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National Mineral Waste Databases as an Information Source for Assessing Material Recovery Potential from Mine Waste, Tailings and Metallurgical Waste

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Abstract: We examined national mine waste registries from 7 European countries, created to fulfil the requirements of the 'Mine Waste Directive' (2006/21/EC), for their potential use as an initial source of information for the valorisation of specific mine waste deposits for their resource recovery. A set of parameters for mine waste valorisation were defined and divided into three groups: the 'basic', the 'metal-centric' and the 'material-centric' group. The 'basic' group of 19 parameters consider properties of the mine waste deposit, including location, history, homogeneity, quantity etc, while the other two groups relate to the two desired material recovery types. The 'metal-centric' group of parameters contains the 6 parameters needed to preliminary assess the potential to valorise mining waste for metal extraction, while the 'material-centric' group contains the 9 parameters needed to consider use of mining waste for the production of different construction materials. National mine waste registries from Slovenia, France, Spain, Italy, UK, Hungary and Portugal were reviewed to determine whether they contain information about each of the parameters. In line with the objectives of the Mine Waste Directive, the national mine waste registries were developed to reduce or prevent environmental damage, and not to enable resource recovery from mine waste. Registries contain most of the information for the parameters in the 'basic' group, less information for the parameters in the 'metal-centric' group, and almost no information to define parameters in the 'material-centric' group. The conclusion is that national mine waste registries could serve only as an initial source of information, and more detailed information must be obtained from other sources. This misses an opportunity to see these sites as a resource, and not only as a potential source of pollution, given the urgent need to find alternative stocks of metals within the EU.

Keywords: tailings; mining; resource recovery; construction materials; metals; raw materials

1. Introduction

The global mining industry is facing several challenges today. For example, the decreasing average grade of mined ore, and the inaccessibility of the deposits, whether being in areas unfavourable for humans to work (i.e., ultra-deep deposits, under the sea, etc.) or where current land use prevents mining. The latter, especially, limits the development of the European mining industry in many countries. Although the mining industry in Europe has been declining over the last few decades, Europe has a long-lasting mining tradition. The oldest mines in Europe are more than 5000 years old, and a golden age for mining was the period of industrial revolution in 19th century [1]. However, due to the economic and environmental pressures, many mines in Europe have been closed down in the 19th and 20th century, and their legacy are, among others, mine waste rock (the material that is extracted but not processed), tailings (material rejected during mineral processing) and metallurgical waste deposits. In this paper, all these types of waste are generally classified as 'mining waste'.

Mineral processing and metallurgical technology in the past were not as efficient as they are today. What was regarded as waste in the past, often can be regarded as quality ore today. For example, Mudd [2] reported that the average grade of mined Cu ore in Australia was 15–25% from 1842 to 1880, and then gradually decreased to around 4% between 1880 and 1940, dropping to around 2% by 2008, while during this time, the production of Cu ore and waste rock were steadily increasing. Today, the largest Cu open pit mines can economically extract Cu ores below 1%. A similar pattern is also observed for Au. In Australia ore with 15–30 g/t Au were extracted during 1850 to 1910, dropping to around 15 g/t during 1910 to 1940, and steadily decreasing to 1–2 g/t in 2008 [2]. In addition, current technologies require a greater variety of raw materials than were needed in the past. In ancient times, from the Bronze Age to the beginning of Medieval times, only seven metals were required to meet human need (Fe, Cu, Ag, Sn, Au, Hg and Pb), with an additional five (Zn, As, Sb, Pt and Bi) being required in Medieval times. Today, almost every naturally occurring element in the periodic table is needed in order to produce all types of goods used by the society [3]. This means that many elements needed to produce new technologies, electronic devices, green technologies, computing etc. were completely disregarded even 50–60 years ago and were deposited as mine wastes (Figure 1). Prime examples are semiconductors (e.g., Ge and Ga), Rare Earth Elements (e.g., Ce, Nd, Eu, Er, Lu) or so-called energy elements, needed for batteries (graphite, Co, Li) [4]. The American Chemical Society [5] has also presented a similar list of Endangered and Critical elements. Elements in this list are grouped into three groups: those which could face limited availability due to future risks to supply (28 elements), those for which supply is at risk due to increased use (7 elements) and finally elements for which future supply is predicted to be at serious risk in the next 100 years (9 elements). The EU also publish its own list of critical raw materials [6], and this list is regularly updated. The 2017 list contains 27 different non-energy raw materials, because risks of its supply shortage and their impacts on the EU economy are higher than those of the other raw materials.

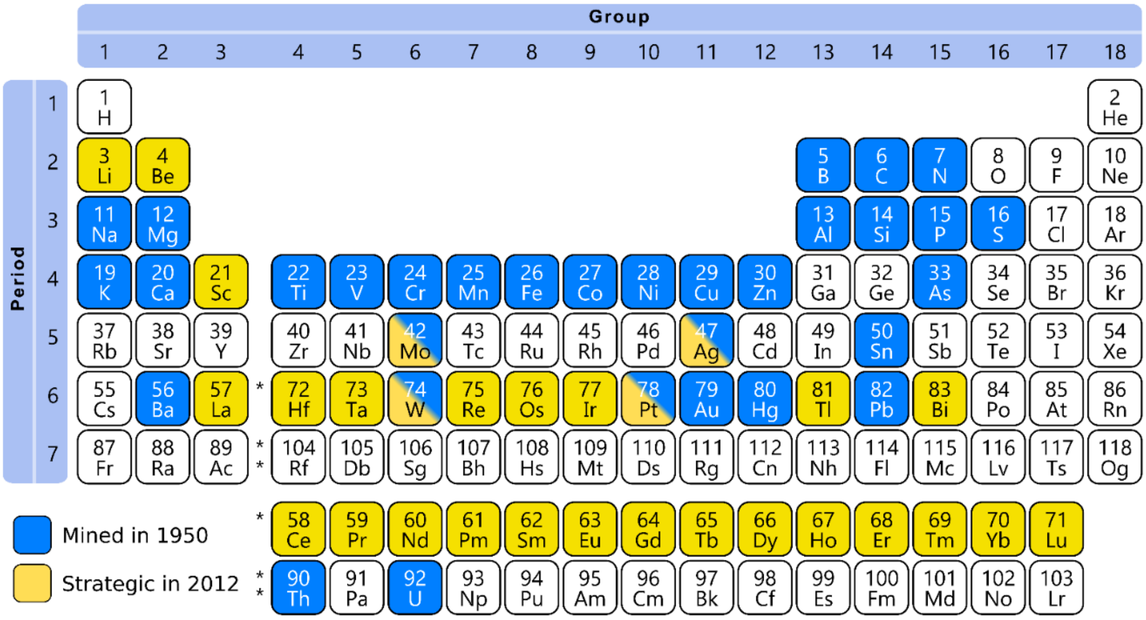

Figure 1. The need of minerals through time (adapted from [7]). Strategic elements were critical elements for the EU economy in 2012.

Very efficient mineralurgical, pyrometallurgical and hydrometallurgical processes have been developed for the recovery of metals from low-grade ores and wastes in the last two decades [8–11], such as in situ leaching, dump and heap leaching, hydrometallurgical processes and agromining, among others. An alternative area of development has been in relation to contaminated land remediation technologies, Sapsford et al. [12] offer a review of many of these approaches and assess their limitations and constraints and technology status. One method of particular interest is the application of electrokinetic techniques, which have potential applicability to the fine-grained materials often found in extractive industry residues. Peppicelli et al. [13] have recently published results of an experimental study of the changes in metal speciation and mobility during electrokinetic treatment of industrial wastes. They also consider the implications of this approach in terms of remediation and resource recovery noting that this type of approach has the potential to convert waste materials into assets by transforming them into viable ore deposits [13].

It is evident that some old abandoned mine waste deposits could be increasingly relevant as sources for raw materials [14], and some of them could, by today's standards, be considered as low-grade ores. Their easy access (located on the surface without significant overburden), already crushed (no need for primary crushing) and potentially containing ore grades which can today be economically exploited, makes them interesting materials for possible future valorisation for resource recovery. If located close to consumption centers, such materials can also potentially be used in construction or as a source for production of construction materials [15]. These deposits are usually located next to historic mines, where the natural environment has undergone many changes in the past and can pose a potential source for future dispersion of pollutants into the environment. Therefore, there may be an advantage in combining resource recovery from mining waste deposits with site rehabilitation processes. This has also been recognised by the EU, funding several projects dealing with material recovery from mine wastes whether, for example, through the Horizon 2020 programme (i.e., Smart Ground or Remediate projects) or the EIT Raw Material network (RIS-RECOVER, RIS-CuRE, RIS-ALiCE and many others).

However, little is generally known about the physical and chemical characteristics of mine wastes, particularly in older deposits. The same is true for their composition below the surface, homogeneity and any secondary processes following deposition. The lack of reliable data about these deposits, combined with the ambiguity in many countries regarding which legislation takes precedence for resource recovery from mine waste deposits (i.e., mineral extraction, waste management, environmental protection etc.) seems to present a barrier to their large-scale reuse. In order to examine the potential for resource recovery from mine waste it is therefore essential that a detailed understanding of the composition and properties of these waste is developed.

One potential source of the composition data and properties of mine wastes is the inventory of mine waste deposits available for each EU member state, and produced according to the EU Directive 2006/21/EC [16] (often referred to as "The Mine Waste Directive"). This directive was a response to two large environmental disasters caused by improper tailings management, the Aznalcollar tailing dam collapse (Spain, 1998) [17,18] and the Baia Mare cyanide spill (Romania, 2000) [19], and one of its principal aims is to prevent similar disasters in the future. According to article 20 of this directive all EU member states are obliged to produce an inventory of closed and abandoned (mine) waste facilities which cause or have a potential to cause serious negative environmental impacts or pose a threat to humans. Such inventories are required to be updated regularly and made publicly available from 1 May 2012.

Another EU document published in 2008 details the Raw Materials Initiative (COM(2008)699) [20], this was not directly linked to the previously mentioned 2006/21/EC directive [16], and was adopted as a response to a perceived potential global threat to the uninterrupted supply of mineral resources which are vital for the EU economic development. This initiative defines three pillars regarding the sustainable supply of raw materials for the EU economy: a fair and sustainable supply from global markets, a sustainable supply from within the EU and a resource efficiency and sustainable supply from secondary raw materials through recycling. This paper addresses the last pillar of the Raw Materials Initiative, because recycling of old and abandoned mine wastes deposits, which are abundant within the EU due to long-lasting mining tradition, could be an interesting source of raw materials for the EU economy. However, before actual mine waste recycling projects can be undertaken many steps are required, the first of which consists of collecting basic information about individual mine waste deposits.

Therefore the main objective of this study is to review a sample of these national inventories, and to provide an assessment of their suitability as an initial source of data for potential resource recovery projects, while a secondary objective of this study is to define the set of most important mine waste valorisation parameters, which could be potentially contained within the abovementioned registries. This will be useful to policy makers who will benefit from an improved understanding of the most critical national mine waste valorisation data gaps and determine steps forward, while the metallurgical and extractive industry will benefit from an initial assessment of the data availability for a set of EU countries to obtain information about the potential for resource recovery from mine wastes.

2. Materials and Methods

The materials used in the study were gathered by literature review, information collected in the extractive waste inventories of seven EU member states, listed in Table 1 (France, Hungary, Italy, Portugal, Slovenia, Spain and United Kingdom) and enquiries to different experts in public and private institutions. These countries were chosen to offer coverage of a range of varying geological conditions, geographical locations and mining legacies in the EU. The work was carried out in the COST (European Cooperation in Science and Technology) action MINEA (Mining the European Anthroposphere), working group 2.1 (WG2.1) - "Resource potential in residues from extractive industries". The steps conducted in this research are presented schematically in Figure 2, and are described in more details in the chapters 2.1 and 2.2.

Figure 2. Methodological approach and the different steps conducted in this study.

2.1. Defining Key Mine Waste Valorisation Data Parameters

In order to evaluate the use of national mine waste inventories as a source of data it was necessary to define the parameters of mine wastes that would be needed to understand their potential for resource recovery. This objective was achieved through a literature review, workshops and review of best practices. A final list was then formulated and refined by experts in the COST action MINEA, WG2.1. The literature review included academic, policy and practice literature, and examples from actual material recovery projects, which were used to develop an initial list of the parameters used to valorise mineral resources. A key study identified was presented by Panagiotopoulou et al. [21], who describes several cases of material recovery from mine waste within the EU and defined the most crucial steps from the idea towards realisation. Other publications used for the literature review were different key reports from the topic [7,14,22–26], as well as CRIRSCO [27], JORC [28], PERC [29] and UNECE [30] classification codes for reporting exploration results, mineral resources and reserves and the references, contained in aforementioned documents. The parameters identified included those related to basic site and commodity information, historical framework, data collection methodology, extractability and accessibility of the secondary resources, the policy and legislative environment, as well as relevant chemical and physical properties. By accessibility we mean if there are any legal, environmental, or societal obstacles for material recovery project, and by extractability we mean whether the material can be extracted and reallocated without posing serious risk to workers and environment. The initial list of parameters was further evaluated and refined by between 40 and 50 experts from the fields of mining, geosciences, material processing and others, who participated in a series of workshops, organized or co-organized by the authors of this study and funded by MINEA network: Ljubljana (23–24.2.2017), Vienna (14–15.12.2017) and Budapest (26–27.11.2018) working group meetings; workshop/conference "Knowledge base for material resources/reserves for construction and demolition waste, landfills and waste incineration residues recovery" (Prague, 24–25.1.2019); workshop "Knowledge base for anthropogenic resource and reserve estimates II" (Brussels, 20.3.2019); and conference "Recovery of secondary raw materials from mining residuals and waste, case studies and best practices" (Berlin, 23.5.2019). During meetings and workshops this evidence was supplemented with data from case studies of resource recovery from mine waste in the EU and globally, with an emphasis on the experiences from different cases from Greece (e.g., Kassandra, Kirki, Lavrion, Tsagli, Domokos, Zidanio, Mantoudi mining areas and others) and from projects identified as relevant by the French Geological Survey BRGM (Pinto Valley, Arizona, USA; Disputada Mine, Chile; Kaltails Project, Australia; Kasese, Uganda, and others). This allowed an identification of the key data needed to implement successful resource recovery from mine waste. The candidate parameters were then further selected and discussed in two moderated roundtable discussions, held in Ljubljana in February 2017 and in Vienna in December 2017 iteratively with the review of inventories. This process resulted in the final list of key mine waste valorisation parameters presented below.

2.2. Review and Assessment of National Mine Waste Inventories

We carefully examined national mine waste inventories (made according to the EU directive 2006/21/EC obligations [16] to ascertain the availability of key data parameters for a preliminary assessment of resource recovery potential of specific mine wastes. Major data gaps on critical information for deposit ranking were identified, and according to the findings recommendations made, to assist a collection of initial information, needed for mine wastes resource recovery project in the future. Seven member states national inventories were reviewed (Table 1) and were compared against the list of parameters needed to evaluate potential for resource recovery, and, where necessary, experts from national authorities responsible for the inventories were consulted to supplement the review (Table 1).

3. Results and Discussion

A set of key mine waste valorisation parameters for material recovery, which could be defined from the information contained within the national mine waste registries, were defined and divided into three groups using an approach similar to that presented in Panagiotopoulou et al. [21]. The 'basic' group of parameters describes the characteristics related to the mining waste deposit, including the location, type of material, data collection methods, history of mine etc., as well as the main drivers and barriers for resource recovery, e.g., legislation, land use restrictions, the availability of data etc. (Table 2). The 'metal-centric' group includes crucial information about properties of mining waste material that should be considered to further extract valuable minerals/metals. The chemical and mineralogical composition of the tailings defines the potential metallurgical or chemical extraction process, while the physico-chemical properties mainly defines the pre-processing activities (drying, grinding, additives, homogenisation, separation etc.) needed before commodity extraction. Finally, the 'material-centric' group describes the key parameters required to assess the feasibility of using mine waste for products for the construction sector. The parameters describing the composition of the material allow us to define the material's ability to form clinker minerals and other binding agents during the production process, as well as the needs of specific additives. Parameters related to the physico-chemical properties allow us to estimate the costs and equipment needed to pre-process source material (grinding, separation, screening etc.). The determination of physical and chemical properties of the potential end-products allows the assessment of the economic viability of resource recovery.

Table 1. Responsible organisation for preparing and keeping the National mining waste registries and basic information about the registries.

Country	Abbreviations	Name	Reference	Total No. of Sites	No, of Sites with Detailed Assessment	Measured Substances
France	GEODERIS	GEODERIS	[31–33]	3144	200	Pb, Zn, As, Cd, Cr, Hg, Cu, V, Mo, Co, Ni, Se, Sb, Tl
Spain	IGME	Instituto Geológico y Minero de España	[34]	370	370	Pb, Zn, As, Cd, Cr, Hg, Cu, V, Mo, Co, Ni, Se
Italy	ISPRA	Istituto Superiore per la Protezione e la Ricerca Ambientale	[35]	650	220	Asbestos, Ag, As, Cd, Cr, Co, Cu, Hg, Mn, Pb, Ni, Tl, Zn, Sb, Sn, Be, V, CN, Fluoride, Aromatic compounds, TPH C>12
UK	BGS EA NIDoE	British Geological Survey Environment Agency (England and Wales) Scottish Government Northern Ireland Department of Environment	[36–40]	404	0	Harmful substances are measured in downstream water and not in waste material
Hungary	MBFSZ	Magyar Bányászati és Földtani Szolgálat	[41]	1046	71	Ag, Au, As, Be, Cd, Cr, Cu, Hg, Mo, Ni, Pb, Sb, Se, Sn, Th, Tl, U, Zn
Slovenia	ARSO	Agencija Republike Slovenije za okolje	[42–44]	173	78	As, Ba, Cd, Co, Cr, Cu, Hg, Mo, Ni, Pb, Zn
Portugal	DGEG, EDM	Direcção Geral de Energia e Geologia	No references	199	39	Cd, Cu, Ni, Pb, Zn, Cr total, Cr6+, Hg, Co, Mo, As

Table 2. Key identified mining waste valorisation parameters.

	Parameter ID	Short Description	Sub Division
Mine Waste Basic Valorisation Parameter	B1	Location, history, mining and processing technology of the site	
	B2	Volume, area and structure of the existing waste deposits	
	B3	Reason for which the mine was abandoned	
	B4	Homogeneity of the tailings	
	B5	Methodology of data collection	
	B6.1	Environmental impacts of mine waste deposit	Actual physical
	B6.2		Potential physical
	B6.3		Actual chemical
	B6.4		Potential chemical
	B6.5		Need for remediation
	B6.6		Remediation costs
	B7.1	Site extractability	Possibility for safe extraction and waste relocation
	B7.2		Revegetation status
	B8.1	Site accessibility	Ownership
	B8.2		Special permits required
	B8.3		Land use restrictions
	B8.4		Other legislative barriers
	B9.1	Data availability	Data managing authority
	B9.2		Language(s)
Metal-Centric Val. Param.	M10.1	Chemical and mineralogical composition	Matrix
	M10.2		Commodity elements
	M10.3		Trace elements
	M11.1	Physico-chemical properties	Grain size distribution
	M11.2		Moisture content
	M11.3		Redox state at different pH
Material-Centric Valorisation Parameters	C10.1	Chemical and mineralogical composition	Type and content of alkali ions
	C10.2		Type and content of alkaline earth ions
	C10.3		Type and content of silicon
	C10.4		Type and content of potentially toxic elements (PTEs)
	C10.5		Type and content of organic substance
	C11.1	Physico-chemical properties	Moisture
	C11.2		Grain size distribution
	C12.1	Potential final products specifications	Mechanical properties
	C12.2		Thermal properties

While reviewing national mine waste registries we identified two special cases. Firstly in Italy, the data for the number of sites with detailed assessment (Table 1) included sites from the whole country which had been subjected to either research projects, or been reclaimed (completed or ongoing) and all Sardinian sites (data published in 2017 registry update) which had been subjected to an additional assessment. In particular in 2009 A.R.A.G.N.A. method (Relative risk analysis applied to abandoned mining sites in Sardinia) was developed by Sardinia Region, considering the peculiarities of mining sites. Currently applied to Sardinian mining sites, the method provides detailed instructions concerning sampling procedures and methods, data processing, characterization, etc. The method has been developed for risk assessment, thus there is a lack of information about minerals and elements that could be of industrial interest. Detailed information is not available in the report published by ISPRA. Secondly, four different authorities are managing the mine waste registry in the UK, with each one is responsible for a specific geographic region, they also used slightly different risk assessment methodologies. The Northern Ireland risk assessment measured downstream water and sediment quality from sites mined for: bauxite, copper, iron ore, lead, coal, lignite and baryte, but no detailed assessment of wastes themselves have been made. Risk assessment was based on the use of Hazard Quotients and As, Cd, Cr, Cu, Fe, Ni, Pb and Zn have been tested. In Scotland, England and Wales the risk assessment was based on elevated metal concentrations in water catchments and known locations of mines, supplemented with local authority information which identified additional sites to be included due to explosive risk or instability.

Key valorisation parameters availability in reviewed national mine waste registries is shown in Tables 3 ('basic' group), 4 ('metal-centric' group) and 5 ('material-centric' group). The analysis of the information in Table 3 shows that the main objective of creating national mine waste inventories was to decrease their potential and actual environmental hazard and impact, with the aim of determining the specific tailings in most urgent need of remediation, and to a lesser extent for their potential for resource recovery in the future (Figure 3a).

Mine waste deposits were generally classified according to their potential for further mobilisation of harmful substances to deposits where there is no or low risk, and deposits of higher risk. Higher risk sites were then assessed in greater detail and, as a result, have more data available. This approach was taken by the majority of countries (Figure 3b). However, the exception is Spain, where only larger deposits were assessed, and UK, where detailed information about specific mine waste deposits are not contained in the national mine waste inventory, but in other databases and reports collected on ad-hoc basis. This demonstrated that national mine waste inventories are an incomplete, and inconsistent, data source for mine waste valorisation for material recovery. The most useful information contained in the inventories is the location of the deposit, the general description of the material, and the estimated quantity of such material, while the detailed assessment of individual deposits focused more on environmental parameters (i.e., concentrations of potentially toxic metal (PTEs), and results of leaching tests, sediment mobilisation or similar). It is apparent that only Italy and Spain have more comprehensive information regarding all listed mining sites in the inventory. In France, Hungary and UK the amount of data for each site is predominantly linked with assessment of the site's environmental risk. In the UK the environmental risk determination was based by presence of receptors and therefore is not necessarily an indication of the concentrations of metals in the wastes; there are thousands of abandoned metal mines in England and Wales yet only around 150 on the inventory [39]. In Slovenia the size of sites was the most relevant parameter (others parameters are linked to the specific type of mine waste), determining further data gathering protocol and in Portugal the data availability is limited to the remediated and active sites.

Another important factor is the local policies and regulations pertaining to resource recovery from mine waste, which is also almost completely disregarded in the national inventories. One very important aspect is the ownership of the tailings (i.e., state, county, municipality, private entity etc.), as well as the indication of key legislations and policy, which regulates mine waste exploitation and processing (i.e., mining legislation, spatial planning on national and local level, environmental protection, waste management etc.). Currently it seems that many relevant regulations apply, including those related to mineral extraction, waste management, land use planning and environmental protection, and practices are not harmonised within the study area (Figure 3c). For example, it is not always apparent whether any resource recovery would be considered as mineral extraction, waste management or remediation, all of which have different regulatory regimes in place. Therefore it is rarely clear which stakeholders would need to be consulted to examine the potential of resource recovery, and many different regulations could apply, making the permitting process less transparent and potentially much more costly and protracted.

Data from Table 4 shows that key 'metal-centric' and 'material-centric' resource recovery valorisation parameters are generally available for larger and high-risk sites, but are mainly focused on the analysis of PTEs. However, the mine waste deposits could be very heterogeneous, depending on the history of ore extraction and processing, as well as the occurrence of secondary processes in the waste column, but the information of PTE levels are generally available only from surface materials [45]. This also limits the usefulness of mine waste registries as a source of information for metal extraction beyond providing only brief information in order to plan more detailed investigations. Another drawback is also that national mine waste registries generally do not contain information about metals that are not classified as PTEs. Many of such metals are regarded as critical elements today (e.g., Li, Ge or rare earth elements) and mine waste dumps could be a source of these raw materials.

Even less information about mine waste is provided regarding the key 'material-centric' valorisation parameters (Table 5). Except for a few cases from the Italian inventory, the information such as content of alkali ions, redox potential, silicon, organic substance etc. was not assessed at all. The only exception are levels of PTEs, measured in larger sites or sites with higher environmental risk. Therefore, we can conclude that national mine waste registries are not useful initial source of information to valorise mine waste for potential material-centric recovery (i.e., to produce construction materials), but do perhaps provide a basis for further search for information from other sources (i.e., papers, reports, projects, archiver etc.).

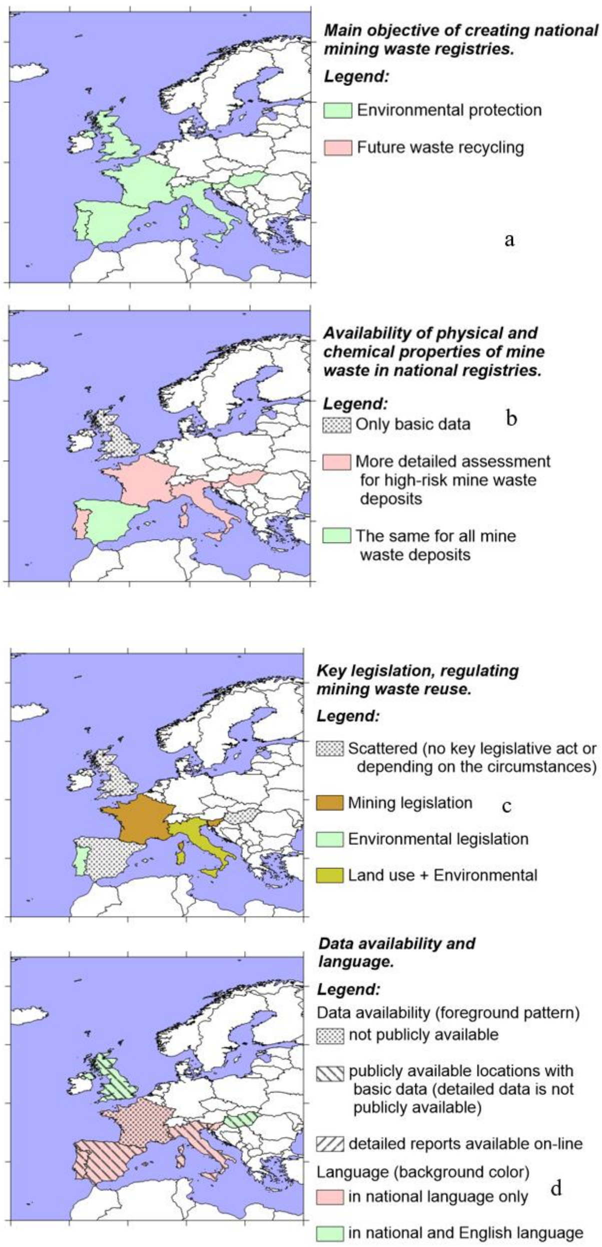

Figure 3. (a) The main country vision for creating national mining waste registries. (b) Availability of detailed mine waste deposit data. (c) Key legislation which regulates resource recovery from mine waste (simplification). (d) Data availability and language used in national mine waste registries.

While assessing specific datasets from the national registries, it also became evident that different countries has different data access policies (Figure 3d). While most countries provide information about locations of mine waste deposits and basic characteristics, it is still very hard to access detailed reports, which contain the information needed for the potential assessment of resource recovery from mine waste. Even if such reports are publicly available, they cannot be found in one place, but are scattered across different locations (i.e., web pages, libraries etc.). Another potential barrier is language, where the information and reports are, with the only exception of Hungary, provided only in the national language. UK, France or Spain are, of course, a special case here, because their languages can be regarded as world languages. But it is not the case for smaller countries such as, for example, Slovenia or Portugal. This barrier can be overcome by hiring translation services, local experts, or use electronic translator services, but initial identification of potential future mine waste recycling projects by international companies can be much easier if data are available in a commonly spoken language. Therefore we can conclude that countries could also contribute to the use of mine waste registries outside the originally designated scope of environmental protection by placing searchable data online in one place, along with all non-confidential details, and to also make them available English. This would be a significant step forward in providing mine waste data in the context of future resource recovery and reuse, and would move towards a more harmonised approach across the EU.

However, the French example represents best practice in the sense of the amount of data contained in the national mine waste inventory. Investigations on closed or abandoned mine sites and mining waste follow a consistent national framework in France. Sites with a responsible owner are usually documented through the mine lease renunciation document, which establishes the respective obligations of the owner and of the administration. For the much larger number of sites without a responsible party, investigations are led by a public agency (GEODERIS) to identify potential risks at the site (mainly geotechnical and environmental) via a tiered approach. A first level of investigation on all sites leads to a selection of sites based on potential risk (ranking) that require further assessment. Subsequent investigations (second level) are then performed at these sites where an evidence of risk was demonstrated or in cases where actual damage is recognised. The highest level of investigation is where a significant risk of adverse health or environmental impact was identified in the vicinity of the site. It can even be applied to local housing ("maison sur depot") [32] when the property is located on waste. Even if these investigations are led by a specialised public agency, they are carried out on behalf of, and funded by, the administration, which keeps their results out of the public domain until the full cycle of investigations has been completed. This can result in long delays in disclosure of site-scale primary information such as waste data.

Within the analysed countries in this study, the UK is a special case. The national mine waste inventories contains only basic data, based on environmental or human health risk. However the British Geological Survey hold a national dataset (BRITPITS) that includes information on every mine location (as point data) in the UK [36]. However, the mine waste inventories have been compiled, often based on this dataset, by the individual regulatory agencies (Environment Agency, The Scottish Government, and the Northern Ireland Department of Environment). The methods used in England and Wales, and Scotland are similar, whereas that used in Northern Ireland differ in their approach. In England and Wales, and Scotland the data from BRITPITs have been used in conjunction with information held by local authorities and to assess the risk from closed and abandoned mines using a source-pathway-receptor approach. These included leaching, erosion, windblown dust and dermal contact/ingestion providing a pathway for pollution, heap, dam, or pond failure resulting from instability, and smoke, heat, dust and gases caused by flammable materials. The receptors included human health, surface and groundwater, protected ecological systems, property, crops and livestock. This was tested against a series of criteria for serious environmental risk (e.g., based on Environmental Quality Standards for surface water quality, meeting the definition of contaminated land). Potential sites were sought via a proforma that was sent to all local authorities requesting information on the sites in their areas with the potential for inclusion on the inventory. This was used in conjunction with information on the location and volume of mine wastes associated with abandoned mines, as estimated by the British Geological Survey [37], and information on water quality taken from a range of sources to develop the inventory. The approach in Northern Ireland was similar except that a hazard quotient was used in the risk assessment process when examining the source-pathway-receptor linkage [38].

Based on the findings of this study, a recommendation for policy-makers and regulative bodies would be to make national mining waste registries available online, together with at least basic data in English. An EU-wide assessment of the resources available in mine wastes is needed to inform decision makers on the management of mineral resources, whether to prioritise new, efficient methods for extracting resources from wastes, or changing policy to simplify resource recovery in the case of expressed interest from the private sector. Detailed information being compiled on a case by case basis does not enable a national or EU-wide strategic assessment of the potential value in these sites and whether they could alleviate some of the concerns regarding raw material supply security from domestic sources. Currently, case by case data that has been collected makes a persuasive case for resource recovery especially where sites are causing adverse environmental impacts, and the potential release of land being used for waste storage and resource recovery can be combined with site remediation. Without this EU-wide assessment it is very hard to assess the potential for raw material supply from mine waste deposits. A shift of scope from environmental protection towards including consideration of material recovery from abandoned mine waste sites is needed in any possible future nation or EU-wide data collection. In the case of potential new data collection or national mine waste registry updates it is suggested that the collection of the following information should be prioritized first: more detailed assessment of the quantities of specific mine wastes deposits and their homogeneity, levels of commodity elements in mine wastes, determination of parameters describing site accessibility and other missing parameters from the "basic" group of parameters. It is also recommend that a case-wise assessment should be made to collect the parameters needed for consideration of metal-centric or/and material-centric mine waste valorisation and materials recovery.

A further recommendation to those exploring the potential for resource recovery from mine wastes would be to use these national mine waste registries to find basic information about potential suitable sites, and then consult other sources of information (Geological Surveys, regional or local authorities) to obtain more data in order to preliminary valorise specific mine waste deposit sites.

Table 3. Key "Basic" valorisation parameter (Pa.) - data availability in different EU countries (AV - Available, NA - Not Available, NAS - Not Assessed).

Pa.	France	Spain	Italy	UK	Hungary	Slovenia	Portugal
B1	AV only for some sites	AV as short description	AV for most of the sites, detailed for some	AV (1)	AV only in mine closure reports	AV as short description of history of mining site	AV as short description of history of mining site
B2	AV, data quality depends on potential risk	AV	AV if provided by Regional Geological Survey	NA in inventory, but in various publications	Estimation, AV in technical operation plans or individual survey reports	Estimation	AV
B3	NAS	AV for larger mines	NA	NA	NA	AV for high risk sites	AV in selected sites
B4	AV for high risk sites with ongoing remediation	NA	NA	NA in inventory, but in various publications	NA	NA	Visual estimation
B5	AV for high-risk sites (2)	AV (3)	AV for deposits investigated with ARAGNA method (Sardinia)	AV as part of the methodology report	NA	AV	AV for remediated sites
B6.1	AV for potential high-risk sites	AV	AV	AV, based on risk assessment (4)	AV	AV for high risk sites	AV for active mines and remediated sites
B6.2	AV for high risk sites with ongoing remediation	AV	AV	AV, based on risk assessment (4)	AV	AV for high risk sites	AV for active mines and remediated sites
B6.3	AV for potential high-risk sites	AV	AV	AV, based on risk assessment (4)	AV	AV for high risk sites	AV for active mines and remediated sites
B6.4	AV for high risk sites with ongoing remediation	AV	AV	AV, based on risk assessment (4)	AV	AV for high risk sites	AV for active mines and remediated sites
B6.5	AV for potential high-risk sites	AV	AV	AV, based on risk assessment (4)	AV	AV for highly risk sites	AV for risk sites
B6.6	AV for high risk sites with ongoing remediation	NAS	AV for specific sites within the remediation projects	Based on risk assessment (4)	NAS	NAS	AV, but possibly confidential

B7.1	AV for high risk sites with ongoing remediation	NAS	NAS	NA	AV for selected deposits	NAS	NAS
B7.2	NA	AV	AV	NA	AV	AV for risk sites	AV for risk sites
B8.1	AV for sites with no responsible owner	NAS	Data in the Environmental protection and Land use plans	NA, but held in BRITPITS and/or the Land Registry	AV for operating mines	Information is AV in land register	AV
B8.2	According to Mining legislation	NAS	Depending on land use restrictions and site hazard characterization, involving local and national authorities	Mineral extraction is subject to planning – likely to be complicated as may fall under environmental regulation	According to Mining legislation	Depending on land use restrictions and site hazard characterization, involving local and national authorities	Mining waste are not classified as waste in the Portuguese Environmental law
B8.3	According to Mining legislation	NAS	Depending on land use restrictions and site hazard characterization, involving local and national authorities	There may be land use restrictions which could include cultural or ecological designations associated with past mining	According to Mining legislation	Determined in national and municipality spatial plans	Determined in national and municipality spatial plans
B8.4	If reprocessing includes activities outside the scope of mining regulations	NAS	Depending on land use restrictions and site hazard characterization, involving local and national authorities	Waste management and pollution control regulations as well as those protecting the natural environment and cultural assets	If reprocessing includes activities outside the scope of mining regulations	Depending on land use restrictions and site hazard characterization, involving local and national authorities	If reprocessing includes activities outside the scope of mining regulations
B9.1	Data in Table 1						
B9.2	National	National	National	National	National and English	National	National

(1) AV, but with cross-referencing to BRITPITS which details type of mine (open cast, underground) but not detailed technology. (2) A guide with methodology has been published [46]. (3) A guide with methodology has been published [34]. (4) This information is not contained within mine waste inventory, but is available for some sites in other reports.

Table 4. Key "Metal-Centric "valorisation parameter - data availability in different EU countries (AV - Available, NA - Not Available, NAS - Not Assessed).

Pa.	France	Spain	Italy	UK	Hungary	Slovenia	Portugal
M10.1	AV for high risk sites with ongoing remediation	AV, not public	AV for investigated sites	NA, but AV for a limited number of mines in other documents	AV	AV	AV for active sites and selected remediated sites
M10.2	AV	AV, not public	AV for investigated sites	NA, as above	NA, only for specific sites in other reports	AV for high risk sites	AV for active and selected remediated sites
M10.3	AV for high risk sites with ongoing remediation	AV, not public	AV for investigated sites	NA, as above	AV for red mud tailings and for other sites containing PTEs	AV for high risk sites	AV for active and selected remediated sites
M11.1	AV for high risk sites with ongoing remediation	AV, not public	AV for investigated sites	NA, as above	AV	Visual estimation for some sites	AV for active and selected remediated sites
M11.2	AV for high risk sites with ongoing remediation	NAS	AV for investigated sites	NA, as above	NAS	NAS	AV for active sites
M11.3	AV for high risk sites with ongoing remediation	pH and electrical conductivity only, not public	AV for investigated sites	NA, as above	NAS	NAS	AV for active sites

Table 5. Key "Material-centric" valorisation parameter - data availability in different EU countries (AV - Available, NA - Not Available, NAS - Not Assessed).

Pa.	France	Spain	Italy	UK	Hungary	Slovenia	Portugal
C10.1	NAS	NAS	AV as potential residues	NA, but AV for a limited number of mines in other documents	NAS	NAS	NAS
C10.2	NAS	NAS	AV as potential residues	NA, as above	NAS	NAS	NAS
C10.3	NAS	NAS	AV as potential residues	NA, as above	NAS	NAS	NAS
C10.4	NAS	AV, not public	AV as potential residues	NA, as above	AV for larger waste sites	AV for high risk sites	NAS
C10.5	NAS	NAS	AV as potential residues	NA, as above	NAS	Visual estimation for some sites	NAS
C11.1	AV for high risk sites with ongoing remediation	NAS	AV for investigated sites	NA, as above	NAS	NAS	NAS
C11.2	AV for high risk sites with ongoing remediation	AV, not public	AV for investigated sites	NA, as above	NAS	Visual estimation for some sites	NAS
C12.1	NAS	NAS	AV for investigated sites	NA, as above	NAS	NAS	NAS
C12.2	NAS	NAS	AV for investigated sites	NA, as above	NAS	NAS	NAS

4. Conclusions

In this study we examined national mine waste registries from seven European member states (France, Hungary, Italy, Portugal, Slovenia, Spain and United Kingdom), developed in accordance with the Mine Waste Directive (2006/21/EC), for its potential use as an initial source of information for the valorisation of specific mine waste deposits for material recovery. Despite the amount of data available, collected for the preparation of national mine waste registries, coverage varies from country to country. Due to the original motivation for its collection being the prevention of PTEs mobilisation into the environment and the long-term mine waste deposit stability, potential future resource recovery or reuse was not considered as the priority. This is reflected in the data content, which makes the national mining waste inventories only a potential source of basic information, i.e., location of mine waste, main based commodity and tailing deposit volume. Only limited, or even no, information is provided in the regard of homogeneity, grain size distribution or content of substances which are not regarded as pollutants, but are important for potential future use of such material (alkali and alkaline earth ions, moisture, redox state etc.). In most cases, there is not sufficient data that can be used in assessing projects for resource recovery from mining waste. Also the legislative, regulative and policy frameworks for material recovery from mine waste are not homogeneous across the EU. The results of this study can be useful for policy makers that could benefit from it by obtaining the most critical nation-wide mine waste valorisation data gaps and determine steps forward, while metallurgical and extractive industry could find the first glimpse of data availability for a set of EU countries to obtain information about mine waste potentials, especially in the light of latest developments in tailings and materials reprocessing (including hydrometallurgical processes, bioleaching, in-situ leaching and others).

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