European mineral intelligence – collecting, harmonizing and sharing data on European raw materials

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Abstract: The major share of raw materials needed to sustain our present lifestyle and even more importantly, required for the crucial green transition, are sourced outside Europe. The European Commission aims to enhance Europe's resilience and strengthen domestic sourcing. Although Europe has a long tradition of mining and extractive activities, it is acknowledged that there are several challenges to achieve European sourcing of certain raw materials such as the critical raw materials. A basic prerequisite to enable access to domestic raw materials is information on raw material occurrences, current and past mining activities, resources and reserves. The Geological Survey organizations (GSOs) of Europe play a key role in generating, compiling, gathering and storing the most up-to-date information as well as long-term data series on raw materials at national and regional levels. Over the last decade, the GSOs have joined forces and taken essential steps to harmonize and share data on raw materials. The results of this co-operation are illustrated as interactive maps on the European Geological Data Infrastructure (EGDI). This paper describes the data compiled in co-operation between the GSOs, and analyses the strengths and weaknesses of, as well as opportunities for and threats towards, the data.

In September 2020, the European Commission published, for the fourth time, an updated list of raw materials critical to the European Union, the so-called critical raw materials (CRM) (European Commission 2020). The European Commission defines critical raw materials as those that are of **significant economic importance for key sectors** of the European economy and whose supply is at **high risk** of interruption due to the concentration of raw materials and/or metal production, and typically because there are **no (viable) substitutes.** In view of the increasing global competition for resources and the fact that most of these CRMs are sourced and supplied from outside the European Union while increasing market concentration is observed (e.g. Mateus and Martins 2021; Shuai *et al.* 2022; Zhang *et al.* 2022), the European Commission presented its strategy to improve Europe's resilience (European Commission 2020). This renewed strategy identifies 'strengthen the sustainable and responsible domestic sourcing and processing of raw materials in the European Union' as one of ten actions derived from the three-pillar approach of the 2008 Raw Materials Initiative. These three pillars are:

(1) access to raw materials on world markets at undistorted conditions;
(2) foster sustainable supply of raw materials from European sources;
(3) reduction of the EU's consumption of primary raw materials (European Commission 2008).

Europe has a long tradition of mining and related activities with evidence for this dating back to the Bronze Age (further information can be found on a map of tourist mine sites in Europe, hosted at EGDI). Although many mines and quarries have been closed over the last decades, many operations are still in production with some newly opened and some under development. Examples are Boliden Aitik (Cu, Au, Ag) in Sweden, KGHM Polska Miedź S.A. Kupferschiefer (Cu, Ag) in Poland, Clara Mine (Ba) Wolfach in Germany, and W Resources (W) Régua in Portugal. However, there are several challenges to achieve a situation with European sourcing of many of the CRM. Challenges

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include, but are not limited to, the lack of appropriate geology, inadequate venture capital investments in both exploration and mining, complex legal systems and time-consuming procedures, insufficient public acceptance, and the lack of mineral processing facilities in Europe, for example (Cann 2016; Nieć *et al.* 2022; Yunis and Aliakbari 2022). The situation in Europe is very heterogeneous, as the 2021 Fraser Institute's annual survey of mining companies (Yunis and Aliakbari 2022) shows. Although only a few European countries are represented in the survey, some are among the top performers in selected categories. For example, the Republic of Ireland ranks first on administrative issues, political stability and jurisdictions in 2021, and excellent on geological database and the availability of labour and skills, the latter for which Finland is ranked first, while Sweden is top in terms of the quality of infrastructure. It is recognized that European bedrock carries significant potential for several raw materials, including CRM (Bertrand *et al.* 2016, 2021; Goodenough *et al.* 2016; de Oliveira *et al.* 2021; Horn *et al.* 2021; Mongelli *et al.* 2021). However, more harmonized knowledge across borders is needed to provide an overview of the potential in Europe for raw materials for the green transition.

The quality of available geological databases is an important component in investment considerations, which is well recognized by the Geological Survey organizations (GSOs). Most geological surveys host data on raw materials in their own national or regional territories, often as maps and/or time-series data, and are designed for national and regional requirements. Data are typically organized in different ways from one region to another due to the different geology, varying geological and scientific traditions, and legal and structural frameworks for example. Previous co-operation within the GSOs community in Europe mainly aimed at ensuring interoperability of data and information with joint research projects, strongly supported by the GSOs umbrella organization EuroGeoSurveys (https://www.eurogeosurveys.org/), which has co-ordinated several efforts over the last decade. This has created a common understanding and the foundation for a central database with harmonized and INSPIRE-compliant data on primary and secondary raw materials (note: INSPIRE is the Infrastructure for Spatial Information in Europe; see also European Commission 2010). Such a transnational dataset has attracted the interest of other stakeholders (e.g. public administration, industry, consultants, policy makers at national and European level) and has led to support from the European Commission for further projects (for an overview of these, see Løvik *et al.* 2018 and Wittenberg *et al.* 2022).

The latest efforts have delivered updated datasets and the integration of data on mineral occurrences and mines (known as the Minerals Inventory) with aggregated data on production, trade, resources and reserves (collectively known as the electronic European Minerals Yearbook (e-MYB)) in the same database. Data are stored in a central database called MIN4EU hosted on the European Geological Data Infrastructure (EGDI), and interactive maps published at the associated website illustrate (amongst other things) the contents of this database. The work was carried out under the auspices of a large network programme *GeoERA* (Gessel *et al.* 2018) where more than 45 national or regional GSOs worked together in 15 separate projects. The programme included four projects that focused on different aspects of raw materials, including ornamental stones for sustainable construction, delineating regions of European prospective for critical raw materials (marine and continental), and updating and expanding already existing European mineral intelligence datasets, as well as the associated database and maps (see Wittenberg *et al.* 2022 for more details on the four projects).

This paper focuses on the processes of collection and harmonization of data for updating and expanding the central database MIN4EU. Co-operation within the programme facilitated the integration of project-generated data into national datasets and subsequently transferral to the central database. Vice versa, the database and associated maps can help in pinpointing areas where data are missing and thereby push for further data collection or sharing.

State of the art

Database structure and EGDI

Data can be stored in different ways, historically typically in paper archives, then in digital spreadsheets, and more recently in more or less sophisticated databases, and with different levels of detail, metadata and interlinkages. While building a database on raw materials, the GSOs followed the data model and standards of INSPIRE, e.g. the use of INSPIRE code lists (Esser *et al.* 2021), extended as necessary for this specific purpose. The overall aim was to establish one single access point for European geological information organized in a spatial data infrastructure for Europe, EGDI, by using existing standards for data exchange as defined by the INSPIRE directive (European Commission 2010). EGDI aims to make data FAIR (**F**indable, **A**ccessible, **I**nteroperable and **R**eusable; Wilkinson *et al.* 2016) making them as valuable as possible to end users.

Other databases with similar data

To our knowledge, MIN4EU is the only database that brings together different aspects of data focused on European raw materials, based on national dataset. However, there are other datasets similar in part to those hosted in MIN4EU as well as databases of similar character covering areas outside Europe. Examples are given below and listed in Table 1.

The British Geological Survey (BGS) holds an open access archive (https://www2.bgs.ac.uk/mineralsuk/statistics/worldArchive.html) of world mineral production data dating back to 1913, with data from 1970 onwards available to download in spreadsheet format (https://www2.bgs.ac.uk/mineralsuk/statistics/wms.cfc?method=searchWMS). Mineral production data are also compiled by the Austrian Federal Ministry of Agriculture, Regions and Tourism who annually publish 'World Mining Data' (WMD) (http://www.world-mining-data.info) covering a limited range of commodities and products. GTK, the Finnish GSO, hosts the Fennoscandian Ore Deposits Database (FODD) with an associated web viewer (http://gtkdata.gtk.fi/fmd/) which compiles and presents data on mineral deposits, mines and geology in the Fennoscandian area, see also Eilu (2012). This database is currently under further development to include wider Nordic spatial coverage (Pasi Eilu, GTK, pers. comm.)

Table 1. *Overview of the databases or repositories on minerals mentioned in the text*

Database or repository	Acronym	Responsible party/ parties	Links (to database, web map services, description etc.)
World Mineral Statistics archive	WMS	British Geological Survey (BGS	https://www2.bgs.ac.uk/mineralsuk/statistics/worldArchive.html
World Mining Data	WMD	Austrian Federal Ministry of Agriculture, Regions and Tourism	https://www.world-mining-data.info
Fennoscandian Ore Deposits Database	FODD	Geological Survey of Finland (GTK)	http://gtkdata.gtk.fi/fmd/
Minerals Yearbook, National Minerals Information Center	MY	US Geological Survey	https://www.usgs.gov/centers/national-minerals-information-center/commodity-statistics-and-information
Exploration, production and trade statistics, Canadian Mineral Statistics	CMS	Natural Resources Canada, Statistics Canada	(https://www.nrcan.gc.ca/science-data/data-analysis/minerals-statistics/mineral-exploration/8854)
Canadian Raw Materials Database	CRMD	University of Waterloo	https://uwaterloo.ca/canadian-raw-materials-database/
Mineral Deposits Database	USMIN	US Geological Survey	https://www.usgs.gov/centers/gggsc/science/usmin-mineral-deposit-database#data
Critical Minerals Mapping Initiative, Critical Minerals in Ores – geochemistry database	CMMI	US Geological Survey, Geoscience Australia, Geological Survey of Canada	https://www.criticalminerals.org https://www.usgs.gov/centers/gggsc/science/critical-minerals-mapping-initiative-cmmi
Ore Samples Normalized to Average Crustal Abundance	OSNACA	University of Western Australia	https://www.cet.edu.au/project/the-osnaca-project/
The Critical Minerals in Archived Mine Samples Database	CMDB	US Geological Survey	https://www.sciencebase.gov/catalog/item/5e616381e4b01d509255c7b6
Geochemical Earth Reference Model	GERM	San Diego Supercomputer Center; Scripps Institution of Oceanography; College of Earth, Ocean and Atmospheric Sciences	https://earthref.org/GERM
UN Comtrade database	UN Comtrade	United Nations Statistics Division	https://comtrade.un.org/data/
Eurostat	Eurostat	European Commission, Eurostat	https://ec.europa.eu/eurostat/web/main/data/database

Globally similar datasets are hosted by geological surveys. One example is the US Geological Survey (USGS), which annually publishes a Minerals Yearbook (https://www.usgs.gov/centers/national-minerals-information-center/commodity-statistics-and-information) that reviews the mineral industries of the USA and of more than 180 other countries. The USGS presents statistical data on minerals and materials and includes information on economic and technical trends and developments. Natural Resources Canada compiles data and hosts Canadian Mineral Exploration statistics (https://www.nrcan.gc.ca/science-data/data-analysis/minerals-statistics/mineral-exploration/8854) and an interactive minerals and mining atlas (https://atlas.gc.ca/mins/en/index.html) which also shows the location of processing plants. The University of Waterloo hosts a (limited) Canadian raw materials database on the production of Canadian commodity materials (https://uwaterloo.ca/canadian-raw-materials-database/).

The USGS also hosts the US Geological Surveys' Mineral Deposit Database (USMIN) (Mauk *et al.* 2021) with the objective of developing 'a comprehensive twenty-first century geospatial database that is the authoritative source of the most important mines, mineral deposits, and mineral districts of the US' (Mauk *et al.* 2021, p. 1). USMIN is a geospatial database of mines, mineral deposits as well as mineral regions in the USA. Geoscience Australia (GA), Geological Survey of Canada (GSC) and the USGS have joined forces in the Critical Minerals Mapping Initiative (CMMI) (https://www.usgs.gov/centers/gggsc/science/critical-minerals-mapping-initiative-cmmi; Kelley *et al.* 2021). Similar to GeoERA, this pools expertise and provides a comprehensive, publicly accessible database of critical minerals in different mineral system types, the Critical Minerals in Ores – geochemistry database (Champion *et al.* 2021)

To improve integrated digital databases and make them more suitable for research and method development, more details of the geochemical, geophysical and mineralogical parameters are required. Some of these parameters are dispersed in various databases such as (but not restricted to) the Ore Samples Normalized to Average Crustal Abundance database (OSNACA) (https://www.cet.edu.au/project/the-osnaca-project/ (Huston and Brauhart 2017) and the Critical Minerals in Archived Mine Samples Database (CMDB) (https://www.sciencebase.gov/catalog/item/5e616381e4b01d509255c7b6) containing chemical and geological information for ore in the USA (Granitto *et al.* 2020). Repositories such as the GERM (Geochemical Earth Reference Model; https://earthref.org/GERM) or the Israel Science and Technology Directory (https://www.science.co.il/earth-science/databases/) echo the high engagement of academia at universities, highlighting the type of data of interest for basic research.

Data collection, harmonization and visualization in GeoERA

The electronic Minerals Yearbook

Production data were collected and provided by the BGS, which has collected and collated global mineral production data for more than 100 years. These data are stored in a BGS database from which an annual publication 'World Mineral Production' is produced (https://www2.bgs.ac.uk/mineralsuk/statistics/worldStatistics.html). Data captured in the BGS database are collected from multiple sources for each country and expert staff perform data analysis, quality control and search for further information to fill in gaps. In co-operation with several other GSOs, time-series data have been updated to 2019 (Fig. 1a)

Trade data (imports and export) are also derived from BGS datasets which have been compiled by the organization since 1913. Data are purchased from a third party, assessed by expert staff on a commodity and country basis to ensure completeness and consistency. Data quality is supported by consulting other databases such as the UN Comtrade (https://comtrade.un.org/data/) and Eurostat (https://ec.europa.eu/eurostat/web/main/data/database). As with the production data, data were shared with the e-MYB via electronic transfer. Examples of export (aluminium alloys) and import (refined cobalt) data in 2018 are shown in Figure 1b and c.

Resources and **reserves data** are available from many different sources and are unique to each deposit. It is important to note that data are often incomplete, absent or compiled in different ways, i.e. industry reported data have significantly different user requirements to those of national-level policy makers (Bide *et al.* 2022). New data were collected on a country-by-country basis, both provided by GSOs and through grey literature research. The GSOs were invited to deliver such overviews with a reference year of 2019; however, only some (in total covering 17 European countries) committed to this task. Where updates were unavailable for a few other countries, these are covered by data collected in a former project (with a reference year of 2013).

Resources and reserves are dynamic entities, dependent on a range of external parameters at the time of assessment and, as such, these are just a snapshot of the state of the industry and depend on the social acceptance of the activity at that stage. Mines are not limited to their original resource or reserve statement but have the potential to grow in the years and decades after discovery as a function of technical, economic, ecological and social developments (Vearncombe and Phillips 2020). A mineral resource is defined as an inferred, indicated or measured natural concentration of material in such form and quantity that a future extraction of a commodity

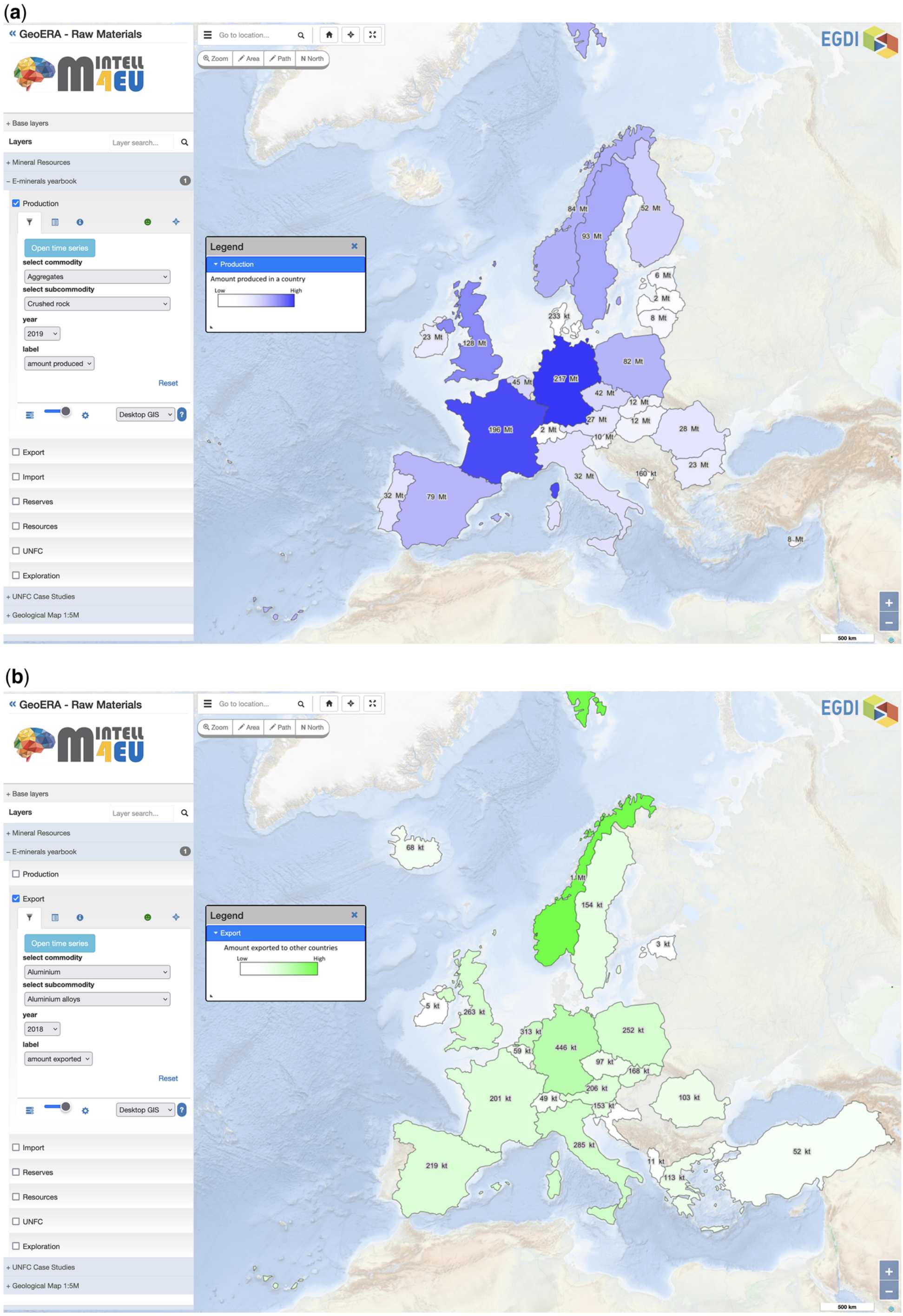

Fig. 1. Examples from the electronic European Minerals Yearbook, as illustrated on the EGDI viewer (incl. links to the layers). (**a**) Production quantities (million or kilo tonnes) per country, for aggregates (crushed rock) for 2019. (**b**) Export quantities (million or kilo tonnes) per country, for aluminium (alloys) for 2018.

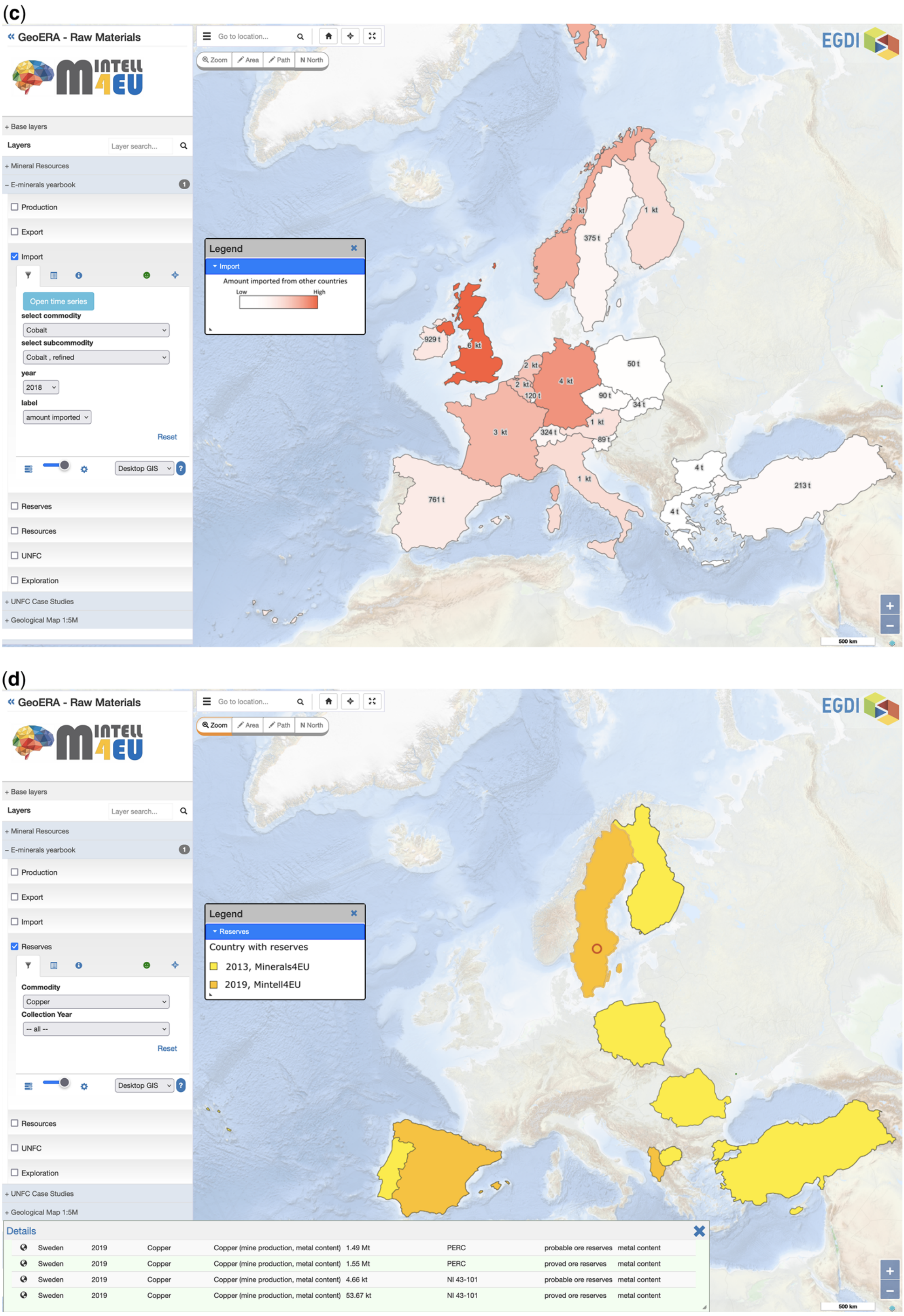

Fig. 1. *Continued.* (**c**) Import quantities (kilo tonnes or tonnes) per country, for cobalt (refined) for 2018. (**d**) Reserves, indications per country, for copper. When clicking on a country (here Sweden), more information appears in a pop-up box ('Details') with details on quantities, classification method etc.

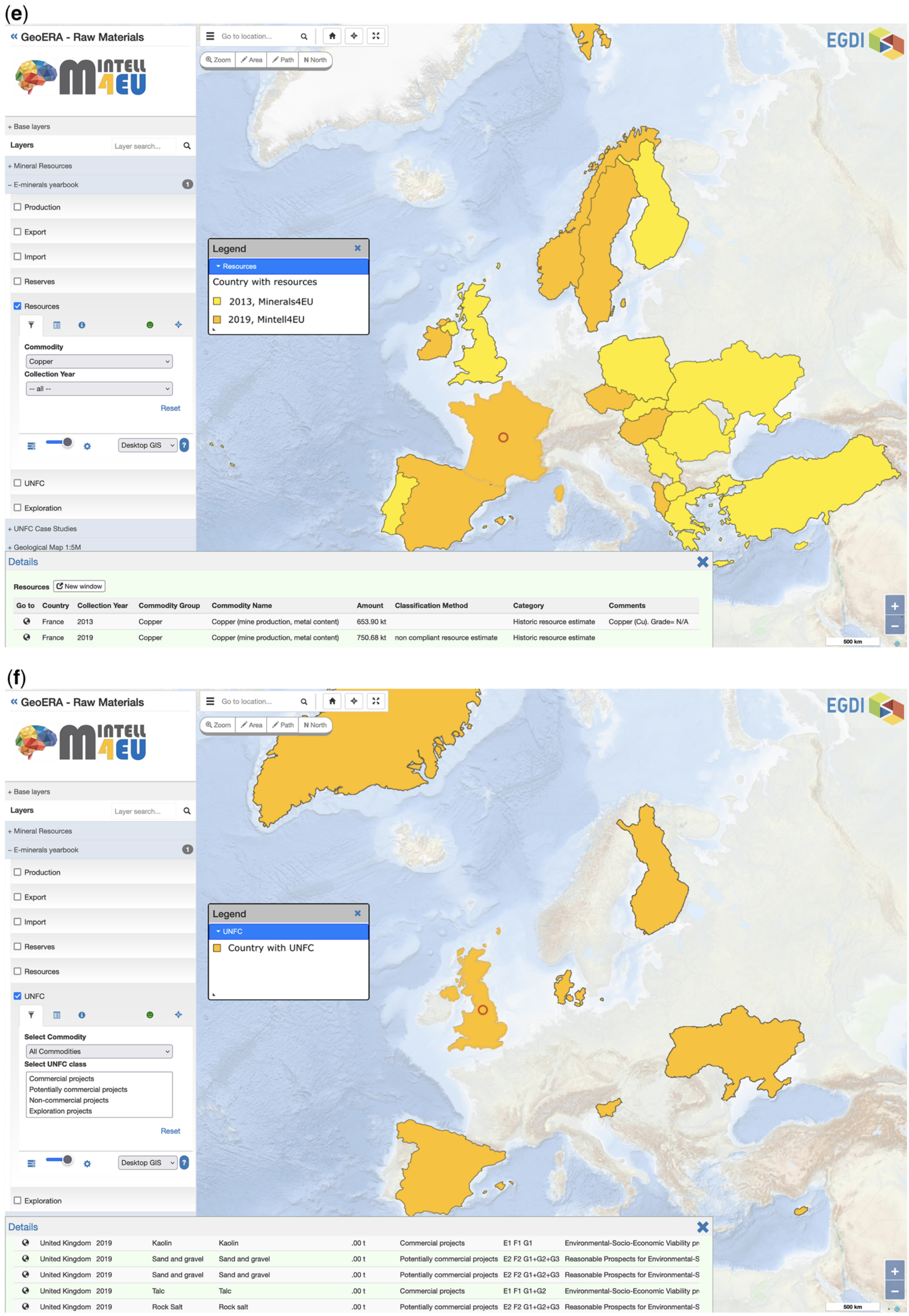

Fig. 1. *Continued.* (**e**) Resources, indications per country, for copper. When clicking on a country (here France), more information appears in a pop-up box ('Details) with details on quantities, classification method etc. (**f**) UNFC data, all commodities per country. When clicking on a country (here the United Kingdom), more information appears in a pop-up box on commodity, quantities, UNFC class and codes, socio-economic viability etc.

is technically and geologically viable (McKelvey and Kleepe 1976; Kelter 1991; UNECE 1997, 2020; CRIRSCO 2012; PERC 2021; Bide *et al.* 2022). Reserves are the part of an identified resource that could be economically extracted at the time of the assessment, considering the modifying factors (these are external influences that need to be considered, such as legal permissions, mining methods, geometallurgy, processing technology, socio-economic and environmental factors (CRIRSCO 2012; PERC 2021; Bide *et al.* 2022). Multiple different reporting methodologies are available for resources and reserves data, depending on the purposes of the data collection and reporting. For the purposes of this project, where possible, data were collected in a CRIRSCO-compliant template (CRIRSCO 2019), used as a global reporting standard for the mining industry. Under these standards, assessments of resources and reserves are signed off by a competent person (CP). A CP is a minerals industry professional responsible for the preparation and signing off reports on exploration results and mineral resources and reserves estimates and who is accountable for the prepared reports (European Commission 2015; CRIRSCO 2019). Thus, these data are compliant. Other types of resources, for which reporting standards are not necessarily used (sand and gravel for example) in a more general sense here, include historical, uncompliant estimates and those following different standards, are non-compliant datasets. In other cases, data were delivered using the United Nations Framework Classification (UNFC) for Fossil Energy and Mineral Resources (UNECE 2020), an international classification system for resource data, including mineral resources. This is focused on the development of a consistent set of definitions across commodity types and international bodies and is not developed with the purpose of investor reporting, in contrast to standards of the CRIRSCO group. We encouraged the data providers to use this methodology, where compliant data were not available, and this was also supported by a test of the UNFC system on raw materials performed under the auspices of this same project (Hokka *et al.* 2021; Simoni *et al.* 2021).

For more details on how data are collected for the e-MYB, see Deady *et al.* (2021) and Wittenberg *et al.* (2022). Examples of reserves, resources and UNFC data are shown in Figure 1d, e and f. In the e-MYB, data for resources and reserves, including non-compliant data, are presented independently to the UNFC data. We do not anywhere attempt to consolidate these figures to give an overall value or tonnage as they are not directly comparable; however, they are complementary and should be used holistically to understand the overall picture in Europe. No doubt that this issue will be given further attention in future projects.

All e-MYB data were transferred electronically to the **MIN4EU** database hosted on EGDI, and different visualizations of data in the e-MYB are shown on the EGDI viewer, as illustrated in Figure 1a–f. The maps are not static but interactive and can be customized to individual user needs, and different datatypes can be layered on top of each other, as harmonized code lists ensure that similar parameters can be compared. An example of the latter is given in Figure 2, where data on zinc production are shown on a map together with the location of zinc deposits. Data can also be downloaded and added to the users own GIS-tools or data collections.

The Minerals Inventory

While data on **mineral occurrences** are in most cases stored in national or regional databases at GSOs, information on the locations of **mines** and quarries (planned, operating, and closed) is not necessarily kept at the surveys as other entities such as ministries, or other responsible agencies may be the data custodians. Therefore, not all parties (hereafter referred to as data providers) are able to share data on mines and quarries. However, thanks to co-operation between the GSOs in several projects, most of Europe is now covered in terms of minerals occurrences. Of the 40 countries covered by the e-MYB, only a few (Bulgaria, Estonia, Iceland, Kosovo, Latvia, Lithuania, Malta, North Macedonia) do not contribute to the Minerals Inventory. Contributions range from a few data on mineral occurrences such as geographical location and the type of commodity, to more comprehensive data on resources and reserves, and by-products for example. The level of detail for the information provided on mines also varies from one data provider to another, as some can mainly provide information on older mining activities while data on ongoing activities can be fully or partially confidential.

Major efforts have been made to harmonize these data and make them comparable across borders, to cover more datatypes, to extend the quality of data (by data control at the provider side, including data check via interactive tools after harvesting of data and via data displays before data release), to expand the geographical coverage, and to automate the data collection (Bahar *et al.* 2021; Kumelj *et al.* 2021). A dedicated harvesting (data collection) and distribution system was developed (Fig. 3) to ensure that national (or regional) data are organized in compliance with the INSPIRE Directive before they are harvested to the central database (MIN4EU) via a WFS (Web Feature Service) Interface Standard. This harvesting system regularly requests and reads data from national WFSs developed specifically for this purpose, and performs automated data quality control procedures, and finally adds updated datasets to MIN4EU, which subsequently makes data

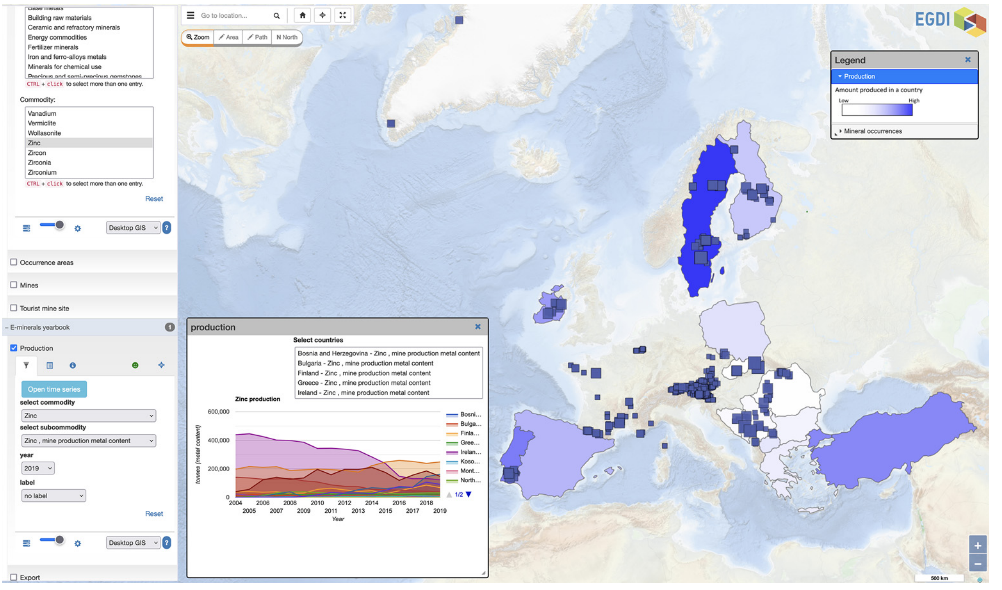

Fig. 2. Combined datasets of mineral occurrences and 2019 zinc production, as illustrated on the EGDI viewer; zinc production (mine production, metal content) in 2019 and deposits (occurrences that have been categorized with regards to 'Importance') across Europe (blue squares). 'Importance' is an INSPIRE-defined indicator of the ranked importance of this commodity compared to other commodities in the deposit and is not representative of the size of the commodity.

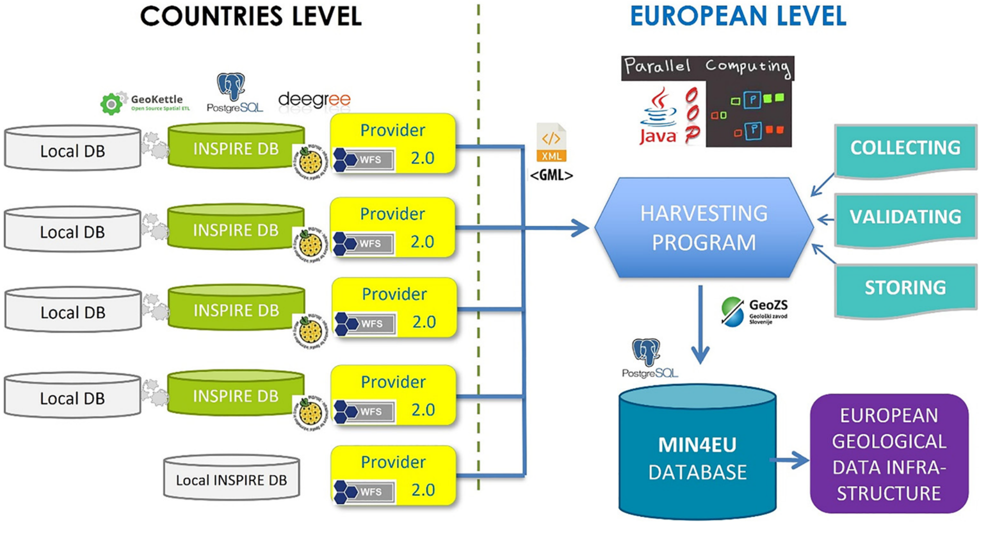

Fig. 3. Harvesting and distribution system. The harvesting system assembles differently collected and organized national data (*Local DB*) into the central MIN4EU database. To do this, national providers must map their data to the INSPIRE classifications (*INSPIRE DB*), using open-source software such as *GeoKettle* (ETL tool) and *PostgreSQL* (RDBMS), and create their own data services (*Provider WFS 2.0*) using software such as *Degree*. The harvesting program developed by *GeoZS* ingests WFS services in the GML format. It is a Java-based parallel computing process that searches the corresponding records from each national data provider for each table in the MIN4EU database created in *PostgreSQL*. The harvesting program not only collects data, but also validates and stores it in the form specified by MIN4EU database. The data are then forwarded to the diffusion database, which allows the data to be displayed on the EDGI portal. Source: adapted from Bahar *et al.* (2021).

available to users through EGDI. In addition, the data can be downloaded from EGDI. So far, not all data holders are ready to implement this harvesting and distribution system and instead provide data in other (stationary) formats. However, the aim is to include as many GSOs or other data holders as possible in this automated procedure to ensure that the data in MIN4EU are updated whenever national data are improved or expanded.

Data on occurrences and mines are illustrated in interactive maps on EGDI. A few predefined maps are already customized, such as a map on CRM occurrences in Europe (Fig. 4a). Users can select which commodities and which level of importance ('Importance' is an indicator of the ranked importance of a commodity compared to other co-commodities in a deposit and is not representative of the size of the commodity) (Fig. 4b).

Strengths, weaknesses, opportunities and threats

To take advantage of digital technologies, we have tried to formulate an assessment and an overall strategy for further development. To do this, we perform a simple SWOT (strengths, weaknesses, opportunities and threats) analysis of the data collected in the MIN4EU database and the processes related to the collection, storage and sharing of the data within the database.

The purpose of the SWOT (Table 2) analysis is to answer the question of on what exactly our future activities should be focused, what we should abandon or strengthen. The first two aspects relate to internal factors, while the second two relate to external factors. The main difference is that with internal factors we have the opportunity to adapt, evolve or in other ways take action. Opportunities and threats refer to external factors over which we have no control and can do nothing directly ourselves, except adapt and adjust the internal characteristics accordingly.

Strengths

MIN4EU represents one central database on mineral resources in Europe, based on an INSPIRE-compatible infrastructure that enables the GSOs

(a)

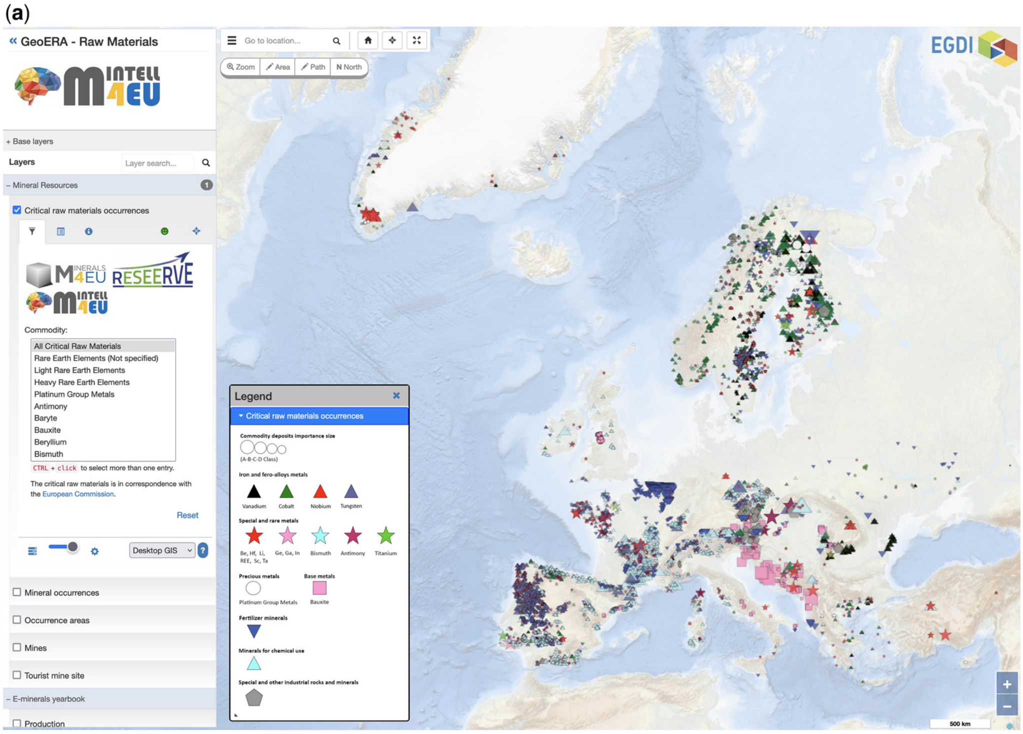

Fig. 4. Examples of mineral occurrences, as illustrated at the EGDI viewer. (**a**) Critical Raw Materials occurrences. The size of the symbol indicates the 'Importance' of the commodity. 'Importance' is an indicator of the ranked importance of this commodity compared to other commodities in the deposit and is not representative of the size of the commodity.

(b)

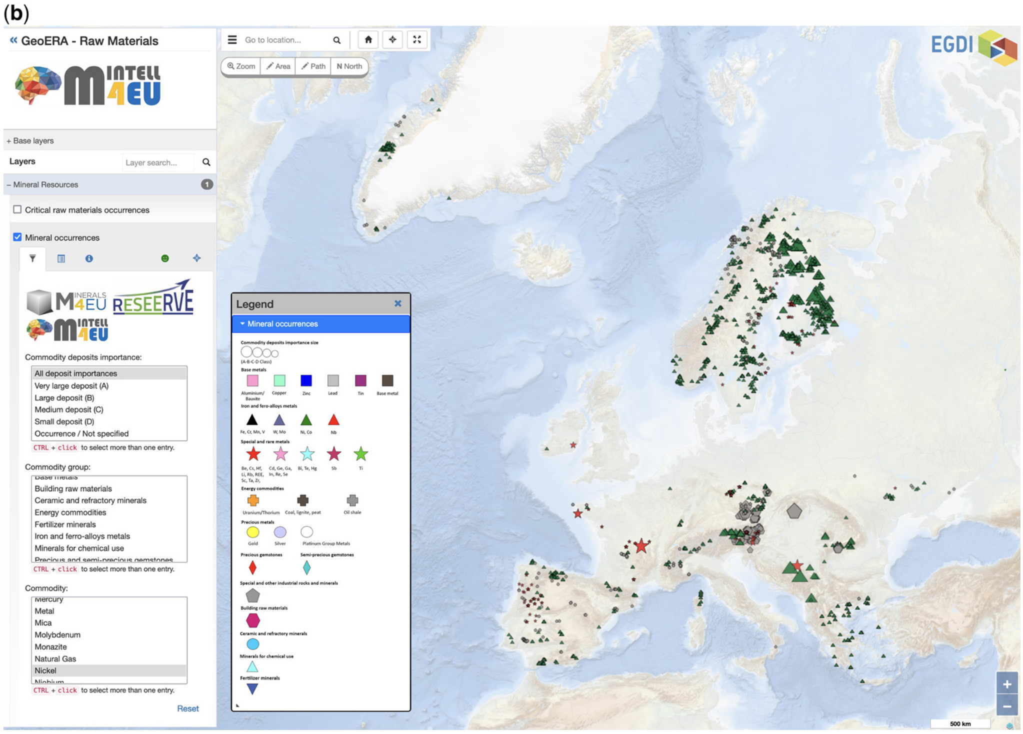

Fig. 4. *Continued.* (**b**) Deposits and occurrences (not specified according to importance) of four battery-relevant elements, cobalt (green triangles), graphite (grey pentagons), lithium (red stars) and nickel (green triangles). Due to the same INSPIRE-defined symbols, cobalt and nickel cannot be distinguished.

and other partners to share mineral information and knowledge, and furthermore help stakeholders to find, view and acquire reasonably standardized and harmonized geo-resource and related data.

The comprehensive dataset on 'production, imports and exports', covering 40 countries and 60 commodities with time-series data dating back to 2004, is a strong tool for obtaining an overview of trends in the European production and trade development over 15 years (2004–19). Data were subject to a thorough quality control by a competent body that has collected these data for more than a century.

Estimates on 'resources and reserves' are compiled from compliant industry statements or assessed (as non-compliant calculations) by the GSOs. The growing use of international reporting codes improves cross-border comparability of reliable data.

Through training and co-operation, national or regional 'data on mineral occurrences and mines' are harmonized with the use of INSPIRE-compliant code lists ensuring that data are comparable across borders. As data are collated from the most competent entities (the GSOs), hosting the primary databases, updates are also reflected in the published European dataset. The automated harvesting system supports the quality control by the GSOs before submitting new data to MIN4EU. In addition, this harvesting and related procedures ensure that data are updated centrally very frequent and very soon after new information is added to national databases.

A major advantage is the well-established network of data providers, including mineral experts and technically expert IT staff, which is a strong draw for attracting new data providers and data users. At the same time, awareness of MIN4EU is improving as its existence is being communicated through different channels such as EGDI infrastructures, EuroGeoSurvey community, the European Commission, research and industry.

The long-term sustainability of datasets or research outputs is often a critical issue as websites or repositories are often forgotten and left without updates after the end of projects or funding. In this case, the MIN4EU database is hosted by EGDI, which ensures its longevity as EGDI is maintained by EuroGeoSurveys. Additionally, the architecture of the EGDI, including the availability of Open Geospatial Consortium (OGC) services for the data in the MIN4EU database, substantially increases the value of the data.

Table 2. *Summary of the SWOT analysis*

Strengths

(1) One central database on mineral resources in Europe.
(2) Standardized methodology (INSPIRE-compliance).
(3) Quality of data:
 (a) comprehensive dataset on production and trade (temporal trends assessed)
 (b) unique compilation on resources and reserves
 (c) comprehensive data on mineral occurrences and mines
 (d) use of INSPIRE-compliant codes.
(4) Technology/Infrastructure setup:
 (a) INSPIRE-compliant database model
 (b) harvesting system for mineral occurrences and mines, automated check for missing or incoherent data
 (c) ensured sustainability (EGDI).
(5) European coverage: all of Europe (40 countries) for the e-MYB, 36 data providers covering 31 European countries for mineral occurrences and mines.
(6) Fully established network of data providers, stakeholders and end users:
 (a) dissemination through different channels
 (b) EGDI infrastructure
 (c) EuroGeoSurvey community
 (d) European Commission
 (e) industry.
(7) FAIR data – licensed CC BY / CC BY ND SA.

Weaknesses

(1) Collecting production and trade data is time consuming and dependent on available financial funds (no permanent financing is guaranteed).
(2) Production and trade data are currently sourced from a non-EU partner.
(3) Challenges related to the collecting of resources and reserve data:
 (a) time consuming
 (b) confidentiality issues
 (c) different level of knowledge and competence among GSOs
 (d) harmonization not fully reached.
(4) Challenges related to mineral occurrences and mines:
 (a) gaps in the spatial coverage of Europe
 (b) lack of data harmonization e.g. in terms of different understanding of code lists among data providers
 (c) national legislation rules and obstacles related to detailed data
 (d) lack of trained/relevant IT staff, not all data providers use WFS standard for data delivery.

Opportunities

(1) Indication of supply chains of interest, e.g. for the European Commission.
(2) Comprehensive overview of relevant commodities across Europe giving indispensable information for future exploration activities possibly leading to new investments.
(3) Wider cross-border usage of UNFC classification for resources/reserves estimates.
(4) Integration of data from other sources.
(5) Advantage in the use of existing technology/infrastructure:
 (a) automated collecting routines can be easy adapt by old/new data providers
 (b) more trainings and workshops
 (c) guidelines are available
 (d) regular data updates.

Threats

(1) Lack of funding for further input and updating of MIN4EU.
(2) The European Commission hesitates to rely on data collected by institutions in non-EU-member states.
(3) Confidentiality/lack of access to data.
(4) Lack of commitment from countries that do not yet add data to MIN4EU.
(5) Lack of commitment or possibilities for existing data providers to add more or to further harmonized data.
(6) Detailed data on geographical position etc. can expose vulnerable information to potential aggressors.

The data in the MIN4EU database are to a high degree FAIR, particularly because the data have complete metadata and have been standardized according to the CGI (Commission for the Management and Application of Geoscience Information under The International Union of Geological Sciences) data model ERML (Earth Resource Markup Language). Data are also available for viewing and download through OGC (Open Geoscience Consortium) web services.

Weaknesses

Due to the wide range of commodities and the large volume of data, collecting and processing of 'production and trade data' is a time-consuming task. This means that transnational validated data are released with some (14 months) delay, and data quickly become outdated. Sharing of data with MIN4EU in the form of the e-MYB has only been possible in dedicated projects, as this requires further resources. Thus, this makes the acquisition of these data vulnerable, as it is highly dependent on a single entity. Hence, dedicated (funded) projects or programmes are needed for future updating of the e-MYB.

The acquisition of 'resources and reserves data' is a time-consuming and resource-intensive task complicated in many cases by confidentiality issues or the lack of reporting requirements for unlisted companies. So far, only some GSOs have committed to this task, both in the most recent and in past projects. Although the GSOs are the organizations with the best possible knowledge and competences for the compilation of these data, different, in some cases non-compliant, codes are still to some extent used, based on traditions and familiarity, and experiences are (Hokka *et al.* 2021) that the level of knowledge and competences among the GSOs also to some extent vary. This makes comparative studies across borders difficult.

Albeit spatial coverage across Europe has been extended, there are still gaps on the European map when it comes to 'data on mineral occurrences and mines'. Looking at the maps on mineral occurrences, it quickly becomes clear that apart from obvious gaps in spatial coverage, the provided information is still not truly harmonized despite the efforts of several initiatives. This echoes the fact that not all data providers share the same level of information (one example is that some data providers do not classify occurrences according to their importance). Differences are even more evident when looking at the map of mines, as fewer countries share these data (for example because other entities such as Ministries of Economy or similar own the data), and there is even an example of a data provider only sharing information on past mining activities. Looking behind the maps and into the database reveals even more differences with the number of code lists that contain input as this can differ significantly from one data provider to another. Furthermore, there are still challenges related to how users interpret code lists, an issue that can only be solved by knowledge exchange, co-operation and more training.

Finally, not all data providers are connected to the automatic harvesting system that would ensure a regular update of the full dataset. About half of the data providers do not provide data in the required standardized WFS format, often due to the lack of trained and relevant IT staff. Instead, they deliver data in tables that are then hosted by key partners to allow harvesting of these (usually) static data, and updates only occur within dedicated (funded) projects or programmes. Again, training workshops are needed to improve the level of automatization.

Opportunities

More continuous (yearly) and timely updates of 'production and trade data' in the e-MYB would provide an excellent overview of the production, import and export of raw materials in Europe and give a good indication of supply chains and weak links therein. The dataset has already attracted interest from the European Commission and other end users for such purposes. The combination of these data with interactive maps of facilities and plants would add value but also poses risks by exposing vulnerabilities to potential aggressors.

A more comprehensive overview of 'resources and reserves' covering the relevant commodities (at least the CRM) across Europe could be an essential platform for further investigations, for land-use planning, and for industry investments. The envisaged introduction of the UNFC code for these purposes in Europe will hopefully lead to its extended use and create a growing platform for cross-border comparison of data.

The spatial coverage can, relatively easily, be extended by including 'data on mineral occurrences and mines' from countries where data are currently missing. Guidelines, online training courses and regular harvesting are already established, making it easy for new users to add their data. Enhancing the level of harmonization of the data will strengthen the potential and raise credibility. Implementing the harvesting system at more data providers will ensure regular updating of the datasets, reflecting the most recent knowledge on raw materials in a region. Information on past mining activities can form the basis for re-evaluating tailings and overburden for possible extraction of possible remaining raw materials for example. Combining spatial data on tailings and dumps with information on geohazards, groundwater vulnerability in the area etc., can help prevent damage at an early stage. This cannot only increase resource efficiency but also reduce negative impacts on nature. When fully harmonized, these data provide indispensable information on the potential for future exploitation activities.

Appropriate data visualizations strengthen messages and enhance their effectiveness. Proper use of graphical elements, appropriate colours and interactive content significantly improve the user experience and can direct attention to important data and indicators. Clear and understandable visualization of complex information, taking into account the context, is part of clear communication that supports decision making. Data visualization is rarely one-size-fits-all, and messages can be lost if it is not tailored to specific audiences. Future mineral data visualization could be improved, with even more focus and customization to provide stakeholders with relevant information, while still providing raw data for interested parties. Combing geological information with other types of data from other sources outside the GSO community (e.g. ongoing exploration, exploration and mining licence areas, location of mineral processing, refining and smelting plants and similar infrastructure etc.) could also improve the appeal of the maps on EGDI. This is possible through the provision of INSPIRE-compliant data and co-operation with the responsible authorities as the EGDI is open to all relevant types of data.

Threats

Although the BGS continues to update and publish ‘production and trade data’ and in many ways continues pre-Brexit co-operation, the European Commission hesitates to rely on data collected by institutions in non-EU-member states. In addition, transferring data from BGS’ databases to e-MYB requires resources (funding). The combination of the data presented thus far with interactive maps of facilities and mineral processing, refining and smelting plants could add value, but such maps could also be misused by aggressors to pinpoint vulnerabilities.

The production of ‘resources and reserves’ estimates requires dedicated (funded) programmes or projects as it is a time- and resource-demanding task. A major threat to the acquisition of data is data confidentiality and inaccessibility.

The lack of commitment from (the few) countries that do not yet provide data, and the inadequate interest of existing data providers to further harmonize and extend data, are consistent problems on the path towards a complete coverage of Europe with ‘data on mineral occurrences and mines’. Lack of funding to ensure further input and updating is another risk that can impede a full picture of raw material occurrences across Europe.

Discussion

Aggregated minerals intelligence in the form of production, trade, and resources and reserves data have different applications. They provide baseline information for a range of stakeholders and end users, particularly those in policy, research, the minerals industry and governance. Some examples of end use include, but are not limited to: (1) researchers (academic, GSOs, industry, government and market analysts), for whom these data are useful for material flow analysis, supply chain analysis, understanding import dependencies, comparing domestic production with local and international markets, and for understanding the resource and reserve dynamics; and (2) policy makers (government, think tanks, lobby groups), for whom these data can be used to highlight bottlenecks and other issues in the supply chain, and inform where policy interventions need to be designed or undertaken at specific points along the supply chain. Obviously, these data are extremely useful for the minerals industry. At the early stages of the supply chain, information on the location of mineral occurrences, deposits with resource and reserve data and exploration expenditures can both inform and influence the decision-making process. The absence of a large mineral processing and metal production sector in Europe (for many commodities) is a well-known bottleneck, but abundant and accessible data on mineral occurrences, production and trade could be used to make business decisions both by industry and governments regarding the development, or not, of this sector.

The overview of the resource and reserve data can be critically important for future planning of mining and minerals projects coming onstream. This dataset could be enhanced by capturing additional data regarding the stage at which a project is – for example, have pre-feasibility or feasibility studies been undertaken, v. maiden resource data announcements. It can also help highlight where there are true gaps in commodity availability and whether prospective regions for particular commodities exist.

Having a proper understanding of the minerals industry in Europe is of high value but would require more details on the status of extraction and further processing (refineries and smelters). Moreover, the high value of such detailed information coupled with spatial information increases the vulnerability and might be of strategic interest.

The interactive data in MIN4EU allow stakeholders to visualize data that are useful to them, while allowing those who would like to delve further into the data the opportunity to use the raw data that sit behind the database. This is further facilitated by the licences in place for data use, CC-BY and CC-BY-ND-SA.

Based on the results from the SWOT analysis, shortfalls and other areas that need further improvement can be identified. Based on this assessment, clearer goals for future improvement such as better geographical coverage, higher quality data, and higher levels of harmonization can be identified. The advantages of MIN4EU are the well-designed data model and data collection processes, the broad network of data providers and users, and most importantly, the fact that it is the first centralized database for mineral resources at the European level.

The biggest challenge is data harmonization, which, despite the technical ability to harmonize and compare data across countries, is the biggest weakness of the data themselves. Countries collect different data depending on their history and mineral legislation, and their understanding of standards also varies. In particular, it would be useful to assess and identify areas where certain minerals do occur, but where detailed information are confidential, or where there are no suitable data providers to contribute to MIN4EU.

Conclusions

The MIN4EU database is the best overview of minerals intelligence currently available in Europe, and the interactive maps provide overviews as well as pinpoint obvious gaps. Despite the weaknesses and threats described, the SWOT analysis reveals several strengths and opportunities of the data compiled by the GSOs. The potentials for further improvements and extensions are numerous, and these need to be addressed in future dedicated (funded) programmes and projects.

The co-ordinated efforts by EuroGeoSurveys and its members over the last decade through the numerous data standardization and harmonization projects in mineral resources that have added content to the MIN4EU database is a remarkable achievement. The European Commission has supported efforts in more projects and a recent proposal to continue these has been granted (the EU Horizon Europe funded Coordination and Support Action (CSA) for A Geological Services for Europe (GSEU)) and efforts will continue from late 2022 and at least for five years hereafter. Finally, EuroGeoSurveys ensures that the EGDI is sustained and the co-operation between the GSOs (in dedicated expert groups, e.g. on Mineral Resources) continues even in the period between projects.

In summary, we conclude that:

- Compilations of aggregated national data as well as the location of mineral occurrences are essential tools for pan-European minerals intelligence.
- Updating and maintaining these data require funding over sustained periods of time to ensure data continuity and robustness.
- The SWOT analysis shows that the dataset already serves as a vital source of information for a wide range of stakeholders but also reveals future potential in expanding data and serving even more purposes.
- High levels of detail and quality of information (in terms of geographical and economical coverages) are of strategic importance, highlighting the need for access to presently restricted and/or confidential data.

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Data availability There are links to all the maps shown in the paper, and all described data are freely available through the European Geological Data Infrastructure webpage: https://www.europe-geology.eu/.

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