Abstract

The accelerating global transition towards environmentally sound energy systems, digitalization, and advanced manufacturing has fundamentally reshaped the importance of raw materials. Once considered abundant or peripheral in a fossil-fuels driven world, raw materials are now central to economic and industrial competitiveness, energy security, and geopolitical stability. This transformation has placed the governance of raw materials at an imperative juncture in the global sustainability agenda. In simple terms, attaining sustainable development demands a surge in raw materials supply. Along these lines, this global shift therefore requires new approaches capable of balancing supply security with environmental protection, social responsibility, and long-term intergenerational equity. In other words, leaving a world without a compromised environment, and exacerbated resources, including raw materials, for the future generations.

With the global sustainability agenda in mind, it is therefore necessary to manage the growing challenge between the rising demand for raw materials and the environmental and social impacts associated with their extraction and processing. As such, the question remains on how to get raw materials from beginning to end, while remaining bounded to the principles of sustainable development. As a solution, sustainable resource management emerges as a foundational practice to ensure that raw materials production, use, and reuse do not undermine sustainability principles. A pillar of sustainable resource management is the ability to identify, quantify, and communicate information on raw materials under conditions of uncertainty. Resource classification renders complex information into its simplest form for utility. In the context of raw materials, classification systems provide the conceptual and operational framework through which confidence in product estimates, technical feasibility, economic viability, and more recently increasing environmental and social considerations are conveyed to stakeholders.

In Europe, resource management has historically been handled at national levels, particularly mining codes being under state's responsibility, which caused a fragmented array of reporting and classification systems across the continent. At the same time, the lack of a harmonized resource classification framework at European Union level lowers the chances for cross-country comparability, and in return strategic planning. Harmonized classification, a common language per se, is increasingly seen as essential for understanding raw materials potential and accessibility at European level, in return supporting strategic autonomy, industrial competitiveness, and sustainability goals.

The United Nations Framework Classification for Resources (UNFC) provides a practical solution. It is a principles-based classification tool that enables consistent, coherent, and robust communication on energy and resource projects across all stakeholders. UNFC is built on a three-dimensional framework that classify projects according to environmental-socio-economic viability

(E axis), technical feasibility (F axis), and the degree of confidence in product estimates (G axis). This structure allows complex project information to be presented in a clear, comparable, and transparent way, and in return, support informed decision-making. UNFC is applicable to both primary raw materials and secondary raw materials. Moreover, UNFC allows the transposition of information from one classification system to UNFC. This is carried through a bridging mechanism to align UNFC with other reporting systems, ultimately paving the way for a common language across different projects, jurisdictions, and purposes, for interoperability of data. Although well established, UNFC has to date been limited in use, mainly in private and public reporting. Moreover, only a handful of countries have formally adopted UNFC at national levels, particularly for minerals inventories, used in support of existing national codes. However, the extensive potential of UNFC is yet to be explored beyond mere inventorying. This dissertation explores how this potential supports sustainable resource management, through full alignment with the objectives, measures, and monitoring requirements of the European Critical Raw Materials Act (CRMA).

CRMA represents a paradigm shift in the European Union's raw materials policy, moving beyond criticality assessments toward a structured system aimed at securing a resilient, sustainable, and diversified supply of critical and strategic raw materials. CRMA positions UNFC as the classification tool, mandated for use on results from National Exploration Programmes, extractive wastes from closed facility, and for risk monitoring and mitigation. CRMA also requires the application of UNFC by industry, as a recognition criterion for Strategic Project application, which encompass extraction, processing, recycling, and substitution projects. On that note, recognized Strategic Projects benefit from priority status through accelerated permitting, coordinated financial support, and enhanced regulatory backing. However, these projects must be evaluated consistently across Member States, monitored over time, and assessed not only in terms of economic viability, but also with regard to environmental, social, governance, and supply chain risks. This creates a clear need for a harmonized, robust, and policy-relevant classification framework capable of supporting decision-making at multiple levels of governance, to which UNFC is suitable for. Therefore, CRMA is read as an accelerator to this research, with an established need for harmonized and quality reporting in UNFC at EU levels, and across the whole critical raw materials supply chain.

Within this broader European landscape, Italy, similar to many other EU Member States, offers a notably common case of decentralized raw materials data, without a binding national classification and reporting system. In addition, Italy has a strong manufacturing industry and therefore requires uninterrupted and secure supply of critical raw materials. Italy initiated action through regulatory reforms to tackle this matter and deliver on the CRMA objectives, notably through Decree-Law No. 84/2024. Yet, work is still in progress. With that said, UNFC and more broadly raw materials classification, are relatively new, underexplored, and unused in Italy. Hence, throughout this dissertation, Italy has been selected as the testing field for exploring how consistent, coherent, and harmonized classification of raw materials across the whole supply chain,

can support the principles of sustainable resource management, and in achieving the objectives of CRMA.

The dissertation therefore covers the application of UNFC across all its provisions in CRMA. It first addresses the role of UNFC in the context of Strategic Projects, through structured methodologies designed to serve three distinct but interrelated user groups: project promoters, UNFC expert evaluators, and policymakers at European Union level. The work on Strategic Projects also includes a workable assessment model for supply potential and associated risks from designated Strategic Projects based on UNFC. The research extends the application of UNFC to National Exploration Programme. Exploration is a critical yet often weakly integrated component of raw materials policy, as early-stage projects are characterized by high uncertainty and limited data. The dissertation presents a tailored methodology for applying UNFC to exploration results. Beyond primary raw materials, the research also addresses the growing importance of secondary raw materials, particularly the application of UNFC to extractive waste, in the context of CRMA's national circularity measures. Additionally, the dissertation further proposes a UNFC-based monitoring framework aligned with the risk monitoring and mitigation provisions as per CRMA. The methodology is designed to monitor extraction, processing, and recycling critical raw materials projects over time. A national monitoring template tailored to the European context is also proposed, to illustrate how UNFC can be embedded within administrative and reporting processes to support proactive risk mitigation.

The overarching objective of the dissertation is to contribute to the practical application of UNFC in support of sustainable resource management through full alignment with the objectives, measures, and monitoring requirements of CRMA. Using Italy as a case study, the research develops scientifically robust, technically sound, and replicable approaches for integrating UNFC into national raw materials management frameworks. While grounded in the Italian context, these approaches are developed to be transferable to other EU Member States facing similar institutional, regulatory, and data challenges. The core research question driving the work examines how UNFC can support the European Union in translating raw materials data into structured knowledge and actionable policy-relevant intelligence for the sustainable management of critical raw materials projects, thereby contributing to the attainment of CRMA objectives.

A key outcome of the dissertation is the development of a first-of-its-kind Italian raw materials inventory based on UNFC. Drawing on the methodologies developed throughout the dissertation, the developed UNFC-based Italian raw materials inventory demonstrates how data from diverse sources can be harmonized within a single UNFC-based structure. Ultimately, the coverage of the whole supply chain supports the development of national raw materials inventories, based on various data sources and types. If inventories from all Member States incorporate UNFC, these could be therefore aggregated into a singular EU-level raw materials inventory, rendering the raw materials intelligence at EU scales more effective. In the case of the Italian raw materials inventory, it provided not only a snapshot of the critical raw materials potential, but also a dynamic tool for strategic planning, policy evaluation, and EU reporting. To

facilitate consistent application, the research also developed UNFC decision-trees aligned with Italian mining legislation and proposed a national UNFC guidance template.

UNFC offers a robust, flexible, and policy-relevant foundation based on a common raw materials language. The dissertation therefore provides both conceptual and practical contributions, with methodologies that can be adopted by other Member States and scaled to European level. At the same time, it opens avenues for the integration of secondary raw materials and international supply chains into UNFC-based inventories. Finally, the dissertation contributes to ongoing literature around advancing applied resource classification within an active regulatory setting and to policy practice, by offering concrete pathways for embedding UNFC within evolving European raw materials landscape.