical Metals Alliance
CMIC	Critical Minerals Intelligence Centre
CMEC	Critical Metals Expert Committee
DfE	Department for the Economy, Northern Ireland
ESMA	The European Securities and Markets Authority. The EU securities markets regulator.
GTK	Geological Survey of Finland
GRI	Global Reporting Initiative
GSNI	Geological Survey of Northern Ireland
ICMM	International Council on Mining and Metals
IFC	International Finance Corporation
IGI	Institute of Geologist of Ireland
IRMA	Initiative for Responsible Mining Assurance

ISO	International Standards Organisation
LARCO	The General Mining and Metallurgical Company SA; nickel-producing mining company in Greece
LME	London Metal Exchange
MINTELL4EU	Mineral Intelligence for Europe, EU-funded project
MIREU	Mining and Metallurgy regions of EU, The MIREU projects aims to establish a network of European mining and metallurgy regions
NERC	Natural Environment Research Council
NICER	National Interdisciplinary Circular Economy Research Programme by UKRI
NGU	Geological Survey of Norway
OECD	Organisation for Economic Co-operation and Development
PanAfGeo	Pan-African support to the EuroGeoSurveys' Organisations of African Geological Surveys. An EU-led capacity building programme in Africa.
SGU	Geological Survey of Sweden
UKRI	United Kingdom Research and Innovation
UN Comtrade	United Nations International Trade Statistics Database
UNECE	United Nations Economic Commission for Europe
UNECE EGRM	United Nations Economic Commission for Europe - Expert Group on Resource Management, formerly the Expert Group on Resource Classification (EGRC)

OTHERS

AAM	Active Anode Material used in the manufacturing of lithium-ion batteries.
CoC	Certificate of Conformity is a document which certifies that the goods or services supplied meet the required standards.
CRM	Critical Raw Material. These are raw materials that are deemed to be economically and strategically important but have a high risk associated with their supply.
DRC	Democratic Republic of Congo.
EV	Electric vehicle.
EIA	An Environmental Impact Assessment is the assessment of the environmental consequences of a plan, policy, program, or actual projects prior to the decision to move forward with the proposed action.
FDI	Foreign Direct Investment, the purchase of an interest in a company by a company or an investor located outside its borders.
FPIC	Free Prior and Informed Consent. This is part of the Declaration on the Rights of Indigenous Peoples and requires States to consult and cooperate in good faith with the indigenous peoples concerned through their own representative institutions in order to obtain their free, prior and informed consent before adopting and implementing legislative or administrative measures that may affect them. This includes exploration and mining projects that may affect indigenous peoples rights, land, territory and resources.

GHG	Greenhouse gas is a gas that absorbs and emits radiant energy within the thermal infrared range, causing the greenhouse effect.
HPSG	High Purity Spherical Graphite, mainly produced from flake graphite.
HS Code	Harmonised system code: The Harmonized System is a standardized numerical method of classifying traded products.
ICE-SRM	International Centre of Excellence on Sustainable Resource Management.
IoT	Internet of Things describes physical objects that are embedded with sensors, processing ability, software, and other technologies that connect and exchange data with other devices and systems over the Internet or other communications networks.
LCA	Life Cycle Analysis. This is a method used to evaluate the environmental impact of a product through its life cycle.
Li-ion	Lithium-ion in the context of lithium-ion batteries.
LST	Land surface temperature is the radiative skin temperature of the land derived from solar radiation. LST measures the emission of thermal radiance from the land surface where the incoming solar energy interacts with and heats the ground, or the surface of the canopy in vegetated areas.
MPL	Mineral Prospecting Licences.
NDVI	Normalised difference vegetation index: a dimensionless index that describes the difference between visible and near-infrared reflectance of vegetation cover and can be used to estimate the density of green on an area of land
NGO	Non-Governmental Organisation.
MFA	Material Flow Analysis. This is an analytical method to quantify flows and stocks of materials or substances.
REE	Rare Earth Element. This is a group of 17 chemically-similar metals that are essential to many applications in new and green technology.
SLO	Social licence to operate. The concept refers to a local community's acceptance or approval of a project or a company's ongoing presence, beyond formal regulatory permitting processes. Here dominantly in the context of exploration and mining projects.

Appendix 2 Glossary

Anthropogenic Resources

See 'Secondary raw materials'.

By-product

By-products are materials that are produced incidentally to the main economic product(s) of a mining operation. They are typically present at very low levels in the ores of the main or parent product. They generally lack their own production infrastructure and make no, or only a minor, contribution to the economic viability of a project. Extraction and processing technologies aim to maximise recovery for the main commodity, so, if recovery of by-products is undertaken, it is commonly inefficient and large amounts may go into waste streams. In addition, data on production and resources of by-products are not always reported so that resource management of these materials is difficult.

Circular Economy

A circular economy is an economic system of closed loops in which raw materials, components and products lose their value as little as possible, renewable energy sources are used and systems-thinking is at the core. It involves practices such as sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and keeping products in use for as long as possible. The possibility of 'resources as a service' is an example of a circular economy practice.

Co-product

Co-products are materials that occur together in nature and are, therefore, generally mined together. All co-products make an economic contribution to the project from which they are sourced. The platinum-group metals and the rare earth elements are examples of co-product groups that are produced together, sometimes in conjunction with other co-product metals such as nickel or copper.

Cradle-to-gate, cradle-to-cradle and cradle-to-grave

These terms originate from Life cycle assessment (LCA) studies and describe the boundary conditions in which such a study is conducted. Cradle-to-gate analysis will study specific environmental parameters (e.g. greenhouse gas emissions) from resource extraction (cradle) to the factory gate. Cradle-to-Cradle analysis includes recycling as an end-of-life treatment of the product. Another term, which is used in this context is cradle-to-grave, which includes the final sink of a material, when it is not recycled, i.e. disposal.

Flow

In the context of material streams (raw materials, secondary raw materials, wastes etc.) or their components, this is the mass per unit time (i.e. tonnes per year) passing through a defined point or set of points or boundary (e.g. waste collection facilities) in a system (e.g. production, consumption and waste). (Also related to 'Stock' as per entry below.)

Geological stocks

Geological stocks represent the geological endowment of a mineral or commodity, unaffected by economic, technical or environmental considerations, within a particular orebody, deposit or project. It is the maximum amount of commodity that may be extracted from that entity.

Life Cycle Assessment (LCA)

Life Cycle Assessment is the analysis of the environmental impacts associated with all stages of the lifecycle of a specific product. It is an important tool for environmental management. The assessment may include identification of different mass and energy flows, as well as emissions of pollutants and wastes into the environment and their ultimate effects on human health, ecosystem function and the use of non-renewable resources. Typical parameters, which are used to measure these impacts are greenhouse gas emissions (CO_2-equivalent), energy use, water use and SO_x and NO_x emissions. Compared to material flow analysis, an LCA is the analysis of one product containing various materials, while MFA analyses the mass flows of one specific material in various products. (see 'MFA').

Material Flow Analysis (MFA)

Material Flow Analysis (MFA) is a tool for investigating material flows and stocks within a system defined in space and time and is based on mass-balance principles. It is used mostly in the management of resources, waste and associated environmental impacts. The detailed analysis of the mass quantities in various products and wastes where a specific material occurs through the supply chain (extraction, processing, manufacturing, recycling, etc.) makes it possible to identify data gaps and material losses. Dynamic material flow analysis can be used to identify future demand and potential supply bottlenecks by using forecasts and scenario analysis. Compared to Life cycle assessment (LCA), MFA focuses on a certain material, occurring in different products, while an LCA analyses the environmental footprint of the production of a particular product, which can contain various materials. (see 'LCA').

Neoproterozoic

The Neoproterozoic Era is the unit of geologic time from 1 billion to 538.8 million years ago

Paleoproterozoic

The Paleoproterozoic Era is a geological time period from 2,500 to 1,600 million years ago.

Battery/product Passport

This is the digital representation of a battery or product (or 'digital twin') that contains information on a variety of metrics, which may include data on ESG performance related to competent extraction and manufacture, to energy use, composition and recycled content. It is designed to help to improve transparency and traceability of a product through its life cycle.

Precambrian

A period geological of time extending from about 4.6 billion to 541 million years ago.

Raw materials

Raw materials are metalliferous minerals, industrial minerals, and construction minerals that have undergone minimal processing and purification and which are used by industry for the manufacture of products. For the purposes of this study they exclude wood and natural rubber.

Reporting Code

A code of practice that sets the minimum requirements for reporting mineral resources and reserves. Reporting Codes are incorporated in the laws of a particular jurisdiction and, therefore, provide a mandatory system for the reporting of mineral resources and reserves. In many cases reporting codes are used at a national level for public authority reporting (national reporting). However, well-established national reporting codes, such as the JORC code, NI 43-101, SAMREC and NAEN code, aligned to the CRIRSCO reporting template are recognised for use in public reporting of mineral resources and reserves used for financial markets. A reporting code incorporates two parts:

- A classification system, which allows the organisation of different levels of geological data in relation to levels of confidence and different degrees of technical and economic evaluation.
- The reporting rules, which prescribe the underlying principles on the reporting of mineral resources, mineral reserves and exploration results based on the reporting terminology and categorisation set by the reporting code classification system.

Reporting Standard

A code of practice that sets the minimum requirements for reporting mineral resources and reserves. Like a reporting code, a reporting standard is recognised by an official body such as a stock exchange regulator for use by companies or other entities in public reporting of mineral resources and reserves. An example is the CRIRSCO-aligned Pan-European Reserves & Resources Reporting Standard (PERC 2013) which is recognised by ESMA and a number of other stock exchange regulators in Europe and elsewhere. However, a Reporting Standard is not incorporated in the laws of a particular jurisdiction. This is what distinguishes it from a reporting code.

Like a reporting code, a reporting standard incorporates two parts:

- A classification system, which allows the organisation of different levels of geological data in relation to levels of confidence and different degrees of technical and economic evaluation.
- The reporting rules, which prescribe the underlying principles on the reporting of mineral resources,

mineral reserves and exploration results based on the reporting terminology and categorisation set by the reporting code classification system.

Reporting template

A template is not itself a standard or a code but is a prototype designed to be used in preparation of new standards or codes. The CRIRSCO template is based upon an agreed set of the common features of standards and codes maintained by the members of CRIRSCO.

Reserve

According to the CRIRSCO definition a 'mineral reserve' is the economically mineable part of a measured and/ or indicated mineral resource. It includes diluting materials and allowances for losses that may occur when the material is mined. Appropriate assessments to quantify the 'modifying factors' which may include feasibility studies, have been carried out and include consideration of and modification by realistically assumed mining, metallurgical, economic, marketing, legal, environmental, social and governance factors. These assessments demonstrate that, at the time of reporting, extraction could reasonably be justified. Mineral reserves are subdivided in order of increasing confidence into probable mineral reserves and proved mineral reserves.

Resource

According to the CRIRSCO definition a 'mineral resource' is a concentration or occurrence of material of economic interest in or on the Earth's crust in such form, quality and quantity that there are reasonable prospects for eventual economic extraction. The location, quantity, grade, continuity and other geological characteristics of a mineral resource are known, estimated or interpreted from specific geological evidence and knowledge. Mineral resources are subdivided, in order of increasing geological confidence, into inferred, indicated and measured categories.

Resource as a service

The concept that materials do not change ownership through their life cycle, but are seen as a service to a subscriber at the centre of this business model. The concept aims to improve traceability of materials and retain the highest value in a circular economy.

Resource management

With regard to minerals, this refers to ensuring the maximum economic benefit is realised and maximum value is added, throughout the lifetime of a project. Traditionally it refers to mining and processing practices but is now commonly applied more holistically to include the complete life cycle of a material within a product.

Responsible sourcing

Responsible sourcing refers to the practice of ensuring social and environmental considerations are considered when materials are sourced. This aims to ensure materials are sourced with minimal environmental damage, while maximising benefits for affected communities. It addresses sustainability risks in global supply chains.

Secondary raw materials

Waste materials that have been identified for their potential of recycling or reprocessing to generate raw materials (potentially displacing the use of primary materials). They include: mining wastes, manufacturing and processing waste, including scrap, and the contents of landfill. They are also referred to as anthropogenic resources (i.e. raw material stocks found in the anthroposphere). For the purposes of this study, only the long-lived, accumulated and hence permanently geo-located sources have been considered, namely mining and landfill wastes.

Stock (Inventory)

In the context of materials, this is the quantity (typically mass or volume) held at a given point (e.g. a landfill) or set of points (e.g. all waste facilities) in a system at a given time (see 'Flow').

Supply chain

The supply chain represents all aspects of a material's lifecycle from extraction (in the case of primary minerals) through to processing, manufacture, use, reuse, recycling and disposal. It is usually represented diagrammatically as an input/ output model of stocks and flows and is conceptualised via MFA. Supply chain mapping allows understanding of how materials flow through society and the economy. The term supply chain is often used interchangeably with 'value chain'.

System of reporting

The term is used in this report to describe a reporting code or standard as they both serve similar purposes (i.e. the reporting of mineral resources and reserves). It is introduced to simplify the use of the terms reporting code and reporting standard where it is impossible to distinguish between the two and, in particular, where the harmonisation of data across Europe is discussed.

Systems Thinking

Systems thinking is a holistic approach to analysis that focuses on the way that a system's constituent parts interrelate and how systems work overtime and within the context of larger systems. It is a shift away from 'liner systems and is a fundamental component of the circular economy.

Appendix 3 List of possible questions for stakeholder interviews

- What do you see as the greatest issue affecting the UKs supply of CRMs (e.g. supply/refining/manufacturing concentration, import dependence, lack of traceability, competition for other consumers etc.)?
- What are the greatest issues with regards to sustainability for CRM supply? This could relate to security of supply, or all aspects related to environment, water/land/energy consumption, emissions throughout the lifecycle, etc.
- How can the UK government (in terms of policy) or research sector (in terms of new data/tools/areas of science) address these issues? Are there any other mineral supply issues, where additional support, policy or legislations by the UK government or research community may be able to usefully help with?
- What are the prospects for supply from indigenous sources for CRMs, both in terms of resource potential and environmental/social issues?
- Complex resource management systems are considered by some to be a solution to lack of standardisation, improvement of issues around traceability and to improve environmental performance. Do you think this is something that could, in effect help with managing supply risks or is this unnecessary and would perhaps make the current situation more complicated? Is it an important step with regards to traceability, sustainability, identification of supply bottlenecks etc. or is it an additional burden on the extractive and manufacturing sectors as additional data would need to be collected and new and additional reporting and data management could be necessary? If the latter what is the solution with regard new data requirements like traceability, emissions data, minimum recycled content etc?
- Do you think a resource management system could help to have more consistent data on CRMs in primary and secondary resources with standardised reporting of resource, including by-products?
- How important do you see the need for detailed mapping and understanding of stocks and flows through supply chains from manufacturing to recycling/end-of-life stages for dealing with supply issues?
- Is lack of consistency around reporting standards, for environmental, social impact and governance reporting and other various obligatory reporting (i.e. resources, production, traceability etc.) a significant issue? If so, what are the standards that need consolidating and how can policymakers help with this – i.e. more regulation, more guidance or clearer standardised regulation?
- Have you heard of UNFC or UNRMS?
- Do you see an opportunity in a holistic, harmonised and unified system such as the UNFC and UNRMS as guidance for governments and industry to manage resources in a consistent and sustainable way (i.e. circularity, environmental and social governance issues) or are current standards and schemes sufficient?
- If more integrated resource management is important, would you be willing to provide extra information on your activities, to bodies like ONS or BGS, if required? What are the main barriers for industry data entering the public sphere, i.e. confidentiality, time constraints in collecting data, complexity in the data, lack of data collection systems etc.?
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British Geological Survey holds most of the references listed below, and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at: https://of-ukrinerc.olib.oclc.org/folio/.

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