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Potential assessment of critical raw materials from European geothermal fluids

Laura Spitzmüller [a,*], Andrea Flores Salinas [a], Valentin Goldberg [a,b], Jens C. Grimmer [a], Rafael Villablanca-Ahues [b], Fabian Nitschke [a]

[a] Geothermal Energy and Reservoir Technology, Institute of Applied Geosciences, Karlsruhe Institute of Technology, Karlsruhe, 76131, Germany
[b] BWG Geochemical Consulting GmbH, Seestraße 7a, 17033, Neubrandenburg, Germany

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ABSTRACT

The energy transition is accompanied by a growing demand for raw materials. The EU Critical Raw Materials Act (CRMA) foresees at least 10% of raw material supply covered by domestic sources. Geothermal fluids have the potential to contribute significantly achieving this target. Beyond the well-known and extensively studied lithium resources in European geothermal fluids, additional potential for other elements exists. We assess the potential of 64 elements in geothermal fluids that are defined as critical and strategic raw materials or raw materials in general under the CRMA. This assessment is based on >4000 geothermal fluid analyses across Europe. In summary, 13 of the 64 assessed elements are identified to provide the largest potential based on (a) their concentrations in geothermal fluids, (b) their ability to contribute to domestic supply and reduce supply-chain risks, (c) their hypothetical market value, and (d) their geostrategic importance. These elements are Li, B, Mg, Si, Mn, Ge, As, Rb, Sr, Cs and Pb with high reliability and Sc and Pd with low reliability. At the lower end of the spectrum are nine elements with the lowermost potentials (Se, Zr, Nb, In, Sn, Te, Ta, Re, Bi) and the Rare Earth Elements. Our evaluation framework simultaneously considers abundance and availability, economic potential and geostrategic and environmental aspects, thereby improving comparability across elements. Having identified these 13 promising candidates, future research can be more effectively focused on detailed resource assessments and the development of targeted extraction strategies.

1. Introduction

Energy transition toward renewable sources entails a rapidly increasing demand in raw materials (Marscheider-Weidemann et al., 2021). The European Union aims to increase its sovereignty and adopted the European Critical Raw Materials Act (CRMA) that foresees at least 10 % of all critical materials used in EU to originate from domestic sources by 2030[2], (CRMA, 2024). The ambition is to contribute to de-risk vulnerable supply chains of many raw materials needed for e.g. energy transition technology, electro mobility, maintenance of energy-intensity industry, information – communication – digital technologies (ICT), and aerospace and defense sectors (Habib et al., 2020; Carrara et al., 2023). As the current eco-political situation powerfully underscores, the control of access to these raw materials effectively means control over a substantial part of the global high-technology economy. Reducing the dependence from third countries is of significant strategic importance to European industry and the broader economy. In addition, European companies are facing considerable pressure from the recently introduced EU Supply Chain Directive (EU Directive, 2024/1760), which imposes strict sustainability requirements throughout the entire supply chain. To maintain economic competitiveness while meeting these regulatory and ethical standards, Europe must expand its local exploration and mining capacities. This is not only economically and geo-strategically essential but also politically foreseen and mandated under the EU CRMA[3], which requires the development of domestic production capacities to strengthen Europe's resilience and strategic autonomy. Ensuring a stable, sustainable CRM supply is therefore fundamental not only for Europe's industrial resilience and global position but also for safeguarding overall societal well-being. In total, 66 chemical (inorganic) elements are listed by the European Commission (European Commission: Directorate-General for Internal Market Industry Entrepreneurship and SMEs, 2023; CRMA, 2024). Of these, 45 of elements are considered to be critical raw materials (CRM) or strategic critical raw materials (SCRM) by the European Commission

* Corresponding author.
E-mail address: laura.spitzmueller@kit.edu (L. Spitzmüller).

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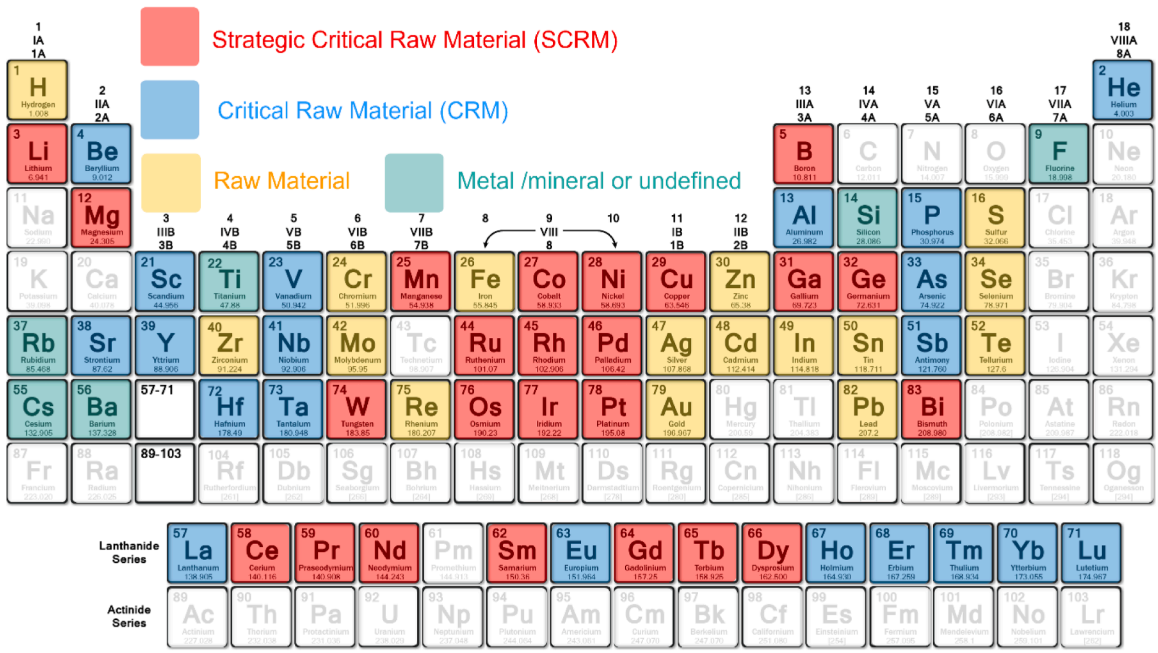

Fig. 1. Strategic critical raw materials (red), critical raw materials (blue), raw materials (yellow) and CRM that are only critical in the metal or mineral form (F as fluorite, Si as either silica sand or pure silicon, titanium as either titania or titanium metal, barium as barite) or undefined (Rb, Cs). Classification according to Raw Materials Information System (RMIS) of the European Commission (2025) (European Commission, n.d.). Rb and Cs are not considered CRM in European regulations, however they are listed as critical by USGS (USGS, 2026) and have high economic potential.

(European Commission, n.d.). A graphic representation of these elements is shown in Fig. 1. The SCRMs are colored red, the CRMs blue, other raw materials (RM) that are neither SCRM nor CRM in yellow and elements where only the pure metal or a specific mineral are considered (S)CRM or where the criticality is not yet established are colored in green. These are fluoride (F), barite (Ba), titanium metal and titania (Ti) and silicon and silica (Si). Rubidium (Rb) and cesium (Cs) are not yet evaluated in the EU CRMA but are listed as critical by USGS (USGS, 2025) and could play a pivotal role in future technologies like quantum computing (Wu et al., 2021; Cohen and Thompson, 2021). Thus, Rb and Cs are included in this evaluation. Furthermore, the focus lays on metals, metalloids and transition elements; the gases H and He are therefore excluded from the further evaluation process.

In recent years, efforts have been made to establish alternative pathways beyond conventional material mining to reduce the negative consequences as for example excessive land use (Sanchez et al., 2025), environmental pollution (e.g. acid mine drainage AMD (Rzymski et al., 2017)), carbon footprint (Nuss and Eckelman, 2014) and societal and human health aspects (Ulimwengu and Sanginga, 2025) and simultaneously to cope for the increasing demand (Elshkaki et al., 2018). One strategy is to increase the recycling rate and efficiency and invest in circular economies (Reck and Graedel, 2012; Nassar et al., 2015). Others investigate an alternative approach: recovery of elements from fluid sources such as sewage and industrial waste waters (DuChanois et al., 2023; Lin et al., 2021), AMD (Chen et al., 2022; Abeywickrama et al., 2024), desalination brine and seawater (del Villar et al., 2023; Ihsanullah et al., 2022; Loganathan et al., 2017) and other natural fluids such as geothermal brines (Bourcier et al., 2005; Harper et al., 1992; Goldberg et al., 2021; Sajkowski et al., 2023).

Particularly, geothermal fluids are attractive as a potential novel resource/reserve for raw materials. For example, compared to hard rock mining, brine mining is a minimal invasive procedure that produces less tailing and less land usage (Goldberg et al., 2021). If raw material extracting is further implemented into geothermal power plant operation, the dual usage of the inherent thermal energy and the fluidic raw material inventory reduces the ecological impact and does not rely on fossil fuels for the extraction process. Additionally, geothermal fluids can be highly mineralized and enriched in raw materials due to water-rock-interaction (WRI) at high temperatures and pressures over elevated timespans (Clark et al., 2010; Aquilina et al., 1997). Commercially harvesting mineral raw materials from geothermal fluids already dates back to the beginning of the 20th century in Larderello, Italy, where it was established even prior to utilization of the thermal energy for electric generation (Allegrini et al., 1992). Here, geothermal fluids were used as a resource for boron (boric acid and borax), ammonium bicarbonate and sulfur (Allegrini et al., 1992). The recently most prominently discussed CRM potentially extractable from geothermal fluids is lithium. Projects in the North German Basin in Germany, the Upper Rhine Graben in Germany and France or in the Salton Sea region in the USA already quantified the local resources and reserves as well as concluded first field demonstrator tests to a pre-commercial scale (Bourcier et al., 2005; Vulcan Energy Resources, 2025; Neptune Energy, 2026). Apart from lithium, geothermal fluids can contain significant concentrations of other elements like boron, manganese and silicon (silica) that have been subject to extraction application/commercialization (Goldberg et al., 2021; Neupane and Wendt, 2017; Pérez et al., 2025). Geothermal locations with successful demonstration of selective element extraction can be found e.g. in Iceland (Svavarsson et al., 2014) (silica), New Zealand (Brown and Bacon, 2009) (silica and boron), Italy (Allegrini et al., 1992; Belova et al., 2009) (boron/boric acid, borax, sulfur) and USA (Bourcier et al., 2005) (silica, zinc). Gallup et al. (1995) reported a pilot scale plant triggering purposely scaling formation containing several metals such as silver, antimony, iron, aluminum, copper and arsenic. Furtherly, they speculated that also precious elements like Au, Pd and Pt could be enriched in the scales. However, the handling of this rather unspecific extraction method is complex as it may also cause accumulation of unwanted elements such as radionuclides and the undefined composition of the scales makes post-treatment necessary, which is likely to share disadvantages of hard rock processing. Selective element removal is therefore more preferred. Additionally, a positive side-effect of extracting minerals or removing metals, is their lowered concentration in the remaining fluids, consequently lowering the risk of their precipitation, reducing risk for scaling formation and reducing the risk of reduced permeabilities in the reservoir, thus increasing overall geothermal power plant efficiency and longevity (e.g. Gallup et al., 1995).

Overall, (geo)thermal fluids present themselves as a valuable, novel resource that needs to be thoroughly studied to assess and quantify the European potential. This study evaluates the potential of 64 elements in European geothermal fluids and identifies the most promising candidates for future targeted resource assessment and extraction method development.

2. Database and methods

We evaluate European (geo)thermal fluid composition. Europe is thereby defined as countries located on the European continent and thus geographically or politically counted as a European country. The evaluation is based on data taken from Reflect database (Kovács et al., 2023) (references therein) and its successor the CRM database (Seres et al., 2026) (references therein) as well as other published chemical analyses of thermal fluids across Europe (Aquilina et al., 1997; Arnorsson, 1984; Bosia et al., 2021; Buric et al., 2015; Calami et al., 1976; Dezayes et al., 2013; Eggeling et al., 2018; Elmi et al., 2010; Fresenius and Kußmaul, 2026; Fries et al., 2025; Göb et al., 2013; Hannington et al., 2016; Herch, 2000; Hermann et al., 2022; Isenbeck-Schröter et al., 2016; Jahja et al., 2024; Jozef et al., 1995; Kaasalainen et al., 2015; Karabelas et al., 1989; Kazakis et al., 2025; Kirnbauer, 2008; Kristmannsdóttir, 1998; Ladner et al., 2008; Loges et al., 2012; Lyubomirova et al., 2020; Michard, 1990; Möller et al., 1998; Möller et al., 2004; Neal and Shand, 2002; Pauwels et al., 1991; Pauwels et al., 1993; Petrovic Pantic et al., 2015; Rosberg and Erlström, 2019; Sanjuan et al., 2001; Sanjuan et al., 2004; Sanjuan et al., 2006; Sanjuan et al., 2010; Sanjuan et al., 2016; Sanjuan et al., 2020; Sanjuan et al., 2022; Sauer, 1977; Skopljak and Vlahovic, 2012; Stober and Bucher, 2005; Stober and Bucher, 2015; Strauch et al., 2024; Toussaint, 2013; Vaute, 1998; Vrba, 1996; Wang et al., 2024; Younger et al., 2016). Additionally, a small fraction (~0.02 %) of the data derives from internal, unpublished reports. For the platinum group elements (PGE) data from outside Europe is shown for reference (McKibben et al., 1990; Gallup, 1998; Harrar and Raber, 1984; Simmons, 2017; Simmons et al., 2018). Details on each element are given in the Supplementary Information (SI) Table A1. In total, over 4000 fluid analyses across Europe have been evaluated to assess their potential raw material content. The selected data include fluid data from wells as well as from thermal springs or thermal spas. The variety of the data sources reviewed in this study certainly reduces their comparability as shown for example by Bosia et al. (2021) who document time-dependent differences in fluid compositions due to natural and operational variations but also inter-laboratory analytical variations. Additionally, 93% of the evaluated analyses derive from 9 countries, namely Iceland, France, Germany, Hungary, Greece, Türkiye, Italy, Bulgaria and the Netherlands, whereas 21 other countries only contribute 7% (Figure S 1). The data evaluated in this study should therefore be seen rather as a range than as absolute values representative for each country.

In general, the data was checked for reliability. Due to partly missing analyses of anions and/or cations, calculating the ion balance was not possible. Unexplainable unrealistic high concentrations were double-checked for possible unit conversion errors and either corrected or discarded. Concentrations below detection limit or given as 0 mg/L were not included. Table A1 in the SI gives the total number of analyses and the minimum, maximum, mean and median concentrations for each evaluated element together with the location and reference for each maximum concentration. Additionally, the used average seawater concentration is given.

2.1. Evaluation methods and selection criteria for criticality and potential assessment

2.1.1. Criticality assessment

For the criticality assessment, the Herfindahl-Hirschman Index (European Commission, n.d.) together with the Economic Importance (European Commission: Directorate-General for Internal Market Industry Entrepreneurship and SMEs, 2023) and the End-of-Life Recycling Input Rate (European Commission, n.d.) was used. Data is given in the SI Table A2. For the HHI the highest values were taken independently of whether it reflects the HHI of Primary Production, Resource or Refinery Production. This decision was made to reflect the overall bottleneck rather than identifying the critical parameter. Still, the specification of the HHI used is given in the SI Table A2. The EoL RIR reflects the overall circularity of the economies.

2.1.2. Potential assessment

For assessing the potential of raw material extraction from (geo) thermal fluids, we considered 3 categories with 3 criteria each. These are: Abundance/availability, economic factor/market assessment and geopolitical/environmental aspects.

Take note that the values are provided cannot guarantee for accuracy or analytical correctness and are solely based on available data by November 2025. Especially for the dynamic Hypothetical European Market Supply and the Hypothetical Market Value, the data indicate rather the potential than real values, as for example, extraction technologies and refinery steps as well as price fluctuations may be rather dynamic than stable parameters. Furthermore, factors such as reservoir size, recharge from the reservoir for the extracted elements and fluid circulation time, thus the possibility of chemical breakthrough and dilution effects are neglected. The values shown here are therefore only indicative for a first assessment of the raw material inventory in (geo) thermal fluids using standardized selection criteria.

2.1.2.1. Abundance/availability

2.1.2.1.1. Concentration P95/P99 (mg/L). Taken from the available database, the P95 or P99 concentration is the 95th or 99th percentile of all the concentrations encountered in European thermal fluids. The selection was made based on the number of data analyses: below 100 P95 and above 100 P99 concentrations were chosen. The reasons behind this selection are that a) if the total number of analyses is high, P99 reflects the highest potential more accurately than P95, however b) if the total number of analyses is low, P99 is equivalent to the maximum value, which might be a one-point outlier and therefore not representative. For more detail on the data evaluation, availability, reliability and distribution see Section 3.3.

Exemptions are made for Ir and Pt, as global concentration distributions instead of European ones have been used, as only one data point is reported within Europe. Additionally, for Ru and Rh the highest reported concentrations are chosen as due to the low number of available data, the P99 and P95 are equal. For Pd, however, the second-highest value was chosen for the evaluation, as the maximum value is an outlier >1.5IQR above Q3. The same applies for Pt and Ir as the maximum reported values are outside of the 1.5IQR above Q3.

2.1.2.1.2. Enrichment factor. P95/99 concentration normalized to the average seawater concentration for the selected element. For more details see Section 3.3 and SI Table A1.

2.1.2.1.3. Hypothetical European Market Supply per year (%/a):. Comparison of the annual European consumption for the selected element according to RMIS Database (European Commission, n.d.) (SI Table A3) and the potential producible commodity mass assuming the P95 or P99 concentration of the element.500 L/s was chosen as a base case scenario with 100 % availability of the thermal water cycle and the extraction plant and an extraction efficiency of 100 % of the element dissolved in the fluid. 500 L/s across Europe is an attainable rate, for example the Nesjavellir power plant in Iceland and the 7 geothermal power plants located in the Upper Rhine Graben (Germany) and the North German basin together reach 510 L/s (Goldberg et al., 2022; Ballzus et al., 2000). However, it should be noted that thermal springs generally have low flow rates. This base case might therefore under- or overestimate the potential for certain elements, but still can be seen as a comparable calculation base for further more detailed, realistic evaluation of element potentials at specific sites.

As not for all elements extraction technologies and respective efficiencies are available, an (unrealistic) extraction efficiency of 100 % is chosen. For the extraction of Li from deep brines, representing one of the most advanced approaches, current projects reach 75 – 95 % (Farahbakhsh et al., 2024).

These decisions were made to reflect the maximum possible attainable concentration under best conditions. A detailed and holistic potential estimation should moreover include other factors, such as the reservoir size, porosity, recharge capability and potential dilution effects in the produced brine caused by the reinjection of the commodity-depleted and re-injected fluid. Therefore, the hypothetical European market supply value as well as the hypothetical market value are only indicative to visualize the potential and are highly dependent on the European consumption data as well as on the chosen concentration values. Thus, to determine the actual potential this evaluation must be re-done with up-to-date consumption data, and concentration and flow rates at specific geothermal sites, realistic extraction efficiencies and detailed knowledge of reservoir parameters.

Exemptions are made for Rb, Cs, Ru, Rh, Ir and Pt as no data on European consumption is available, therefore their hypothetical share of the global market is calculated.

2.1.2.2. Economic factor/Market assessment

2.1.2.2.1. Hypothetical market value ($/a). Calculated analogous to the hypothetical European Market Supply, but multiplied by the price per kg of the element or compound (details on price selection see below). Hypothetical market values should be interpreted with caution due to price volatility. Further, CAPEX, OPEX and costs related to development and implementation of extraction processes and refinery step related costs are not included.

2.1.2.2.2. Price (US$/kg). A complete list of the prices per kg of element can be found in the supplementary with source and date. Take note that calculations were made to determine the price for the element using the molar weight wherever needed (see also SI Table A5).

The prices per kg element are spot prices. For the industrial minerals, spot prices from commodity exchanges are publicly available and therefore mostly stable and reliable. Prices for Ag, Al, Au, Co, Cu, Ga, In, Ir, Mo, Nd, Ni, Pb, Pd, Pt, Rh, Ru, Te, Sn and Zn were taken from Daily Metal Price (Daily Metal Prices, n.d.) which displays public exchanges such as the London Metal Exchange (LME) and the New York Mercantile Commodity Exchange (COMEX). For the minor elements, prices from Shanghai Metals Market (SMM) (SMM Information and Technology Co. Ltd., 2026) were used, which means they likely do not reflect the prices of long-term contracted trades neither do they typically include VAT, shipping or taxes. Indeed, for certain elements, the estimated European prices range several magnitudes above the reported spot prices by SMM (Deutsche Rohstoffagentur DERA, 2025). The German Mineral Resources Agency (Deutsche Rohstoffagentur DERA, 2025) reports that especially for the following elements, European prices are considerably higher: Y (+1450 %), Gd (+400 %), Ga (+320 %), Tb (+270 %), Dy (+260 %), Ge (+160 %), Sb (+120 %), Bi (+110 %), Te (+110 %), W (+10 %).

Furthermore, it must be considered that prices reported are partly ex-works (EXW), Free Carrier (FCA), in warehouse, direct to costumer (DTC/D2C) or Free on Board (FOB) prices. Additionally, as for most elements no established extraction method from geothermal fluids exists, it is uncertain to predict the end-product commodity and quality. For estimating the economic factors, we consider therefore the prices of the purest grades. All information is given in the SI Table A5 with indication on commodity, grade and trading data.

2.1.2.2.3. Global market size (t/a). Data taken from the RMIS website (European Commission, n.d.) and for Rb and Cs from USGS (USGS, 2026).

All data is given in SI Table A3 with indication whether the market size is given for the extraction or processing stage or both together. For some elements no such specification was available. It should be noted therefore, that the values likely not reflect accurately to global market sizes.

2.1.2.3. Geopolitical and environmental aspect

2.1.2.3.1. EI – economic importance. Data taken from the European Commission (European Commission: Directorate-General for Internal Market Industry Entrepreneurship and SMEs, 2023). Take note, for Rb and Cs, there is no data available. EI above 2.8 is considered critical.

2.1.2.3.2. SR – supply risk. Data taken from the European Commission (European Commission: Directorate-General for Internal Market Industry Entrepreneurship and SMEs, 2023). Take note, for Rb and Cs, there is not data available. SR above 1 is considered critical.

2.1.2.3.3. GWP – global warming potential (kg $CO_{2\ eq}$/kg). Data taken from Nuss and Eckelman (Nuss and Eckelman, 2014) and for F, Si, P and S from Feix and Hache (Feix and Hache, 2025). No data available for Rb and Cs. Nuss and Eckelman (Nuss and Eckelman, 2014) evaluated the cradle-to-gate production GWP of 63 metals while data from Feix and Hache (Feix and Hache, 2025) compiled reported GWP of 50 metals. Although data from Feix and Hache (Feix and Hache, 2025) is more recent, data from Nuss and Eckelman (Nuss and Eckelman, 2014) was preferred as all values originate from one source instead of multiple, which results in an in-itself concise evaluation as the underlying evaluation mechanism was equal for all elements. High GWP of cradle-to-gate production of metals indicates that non-traditional mining strategies like brine mining might be attractive alternatives.

Elements are evaluated to determine their potential of being mined from fluids. Sorting criteria are:

- **Highest potential:**
  - >1 % hypothetical European Market Supply
  - >1 M $ hypothetical annual market value
- **Medium-to-high potential:**
  - >0.1 % hypothetical European Market Supply
  - >0.1 M $ hypothetical annual market value
  - SR & EI > threshold, element strategic
- **Medium-to-low potential**
  - <0.1 % hypothetical European Market Supply
  - <0.1 M $ hypothetical annual market value
  - SR & EI > threshold
- **Lowest potential**
  - <0.01 % hypothetical European Market Supply
  - <1000 $ hypothetical annual market value
  - SR &/EI < threshold
  - P95/P99 concentration <0.01 mg/L

Precious metals and Rare Earth Elements & Yttrium (REY) are evaluated separately due to extremely high prices (precious metals) and

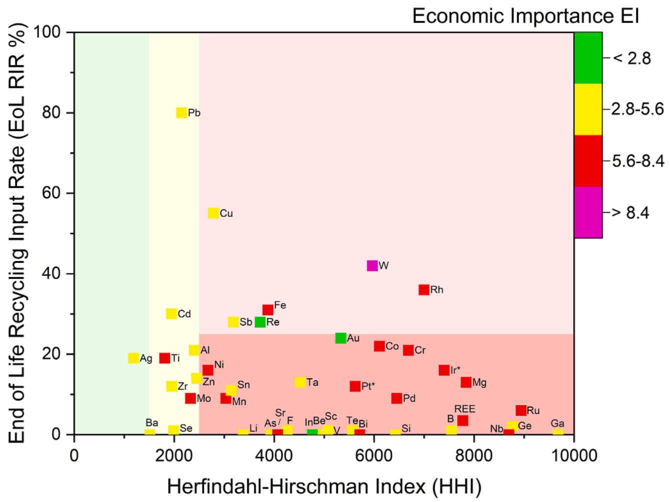

Fig. 2. End-of-Life Recycling Input Rate (EoL RIR) over Herfindahl-Hirschman Index (HHI) and economic importance (EI). EoL RIR above 25% are targeted by EU CRMA. HHI reflects the market concentration, values below 1500 are well-distributed markets, 1500–2500 moderately concentrated and above 2500 highly concentrated market, with 10 000 being a pure monopoly. EI above 2.8 is considered a criticality threshold. Not shown are P, S, Rb, Cs, Hf and Os. REE are grouped together.

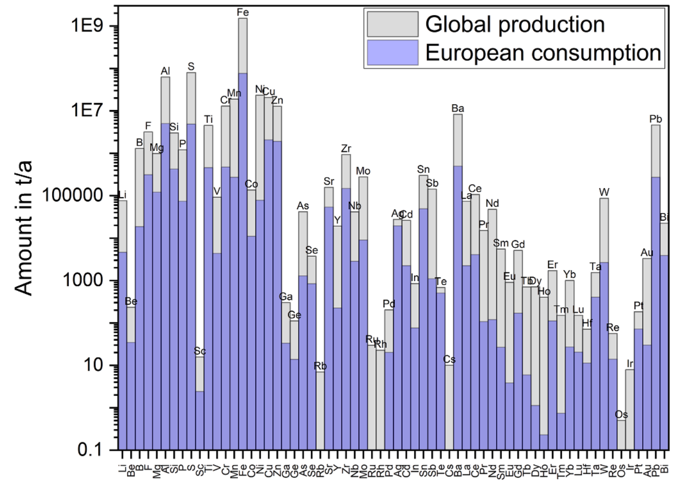

Fig. 3. Market volumes for the evaluated elements. For Rb, Ru, Rh, Cs, Os and Ir no data on European consumption available.

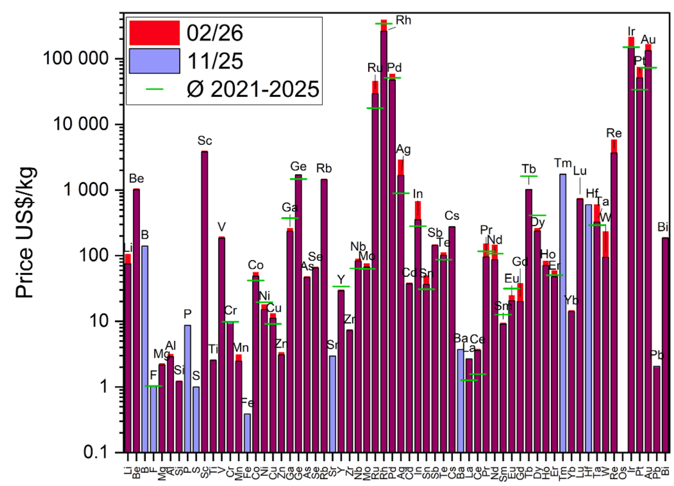

Fig. 4. Prices in US$ per kg of element. Data presented in the SI Table A5 with respective sources. Comparison between prices from 11/25 and 02/26 underscore the volatility of the market. Partly, average prices from 2021–2025 were available by DERA (Deutsche Rohstoffagentur DERA, 2025) and shown here as green lines.

high geostrategic importance (REY).

3. Results and discussion

3.1. Criticality assessment

The Economic Importance (EI) consists of values for the respective NACE sectors (Statistical Classification of Economic Activities in the European Community "Nomenclature statistique des Activités dans la Communauté Européene") and the substitutability of the elements. Threshold for criticality is for EI above 2.8. The Herfindahl-Hirschman Index is part of the Supply Risk calculation (European Commission: Directorate-General for Internal Market Industry Entrepreneurship and SMEs, 2023) and is an indicator of market distribution. HHI below 1500 indicate unconcentrated markets (competitive), 1500–2500 moderately concentrated and above 2500 highly concentrated (anti-competitive) markets with 10,000 being a pure monopoly. End-of-Life Recycling Input Rate quantifies the input by recycling to the material supply chain. EU CRMA aims for an EoL RIR above 25% by 2030. Fig. 2 shows the EoL RIR over the HHI for several raw materials color-coded according to their EI. Raw materials of high economic interest that fall in the area below 25 % EoL RIR and above 2500 HHI are especially critical/vulnerable. These are Ni, Mn, Sr, Bi, Pt, Co, Pd, Cr, Ir, Mg, REE, Nb and Ru. Fe, Rh and W are likewise critical/vulnerable but have an EoL RIR above 25%. On the other hand, Ga and Ge have HHI near-monopoly with minimal EoL RIR. Pb has an outstanding EoL RIR of approx. 80 %. Take not that nor for all elements HHI and EoL RIR were available; i.e. not shown here are P, S, Rb, Cs, Hf and Os. Furthermore, REE are not shown individually.

Considering the predicted compound annual growth rates (CAGR) for the elements (SI Table A4), the EoL RIR must grow simultaneously at the same rate to cope for the increasing demand, a scenario that is likely unrealistic to achieve. Therefore, the EoL RIR are rather a momentary status and should be considered together with the CAGR. Coupling these parameters, elements such as lithium strongly move into focus.

3.2. Market sizes

Data on global production and European consumption in metric tonnes per year are taken from the European Commission (European Commission, n.d.) (SI Table A3) and visualized in Fig. 3. Fe and iron ores are the biggest market contributor, followed by other industry-relevant elements like Al, S, Cr, Mn, Ni, Cu, Zn, Ba (barite) and Pb. Elements with the smallest markets are Be, Sc, Ga, Ge, Rb, PGE (Ru, Rh, Pd, Os, Ir, Pt), Cs, Hf and Re. For Ru, Rh, Os and Ir (PGEs) and Rb and Cs no individual data on European consumption are available. Further, for global market sizes of Rb and Cs estimations from USGS (USGS, 2025) are taken.

Prices are taken from Shanghai Metals Market (SMM, for the minor elements) and LME & COMEX (for the major industry elements) and are all listed in SI Table A5. Fig. 4 shows the prices of the elements (see Section 2.1.2 and SI Table A5 for details on the commodity) and their changes between November 2025 and February 2026. While for Be, Mg, Al, Si, Sc, Ti, V, Cr, Zn, Ge, As, Se, Rb, Y, Zr, Nb, Cd, Sb, Cs, La, Ce, Sm, Tb, Yb, Lu, Pb and Bi the prices remained stable (<10% difference) in this period, increasing prices are reported for Li, Mn, Co, Ni, Cu, Ga, Mo, Ru, Rh, Pd, Ag, In, Sn, Te, Pr, Nd, Eu, Gd, Dy, Ho, Er, Ta, W, Re, Ir, Pt and Au with strongest increase for Pr (+60 %), Re (+61 %), Nd (+70 %), Ag (+75 %), Ta (+86 %), Gd (+91 %), In (+92 %) and W (+150 %).

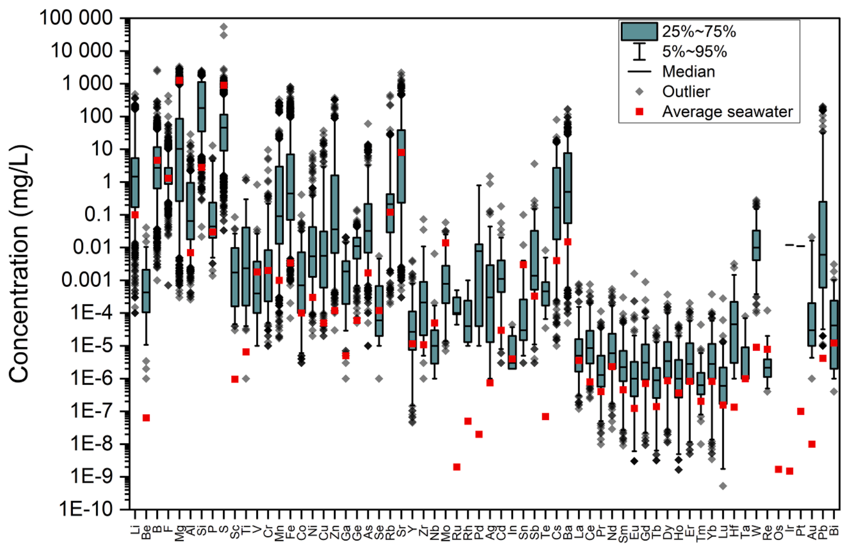

Fig. 5. The concentration of raw materials in European thermal fluids. For comparison, the average seawater concentration is provided (see also SI Table A1).

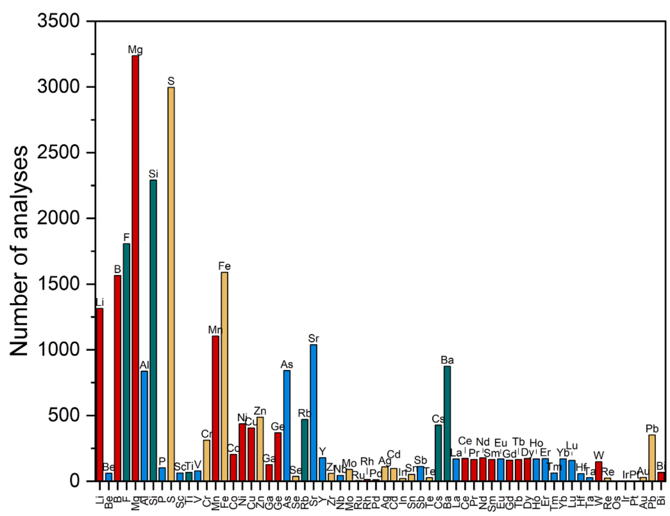

Fig. 6. Total number of analyses where the specific element was measured and above detection limit. The color coding follows the coding applied in Fig. 1 and is: red SCRM, blue CRM, yellow RM, green metal/mineral/not assessed.

Wherever available, the average price between 2021–2025 is displayed with data taken from DERA (Deutsche Rohstoffagentur DERA, 2025). The prices for F, Cr, Ge, Mo and Te have been stable. For Ga, Y, Sm, Eu, Tb and Dy historic prices were higher than current, although it must be considered, that prices in Europe can be considerably higher than displayed here (see Section 2.1.2). Strong increases compared to historic average ranges can be found for Ru, Ag, In, Pt and Au.

3.3. European thermal fluid composition and data availability

From Fig. 5, Fig. 6 and Table A1 it can be seen that among the raw materials identified in Fig. 1B, Mg, Si, S, Sr and Ba have the highest concentrations (consistent with data evaluated by Clark et al. (2010)) and that these elements are also among the frequently analyzed elements, while minor accessories such as Be, V, Ga, Se, Nb, In, REE, Hf, Ta, Re and Au (consistent with data evaluated by Clark et al. (2010)) are among the least analyzed elements. This peculiarity certainly represents a major bias in the data as the less analyses exist the higher is the possibility that the available values might not be representative which should be kept in mind for the following potential assessments.

Rb, Sr, Cs and Ba are large ion lithophile elements (LILE) and characterized by high fluid mobility (Zack and John, 2007), a property that is also reflected by their high concentrations in thermal fluids. As expected, alkali and alkaline earth elements are the major constituents of cations of thermal fluids (Clark et al., 2010) and thus also the highest number of analyses exist. On the other side, Ti, Zr, Nb, Hf and Ta are considered mostly immobile in fluids (Zack and John, 2007) as they are part of the high-field strength elements group (HFSE). In comparison to average seawater concentration Hf and Ti show a relative enrichment in thermal waters compared to seawater which could be potentially related to a temperature dependence of mobilization but also might be caused by pH-values out of the neutral range and redox potential (Hevesy, 1925; Ziemniak et al., 1993; Schmidt and Vogelsberger, 2009). Si has the highest concentration in the lithophile group. This is explainable by the temperature and pH-dependent concentration, which is well-known and often used for calculation of the fluid temperature (Fournier and Rowe, 1977). Mn concentration in thermal fluids shows a broad range spanning several orders of magnitude which might be related to its redox-sensitivity (Ming et al., 2024). Clark et al. (2010) found increasing mean concentrations with increasing temperature for Sb, As, Ba, Cd, Cr, Cu, Pb, Se, Al, Fe, Mn, Ag, S and Zn with Pb, Se, Ba and Cu showing drastic increases of mean concentrations for moderate-temperature geofluids compared to high-temperature geofluids (e.g. Pb 1600-fold). Be and F do not show any significant temperature dependency. Mg is known to inversely depend on the temperature and the maturity of the fluids (Fournier and Potter, 1979). Boxplots showing the datapoint distribution of each element can be found in the SI.

3.4. Comparison to average seawater

When assessing the potential of raw material extraction from thermal fluids, not only concentration is decisive but also comparison to other more easily accessible resources such as seawater assists evaluation. However, seawater composition and elemental concentration has a spatiotemporal component and therefore varies. For example, some elements show a clear depth dependency while others remain steady (Nozaki, 1997):

- Increasing with depth: Be, Sc, Ti, Cu, Zn, Ga, Se (depends on ionic state), Y, Zr, Rh, Pd, Ag, La, Pr, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu
- Increasing to a certain depth, then decreasing: P, Si, Mn, Fe, Ni, Ge, Cd, Ba, Bi
- Steady: Li, B, Mg, V, As, Rb, Sr, Mo, In, Sb, Cs, Ce, W, Re, Pt, Au

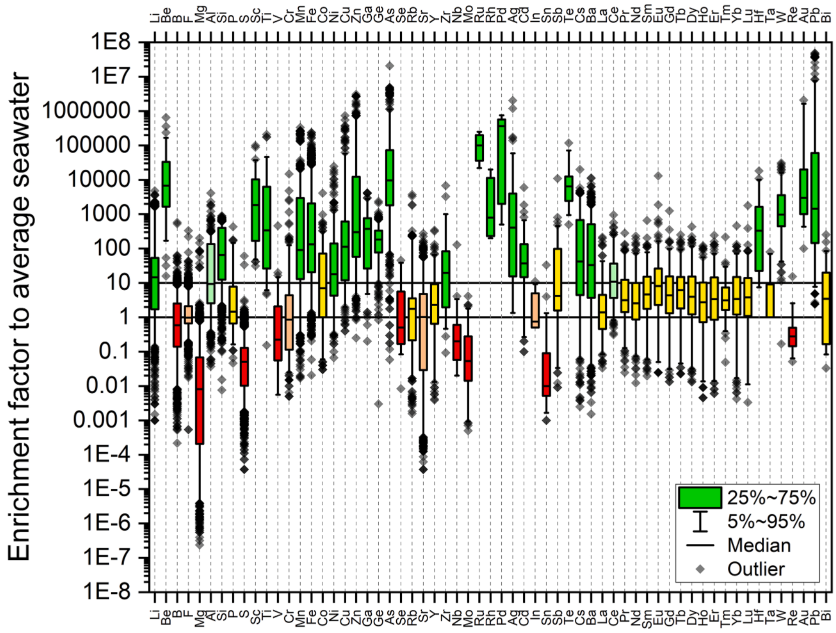

Fig. 7. Enrichment factors to average seawater composition. Color coding according to the median value with red depleted compared to seawater and green enriched compared to seawater. Due to inhomogeneities in the definition of average seawater, the area between 1 and 10 is considered a transition zone between depletion and enrichment, the boxplots with medians falling in this area are yellow-coded. Elements with medians near the boundaries are coded in light orange or light green, depending on the location of the mean. Note that Os, Ir and Pt are not shown.

- Decreasing with depth: Al, Sn, Te (depends on ionic state), Pb
- No/not enough data: Nb, Ru, Hf, Ta, Os, Ir

For the comparison of the raw material inventory across European thermal fluids we used the average upper seawater concentrations from the from a European perspective most accessible Atlantic Ocean and Mediterranean Sea (see SI Table A1). This comparison is chosen as seawater might be an alternative easily accessible and valuable source of (SC)RM and serves therefore as a baseline comparison to assess whether elements are enriched or depleted in thermal fluids (Fig. 7). Elements of interest that potentially might be extracted economically and/or feasible from seawater or desalination fluids are Li (del Villar et al., 2023; Ihsanullah et al., 2022; Loganathan et al., 2017; Zhang et al., 2021), B (del Villar et al., 2023; Ihsanullah et al., 2022) Mg (del Villar et al., 2023; Ihsanullah et al., 2022; Loganathan et al., 2017, Zhang et al., 2021, Shahmansouri et al., 2015), Si (Shahmansouri et al., 2015), Ga (del Villar et al., 2023), Rb(del Villar et al., 2023; Ihsanullah et al., 2022; Loganathan et al., 2017, Ortiz-Albo et al., 2019), Sr (del Villar et al., 2023; Loganathan et al., 2017; Zhang et al., 2021; Shahmansouri et al., 2015), In (Ortiz-Albo et al., 2019) and Cs (Ihsanullah et al., 2022; Zhang et al., 2021; Shahmansouri et al., 2015; Ortiz-Albo et al., 2019). To narrow down the target elements for geothermal raw material extraction, an enrichment by a factor of 10 relative to the median concentration in the mean sea water was defined as the threshold value. This enrichment factor is met for: Li, Be, (Al), Si, Sc, Ti, Mn, Fe, Ni, Cu, Zn, Ga, Ge, As, Zr, Ru, Rh, Pd, Ag, Cd, Te, Cs, Ba, (Ce), Hf, W, Au and Pb. With a median geothermal concentration above 1 mg/L Li, B, F, Mg, Si, S and Sr are further attractive, indicating that relatively low hurdles exist for Li and Si extraction from geothermal sources in >50 % of the evaluated locations. Contrarily, for elements like B, (F), Mg, S, V, (Cr), Se, (Sr), Nb, Mo, (In), Sn and Re the majority of geothermal fluids are depleted compared to average seawater reducing their attractiveness at broad range. Still, depending on the number of available analyses (e.g. B, Mg, S) a significant part of the fluids could be enriched and of high potential.

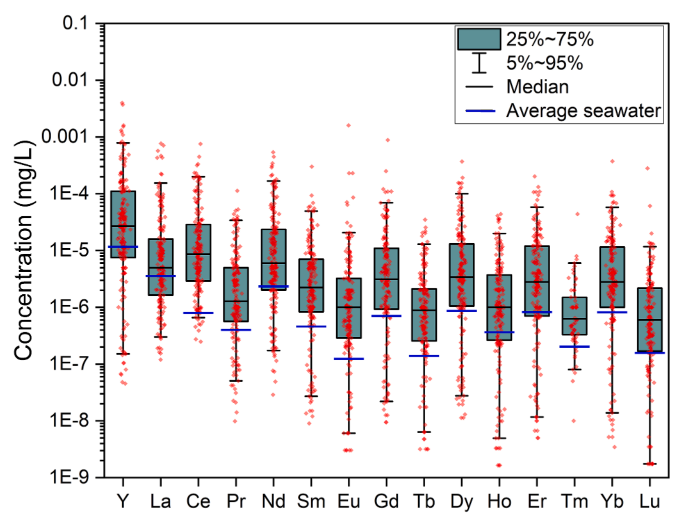

Fig. 8. REY concentrations in European thermal fluids. For comparison, the average seawater concentration is displayed.

3.5. *Special case: rare earth elements & yttrium (REY)*

The rare earth element group contains 17 elements: the 15 lanthanides, yttrium and scandium which are grouped together due on their chemical similarity and similar ionic radii. These elements are: scandium (Sc), yttrium (Y), lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), promethium (Pm), samarium (Sm), europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb) and lutetium (Lu). As only radionuclides with short half-life from Pm exist, it does not occur naturally and is therefore excluded in this section. Sc is officially counted as one of the REY by the International Union of Pure and Applied Chemistry (IUPAC) (Connelly et al., 2005), however, Klimpel and Bau (2023) recently suggested to reconsider this classification

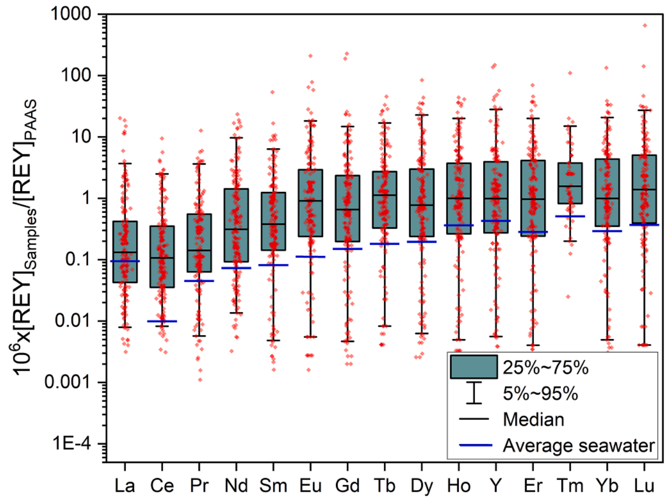

Fig. 9. PAAS-normalized REY pattern in thermal fluids across Europe. For reference, the PAAS-normalized average seawater concentration is plotted. Note that Y is displayed next to Ho due to chemical similarity.

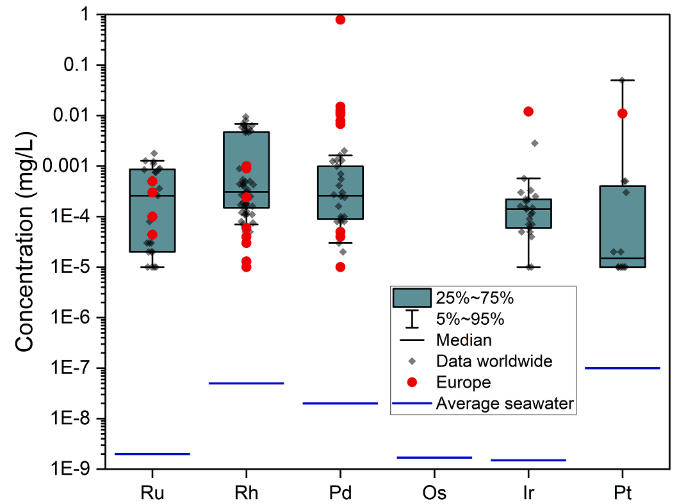

Fig. 10. Concentration of PGEs in thermal waters across Europe (red dots) compared to available data distribution worldwide (boxplots). For convenience, the average seawater concentration is given. For Os, there is no data available in Europe and worldwide. For discussion, see text.

especially in the framework of waters due to the different fractionation of Sc compared to other REY. This different behavior is also reflected by the evaluated fluid data: Sc concentrations are considerably higher compared to REY and seawater. Therefore, we evaluate Sc separately from the other REY.

In general, the REY have low concentrations in range from low ppt to ppb as expected from the relatively insoluble group of trivalent ions (Fig. 8). Given the overall low concentration and costly analysis of REY, these elements are rarely analyzed and thus available analyzes are often clustered. Data shown here are taken from Czech Republic (springs), Bulgaria (springs), Serbia (springs), Türkiye (geothermal wells), UK (Cornwall geothermal wells), Germany (Upper Rhine Graben (URG), North German Basin (NGB)) and France (URG, Pyrenees). It cannot be ruled out that reservoirs with higher REY concentration exist, as for example Smith et al. (2017) found REY above 1ppb correlating with fluid's acidity (below 4–4.5) with La, Ce and Nd being the most abundant.

Generally, to analyze REY patterns, normalization to a standard material must be performed to smooth the zig-zag pattern (Oddo-Harkins rule) (Tepe, 2016). The concentrations are normalized to Post Archean Australian Shale (PAAS, Fig. 9) as recommended for fluids (Tepe, 2016). The normalized pattern shows an increase from LREE to HREE, which in accordance with data from Möller et al. (1997) reported for REY mineralization of thermal waters resulting from water-rock-interactions (Drüppel et al., 2020). A very slight negative Ce anomaly can be observed which is caused by fractionation due to oxidation of Ce^{3+} to Ce^{4+} and subsequent sorption onto metal (hydr-) oxides/particles known as oxidative scavenging effect. This effect is often associated with oxic conditions. As geothermal environments are typically anoxic, this anomaly could be due to sampling from thermal springs being in contact with atmosphere. Further, a slight positive Eu anomaly can be seen which is typical for high temperature aqueous systems where Eu^{3+} is reduced to Eu^{2+} and depleted into feldspars (Tepe, 2016). No anthropogenic Gd anomaly is observed which indicates that the thermal waters have not been in contact with anthropogenic wastewaters (Schmidt et al., 2019).

3.6. Special case: platinum group elements (PGE)

The platinum group elements (PGE) ruthenium (Ru), rhodium (Rh), palladium (Pd), osmium (Os), iridium (Ir) and platinum (Pt) are considered mostly immobile and insoluble with concentrations in low ppb ranges (McKibben et al., 1990). In general, their transport behavior remains largely unknown, but they are supposed to be transported as chloride, hydroxide, ammonia or bisulfide complexes or combinations of those especially under acidic conditions (Wood et al., 1992). Recent study suggests, that the PGEs might be transported in hydrothermal fluids by trisulfur radicals (Pokrovski et al., 2021). In European thermal fluids, PGEs are seldomly measured or mostly below detection limit. Indeed, no data was found for Os and only one data point for Ir and Pt, respectively (Eggeling et al., 2018). For comparison, worldwide data was used in Fig. 10 to plot box diagrams, European data is consequently shown as red dots. For Ru, European data fits in the worldwide data range, as well as European Rh that plots on the lower range. Pd measurements are not consistent with data found worldwide. Pd measurements could potentially be influenced by the matrix and disturbed by other ions (Stammeier et al., 2025), leading to false high concentrations. Therefore, in the following sections the largest Pd concentration is excluded from further evaluation.

Worldwide, no (reliable) data on osmium in geothermal fluids could be found. The only data above detection limit is given by Sajkowski et al. (2025) for leaching/element mobilization experiments using volcanic rocks in New Zealand with Os concentration reaching up to 0.7 μg/L (7.6×10^{-4} mg/L) which is in range with the other PGEs. However, as Os is generally not measured or below detection limit, Os is excluded from further evaluation. The discrepancy between the relatively high concentration encountered in the lab-scale element mobilization experiments (Sajkowski et al., 2025) and the lack of data in natural geothermal systems might indicate that the transport mechanism of Os is predominantly colloidal, thus transport range is limited (Spitzmüller et al., 2025). This assumption may be supported by observations from Helz et al. (2000), Williams et al. (1997) and Yin et al. (2026).

3.7. Potential assessment

3.7.1. Elements with the highest potential

13 elements out of the 64 evaluated show the highest overall potential for being extracted from thermal fluids. They all have a hypothetical European Market Supply higher than 1% per year, hypothetical market values of >1 M US$/year and are of geostrategic importance. These are: Li, B, Mg, Si, Sc, Mn, Ge, As, Rb, Sr, Pd, Cs and Pb. 10 of these 13 elements are strategic critical and critical raw materials.

3.7.1.1. Li. Lithium extraction from geothermal fluids is already subject of many recent research initiatives (Neupane and Wendt, 2017;

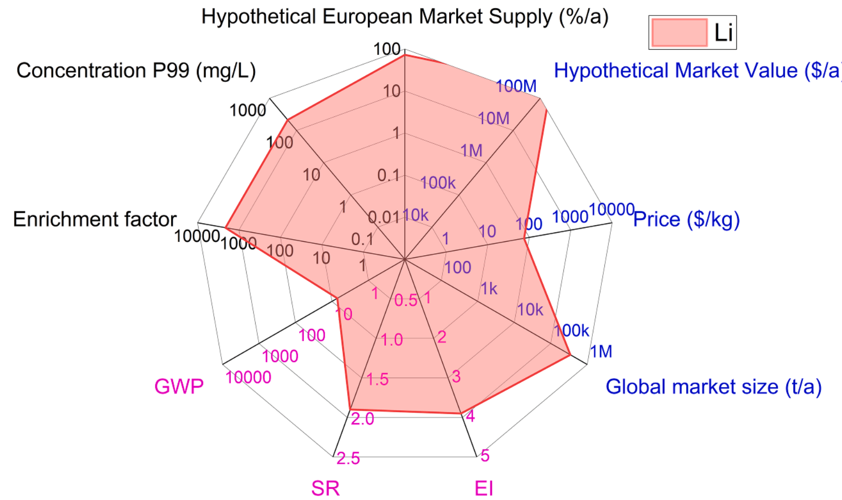

Fig. 11. Potential assessment of Li mining from geothermal fluids in Europe. Enrichment factor of P99 concentration compared to average seawater, GWP global warming potential (in kg $CO_{2\ eqv}/kg_{element}$), SR Supply Risk, EI Economic Importance.

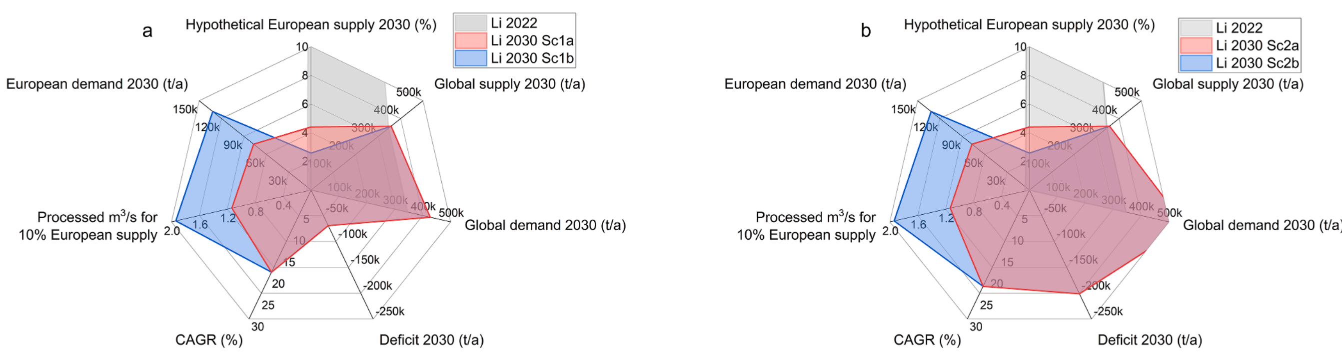

Fig. 12. Lithium potential by 2030 using forecast given by DERA. P99 concentration used, Hypothetical EU Market Supply with 500L/s. Processed m^3/s to cover 10 % of European demand by 2030 assuming 100% availability and extraction efficiency. Grey area indicates 2022 reference case.

Belova et al., 2009; Slunitschek et al., 2025; Liu et al., 2021; Ventura et al., 2016; Addleman et al., 2015; Zhang et al., 2023; Toprak et al., 2024; Harrison, 2014; Abe and Chitrakar, 1987; Kong et al., 2025; Brown, 2016) and projects such as UnLimited (Hydrosion GmbH, 2022), EuGeLi (ERAMET, 2021), LiMo-Praxis (Faunhofer Institut für physikalische Messtechnik IPM, 2025), LICORNE (LICORNE, 2024) and Li^{+}Fluids (Bundesanstalt für Geowissenschaften und Rohstoffe BGR, 2025). Indeed, lithium presents itself as an ideal candidate with high ranking in all evaluated categories (Fig. 11): abundance/availability, economic factor/market assessment and geopolitical & environmental aspects. The 99th percentile concentration is in the range of ~200 mg/L, although this is below concentrations in salar brines in the South-American Li-Triangle (~1500 ppm (Xu et al., 2021) up to 5000 ppm (Garcés and Alvarez, 2020)) and below the Li-concentration in spodumene (Australia, 1–2 wt.-% (Tianqi Lithium Coporation, 2022)), the concentration in geothermal fluids is still considerably high. Assuming extracting 100 % of Li from 500 L/s (or 90 % extraction from 555 L/s) across Europe could cover approx. 70 % of the European demand (data Schmidt (Schmidt, 2023)) and simultaneously has a hypothetical market value of 250 M US$/a. This is a great chance to a) fulfill the CRMA requirements and b) create additional income source for faster amortization of both geothermal power plant and extraction installations. However, European Li demand/supply data from 2022 does not reflect accurately the increasing demand for Li predicted in the future industrial landscape in Europe. Indeed, the Li market is expected to have CAGR of 9–20 % (see Table A4) mainly driven by the increasing demand for batteries (e.g. energy storage, EV) while the EoL RIR is nearly 0 %. For Europe, Schmidt (2023) predicts a demand of approx. 70–120k t (elemental) Li by 2030 in comparison to approx. 4k t in 2022, again mainly driven by the planned battery facilities across Europe. Furthermore, global demand is expected to outgrow the predicted global supply by 2030 up to several 100k t per year. Although it is currently uncertain whether these forecasts materialize by 2030, it is likely, that additional resources need to be considered to keep up with the growing demand. Fig. 12 considers future development in Li demand and indicates that by 2030, approx. 1–2 m^3 per second of geothermal fluid with P99 concentrations must be treated to cover 10 % of the predicted Li demand of Europe in contrast to approx. 0.07 m^3/s as by 2022.

For future projections, the increasing demand for future/renewable technologies and batteries need to be considered, thus the evaluation must be re-considered with newer available data to reflect accurately the market developments.

3.7.1.2. Si, Mn. Si and Mn show similar patterns (Fig. 13c and e): having high concentrations, high enrichment, significant hypothetical European market supply and hypothetical market value, huge global market and high EI values as well as SR above threshold.

For Si, already some extraction strategies exist (Bourcier et al., 2005; Brown and Bacon, 2009), while for Mn extraction from geothermal is on a lower TRL level and not commercially established but already has been on demonstration scale in Salton Sea in the 1980s (Addleman et al., 2015; Harrison, 2014; Schultze and Bauer, 1982; Flynn et al., 1986). Successful Si extraction is commercially operated in New Zealand where a coagulation technique is used to extract colloidal silica that finds

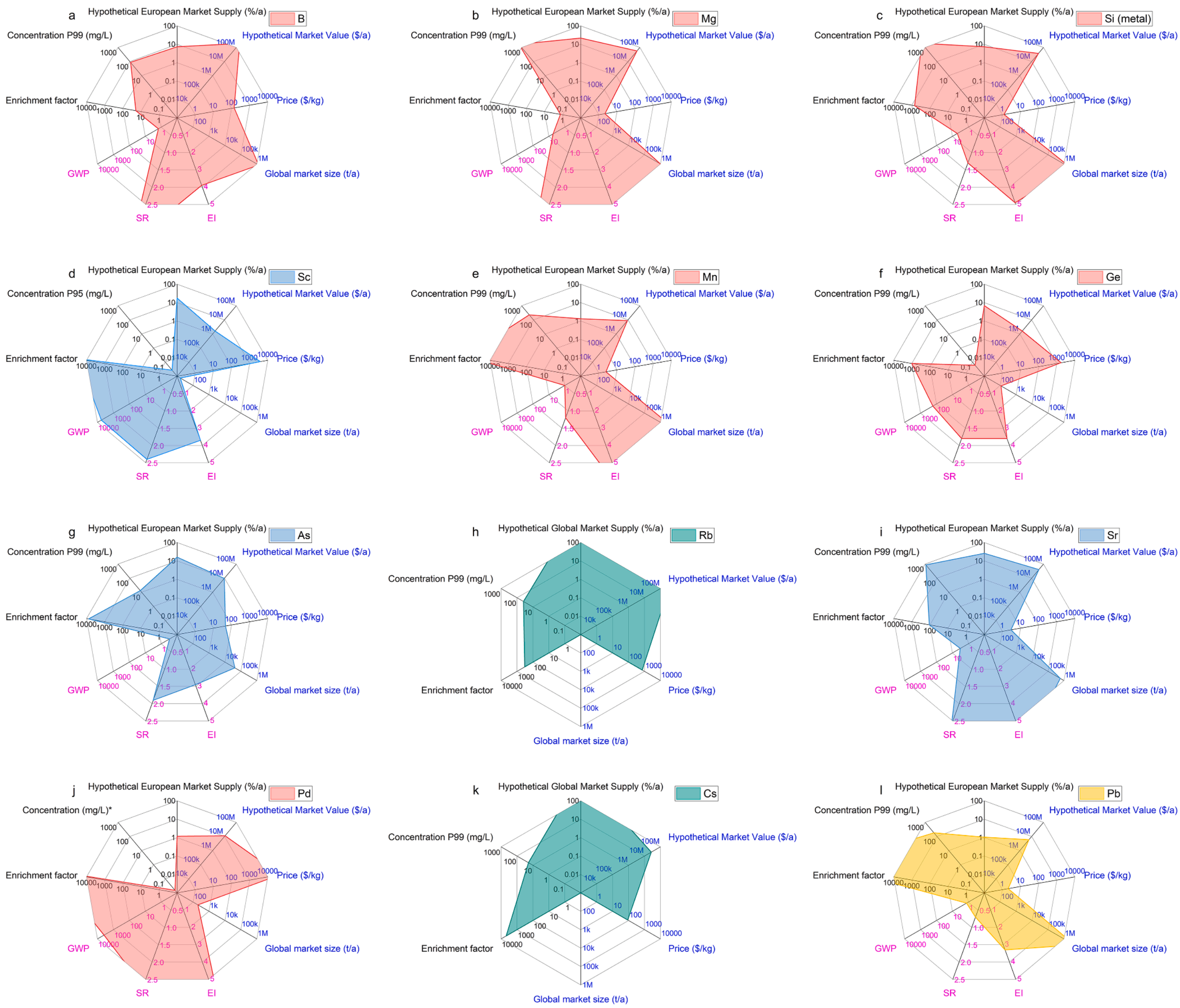

Fig. 13. Elements with the highest potential for extraction from thermal fluids based on the selected categories without lithium. Take note that for Rb and Cs, the criticality is not established. The color coding follows the coding applied in Fig. 1 and is: red SCRM, blue CRM, yellow RM, green metal/mineral/not assessed. * for Pd, the second highest value was chosen, as the total number of available analyses is low and the highest concentration is an outlier (see Section 2.1.2).

application e.g. in automotive industry (Geo40™, 2026). However, this technique is limited to low TDS fluids. The main challenges to implement silica extraction in geothermal context remain the impact of interfering ions and the quality of the extraction end-product. E.g. to obtain metallic silica, refinery steps must be considered. Additionally, removing silica from solution generally has advantages as it enhances the attainable heat yield from geothermal fluids, as silica scaling is one of the main limitations in geothermal power plant efficiency (Gunnarsson and Arnórsson, 2005). Consequently, there exist techniques to remove silica from geothermal fluids with focus on the removal process but not on the end-product (Spitzmüller et al., 2021; Goldberg et al., 2023).

3.7.1.3. B, Mg. B (Fig. 13a) has successfully been extracted from geothermal fluids in e.g. Larderello (Italy) in the form of boric acid and borax (Allegrini et al., 1992), compounds that might need additional refinery steps. Further extraction technologies are reported by (Belova et al., 2009; Yilmaz et al., 2008). The price assumed for B is based on trading code 28,045,010 for pure boron and is approx. 140 US$/kg. However, other sources report a price of approx. 0.6 US$/kg (per boron content, see SI Table A5). The price and thus the hypothetical market value of B should therefore be reconsidered if more reliable data is accessible.

Similar applies to Mg (Fig. 13b), the low price affects to hypothetical market value negatively. However, Mg has another major weakness as even the P99 concentration is approx. equal to the average seawater concentration. It might be therefore more straightforward to extract Mg from seawater or spent desalination fluids (del Villar et al., 2023) and not from geothermal fluids, although there are already some extraction methods under consideration (Neupane and Wendt, 2017; Premuzic et al., 1994; Stringfellow and Dobson, 2021). Indeed, as Mg is one of the major interfering ions for successful Li extraction (Yong et al., 2024), removing Mg from geothermal fluids still has advantages, even though it must not be the main target of extraction but could be considered for extraction in a framework of a pre-processing step for subsequent Li extraction. As the preferred compound is metallic Mg, extracted Mg might need subsequent post-processing steps for which geothermal energy could be used.

3.7.1.4. Sc, Ge, Pd. Sc, Ge and Pd show similar patterns (Fig. 13d,f,j).

For all of them the major hurdles lie in the overall low concentrations in fluids and the small market volumes. Yet, due to the niche markets, the hypothetical European supply by (geo)thermal sources is significant. Furthermore, all elements are enriched in geothermal fluids compared to average seawater concentration and especially for Pd (PGE) and Sc, the GWP of conventional mining is extraordinarily high which makes alternative mining strategies attractive.

Sc is used for high-strength Al-Sc alloys and as electrolyte in certain fuel cells such as solid oxide fuel cells (SOFC) (Marscheider-Weidemann et al., 2021). Recently, the Scandium International Mining Corporation announced the Nyngan Scandium Project (Scandium International Mining Corp. 2026), the world's first Sc-only open pit mine, in Australia with expected Sc-oxide product volume of nearly 40 t Sc_2O_3 (~26 t Sc) per year. Additionally, Scandium Canada announced together with Rio Tinto the Crate Lake Project in Canada with inferred approx. 5000 t of Sc_2O_3 in total in hard rock deposit (Scandium Canada Ltd., 2025; Rio Tinto, 2026) and a capacity of 9 t/a (~5.9 t Sc). Sc market is expected to grow up to 2000 t/a over the next 20 years if resource

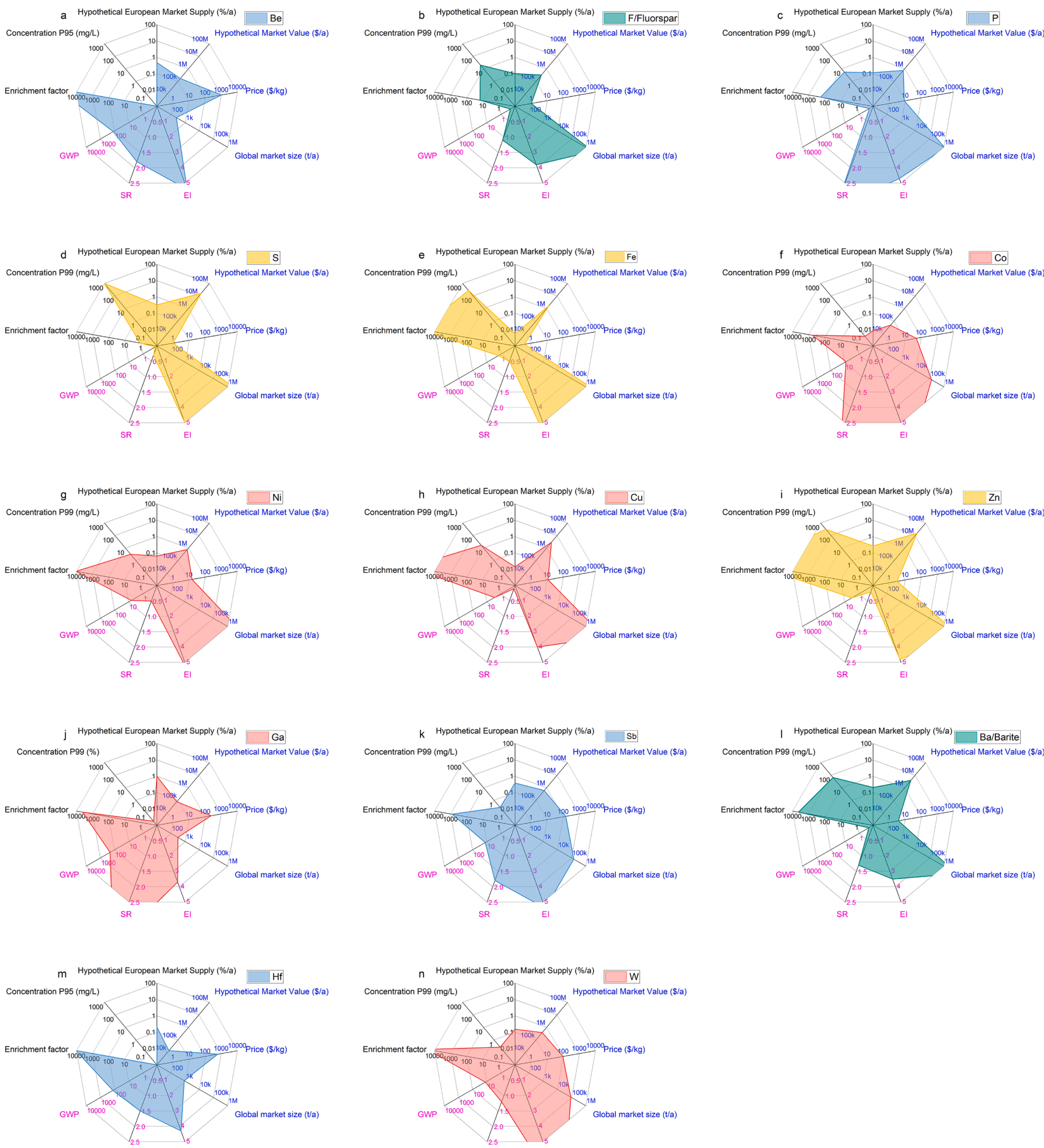

Fig. 14. Elements with a medium-to-high potential. Color coding analogue to Fig. 1: red SCRM, blue CRM, yellow RM, green metal/mineral/not assessed.

availability permits. Currently, there exist neither an established Sc extraction technology from geothermal fluids nor is it considered. There exist some efforts for Sc recovery from industrial waste (Chi et al., 2023; Zou et al., 2020) and coal ash (Kamunur et al., 2025), yet no technology is commercially employed. The major challenge for Sc will most likely be the low concentrations. However, as Sc analyses are not among the standardly measured elements in fluid analyses, further analyses including Sc are needed to achieve a better representation of the element and to draw more accurate conclusions about its potential. Currently, assuming treatment of 0.5 m^3/s with 100 % extraction efficiency could yield in P95 case 0.6 t/a and, with the highest known/measured concentration in European fluids, 1.3 t/a which could potentially cover >50% of current European demand (2.4 t/a).

Pd, which is one of the Platinum-Group Elements (PGE), is underrepresented in analyses and prone to analytical uncertainties (Stammeier et al., 2025). However, still it is highly enriched in the analyzed thermal fluids compared to average seawater and due to the niche market, the hypothetical European supply by extraction from thermal fluids could cover potentially approx. 1.2 % of the European demand. Furthermore, due to the high price, Pd has a high hypothetical market value despite low concentrations. Currently, there exist no targeted extraction strategy for Pd, but PGEs are listed to have a high potential revenue if possible to extract (Simmons, 2017; Simmons et al., 2018; Simmons et al., 2018; Yadav et al., 2024). Gallup (1998) also listed Pd and Pt as interesting for recovery specifically from geothermal fluids and Yadav et al. (2024) proposed a potential extraction scheme applying ion exchange processes for precious metal recovery including Pd and other PGEs from geothermal fluids.

Ge concentrations in (geo)thermal fluids are low, but the hypothetical market value is high due to high price. Furthermore, as the European market size is small, the hypothetical European market supply by geothermal resources is above 10 %, which makes Ge recovery interesting. For Ge recovery some efforts in developing suitable methods exist such as reported by Addleman et al. (2015), however no technique is yet commercially operated or implemented in geothermal power plant. In general, reported Ge concentrations must be evaluated cautiously, as it is suspected to potentially not be accurately measured by standard sampling-measuring procedures. Filella and Rodríguez-Murillo (2025) suggests that Ge could be underestimated in fluid analyses where only the dissolved fraction is analyzed as it might be part of colloidal fraction. Typically sampling procedures include filtering which removes colloidal fractions above the filter mesh size. Further, it might be considered that potentially Ge attaches to colloids that can form during cooling of thermal fluids, a known process especially if the thermal fluids are exposed to atmospheric conditions (p-T-changes and oxygen) or due to oversaturated species (Bordvik and Naess, 2023; Mori et al., 2019; Tamura et al., 2019), processes that could result in a relatively lowered Ge concentration in the total dissolved fraction.

3.7.1.5. As, Pb. As has adverse effects on human health, which is the root cause for established extraction methods to reduce the As concentration in drinking water (Nicomel et al., 2016) and likewise several efforts have been made to implement As removal techniques in geothermal (Harper et al., 1992; Premuzic et al., 1994; Buisson et al., 1979; Mroczek et al., 2019; Rothbaum and Anderton, 1975; Shannon et al., 1982). Mroczek, et al. (Mroczek et al., 2019) successfully conducted field tests at pilot plant scale in New Zealand and removed simultaneously silica and arsenic from geothermal fluids. Therefore, As has an overall high potential and relatively low hurdles for implementation at an industrial scale into geothermal.

Pb (Fig. 13l) is not a critical or strategic raw material, but a raw material with also projected growth in future (CAGR 3%, SI Table A4) with application in batteries, for PV and wind turbines. Pb has a relatively high EoL RIR of 80 % indicating an already high circularity in the economy. Still, geothermal fluids might be attractive as a novel resource. Especially highly mineralized geothermal fluids in the North German basin can be significantly enriched in Pb up to several hundreds of mg per liter (Kovács et al., 2023). The major obstacle for Pb recovery from geothermal is the occurrence of radioactive Pb isotopes (e.g. ^{210}Pb) that pose significant health risks and makes recovery challenging. Pb often occurs in geothermal environment as scaling in form of galena (PbS) which has high risk of co-precipitation and lattice substitution by radioactive elements like U and Th. On the other hand, precipitation Pb as PbS leads also to co-precipitation of other heavy metals, which in fact are also mostly raw materials. Therefore, mastering controlled PbS precipitation could be a source of several raw materials from geothermal.

3.7.1.6. Rb, Sr, Cs. For Rb and Cs (Fig. 13h,k), the detrimental fact is their small market size which is estimated to be currently <10 tonnes per year globally (USGS, 2025). Therefore, the extraction Rb and Cs from geothermal could have the potential to cover approx. 8000 % of global annual Rb consumption and approx. 2500% of global annual Cs consumption. However, Currently, there is no dedicated mine, both elements are rather mined as a by-product of Li extraction of e.g. lepidolite. Canada and Australia recently concessioned/announced new resources for Rb mining (Mt Edon Critical Mineral Project (Everest Metal Corporation, 2025) and Seymour Project (Green Technology Metals, 2026)) and also the interest in brine mining increased (del Villar et al., 2023; Ihsanullah et al., 2022; Loganathan et al., 2017; Ortiz-Albo et al., 2019). For Rb and Cs, there exist already some efforts for development of extraction technologies (Neupane and Wendt, 2017; Choi et al., 2019; Zhang et al., 2014; Chen et al., 2022). The major hurdle for geothermal Rb and Cs extraction however is the risk of an oversupply and thus to decrease of the prices and collapsing markets.

Sr (Fig. 13i) is one of the major components of geothermal fluids as it is from the alkaline earth group and a LILE (Zack and John, 2007). Unlike Rb and Cs, Sr has a decent market size and a huge market potential. Some efforts have been made for extraction from spent desalination brines (del Villar et al., 2023) but also extraction from geothermal has moved into focus (Sengun Cetin et al., 2024; Regenspurg et al., 2026).

3.7.2. Elements with medium-to-high potential

Elements at the border to high potential are Zn and Ga due to high hypothetical market value and high hypothetical European market supply, respectively. Elements at the border to medium-to-low potential are Fe, Co, Ni and Cu due to hypothetical European market supply below 0.1%, however for Fe, Ni and Cu their high hypothetical market value increases their attractiveness. Co is an outlier due to its high economic importance and high supply risk increasing its geostrategic importance.

3.7.2.1. Co, Sb, W. Co, Sb and W (Fig. 14f,i,n) show similar potential pattern: they are of high economic interest and strongly enriched in thermal fluids compared to average seawater, but their concentrations are below 1 mg/L. This, together with the relatively low hypothetical market potential lowers the overall potential. However, those elements could be candidates for by-product extraction together with others in a cascade-scheme extraction process, but are not likely to be the main target. For Co, there exist considerations about extraction processes from geothermal fluids (Neupane and Wendt, 2017) but on a low TRL. For Sb there exist more sophisticated extraction processes for removal from drinking water (Mubarak et al., 2015) but no implementation in geothermal contexts has been attempted yet. For W considerations exist for extraction from industrial wastewater (Wen et al., 2026).

3.7.2.2. P, S, Fe, Ni, Cu, Zn. All these elements have in common their high concentration and relatively low SR (except for P, Fig. 14c,d,e,g,h,i). Hypothetical European market supply is below 1 % which is related to the high demand and generally large market volumes. However, Fe, Ni,

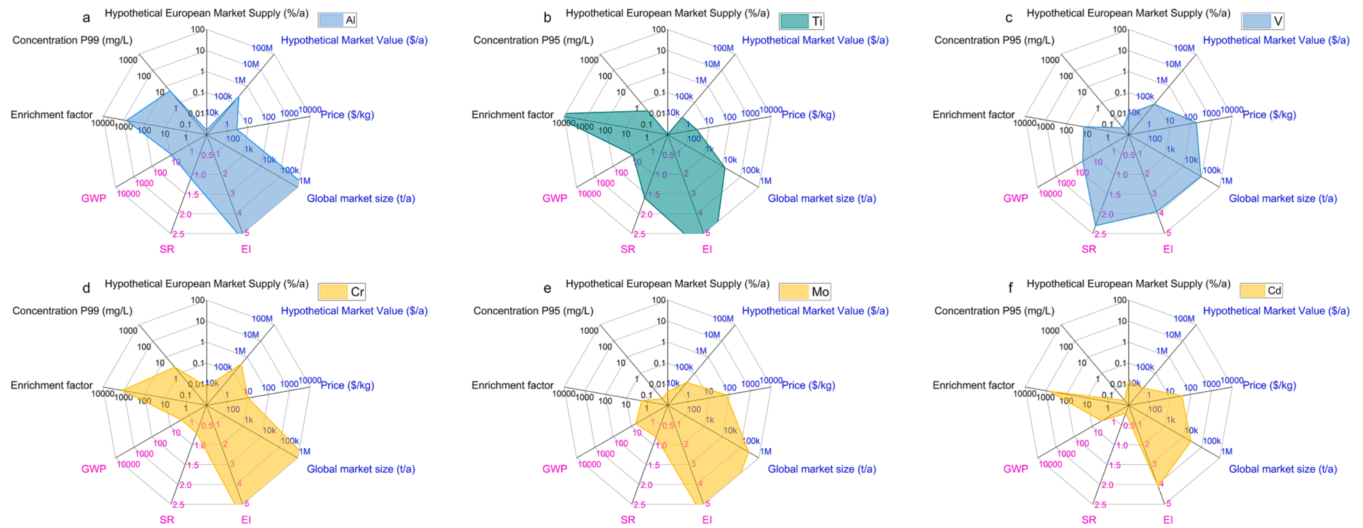

Fig. 15. Elements with a medium to low potential. Color coding analogue to Fig. 1: red SCRM, blue CRM, yellow RM, green metal/mineral/not assessed.

Cu and Zn are attractive as they are base metals for industry applications. Having a potential additional reserve within Europe can lower the relative supply risk. Although today it might not be economic nor feasible under current conditions, extraction might take place in future or might take place as by-product in a cascade extraction scheme, but the elements are not likely to be the main targets as also their hypothetical market value is relatively low due to low prices.

As example for a possible by-production is the CuLi Well project (Helmholtz SynCom Projects, 2026), where Cu extraction from geothermal is coupled with Li extraction, which could serve as a pilot project for a cascading scheme extraction process.

3.7.2.3. F. (Fluorspar), Ba (barite). F and Ba (Fig. 14b,l) themselves are not directly considered critical, but in mineralized form of fluorspar and barite. The F and Ba markets are vast, therefore only a fraction of European demand could potentially be covered by geothermal sources. Due to market sizes, also prices are relatively low. For F recovery from geothermal some methods exist (Zhang et al., 2023; Zhang et al., 2022).

3.7.2.4. Be, Ga, Hf. Be, Ga and Hf (Fig. 14a,j,m) are elements with small markets and low concentrations in geothermal fluids. However, they are highly enriched compared to average seawater and have the potential to contribute to >0.1 % of current European demand. Further,

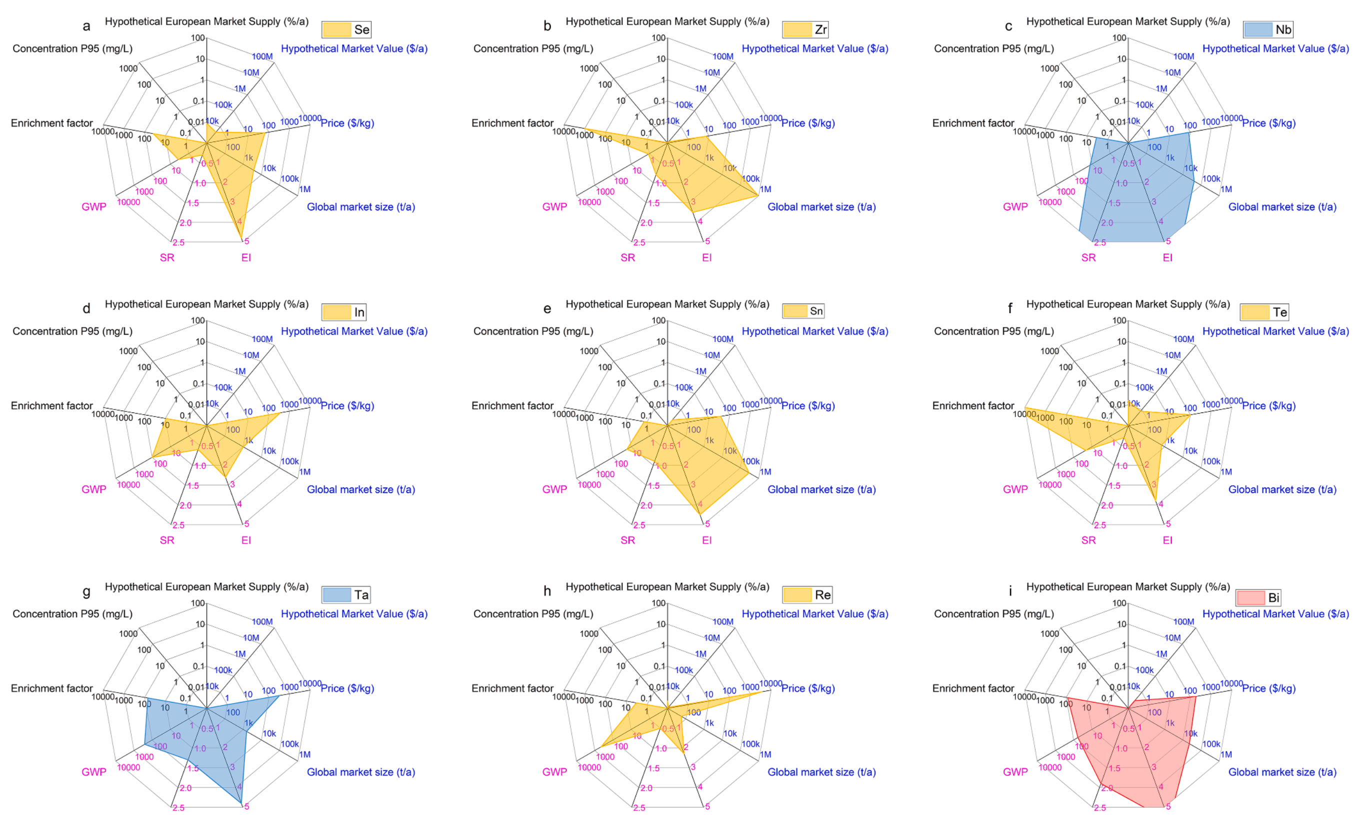

Fig. 16. Elements with the lowest potential. Color coding analogue to Fig. 1: red SCRM, blue CRM, yellow RM, green metal/mineral/not assessed.

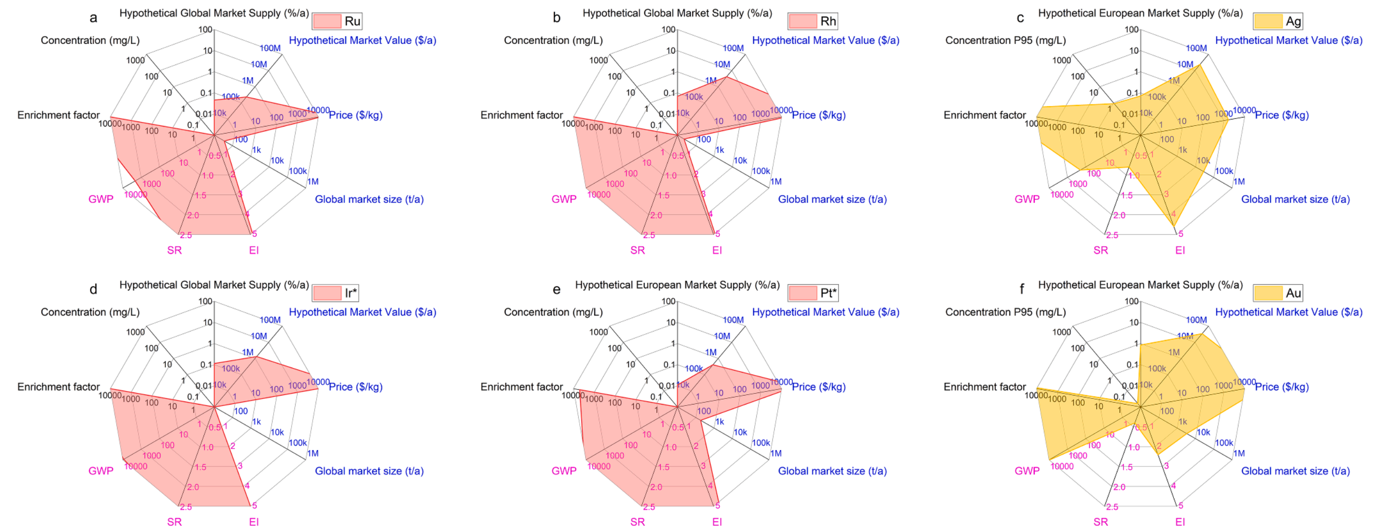

Fig. 17. Precious metals. Color coding analogue to Fig. 1: red SCRM, blue CRM, yellow RM, green metal/mineral/not assessed. For Ir* and Pt* worldwide concentrations are taken.

they have high SR, EI and high GWP which makes alternative extraction strategies attractive. Especially Ga has an extraordinarily high projected CAGR of approx. 35 % (SI Table A4). For all of them there is no established extraction technology. For Ga discussions raised for extraction from spent desalination brine (del Villar et al., 2023) and for Be efforts for removal from drinking water due to its toxicity are reported (Arar, 2021; Gatewood and Sneddon, 1990), while for Hf only considerations in combination with zirconium refinery are explored (Amaral et al., 2020; Greenberg and Foos, 1959).

3.7.3. Elements with low-to-medium potential

3.7.3.1. Al, Ti (metal). Al and Ti (Fig. 15a and b) are mostly considered incompatible, insoluble elements in fluids and Ti is part of the HFSE (Zack and John, 2007). Both elements have vast markets and high economic importance. However, as the fluid concentration is, as expected, relatively low and due to large market size, the hypothetical European supply is low. For Al some efforts on developing extraction methods exist (Premuzic et al., 1994), for Ti there is no method available. Indeed, Ti-doped adsorbents are mostly used in the framework of Li extraction, as they are considered mostly insoluble in thermal fluids (Sujoto et al., 2024). Al and Ti have relatively low potential for being recovered from geothermal due to their low prices, relatively low concentration and market volume.

3.7.3.2. V, Cr, Mo, Cd. V, Cr and Mo (Fig. 15c,d,e) are present in geothermal fluids in hexavalent state and thus can form anionic complexes which make their behavior differ from other cations. Generally, the potential for recovery of V, Mo and Cd is relatively low due to low concentrations paired with low prices. The global and European market sizes are exceeding the hypothetical contribution by recovery from geothermal fluids by far. For Cr, the potential is medium as the fluid concentration is in the mg/L range, thus having a hypothetical European market supply >0.01 %. Cr, Mo and Cd are not classified as critical raw materials.

3.7.4. Elements with the lowest potential

It must be considered for the elements with the lowest potential that they are also the elements with the lowest number of available analyses. This could be due to their general low fluid mobility and absence in geothermal fluids but it cannot be ruled out by default that there are no regions with higher concentrations which might then result in a more positive re-evaluation of these elements. Additionally, due to low availability of data, analyses' locations are highly clustered.

3.7.4.1. Nb, Ta, Bi. Of the elements with the lowest potential, only three are (S)CRM: Nb, Ta and Bi (Fig. 16c,g,i). Nb and Ta are HFSE (Zack and John, 2007), which are characterized i.a. by low fluid mobility, therefore their low concentrations meet the expectations. Bi is the only strategic critical material, that has very low potential, due to ultra-trace element concentration.

3.7.4.2. Se, Zr, Sn. Se, Zr and Sn (Fig. 16a,b,e) are of high economic importance but with relatively low supply risk (stable supply chains). The global market size is decent, however, due to their low concentrations in geothermal fluids, the hypothetical European market supply is negligible.

3.7.4.3. In, Te, Re. In, Te and Re (Fig. 16d,f,h) have in common that the concentrations are low as well as the hypothetical European market supply and the hypothetical market value. They are not ranked as strategic raw materials but are nevertheless of economic interest. For Re, the concentrations in geothermal fluids are approx. equal to concentrations encountered in seawater. However, it must be noted that the majority of Re analyses are available from Iceland (Kaasalainen et al., 2015) and only one value from a Cornish geothermal well (Strauch et al., 2024), where the concentration is about 10x higher than encountered in Iceland which might explain the small enrichment factor compared to seawater. Still the concentration in the Cornish geothermal site is in the ppb range (2×10^{-5} mg/L), which does not change the evaluation. In and Te are rarely analyzed and were only found in mineral waters from Bulgaria (Lyubomirova et al., 2020) and thermal springs in Greece (Kazakis et al., 2025) which might not reflect accurately the majority of deeper geothermal, more mineralized fluids. For Te one data point was available from a highly-mineralized (~126 g/L) geothermal well fluid in Bruchsal (Eggeling et al., 2018) (Upper Rhine Graben, Germany) with a concentration in the lower ppm range (8×10^{-3}mg/L), indicating that with more available data Te might shift to the medium-to-low category.

3.7.5. Special case: precious metals

3.7.5.1. PGE: Ru, Rh, Ir, Pt. From the platinum group elements, Pd is already considered in highest potential category due to its relatively high fluid concentration (Fig. 13j). Other PGEs (Fig. 17a,b,d,e) are a

Fig. 18. REY elements. Color coding analogue to Fig. 1: red SCRM, blue CRM, yellow RM, green metal/mineral/not assessed.

peculiar case as their concentrations are low ppb levels, but still due to their extraordinary high prices, strong enrichment compared to average seawater, geopolitical importance and environmental footstep of conventional mining, extraction from thermal waters might be a considerable alternative. Ir and Pt are not measured or are below detection limit in European fluids except for one location (Eggeling et al., 2018), therefore for this evaluation, data from global sources were assessed. As discussed before, data on European consumption is not available for Ru, Rh and Ir, therefore the hypothetical global market supply is shown for these elements in Fig. 17. The major hurdle is their low concentration; however, their high prices might amortize the investment in extraction technology development. Indeed, it is reported that PGEs could have a high revenue potential if possible to extract from geothermal (Gallup, 1998; Simmons, 2017; Simmons et al., 2018; Simmons et al., 2018; Yadav et al., 2024).

3.7.5.2. Ag, Au. Ag and Au (Fig. 17,f) are other precious metals, that are like the PGEs of extraordinary high value while enriched in thermal

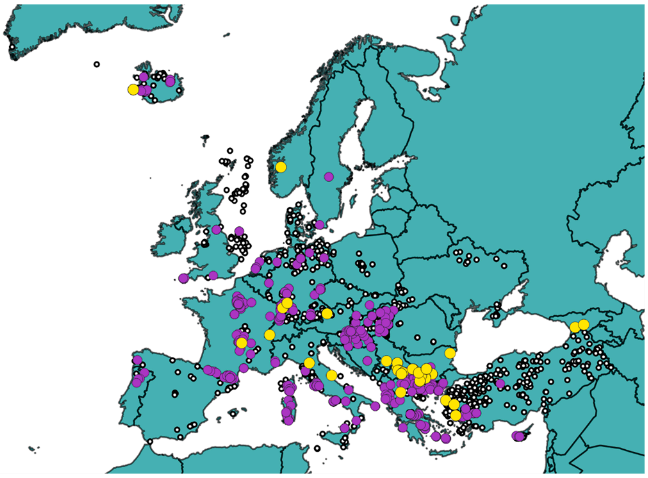

Fig. 19. Map of Europe in Lambert Azimuthal Equal-Area (LAEA) – EPSG:3035 projection. White dots with black outline show the locations of evaluated data with violet dots highlighting locations where Li concentrations were measured and yellow dots indicating Sc locations. Note that the yellow dots lay over the violet ones, i.e. at the Sc locations there can also be a Li location. The south-western Sc location in the URG is placed arbitrary as it derives from an internal unpublished report. Take note that map lines do not necessarily depict accepted national boundaries.

fluids compared to average seawater. However, their supply risk and economic importance ranks below those of the PGEs. While their concentration is low, their hypothetical market values is, analog to PGEs, high.

3.7.6. *Special case: rare earth elements & yttrium (REY)*

The REY show similar patterns (Fig. 18): while their geopolitical importance is indisputable, their concentration in thermal waters is negligible just as their hypothetical market value. In fact, only Yttrium might have a hypothetical market value of above 1000 $/year. Except for Dy and Ho, the hypothetical European market supply is below 0.1 %. Still, even if their hypothetical market value is low, in future it might get important to explore alternative sources as these elements are of high strategic importance for future technologies. It might be worth to consider mobilization techniques as their concentration in hard-rock deposits is higher than in fluids (Drüppel et al., 2020). Sener et al. (2021) attributed HREE from aqueous sources a relatively high potential to meet the global demand. However, as for geothermal fluids there is low data accessibility on REY concentrations, up to date the most promising fluid REY source is AMD. There exist several attempts of developing extraction techniques applying for example, nanotechnology approaches (Liu et al., 2021; Elsaidi et al., 2018; Dai et al., 2026), advanced sorbent technologies (Addleman et al., 2015) and bioengineering (Jiao et al., 2017). Stringfellow and Dobson (2020) reviewed US-DOE funded research projects for REE extraction from geothermal. They concluded that extraction might be feasible from ppb levels (40–100 ppb) of REE concentrations, however currently there is no implementation in geothermal power plant operation.

4. Reliability of the potential assessment on the examples of Li and Sc

The evaluation of the raw material potential from (geo)thermal fluids relies strongly on assumptions and simplifications to enable comparability between the elements. To point out these discussion points we will use Li and Sc as exemplary elements. Both elements are evaluated as highest potential, however the reliability of this assessment differs. First of all, the concentration/fluid data quality used cannot be verified independently, as openly published data are used and re-measuring is not feasible. Especially for data from older sources or generally secondary data (e.g. data reported in databases), human-made mistakes derived from conversion or unit errors might be possible as well as inconsistencies in sampling and analyzing procedures. Therefore, outliers were checked for reliability. Generally, the higher the number of available analyses, the more comprehensive and reliable the evaluation, as falsely reported values are losing their impact on the P95 and P99 interval values. At the example of Li vs. Sc, for Li 1313 measurements across Europe exist, while for Sc only 62 could be found with concentrations above detection limit (Fig. 19). Especially for Sc, there are two factors coming together: the low concentration and the “exotic” nature of the element which is why it is often omitted in fluid analyses. These factors result in a lower reliability of the Sc evaluation compared to the Li evaluation, as due to the low number of available analyses, it cannot be ruled out that the data reflects a) only the lowest concentrations, b) only the highest concentrations or c) are representative for Europe. Fig. 19 shows a map of Europe with the locations of evaluated fluid analyses (black-white dots) versus the locations with Li concentrations measured and locations where Sc was reported. For Sc, most values derive from Southeastern Europe with accumulation in Serbia and Bulgaria, while for Li data are distributed all across Europe with cumulations in the major geothermal areas: Iceland, URG (France-Germany), Paris basin (France), NGB and Molasse Basin (Germany), Apennine region (Italy), Cornwall (UK) and Türkiye. Furthermore, data from mostly thermal springs and spas are located in the Pyrenees (Spain-France), Serbia, Bulgaria, Greece, Albania, Hungary, Slovenia and Croatia.

Apart from the data sources and concentrations, the definition of critical raw materials is complex. In our simplified evaluation, we waived wherever possible the distinguishing of the commodities: e.g. whether only the metallic form, the elemental form or a compound is the critical raw material. Furthermore, for estimating the hypothetical market value, we chose the most refined forms (a list of all element prices can be found in SI Table A5). For Li, the price strongly depends on the commodity, e.g. LiOH, LiCl, Li (elemental) and battery grade Li. Additionally, refinery steps after extraction might be necessary as the extraction product might not meet the quality standard or the desired commodity form. This must be kept in mind but cannot be evaluated simultaneously for all the elements. For example, for Sc there exist not yet any methods for extraction from geothermal fluids, thus the extraction product composition is unknown. Another factor that cannot be considered yet is the potential of extraction groups, i.e. if elements could be extracted as by-products in already more established techniques. E.g. for some Li extraction techniques prior removal of Mg might be necessary, making Mg and Li a potential extraction group. Likewise for the heavy metals, a potential group extraction by precipitating in sulfides would facilitate their recovery.

Another factor is the availability of data on the market sizes, consumption, production and trading transparency. Not for all elements, trading is public and often bound to agreements between the primary producers and end-users that are not communicated publicly. Sc as a niche product with small market sizes, consumption and production (about 20 t/a globally), shows that trading transparency is not guaranteed. Contrarily, while Li has a relatively open market and decent market size, consumption and production, import of Li as a primary product and import of Li-batteries as an end-product is distinguished for European consumption (Schmidt, 2023). With the planned upcoming Li-ion battery facilities in Europe however, the demand of primary Li in battery grade will strongly increase. Another point complicating the European consumption data is the differentiation in Li consumption from import only and the contribution by recycling and circular economics. Therefore, for future projections these points must be considered. While it is a complex task for Li, that is however already approached by DERA, it is mostly impossible for Sc. Rio Tinto (Rio Tinto, 2026), Scandium Canada Ltd. (Scandium Canada Ltd., 2025) and Scandium International Mining Corp. (Scandium International Mining

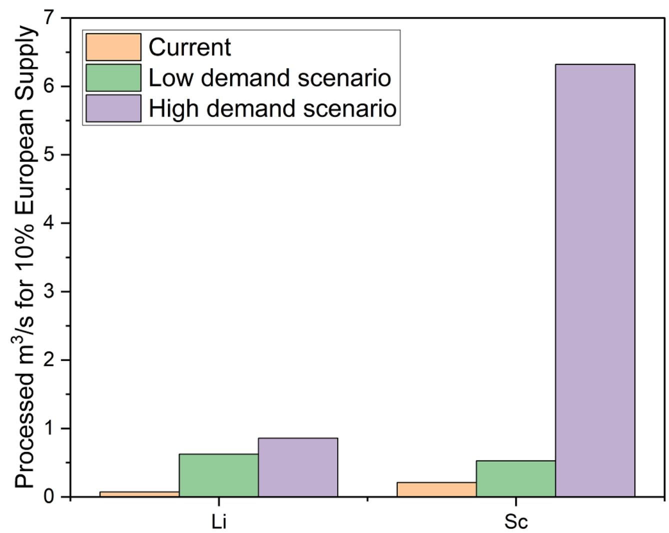

Fig. 20. Processed m^3/s to hypothetically cover 10% of European demand assuming 100% extraction efficiency and availability. Current situation for Li from Schmidt (Schmidt, 2023), for Sc from RMIS (European Commission, n.d.). Low/High demand scenario from DERA (Marscheider-Weidemann et al., 2021).

Corp. 2026) suppose that the limiting factor for Sc consumption is the low production and will increase with availability. DERA estimates the Sc demand to be depending on sustainability goals between 6–72 t/a by 2040 with SOFC as main sector (Marscheider-Weidemann et al., 2021).

Employing predicted consumption development of Li and Sc by DERA (Marscheider-Weidemann et al., 2021), the processed m^3/s needed for supplying 10 % of Europe's demand by 2040 can be approximated (Fig. 20). While 10 % the current Li demand could have been covered by processing 0.07 m^3/s with 100 % availability and 100 % extraction efficiency, approx. 0.6 m^3/s and 0.86 m^3/s will be needed to be processed by 2040 for the low and high demand scenario, respectively. For Sc the processed amount would increase from 0.2 m^3/s to 0.5 m^3/s in the low demand scenario and to 6.3 m^3/s in the high demand scenario. This comparison underscores the volatility of the evaluated parameters especially regarding the hypothetical European market supply that does not take future market developments into account.

5. Summary

Fig. 21 shows the evaluation of the potential analyses of the strategic critical raw materials, the critical raw materials and the raw materials present in geothermal fluids. The color-coding is according to their ranking: green is high potential, yellow medium-to-high potential, orange low-to-medium potential and red low potential. Blue refers to the precious metals and grey to the Rare Earth Elements (REY), both groups cannot be ranked by the applied criteria. The shading of the color indicates the number of available analyses in Europe and is thus an (indirect) indicator on the reliability of the ranking. If the available analyses are <100, the encountered concentrations might a) not reflect accurately the overall concentrations due to localized effects and b) could be extraordinarily high or low compared to other regions where no data is available. As comparison values are missing, the overall distribution of the resource in Europe is unclear. Conclusions drawn from these elements must be handled with caution and the respective elements should be re-evaluated once more data is available to accurately reflect the pan-European distribution.

The evaluation reveals 13 elements with high potential for extraction from geothermal. These are: Li, B, Mg, Si, Sc, Ge, As, Rb, Sr, Pd, Cs and Pb. For Li, B, Mg and Si there exist extraction processes from geothermal fluids on a relatively high TRL which makes them the most attractive targets. Likewise, Rb and Cs were put into focus for extraction as they behave similarly and are like Li part of the alkali group, however their detrimental factor is the extremely small global market size of <10t/a. Mn has been demonstrated to be successfully recovered from geothermal in the 1980s and further development of extraction strategies is currently under research (Ventura et al., 2016; Pawar et al., 2023; Feng

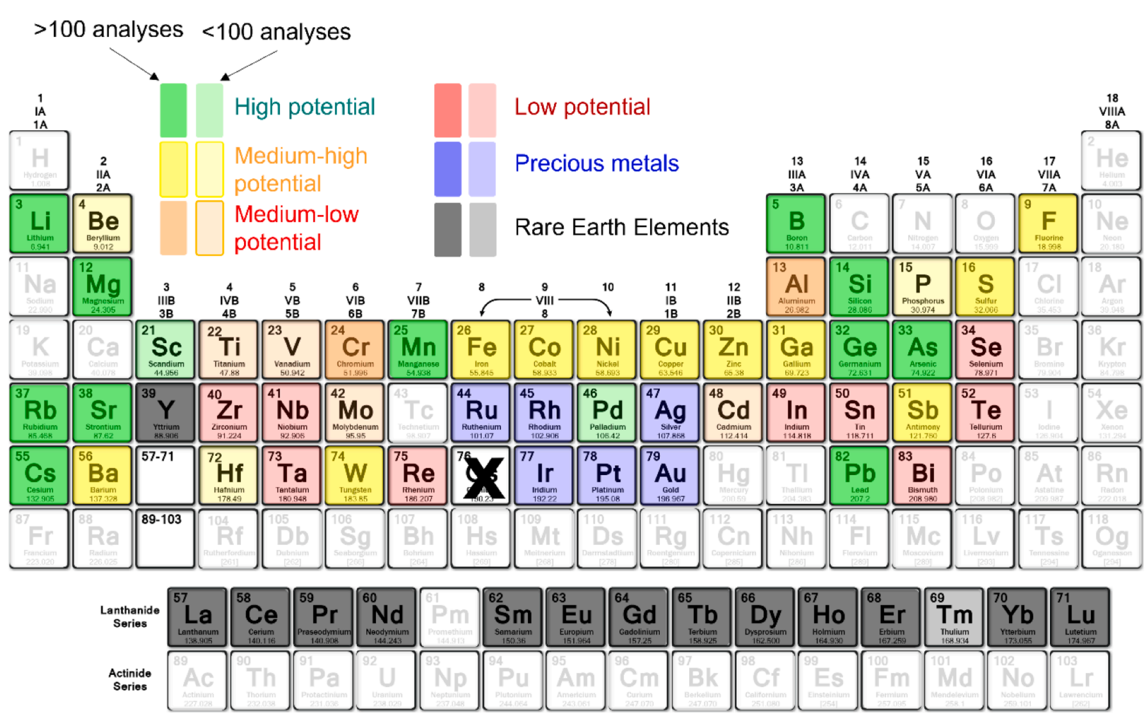

Fig. 21. Evaluation of potential analyses of (SC)RMs present in geothermal fluids. The ranking is high potential, medium-high potential, medium-low potential and low potential. The precious metals and Rare Earth Elements (REY) are excluded from the ranking and evaluated separately. The color intensity indicates the number of analyses and thus indirectly the reliability of the ranking. Os cannot be evaluated.

et al., 2022). As has been successfully removed from geothermal but not with the purpose of recovery (Mroczek et al., 2019). Pb has be removed frequently from fluid resources due to its toxicity but implementing in geothermal is complex as it must be handled with caution to prevent co-precipitation of radionuclides. Ge, Sc and Pd have not been in focus yet due to their low concentrations in geothermal fluids. However, they might have a high potential as well and should be analyzed more frequently to accurately reflect the concentration distributions across Europe. Especially for Sc and Pd the data situation is thin (<100 analyses).

Further elements with high concentrations that could facilitate developing selective extraction processes are S, Fe, Ni, Cu, Zn and Ba. These elements could be targeted for extraction although their overall potential is lower compared to the high potential category elements. From a strategic and economic viewpoint also Co, Ga, Sb and W might be considered. Despite their trace/ultra-trace concentrations, also the precious metals (PGEs, Ag and Au) possess a considerably high market value. In summary, 13 elements have a high potential, 14 a medium-to-high potential, 6 a medium-to-low potential and 9 a low potential based on currently publicly available data sources. From the remaining 22 elements, 1 is not evaluable, 6 are precious metals and 15 are Rare Earth Elements.

This evaluation underscores the potential of (critical) raw material extraction from geothermal fluids and can help streamlining future targeted extraction developments by focusing on elements with a high and medium-to-high potential or by creating cascade-scheme extraction processes targeting groups of elements.

CRediT authorship contribution statement

Laura Spitzmüller: Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Andrea Flores Salinas:** Writing – review & editing, Validation, Investigation, Conceptualization. **Valentin Goldberg:** Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition, Conceptualization. **Jens C. Grimmer:** Writing – review & editing, Conceptualization. **Rafael Villablanca-Ahues:** Conceptualization. **Fabian Nitschke:** Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.geothermics.2026.103770.

Data availability

Data will be made available on request.

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