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GEOTHERMAL PLANTS AND CRITICAL MINERALS DISTRIBUTION: A PRELIMINARY SPATIAL DATASET FOR CO-PRODUCTION SCREENING

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EXTENDED ABSTRACT

Le materie prime critiche (*Critical Raw Materials, CRMs*) quali litio, cobalto, boro, germanio ed elementi di terre rare sono componenti essenziali per le tecnologie moderne, inclusi sistemi di accumulo energetico, veicoli elettrici, turbine eoliche ed sistemi elettronici avanzati. Le loro catene di approvvigionamento sono fortemente concentrate in un numero limitato di Paesi e risultano vulnerabili a rischi geopolitici, ambientali e sociali. In risposta, l'Unione Europea e gli Stati Uniti hanno sviluppato strategie dedicate all'approvvigionamento di CRMs, che promuovono la diversificazione delle fonti, il riciclo, la sostituzione.

In questo contesto, cresce l'interesse verso fonti non convenzionali di CRMs che possano essere sviluppate sfruttando infrastrutture esistenti e con un impatto ambientale inferiore rispetto all'attività mineraria tradizionale. I sistemi geotermici sono sempre più riconosciuti come risorse a duplice utilizzo, in grado di fornire energia rinnovabile e, al contempo, consentire il recupero di elementi critici disciolti nelle salamoie geotermiche. Numerose operazioni geotermiche producono infatti fluidi caldi contenenti litio, rubidio, cesio, boro, silice e, in alcuni casi, concentrazioni di elementi di terre rare.

Studi recenti e progetti pilota in aree geotermiche ad alta entalpia, come il Salton Sea (USA) e l'Upper Rhine Graben (Europa), hanno dimostrato la fattibilità tecnica dell'integrazione di processi di estrazione diretta del litio con la produzione di energia elettrica e calore. La co-produzione potrebbe migliorare significativamente l'economia dei progetti geotermici e contribuire alla sicurezza dell'approvvigionamento di CRMs, a condizione che i processi di recupero siano compatibili con la gestione dei serbatoi, i vincoli di reiniezione e i requisiti di sostenibilità a lungo termine. In alcuni casi, il valore potenziale dei minerali recuperabili può superare quello della sola produzione energetica.

Tuttavia, la valutazione della fattibilità della co-produzione geotermia–CRMs su scala regionale o globale rimane complessa. Le informazioni disponibili sono attualmente frammentate in dataset separati: registri di impianti geotermici esistenti, database di giacimenti minerari e raccolte di dati di chimica dei fluidi, che differiscono per copertura spaziale e temporale, definizioni degli attributi e finalità. Questa frammentazione limita la possibilità di ottenere una visione coerente dell'infrastruttura geotermica globale nel contesto della mineralizzazione, di confrontare tecnologie di impianto e di pianificare campagne di campionamento mirate.

Il presente lavoro risponde a questa esigenza proponendo la costruzione di un database preliminare di tipo open-source. Il database combina cinque principali *dataset open access*: (*i*) il *JRC Geothermal Power Plant Dataset*, (*ii*) il *Global Geothermal Power Tracker (GGPT)*, (*iii*) il *database* globale USGS delle materie prime critiche, (*iv*) il *dataset* EGDI-CRM per l'Europa e (*v*) il *dataset* REFLECT. I *dataset* JRC e GGPT forniscono informazioni complementari sugli impianti geotermici a livello globale, includendo localizzazione, capacità installata e tipologia tecnologica.

I *database* USGS-CRM ed EGDI-CRM contribuiscono invece a descrivere i contesti di mineralizzazione in roccia per le principali materie prime critiche, consentendo di inquadrare gli impianti geotermici all'interno di aree potenzialmente favorevoli alla presenza di CRMs. Inoltre, il database REFLECT introduce la dimensione fluida, mettendo a disposizione dati a scala di pozzo sulle proprietà dei fluidi geotermici per sistemi selezionati in Europa, permettendo così di integrare le informazioni su infrastrutture e contesto geologico con le caratteristiche chimico-fisiche delle salamoie geotermiche. Tutti i dati sono armonizzati in un sistema di riferimento spaziale comune, consentendo una mappatura coerente degli impianti geotermici e delle occorrenze di CRMs.

Il contributo principale del lavoro è la realizzazione di un quadro dati trasparente e riproducibile, pensato non per fornire stime quantitative delle risorse, ma come piattaforma di confronto e selezione preliminare dei siti. Tale approccio può costituire un prerequisito per analisi multicriterio, studi di fattibilità e lo sviluppo sostenibile della co-produzione di energia geotermica e materie prime critiche.

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ABSTRACT

Geothermal systems have the potential to co-produce renewable energy and critical raw materials (CRMs) from mineral-rich brines; however, existing information about their potential is scattered across uncoordinated datasets. This work develops a QGIS-based global database to support the assessment of CRM co-production from geothermal systems. Five open-access datasets were analyzed within a spatial framework: the Joint Research Centre (JRC) Geothermal Power Plant dataset, the Global Geothermal Power Tracker (GGPT), the U.S. Geological Survey (USGS) global distribution of critical minerals, the European Geological Data Infrastructure (EGDI) CRMs' occurrences, and REFLECT European Geothermal Fluid Atlas. JRC and GGPT together provide complementary information on geothermal power plants worldwide, while USGS-CRM and EGDI-CRM supply data on hard-rock mineralization settings for key critical raw materials. Moreover, the REFLECT database adds the fluid dimension by providing well-level data on fluid properties for selected European geothermal systems, allowing plant and mineralization information to be complemented with geothermal brine properties. Rather than presenting a single, fully developed case study, the paper outlines how the integrated database can be used in future analyses, including tracking temporal changes in geothermal deployment and critical mineral reports; integrating REFLECT-compatible fluid chemistry for selected fields; and assessing plant and critical mineral proximity for scaling-related problems.

Keywords: *geothermal-CRM co-production, critical raw materials, geothermal brine, lithium recovery, GIS-based data integration*

INTRODUCTION

Critical raw materials (CRMs) such as lithium, cobalt, boron, germanium and rare earth elements are essential for low-carbon, renewable energy-driven technologies, including batteries, electric vehicles, wind turbines and advanced electronics (Mathieux *et alii*, 2017; Hofmann *et alii*, 2018). Their supply chains are concentrated in a limited number of producing countries and are vulnerable to geopolitical, environmental and social risks (Kalantzakos, 2020; Dou *et alii*, 2023; Bhamra *et alii*, 2025). The European Union and the United States have published CRM lists and strategies that emphasize diversification, recycling, substitution and the development of primary sources (Nassar *et alii*, 2025). In this context, there is growing interest in non-traditional sources of CRMs that can be developed within existing infrastructure and with a smaller land-use and environmental footprint than conventional mining activities (Shiquan & Deyi, 2023). Recent studies on extractive waste management highlight the growing importance of secondary raw materials recovery in Europe, particularly in sectors where large volumes of industrial and quarry waste remain underutilized. In this context, the valorization of waste streams and the identification of alternative mineral resources are increasingly relevant for supporting sustainable critical raw materials supply chains and resource preservation strategies. (Dino *et alii*, 2017)

Geothermal systems are increasingly recognized as potential dual-use resources, capable of producing both renewable energy and critical raw materials. In addition to providing low-carbon electricity and heat, many geothermal operations extract hot brine that contains dissolved minerals, including lithium, rubidium, cesium, boron, silica and, in some cases, trace concentrations of rare earth elements (Stringfellow & Dobson, 2021; Toba *et alii*, 2021; Warren, 2021; Sajkowski *et alii*, 2023; Szanyi *et alii*, 2023a). Multiple studies have demonstrated significant potential for mineral extraction from geothermal brine. Key advantages include no mining costs, lower water volume to be treated, and minimal environmental impact (Bourcier *et alii*, 2005; Szanyi *et alii*, 2023b).

Both the European Union and the United States have actively funded research to develop extraction technologies for critical minerals, through initiatives such as U.S. Department of Energy programs and EU research and innovation frameworks, particularly targeting lithium and rare-earth elements. Despite demonstrated technical feasibility, significant challenges remain in achieving economically sustainable extraction processes at scale. The approach aligns with sustainable development goals, transforming geothermal energy production into a multi-resource recovery system (Thomas *et alii*, 2014; Stringfellow & Dobson, 2021).

Recent pilot projects in high-enthalpy fields (*e.g.*, Salton Sea, Upper Rhine Graben) demonstrate the technical feasibility of integrating direct lithium extraction and related separation processes with power production (Paranthaman *et alii*, 2017; Marthi & Smith, 2019; Fries *et alii*, 2022; Dobson *et alii*, 2023; Goldberg *et alii*, 2023). Co-production of geothermal energy and critical materials could, in principle, improve project economics and contribute to domestic CRM supply, provided that recovery processes are compatible with reservoir management, reinjection constraints and sustainability requirements (Szanyi *et alii*, 2023b). The potential mineral value could substantially exceed revenue from power production alone. In the Upper Rhine Valley (Germany), the Phase One Lionheart geothermal-brine project is designed to produce 24,000 t/y of lithium hydroxide monohydrate, expected to meet ~12% of Europe's projected 2030 lithium hydroxide demand, while co-producing renewable heat and power from the same brine. In the Upper Rhine Graben, geothermal brines targeted for lithium co-production can also be rich in base metals. For example, Soultz-sous-Forêts reports represent concentrations of about 3,000 mg/L Zn and 300 mg/L Pb, suggesting possible additional zinc/lead byproducts alongside lithium and geothermal energy (Sanjuan *et alii*, 2016; Goldberg *et alii*, 2023; Kölbel *et alii*, 2023). In Italy, Campi Flegrei (Mofete) geothermal system, lithium is reported to reach ~480 mg/L in deep-reservoir fluids (*vs* ~28–56 mg/L in intermediate/shallow reservoirs), consistent with mixing between magmatic, meteoric, and marine-derived waters (Dini *et alii*, 2022). A hypothetical 1000-MWe Salton Sea plant could recover 14-31% of US manganese demand plus substantial zinc and lead (Maimoni, 1982; Bourcier *et alii*, 2005).

However, the feasibility assessment of such co-production at a regional or global scale is challenging. Information relevant to geothermal–CRM co-production is currently scattered across separate datasets. Geothermal plant registries, such as the JRC Geothermal Power Plant Dataset and the Global Geothermal Power Tracker, focus on infrastructure and technology, including location, capacity, turbine type, and related parameters. (Global Energy Monitor, 2025; Joint Research Centre Data Catalogue, 2018). Mineral resource compilations, including the USGS global distribution of selected critical mineral mines and deposits, and the more recent EGDI-CRM dataset for Europe, document hard-rock mineral occurrences and deposits, not necessarily the ones dissolved in fluids (U.S. Geological Survey, 2017; European Geological Data Infrastructure Metadata Catalogue, 2025). Fluid chemistry datasets such as the REFLECT European Geothermal Fluid Atlas provide well- or field-scale measurements of temperature, salinity, major ions and dissolved silica, but they are geographically limited compared with plant and mineral datasets (Reflect H2020 Project, 2020).

The above-described datasets differ in spatial and temporal coverage, attribute definitions and intended use. These discrepancies create several barriers. First, they make it difficult to build a consistent global picture of geothermal infrastructure and technology in the context of co-production, for example, to compare the regional dominance of dry-steam, flash or binary/ORC plants before and after 2018. Second, they limit the possibility of siting geothermal operations within a broader mineralization context, which is important both for identifying favorable geological settings and for anticipating scaling issues. Third, without a common spatial backbone, it is difficult to design sampling campaigns or pilot projects that link plant technology, mineralization setting and fluid properties in a reproducible way.

There is therefore a need for a open access database that brings together key information relevant to geothermal–CRM co-production: global geothermal plant registries, global and regional critical mineral occurrence datasets, and where available, fluid chemistry information. The purpose of such a database is not to provide detailed resource estimates, but rather to create a consistent platform for screening and comparison: identifying where geothermal infrastructure exists, what technologies are used, whether the infrastructure is located in CRM-bearing regions, and where fluid data can be added. This integrated spatial view is a prerequisite for multi-criteria site selection, and the design of follow-up investigations.

The present paper addresses this need by constructing an open-source database that combines four major open access datasets: (*i*) the JRC Geothermal Power Plant Dataset, (*ii*) the Global Geothermal Power Tracker, (*iii*) the USGS global critical-minerals geodatabase, and *(iv*) the EGDI-CRM occurrences dataset. These datasets are brought into a common coordinate reference system to enable consistent mapping of geothermal plants and critical mineral occurrences. The REFLECT fluid chemistry dataset is treated as an outlook and integration target. We will discuss how selected fields could be enriched with fluid properties where such data are available. The primary contribution is a transparent, reproducible data framework that can be used and extended by those working on geothermal resource assessment, sustainable exploration and the emerging field of geothermal–CRM co-production.

DATA SOURCES AND DESCRIPTION

The JRC Geothermal Power Plant Dataset is a global inventory of geothermal power plants compiled by the Joint Research Centre of the European Commission for technology and market assessments of geothermal energy. It was created in 2014 and has been updated continuously since then. It was documented in detail in the 2018 technical report. The dataset provides plant-level information, including facility name, country and location (by coordinates), operating status, installed capacity, turbine type (*e.g*., dry steam, flash, binary/ORC), commissioning year, and basic ownership details. Records are delivered as geospatial data through the JRC data catalogue under an open EU license. In this work, the JRC dataset is used as a baseline global infrastructure layer, defining the spatial distribution and technological configuration of geothermal power plants as of the 2018 release (Joint Research Centre Data Catalogue, 2018).

The Global Geothermal Power Tracker Dataset, developed by Global Energy Monitor (GEM), is an independent, unit-level database of geothermal power facilities worldwide. It documents individual geothermal plant units, which may comprise one or more turbines, reporting location, capacity, owner, project status (operating, announced, under construction, decommissioned), installed turbine type (flash, binary, dry steam), and start year. Facilities are generally included above a minimum capacity threshold (≈30 MW), and the dataset is updated regularly. The present study uses the March 2025 release accessed via GEM's data request interface under a Creative Commons (CC) BY 4.0 International license (Global Energy Monitor, 2025). In the constructed database, GGPT serves as a complement to and update of the JRC dataset, particularly for post-2018 projects and for cross-checking plant locations, status, and turbine type. To assess how the two sources relate in practice, their spatial distribution and degree of overlap at both the global and European scales have been examined (Fig. 1).

The U.S. Geological Survey global critical minerals geodatabase provides point and polygon layers for mineral deposits, mines, and districts for 23 minerals considered critical to the US economy and national security as of 2017. Attributes include

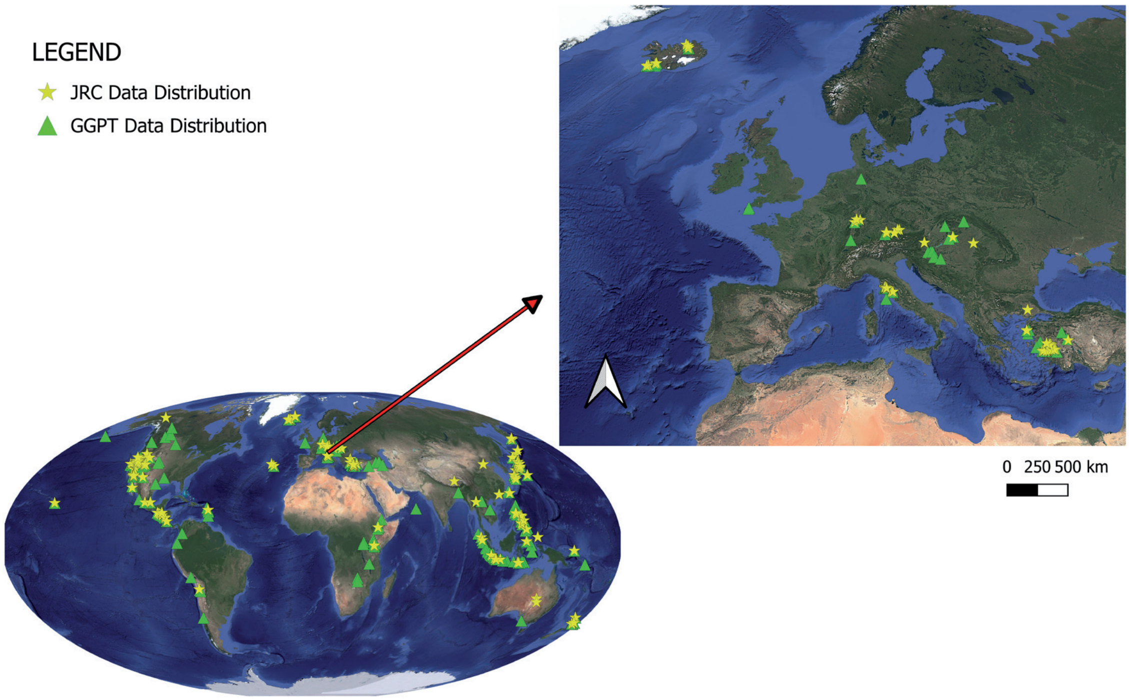

Fig. 1 - Global and European distribution of geothermal power plants based on the JRC and GGPT dataset, visualized using QGIS

deposit name, geographic coordinates, deposit type, associated minerals, and references to the underlying geological and resource assessment work. The data are released as a geodatabase under public domain. In this study, the USGS critical minerals dataset is used as a global hard-rock mineralization layer, providing spatial context on the distribution of lithium, rare earth elements, antimony, cobalt, and other CRM-relevant minerals. These data are not interpreted as mineral-rich brine resources. Instead, we use them as geological background information and as indicators of broader mineralized regions (U.S. Geological Survey, 2017).

The European Geological Data Infrastructure CRM 2024 dataset (part of the Geological Service for Europe / GSEU project) provides an inventory of critical raw materials deposits and occurrences across Europe, compiled and standardized by EuroGeoSurveys (European Geological Data Infrastructure Metadata Catalogue, 2025). Delivered through the European Geological Data Infrastructure (EGDI), the dataset includes point and polygon features describing mineral occurrences, deposits and reserves, with attributes such as deposit type, status, and national identifier. The 2024 release covers CRM resources as defined by the 2023 EU CRM list and is intended to provide mineral resource information across Europe (Albert *et alii*, 2025). Within the created database, EGDI-CRM is used as a regional, high-resolution layer for Europe that complements and refines the global USGS critical minerals dataset. It is particularly significant for Italy and other European geothermal regions, where it provides a more detailed and harmonized view of hard-rock CRM occurrences. Similar to USGS, EGDI features are interpreted strictly as hard-rock mineralization context, not as proxies for dissolved-phase concentrations in geothermal fluids (Fig. 2).

The REFLECT European Geothermal Fluid Atlas is an online platform and database developed under the EU-funded REFLECT project to provide information on geothermal fluid properties across Europe (Reflect H2020 Project, 2020) The atlas compiles well- and field-scale data from more than 20 countries, including the geographic and geological settings, depth ranges, and measured physical, chemical, and microbial properties of geothermal fluids (*e.g.*, temperature, salinity/TDS, pH, major ions, dissolved gases, *etc.*) (Table 1). The REFLECT fluid atlas is not a global dataset, but for European regions where coverage exists, it offers the missing fluid dimension that infrastructure (JRC, GEM) and mineralization (USGS, EGDI-CRM) layers cannot provide. In the present work, REFLECT is treated primarily as an outlook and an integration target. It illustrates how future versions of the current database could link plant locations and mineral occurrences to fluid chemistry, thereby enabling co-production evaluation in terms of scaling propensity and reinjection compatibility. Outside REFLECT's current spatial coverage, the need for REFLECT-compatible sampling and reporting is highlighted as a prerequisite for moving towards commercial-scale projects (Fig. 3).

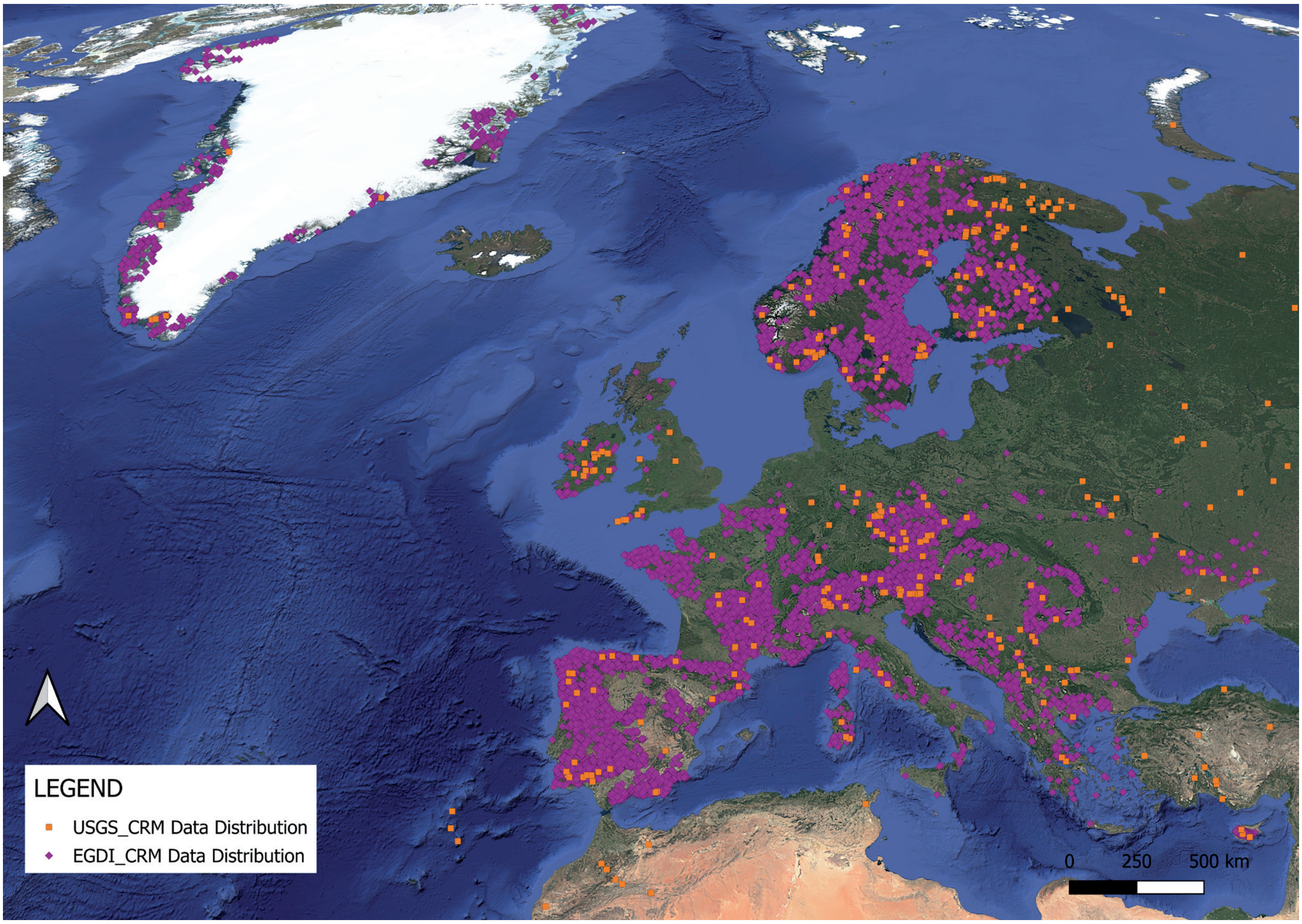

Fig. 2 - European distribution of critical raw material based on the USGS and EGDI dataset, visualized using QGIS

DATABASE CONSTRUCTION

All datasets were first imported into QGIS and projected to a common geographic reference system (WGS 84, EPSG:4326) to ensure consistent global coverage and facilitate exchange. For any future distance- or area-based analyses, users are advised to reproject the database to an appropriate CRS (*e.g.*, global Mollweide).

For power plants (JRC and GGPT datasets), the attributes include plant identifier, name, country, geographic coordinates, status, installed capacity, commissioning year, and turbine technology (dry steam, single flash, double flash, binary/ORC *etc.*). For mineral datasets (USGS and EGDI-CRM), attributes are deposit/occurrence identifier, name, coordinates, and deposit/occurrence type. Basic record linkage was performed within each pair of layers to identify overlapping or complementary coverage. For geothermal plants, JRC and GGPT records were compared using a combination of name normalization (lowercasing, removal of punctuation and extra spaces) and nearest-neighbor searches within a conservative distance threshold (5000 meters). Matched records were flagged, and non-matched entries were retained as JRC-only or GGPT-only plants. For mineral occurrences, the USGS and EGDI-CRM datasets were not merged into a single layer; instead, both were integrated into the same schema to enable comparison or overlaying, with EGDI providing higher-resolution regional coverage for Europe. Throughout the construction process, quality control flags were introduced. These include a source field indicating the original dataset, a match flag (for matched *vs* unique records), and a match-distance field where nearest-neighbor joins were used. No attempt was made to interpret mineral occurrences as dissolved-phase concentrations; USGS and EGDI-CRM are used as hard-rock geological contexts that may indicate broader metallogenic provinces or potential scaling environments.

The final database is delivered as a GeoPackage (with shape file exports for compatibility), containing separate but inter-operable layers for geothermal plants and mineral occurrences, along with a concise data dictionary. This structure is intended to support a range of future applications, such as global

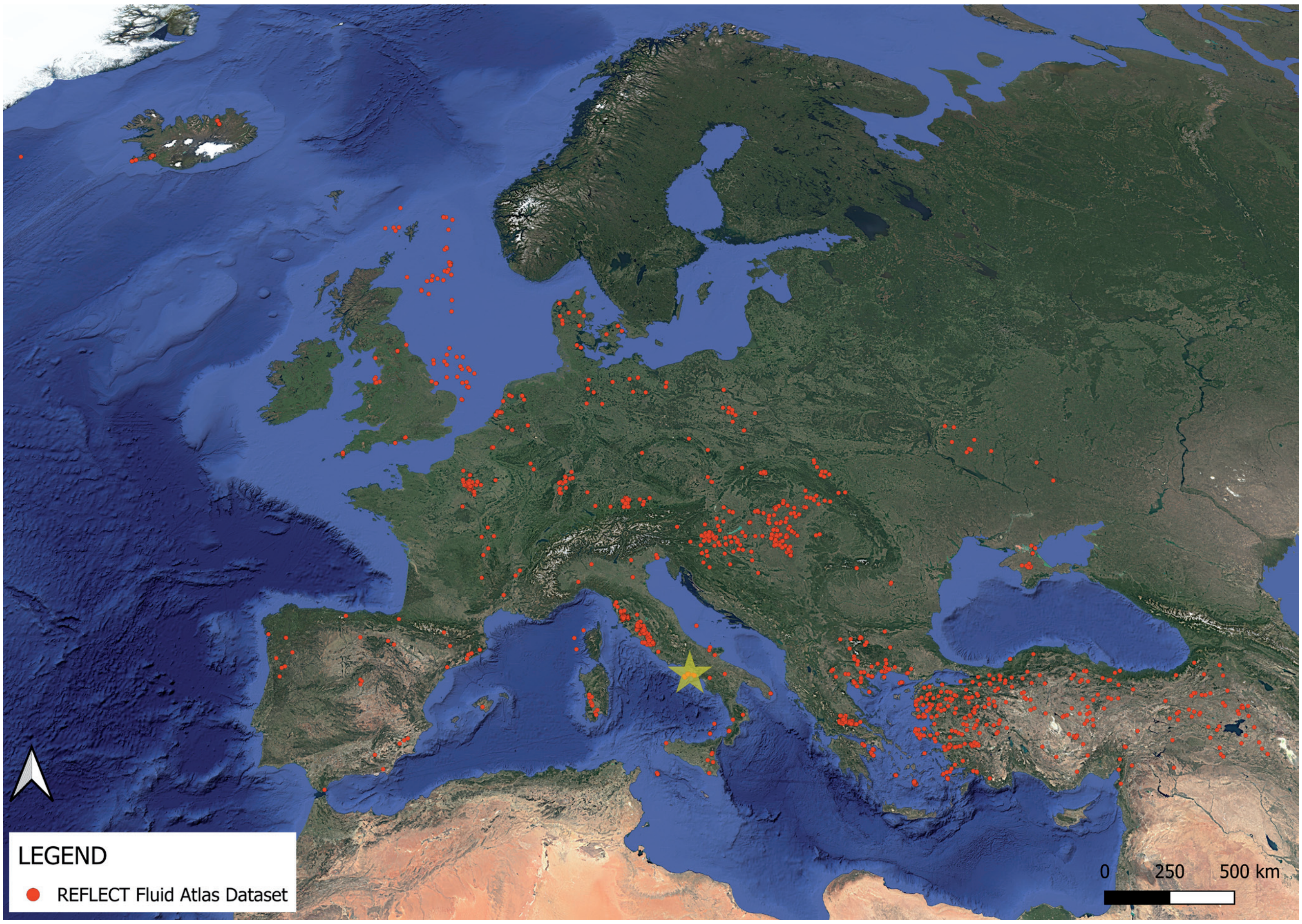

Fig. 3 - Spatial distribution of geothermal fluid data from the REFLECT European Geothermal Fluid Atlas

comparisons of geothermal technology distribution, regional assessment for co-production opportunities, and the integration of fluid chemistry datasets like REFLECT where available.

DISCUSSION

The created database demonstrates how combining geothermal plant datasets (JRC and GGPT) with the available fluid properties dataset (REFLECT) can move geothermal assessment beyond power generation toward resource quality and co-production feasibility. By structuring the database, the plant records can be linked to fluid chemistry where available, and the framework creates a pathway for screening co-production opportunities using a set of criteria (*e.g.*, salinity, key major ions, trace metals, and scaling indicators). In parallel, integrating mineral-resource information (USGS and EGDI) add a mineral-occurrence dataset to the workflow, enabling systematic linking of geothermal sites to regional mineralization settings. This combination supports transparent prioritization of candidate areas for co-production by bringing together infrastructure, fluid properties, and mineral-occurrence context within a single database structure.

At the global scale, geothermal capacity remains unevenly distributed, with North America and Europe accounting for a large share of installed power while other regions contribute smaller fractions. Turbine technology is dominated by ORC/binary units, with substantial flash installations and a smaller proportion of dry-steam plants. This technology mix is not only a power-system descriptor; the turbine pathway strongly influences phase partitioning and the availability, temperature, and chemistry of the produced liquids after power generation, thereby setting the practical bounds for mineral co-production. In this sense, the combined JRC–GGPT combination does more than expand coverage; it improves the interpretability of co-production potential by clarifying plant status, location, and turbine type for newer or rapidly changing projects, which is essential when linking infrastructure to chemistry and mineral context.

For Italy, the geothermal plant datasets confirm Tuscany (Larderello–Travale/Radicondoli and Monte Amiata) as the national geothermal core. The turbine fleet is dominated by steam-dominated/dry-steam production at Larderello–

Fluid_sample	Well_id	Local_id_f	Country	nuts2_name	Well_depth	Analysis_year	dominant_phase	Temp.	Li_mg/l
W_IT_974_FS_001	W_IT_974	Pozzo parco Cuma	ITALY	Campania	240	1985	Liquid	36	0.4
W_IT_975_FS_001	W_IT_975	Damiani	ITALY	Campania	38	1994	Liquid / Gas	51	0.58
W_IT_976_FS_001	W_IT_976	Hotel tennis	ITALY	Campania	75	1994	Liquid / Gas	85	0.82
W_IT_979_FS_001	W_IT_979	Terme di Agnano	ITALY	Campania	38	2003	Liquid / Gas	37.6	1.14
W_IT_986_FS_001	W_IT_986	Carta romana	ITALY	Campania	28	1992	Liquid / Gas	32	0.1
W_IT_988_FS_001	W_IT_988	La gondola ii	ITALY	Campania	70	1992	Liquid / Gas	96	4.5
W_IT_989_FS_001	W_IT_989	Acque Termominerali	ITALY	Campania	10	1984	Liquid / Gas	42.5	0.6
W_IT_990_FS_001	W_IT_990	Aphrodite	ITALY	Campania	100	1995	Liquid / Gas	90.3	3
W_IT_991_FS_001	W_IT_991	Ibsen	ITALY	Campania	130	1995	Liquid / Gas	45.1	0.43
W_IT_992_FS_001	W_IT_992	Terme Comunali	ITALY	Campania	20	1984	Liquid / Gas	44.5	0.62
W_IT_993_FS_001	W_IT_993	S. Maria	ITALY	Campania	100	1984	Liquid / Gas	47	0.05
W_IT_995_FS_001	W_IT_995	La pergola	ITALY	Campania	50	1995	Liquid	53.5	0.3
W_IT_996_FS_001	W_IT_996	Tusculum	ITALY	Campania	60	1984	Liquid	41.8	0.09
W_IT_999_FS_001	W_IT_999	S.lorenzo ii	ITALY	Campania	40	1984	Liquid	60	0.8

Tab. 1 - A subset of the REFLECT geothermal fluid dataset attribute table for the highlighted samples with star in Fig. 3

Travale, with flash-based configurations and add-on binary/ORC recovery particularly relevant at Monte Amiata. In the present database, REFLECT also provides Italian site-level fluid properties, enabling chemistry-informed screening when data are available, rather than relying on infrastructure alone. These observations are consistent with the national-scale synthesis of lithium potential by Dini *et alii* (2022), which highlights that Li-rich geothermal fluids occur beyond Tuscany, with notable potential in Campania (Mofete/Campi Flegrei) where lithium reaches ~480 mg/L in deep-reservoir liquid and remains ~28–56 mg/L in intermediate to shallow reservoirs. Dini *et alii* further indicate that thermal waters exceeding 10 mg/L Li are concentrated especially in Emilia-Romagna, Campania, and Tuscany, and that some of the highest values occur in saline brine of the Northern Apennines foredeep associated with hydrocarbon reservoirs, supporting a wider Italian set of targets for co-production screening than power-plant locations alone would suggest.

Mineral-occurrence layers from EGDI and USGS sources are therefore used only as geological context (they indicate whether a geothermal site lies near known mineralization and may flag elements that could matter for scaling or not), but they do not indicate what is dissolved in the produced fluids. Instead, these layers help identify which sites could be targeted first for standardized REFLECT-style fluid sampling, so that follow-up work can determine the most suitable pathway at each site (for example, brine-based lithium extraction where produced brine is available versus steam/condensate-based valorization and scaling management in steam-dominated systems).

LIMITATIONS AND FUTURE WORK

The database presented here is constrained by some limitations and sources of uncertainty, which users should consider when applying it. The underlying datasets differ in reference year, update frequency and inclusion criteria. As a result, the database is inherently asynchronous, and apparent gaps may reflect differences in compilation dates rather than true absence of plants or mineralization. Moreover, there are coverage biases. JRC and GGPT coverage are uneven across regions, and USGS and EGDI-CRM represent known, documented mineral occurrences, not an exhaustive census of mineralization or resource potential. The database is therefore more suited to contextual evaluation rather than resource quantification. Furthermore, location accuracy and record linkage introduce positional uncertainty. Plant and mineral occurrence coordinates originate from heterogeneous sources with varying precision. Matching JRC and GGPT records relies on name normalization and nearest-neighbor searches within a finite distance threshold, and some plants may be mismatched or remain duplicated.

Future work will focus on both extending and applying the database. On the data side, the structure is designed to accommodate new releases of plant registries (JRC, GEM), updated mineral occurrence layers (USGS, EGDI-CRM) and emerging national datasets, so that temporal changes in geothermal deployment and critical mineral reporting can be tracked explicitly rather than being treated as a static picture. A key next step is the systematic linkage to fluid chemistry datasets such as REFLECT allowing selected fields to be enriched with field-level information on temperature, salinity, major ions, and where available, lithium and other CRM concentrations. On the application side, the database can support regional criteria assessments for pilot selection, integration with land-use and environmental constraints, and more detailed case studies where plant, fluid and mineralization information can be combined with techno-economic models.

Data availability

The original datasets used to construct the database are all open access. The JRC Geothermal Power Plant Dataset can be obtained from the European Commission's Joint Research Centre data catalogue. The Global Geothermal Power Tracker (GGPT) is available from Global Energy Monitor following free registration. The U.S. Geological Survey's global distribution of critical minerals is available as a public data release. The EGDI-CRM dataset can be accessed through the European Geological Data Infrastructure (EGDI) portal, and the REFLECT European Geothermal Fluid Atlas is accessible via the REFLECT project website.

The GIS database produced in this study (GeoPackage format) has been deposited in Zenodo and is openly accesible under an open license at :http://doi.org/10.5281/zenodo.19065166

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