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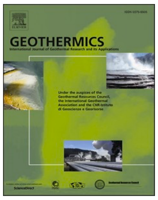

Perspectives of co-extraction of geothermal heat with the critical raw materials lithium and copper from sedimentary basin fluids on the example of the North German Basin

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ABSTRACT

The co-extraction of critical raw materials (CRMs) and heat from geothermal fluids offers a promising approach to simultaneously address the increasing global demands for both, metals and energy. In brines from sedimentary basins, high concentrations of lithium and other CRMs such as copper, are emerging as an attractive complementary resource for mining, because these types of geological settings are ubiquitously occurring within the continental crust. In this contribution, we investigate the North German Basin as an example for an underexplored sedimentary reservoir, with lithium (and to a minor extend copper) serving as representative CRMs. We summarize the current state of knowledge and main perspectives that are relevant for co-extraction of CRMs and heat. We identified five key controlling factors: (1) the source and mobility of lithium in geothermal brines; (2) the feasibility of brine production from a low-permeability sandstone reservoir including exploitation, management, and sustainability of extraction by considering potential lithium co-production rates on the example of a well in the North German Basin; (3) thermal-hydraulic challenges in combined heat and lithium production; (4) suitable material selection to prevent severe corrosion and associated damages; and (5) environmental, social, governance aspects, as well as life cycle assessment of such co-production. In conclusion, the current data indicate that sedimentary basins fluids offer great potential for co-extraction of geothermal heat and critical raw materials (CRM) like Li and Cu, but at current state more demonstrators are needed to prove the technical and economic feasibility of CRM and heat co-extraction.

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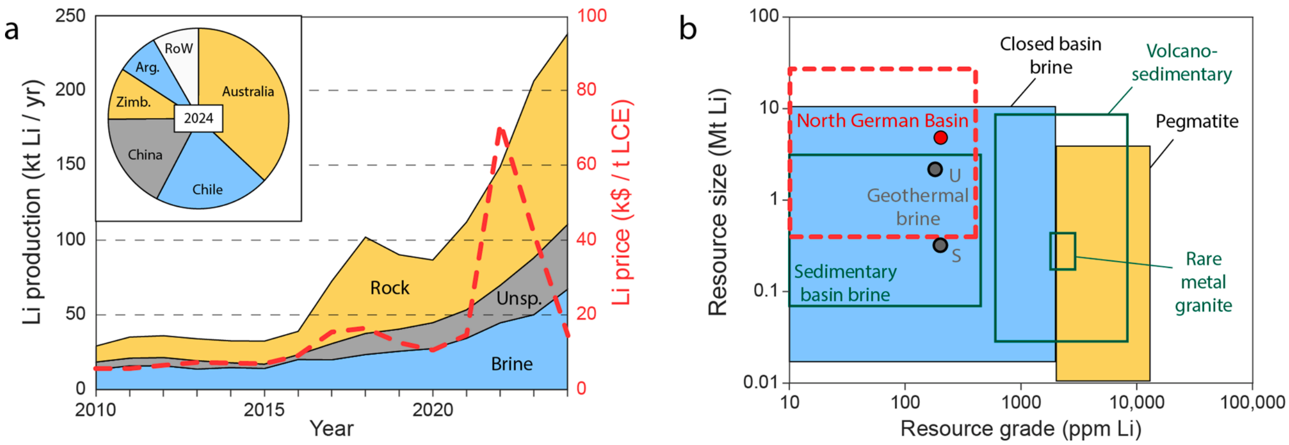

Fig. 1. *Global Lithium production and resources.* **a,** Li production from 2010 to 2024 categorized by source and country (blue: brine (Chile, Argentina), yellow: rock (Australia, Zimbabwe, Brazil, Canada, Namibia, Portugal), and grey: unspecified (China, USA), after Mudd (2021) and Gardiner et al. (2024), with data from USGS (2011) and BGS (2010). Inlay: relative distribution of Li production in 2024 (USGS, 2011), (BGS, 2010); Zimb.: Zimbabwe, Arg.: Argentina, RoW: Rest of the World). Li prices (red line) are yearly averages (USGS, 2011). **b,** Resource grades (ppm Li) and sizes (Mt Li) of Li resource types with current production (blue: closed basin brines, yellow: pegmatites) and potential future resources (green boxes: volcano-sedimentary, rare metal granite, and sedimentary basin brines; grey circles: geothermal brines of the Upper Rhine Valley (U) and Salton Sea (S)) (Benson et al., 2025) and North German Basin (red circle) (Alms et al., 2025) show the average (red circle) and range (red box) of resource grades and size probabilities (P10, P50, P90).(For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

1. Introduction

Raw materials are defined as critical (CRMs) if they are of high economic significance and suffer from a large supply risk (European Commission, 2011; Schicho and Tercero Espinoza, 2024), which can depend on the specific demands of a given region as well as on its local resource availability and production, e.g. in the EU (European Union, 2024) and the US (U.S. Department of Energy, 2023). In particular, the supply of CRMs is a strategic security question for Europe's ambition to deliver the Green Deal as formulated in the Critical Raw Materials Act (CRMA) (European Union, 2024). The energy transition requires both, the development of new sustainable energy and the discovery and exploration of new mineral resources to enable its technical feasibility (IEA, 2021). Geothermal and mineral resources are both controlled by geological processes and fluid-rock reactions (Ingebritsen et al., 2025). Although the co-extraction of CRMs and heat from deep fluids in sedimentary basins has the potential to diversify the global supply of metals and energy toward more individual domestic productions so far it remains as an underexplored technology.

Geothermal brines are typically hot and saline fluids extracted from deep reservoirs. Their composition is influenced by fluid-rock interaction over geological time scales at a wide range of temperatures and pressures. Depending on the rock formations, this process can lead to enrichment in various elements, including some defined as CRMs. The combination of high measured concentrations of elements such as lithium (Li) and the typically high flow rates prevailing in geothermal power plants opens the perspective of a promising resource for CRMs, which are essential for modern technologies, including batteries, electronics, and renewable energy systems (Calderon et al., 2024; Graham et al., 2021). As the global demand for CRMs surges, driven particularly by the transition to low-carbon technologies, the potential of geothermal brines as a complementary source is gaining scientific and industrial attention.

Sedimentary basins form the largest geological structures in the continental crust with certain regions or formations providing reservoirs with potential for heat extraction. While geothermal production rates from these resources may not be comparable to systems in volcanic areas, they are globally more abundant and may thus serve as a local heat supply. Co-extraction of heat and raw materials from sedimentary basins offers new perspectives to combine two sub-economic resources to one economically viable resource. The European Permian Basin is a well-studied sedimentary basin, historically used for traditional mining for copper, coal, oil and gas, but also for geothermal production, and serves to investigate the future potential of such co-extraction concepts.

This contribution focuses on the CRMs Li and Cu. Lithium is known to occur in considerable concentrations in certain geothermal brines, and several companies are pursuing its extraction. Copper, by contrast, has received less attention in this context. However, Cu is known to occur sometimes in large quantities in mineral precipitates (scales) within geothermal systems in sedimentary basins (Regenspurg et al., 2015) and has so far rather been recognized as an operational challenge for geothermal plants (Blöcher et al., 2015) than as an economic opportunity. We present the current state of knowledge, feasibility and economic assessment of the co-production of Li and Cu from fluids together with geothermal energy, using the North German Basin (as part of the European Permian Basin) as a case study.

2. Global demand, resources and co-extraction of the CRM (Li) from sedimentary basin fluids

The criticality of CRM such as Li is a dynamic parameter that can vary in time and between economies, because it depends on the respective availability and usage (Gardiner et al., 2024). Lithium occurs naturally in minerals such as spodumene, lepidolite, petalite and zinnwaldite as well as in brines in salt flats and geothermal fields as carbonates, chlorides and hydroxides. Lithium is widely used in rechargeable batteries for electronics and electric vehicles, and also plays a crucial role in the production of ceramics, glass, and pharmaceuticals.

Global demand for Li has grown substantially, with projections forecasting a demand growth for Li by up to a factor of about 40 in 2020–2040 (IEA, 2021). Lithium production almost tripled between 2020 and 2024, from approximately 87 to 238 kt total Li production per year (Fig. 1a; (USGS, 2011; BGS, 2010)) (463 to 1267 kt Li carbonate equivalent (LCE) per year) globally, with battery applications accounting for more than 70 % of total Li consumption (IEA, 2021; Statista Research Department, 2025; Schmidt et al., 2023). Projections by McKinsey (Azevedo et al., 2022) and the German Mineral Resources Agency (DERA) as part of the Federal Institute for Geosciences and Natural Resources (BGR) (Schmidt et al., 2023) indicate that global Li demand increases further to approximately 3–4 million metric tons LCE by 2030 depending on the scenario and technological developments in

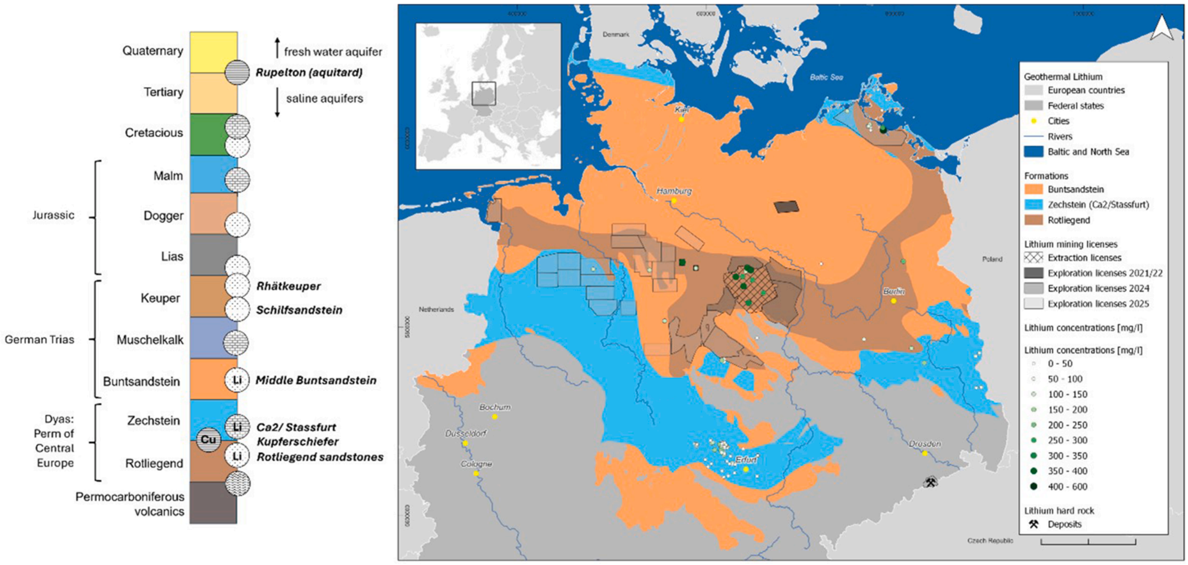

Fig. 2. *Geology of the North German Basin.* Left: Stratigraphic profile in the NGB with horizons marked for geothermal energy or CRM production; Right: Map of the three geological formations carrying increased amounts of Li with marked areas of mining licenses.

battery chemistry.

This growth is mainly driven by the rapid proliferation of electric vehicles (EVs). The global EV stock is projected to reach from approximately 10 million in 2020 to at least 230 to 240 million vehicles by 2030, with battery-EVs constituting the majority (IEA, 2021; Graham et al., 2021). In addition, stationary energy storage systems represent a second major growth segment. As the share of intermittent renewable energy sources, such as wind and solar continues to rise, the demand for storage solutions becomes critical for maintaining grid stability with Lithium-ion batteries being increasingly deployed, further driving global Li demand (Calderon et al., 2024).

Geopolitical considerations are becoming increasingly important for the security of global Li supply. At present, production and processing are heavily concentrated in few regions (Australia, Chile, and China) which together account for about 75 % of global Li production in 2024 (Fig. 1a; (IEA, 2021; USGS, 2011; BGS, 2010; Schmidt et al., 2023; Balaram et al., 2024; Altiparmak, 2023)). This concentration increases the risk of supply chain disruptions due to geopolitical tensions or trade conflicts in key producing countries. In response, governments, particularly in Europe, are intensifying efforts to diversify supply sources and strengthen domestic production capabilities (Graham et al., 2021). Moreover, over 50 % of current Li production takes place in regions facing extreme levels of water stress, raising additional environmental and sustainability concerns (IEA, 2021). Global Li production currently relies on mining from pegmatites (~65 %) and closed-basin brines (salars; ~35 %) (Fig. 1a; (Benson et al., 2025)). Lithium-pegmatites are classical "hard-rock" mineral deposits (Goodenough et al., 2025) with typically high ore grades (yellow box, Fig. 1b), which can be explored and mined with established methods and approaches of the mineral industry. In 2017, Li production from pegmatites have experienced a strong increase following an increase in Li price (Fig. 1a). In contrast, reserve calculations for Li mining from brines is challenging (Munk et al., 2016). Occurrences of economically viable Li-salars are geographically limited, because they require the favorable conjunction of multiple geological parameters, such as aridity and closed-basin architecture (Munk et al., 2025). Li production from closed basin brines has been continuously increasing within the last decade (Fig. 1a) and is characterized by lower resource grades but comparable resource sizes to pegmatite deposits (Fig. 1b).

New emerging types of Li resources with potential for mining (green boxes, Fig. 1b) include volcano-sedimentary deposits (Putzolu et al., 2025), where high Li concentrations can occur in clay minerals formed by hydrothermal alteration. Another potential Li resource are rare-metal granites, e.g., Li-rich micas of the Zinnwald/Cinovec deposit in the Erzgebirge/Krušné Hory Province in Germany and the Czech Republic (Burisch et al., 2025).

Sedimentary-basin and geothermal brines are also considered as potential future resources, e.g., in Salton Sea (California, USA; (Azevedo et al., 2022)) or in the Upper Rhine Graben (URG) in Germany (Sanjuan et al., 2022; Drüppel et al., 2020) with estimates of Li being comparable to closed-basin brine resources and hence may provide an economically viable future resource (Fig. 1b). First estimates of the potential of the North German Basin (Alms et al., 2025) are in the same range and even exceed the resource size of known geothermal and closed basin brines (Fig. 1b).

First pilot projects for co-extraction of Li and heat are currently planned by several companies worldwide (e.g. new Zealand, Japan, USA, and within the EU) (Busse et al., 2024) and some have already been established (e.g., Salton Sea (California, USA (Busse et al., 2024)), Cornwall (UK (Szanyi et al., 2023)), Saskatchewan (Canada (Prairie Lithium)) and the URG (Germany and France (Kölbel et al., 2023; Ruberti, 2024)). Apart from the sites in Cornwall (UK, targeting granite rocks), most of those locations are situated within sedimentary basins, which are one of the major tectonic units in the world, covering around 60 % of the worlds land surface (excluding oceans) with 483 sites in total (Dou and Wen, 2021).

Despite numerous press releases from companies stating that they have successfully extracted Li, this usually only amounts to a few grams and thus represents rather a proof of concept. Although, some of the mentioned projects are near-commercial geothermal Li sites, currently (year 2026), no commercially operating geothermal Li extraction site exists worldwide. Those companies that are at pilot and near commercial state claim different amounts of expected output on their respective internet websites or press releases. For example, the Geothermal Engineering Ltd (GEL) facility near Redruth, Cornwall claims to initially producing ~100 t/yr of Li with plans to scale up significantly (Stallard and Stephens, 2026). The Hell's Kitchen project in Salton Sea in the Imperial Valley is aiming at tens of thousands of tons of Li hydroxide annually once in commercial operation (Vulcan Energy Resources, 2026) and Vulcan Energy targets a full-scale commercial output of ~24 000 t/yr Li hydroxide in the URG, however, without clear timeline (Cariaga, 2025).

Regarding the estimation of technological maturity, it should be emphasized that DLE is already operating at commercial scale for brines from salt flats in China and Argentina (Razmjou, 2024), but not yet for geothermal systems where pressure maintenance is mandatory. As technological maturity must always be assessed with respect to the specific resource, it is difficult to assign a clear maturity level for geothermal fluids. Since most of the approaches are proprietary technologies, detailed information on operating conditions, efficiencies, and costs is generally not disclosed. Assessments of the Technology Readiness Level (TRL) can therefore only be based on company communications and are subject to uncertainty, as independent verification is lacking. For example, the available information often does not clearly indicate whether a field study represents a prototype demonstration in a relevant environment, corresponding to TRL 5 to 6, or a long-term demonstration under real operating conditions, corresponding to TRL 6 to 7.

2.1. *The north German basin (NGB) - an underexplored sedimentary reservoir*

The North German Basin (NGB) or Northern European Permian Basin, as part of the Central European Basin System, is an extensive intracratonic sedimentary basin (Bayer et al., 1999) hosting a variety of formations that show significant geothermal potential due to their thermal gradient, porosity-permeability characteristics, and structural settings (Franz et al., 2018). We use it as a case study for demonstrating the benefits, risks, and challenges for co-extraction of heat and CRM from deep sedimentary brines.

Basin formation began with rifting in the Late Carboniferous (~300 Ma), driven by lithospheric thinning marked by intensive volcanism (Scheck-Wenderoth and Lamarche, 2005). In the following, thermal subsidence and sedimentary deposition occurred. The basin’s evolution reflects a complex interplay of extensional and salt tectonics, and foreland basin influences, with sediment thickness exceeding 10 km in some depocenters. These formations have been investigated for geothermal utilization (Blöcher et al., 2015; Frick et al., 1980) (Fig. 2, left). Although with increasing depth, normally the permeability decreases, in areas affected by salt tectonics the secondary porosity and fault systems can enhance permeability also in those deeper reservoirs (Franz et al., 2018). While for shallower geothermal projects, the Jurassic and Lower Cretaceous carbonates and sandstones, present the main geothermal prospects (Feldrappe et al., 2007), the primary targets for deep geothermal developments are the Triassic aquifers from Buntsandstein, Muschelkalk, and Keuper (Frick et al., 1980; Virchow et al., 2024). In formation fluids above the Buntsandstein no increased concentrations of CRM were identified so far. The Buntsandstein is composed of fluvial sandstones and conglomerates, with a brine salinity reaching up to 400 g/L TDS (Hesshaus et al., 2013) and variable Li concentrations that reach up to 190 mg/L (Alms et al., 2025). The base of the Buntsandstein is formed by Zechstein evaporites, which normally acts as an effective seal and is of limited interest for geothermal exploitation. An exception here is the Stassfurth carbonate, with up to 300 mg/L Li (Alms et al., 2025). A thin layer of Kupferschiefer separates the Zechstein salts from the Rotliegend clastic sedimentary rocks. Brines from the Rotliegend are of higher temperatures (> 100 °C) and contain generally high Li concentrations (100 to 600 mg/; (Alms et al., 2025; Regenspurg et al., 2010)) making it a target for Li exploitation as indicated by increased mining licenses given in the area (Fig. 2) . First resource estimates for the NGB indicate a capacity of 4.73 Mt Li, within a possible range of 0.39 to 26.51 Mt Li (Fig. 1b; (Alms et al., 2025)). Rotliegend brines are highly saline (200–300 g/L) and contain also various other CRMs in increased concentrations (e.g., Sr, He; (Regenspurg et al., 2015; Regenspurg et al., 2010)) but also naturally occurring radionuclides such as radium (^{226}Ra, ^{228}Ra) and lead (^{210} Pb; (Regenspurg et al., 2014)). Scales precipitating from this brine consist predominantly of Pb and Cu (Regenspurg et al., 2015). The sandstones of the Rotliegend deposited in arid fluvial and aeolian environments and exhibit only locally high porosity (up to 25 %) and moderate to high permeability only in fractured zones. So far. The area is primarily used for gas production with only few deep geothermal projects and no Li extraction plant. For an economically successful co-production of heat and CRM, productivity enhancement methods may be required to increase flow rates.

3. Origin and mobility of the CRM Li and Cu in geothermal brines

To assess the sustainability of a CRM coproduction, the origin, flow paths and flow velocities of the respective brines but also the possible replenishment of the CRM from the reservoir rock must be known.

3.1. *Lithium enrichment processes in brines*

Numerous studies are currently dealing with the linkage between brine genesis and mechanisms of Li enrichment (Munk et al., 2025). A classification explaining the Li concentration evolution was proposed for closed basin brines (salars), sedimentary basin (oilfield)-, and geothermal brines (associated with geothermal energy usage) (Munk et al., 2025) that suggested three main mechanisms. The first process is evaporation of seawater: Especially in closed basins, evaporation is thought to be the major cause for both the high salinity and Li enrichment (Connolly et al., 1990a, 1990b; Eccles and Berhane, 2011; Butler et al., 2025) also explaining the frequently observed correlation between Li concentrations and salinity (Dugamin et al., 2023). Furthermore, the chloride concentration in such brines is often close to the halite saturation supporting the evaporative imprint (Dugamin et al., 2023). However, the maximum enrichment of Li in purely evaporative brines is capped by the solubility product of evaporite minerals (Dugamin et al., 2023) with a calculated maximum Li concentration of 1 mg/kg in a halite saturated fluid (Dugamin et al., 2024). Although studies have shown that the concentration of Li in seawater was variable over time and in some cases up to 7 times higher than today (e.g., Jurassic, Cretaceous) (Weldeghebriel and Lowenstein, 2023), the Li concentration in many brines cannot be explained solely by evaporation (Dugamin et al., 2023; Dugamin et al., 2024).

The second process is the dissolution of evaporites: A strong relationship exists between the presence of massive evaporative layers and extended Li concentration in brines of sedimentary basins (Dugamin et al., 2023). When salt deposits that are the result of evaporative periods are expulsed (e.g., by compression) or dissolved (e.g., by circulating meteoric water), Li that is incorporated into these salts or trapped in fluid inclusions (Davis et al., 1983), is re-released, concurrently increasing the salinity and Li content (Butler et al., 2025; Dugamin et al., 2023; Davis et al., 1983; Michael and Bachu, 2002; Michael et al., 2003; Gupta et al., 2012; Huff and Grasby, 2016). Additionally, dissolution of marine evaporite minerals can be a source of Li (Huff and Grasby, 2016; Huff et al., 2019). Evaporated water relics can also be trapped in and released from sedimentary rocks (Coffey et al., 2021).

The third imprinting factor is water-rock interaction (WRI) that often also modifies the evaporative brine composition (Butler et al., 2025; Michael and Bachu, 2002; Araoka et al., 2014; Yu et al., 2024). This process is specifically important in settings where Li enrichment exceeds the levels expected from simple seawater evaporation trends. Lithium-rich rocks must be available that contain minerals from which Li can release under the given conditions (Dugamin et al., 2023). This explains the variability of brine composition in different geological provinces and settings (e.g., (Sanjuan et al., 2022; Alms et al., 2025; Gourcerol et al., 2024)). In silicic aquifers often the Li concentration increases with increasing temperature, because Li is often incorporated into the structure of silicates, which dissolve with increasing temperature and release Li simultaneously (Sanjuan et al., 2022; Coffey et al., 2021). The source of Li in formation fluids in the context of WRI has

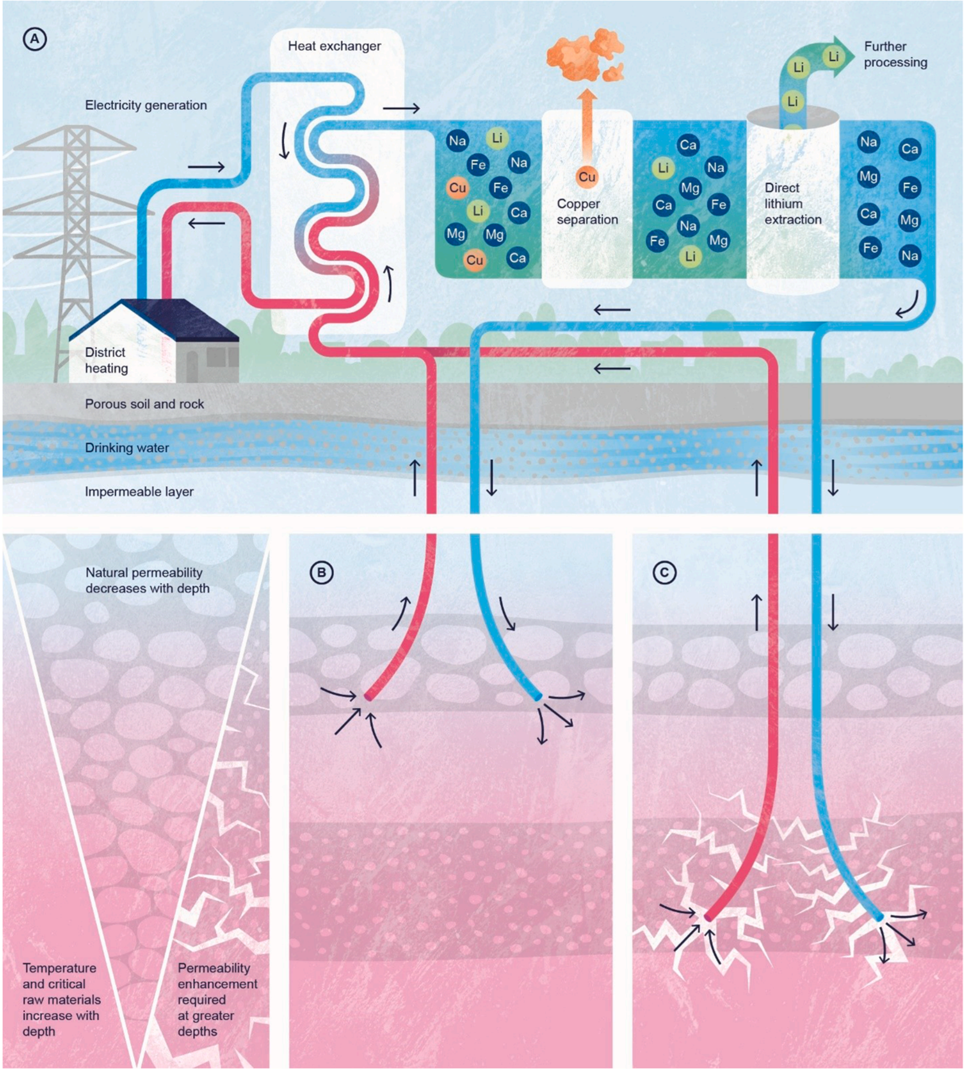

Fig. 3. *Co-extraction of CRMs and heat from geothermal fluids.* **A:** Geothermal doublet (with production and injection well) and above ground facilities with Cu and Li extraction processes and heat exchanger; the heated water can be used for heating or electricity production. The wells penetrate drinking water formations and impermeable layers to reach deep formations of sufficiently high temperatures and CRM content, B) The wells end in a well-permeable but not very deep sedimentary layer. C) The target formation is a tight formation and reservoir enhancement methods are required (EGS) to increase the permeability. Bottom left: General increase of temperature and CRM and decrease of permeability with increasing depth.

been related to weathering of vitric volcanic rocks, plagioclase, hectorite mudstone, Li bearing clay minerals, mica or chlorite (e.g., (Drüppel et al., 2020; Dugamin et al., 2023; Dugamin et al., 2024; Benson et al., 2017; Boschetti, 2022; Humphreys et al., 2023)). In geothermal brines of Cornwall or the URG, Li release is attributed to hydrothermal alteration of granitic phyllosilicates like muscovite, biotite and chlorite or fluid-sandstone interactions at temperatures above 200 °C (Sanjuan et al., 2022; Drüppel et al., 2020; Jungmann et al., 2025; Searle et al., 2024). Lithium shows a low sorption affinity towards reservoir minerals as compared to other cations leading to its passive enrichment after its release over time (Drüppel et al., 2020). Apart from Li, also other CRM and metals like Rb, Cs, Sr, Ba, Zn and Pb are released during alteration e.g., of biotite to chlorite (Jungmann et al., 2025). However, the mobilization of elements by WRI is not unidirectional as alteration products like illite or chlorite will incorporate them during formation (Drüppel et al., 2020; Jungmann et al., 2025).

Li content in brine is also controlled by time, migration pathways, and mixing processes (Munk et al., 2025; Butler et al., 2025; Dugamin et al., 2024; Jungmann et al., 2025). Very slow fluid flow, recharge rates, or the prevention of fluid mixing is a prerequisite to assure that Li enriched in reservoirs is not diluted with Li-poor solutions. This is often the case in tectonically stable settings like cratons (Dugamin et al., 2023). However, Li-rich fluids often show (isotopic) chemical signatures of evaporative and meteoric influence (Jungmann et al., 2025). In this context, the effect of meteoric water is less significant for dilution but could be relevant as a solvent e.g., of halite (NaCl) and as transport medium of Li (Davis et al., 1983).

For the NGB, and other sedimentary basins, the Li source and mobility have been hardly investigated. An exception is the Groß Schönebeck geothermal well, where the Li content was measured in rocks of 23 different formations between 1000 and 4000 m depth. Highest Li content was found in the Rotliegend sandstones (80 −200 mg/kg); Regenspurg et al., 2026). Corresponding formation fluids not only contain high amounts of Li (200–230 mg/L), but also other CRMs such as Sr (up to 1900 mg/L) and heavy metals (Pb, Cu, Zn).

Although generally, a correlation between temperature/depth and Li content in brines can be observed (Fig. 3), it is yet unclear why the three Li-rich formation fluids in the NGB show often site-dependent variable concentrations (Fig. 2) and why all rocks and formation fluids above the Buntsandstein hardly contain any Li at all. The current hypothesis consider as the main primary Li source in the NGB either the magmatic rocks at the bottom of the basin, as described for Li-rich brines in SW Germany (Stober et al., 2023) or the Zechstein evaporites, where Li is bound to phyllosilicates (Mertineit and Schramm, 2019).

The numerous possible origins, release mechanisms and influences on the concentration of CRM in brines impedes forecasting and exploration for co-extraction. Sources of specific CRM such as Li are likely variable across a larger sedimentary system and are present at locations with different stages of brine genesis and modification (Butler et al., 2025). Thus, apart from the above-mentioned parameters, it is necessary to have a clear picture of the geological, hydrogeological and stratigraphic setting of regions where brines are intended to be used for Li extraction (Coffey et al., 2021). Besides the origin and long-term evolution of a brine, also the extent, nature and kinetics of Li replenishment after (commercial Li) extraction needs to be understood. Current knowledge is based on simple laboratory experiments, which, however, cannot adequately reflect the complexity of a geothermal reservoir e.g., with respect to contact time, rock surface area, porosity, rock volume from which the subsequent Li supply is delivered, and flow characteristics (Houston et al., 2011; Goldberg et al., 2022a).

3.2. Copper occurrence in geothermal brines of the North German Basin (NGB)

Global Cu production is currently dominated by porphyry Cu deposits (~75 % (Park et al., 2021)). The global demand is projected to increase by a factor of 2.7 from 2020 to 2040 (IEA 2021), calling for additional resources for future supply. About 10 % of global Cu production comes from stratiform Cu deposits. The NGB/Southern Permian Basin is one of three major basins worldwide that host significant Cu mineralization in the type-locality of the “Kupferschiefer” (Hitzman et al., 2010). The genesis of these deposits is still debated (Mohammedyasin et al., 2023) and active mining is limited to a few locations in Poland. Fossil ore-forming and recent geothermal fluids may derive from the same source rocks. The occurrence of high amounts of dissolved Cu in the geothermal brine is to be expected for Rotliegend formations (Hitzman et al., 2010; Blundell et al., 2003; Cathles et al., 1993) and therefore, this formation is also considered as potential source for Cu co-extraction. Although typically < 6 mg/L Cu were measured in brines, native Cu was found as the most prominent scale (precipitate from brine) clogging a geothermal well for about 200 m during fluid production (Regenspurg et al., 2015; Regenspurg et al., 2010). This Cu likely is leached from the underlying volcanic rocks by circulating saline brines through faults thus forming mobile, aqueous Cu chloride complexes. This enrichment is also associated with the formation of the overlying Kupferschiefer deposit, where Cu precipitation occurred by redox processes in Cu-rich brines (Blundell et al., 2003).

4. Reservoir exploitation, management, and sustainability of extraction

4.1. Potential lithium and heat co-production from one single well in a sedimentary basin

Worldwide the vast majority of geothermal energy is produced from hydrothermal systems that require a high reservoir transmissivity (permeability * reservoir thickness) of > 10 Dm, to achieve economic production rates of 50–150 L/s (5–50 MWth) (Mijnlieff, 2020). A typical hydrothermal doublet in a sedimentary basin includes one production and one injection well (Fig. 3). In the NGB, there are currently three research and five commercial sites that utilize hydrothermal energy from intermediate deep Mesozoic reservoirs with production rates range from ~5 L/s (Neuruppin; 1.4 MWth) to ~50 L/s (Schwerin; 5.7 MWth) (Bundesverband Geothermie 2025). More than 50 sites are in the planning stage. The Li concentrations in these projects are, all below 10 mg/L. Due to the limited permeability of the Permian Rotliegend formation (Blöcher et al., 2016), there is no commercial geothermal utilization of those higher temperature Paleozoic resources. However, since these formation brines are enriched in Li, feasibility studies and theoretical calculations are ongoing (Table 1). For example, assuming a mean Li concentration of 200 mg/L (between 100 and 400 mg/L; (Alms et al., 2025)), an extraction efficiency of 75 % (between 60 % and 100 %), continuous production, and an LCE (lithium carbonate equivalent) conversion factor of 5.323 (1 ton Li results in 5.323 tons LCE) one could produce 25 tons LCE/year (between 10 and 67 tons LCE/year) per 1 L/s production rate (Table 1).

Table 1
Calculation demonstrating the influence of flow rate, extraction efficiency and concentration on Li production capacity.

Flow rate [L/s]	Li extraction efficiency [%]		Li concentration [mg/L]		Yearly Li production capacity [tLCE/a]		
	min	max	min	max	min	max	mean
5	60 %	100 %	100	400	50	336	193
50	60 %	100 %	100	400	504	3357	1930
150	60 %	100 %	100	400	1511	10,072	5791

The production data represent only a simplified potential estimate, neglecting factors such as maintenance downtime or Li depletion during raw material production. Nevertheless, the results indicate that the resource potential scales linearly with two technical parameters: the extraction efficiency of the DLE technology and the quality of the reservoir, expressed by the flow rate.

The Rotliegend formation is the deepest sedimentary unit of the NGB and exhibits significantly higher temperatures than all other potential geothermal reservoirs in the basin. It also hosts the highest Li concentrations of all sedimentary layers of the NGB. However, the Rotliegend formation typically has low permeabilities allowing production rates of typically <10 L/s. The Groß Schönebeck geothermal research site for example could currently produce 2 L/s with an extreme pressure drawdown of 10 MPa (Regenspurg et al., 2024). These flow rates are too low for heat or Li production. Thus, in most locations productivity enhancement methods such as hydraulic or chemical stimulation and/or advanced drilling techniques such as radial jet drilling, micro turbine drilling, multilateral wells, or extended reach wells are required (Horne et al., 2025). Enhanced geothermal systems (EGS) with elevated Li concentrations include for example United Downs (Farndale and Law, 2023), Insheim (Sanjuan et al., 2022), and Rittershofen (Goldberg et al., 2022a, 2022b).

4.2. Long-term reservoir performance and sustainability

Geothermal energy production requires high permeability reservoirs that can either be given by matrix permeability of a porous rock such as sandstone (e.g., NGB), fracture permeability of a non-porous rock such as granite (e.g., URG), or karst permeability of a non-porous limestone (e.g., Molasse Basin). For Li production, a high porosity is mandatory, as large volumes of brine are required where the Li is stored as opposed to heat which is stored both in the fluid and in the solid rock.

A central challenge in geothermal reservoir exploitation is the risk of thermal breakthrough (Blöcher et al., 2015) – the point at which the cold front from the injection well reaches the production well, leading to a decline in production temperature. Analogous to a reduction in temperature, continuous extraction of CRM will also result in a depletion of the reservoir’s resource content (Fig. 3). However, a dissolved resource and its depletion represent a process of (reactive-) transport, which behaves differently from the propagation of a thermal signal. Different numerical models and tracer tests have indicated that especially in fractured reservoirs, solute breakthrough can occur significantly faster than thermal breakthrough (Goldberg et al., 2023; Egert et al., 2020; Banshoya et al., 2025). This becomes apparent in multi-stage EGS, where parallel production and injection wells are connected via many high permeability fractures that serve as fluid pathways and heat exchanger areas. Recent multi-stage EGS projects showed stable circulation rates of up to 100 L/s (Fervo Energy, 2024). Such a system could lead to the required flow rates and could also sustain stable production with high temperatures for some years, but the chemical breakthrough would occur within a few days and result in a significant drop in Li concentrations (Hofmann et al., 2022). This is because the same water (from which the Li is extracted) is circulated through the fractures over and over again and inflow of fresh reservoir fluid is limited. A matrix-dominated EGS concept, such as the one previously demonstrated in Groß Schönebeck, would be a potential solution to this dilemma as in this case the flow of Li-bearing brine to the wells is enhanced by multiple fractures, but the fractures do not connect both wells with each other. Another option for sustainable Li extraction involves reinjecting the produced brine into a hydraulically isolated formation, such as a depleted hydrocarbon reservoir. In this case a natural reservoir recharge or other ways of pressure maintenance must be found.

A general risk during long-term operation of a geothermal reservoir is a decrease in productivity or injectivity as a consequence of reduced permeability due to precipitation or fines migration clogging the pores and fractures of the reservoir rocks. Minerals or amorphous phases precipitate (forming scales) due to changes of the fluid chemical equilibrium as a result pressure- or temperature decline or by mixing with fluids of different composition. In geothermal heat projects scaling mainly occurs due to the temperature drop after heat extraction or degassing after pressure reduction (Phillips et al., 1977; Helali et al., 2024; Luo et al., 2023c). The co-production of CRM could involve additional scaling risks depending on the metal extraction methods: for example, if the method requires a reduced flow-rate (leading to larger temperature decline between the reservoir and the top of the production well) or a stronger temperature decline, the scaling risks increase. Moreover, the extraction method itself could release certain chemical components (e.g., Mn^{2+} when using an MnO_2 adsorption material (Li et al., 2018; Feng et al., 1992)), which in turn could precipitate again as solid manganese species. Sometimes, also pH adjustments are necessary for optimized extraction, which in turn would result in a change of the chemical equilibrium. These reactions have to be carefully considered before field-scale application. To prevent scaling, often additives ("inhibitors") are added to the produced formation fluid to keep the metals dissolved even after the heat exchanger. However, these typically organic components could affect the efficiency of the extraction method or even increase the dissolution of the extraction material. Therefore, before application of an extraction method (chapter 5), the interaction between the formation fluids and potential additives needs to be carefully considered.

Due to the complexity of the operations and the heat and Li transport in geological environments, geothermal reservoir simulations including Li transport (and possibly leaching) would be required to plan a sustainable heat and Li production if sufficient information of the subsurface is available. This includes reservoir geometry, thermal, hydraulic (and potentially mechanical) reservoir properties, initial and boundary conditions as well as reservoir fluid properties. Coupled thermo-hydro-(chemical)-(mechanical) models are state-of-the-art in the geothermal industry (Pandey et al., 2018; Xu et al., 2006; Cacace and Jacquey, 2017). However, because of the complex chemical reactions involved in reactive transport, such models still require simplification and significant improvement.

4.2.1. *Case study: increase and decrease of production rates at the geothermal site in Groß Schönebeck*

At the research site Groß Schönebeck (GrSk), located in the NGB, geothermal technologies for fluid production have been investigated for more than 20 years. Here, a well doublet (E GrSk 3/90 and Gt GrSk 4/05 A(2)) was drilled into four km deep sedimentary and volcanic Rotliegend formations. The reservoir is accessed via a matrix-dominated EGS with four artificial fractures. Hydraulic stimulation resulted in an increase of productivity from ~0.3 L/s/MPa (2001) to 2.1 L/s/MPa (2003) for well E GrSk 3/90 and from ~0.7 L/s/MPa to 4.1 L/s/MPa for Gt GrSk 4/05 A(2).

The GrSk brine contains around 200 mg/L Li (Regenspurg et al., 2010). Initial calculations, assuming an extreme pressure drawdown of 10 MPa and 100 % Li extraction efficiency, indicate a production of approx. 12.6 tons Li or 67.1 tons LCE per year with 2 L/s production rate. With the maximum productivity index directly after the stimulations and 10 MPa pressure drawdown up to 1371 tons LCE could be produced per year from this well. However, during circulation tests between 2011 and 2013, the injectivity of well E GrSk 3/90 declined to 1.1 L/s/MPa and the productivity of Gt GrSk 4/05 A(2) to 0.2 L/s/Mpa (Blöcher et al., 2016; Christi et al., 2025).

The decline in production was attributed to various processes that can generally occur in hydrothermal systems in sedimentary basins (Blöcher et al., 2016): (1) Wellbore fill caused by mineral precipitation (e.g., baryte), clogging the well and reducing the flow ability (Regenspurg et al., 2015) (2) Increase of wellbore skin due to precipitation at the wellbore vicinity (electrochemical reaction between the carbon steel casing and more noble dissolved metals) thus clogging the casing perforations (3) chemical or mechanical closure of stimulated fractures (4) Reduction of relative permeability due to 2-phase-flow, after formation of a free gas during production in the reservoir .

For each process, mitigation techniques have been suggested: The long-term precipitation and sedimentation of secondary minerals can be avoided by a constant production temperature, avoidance of pressure loss and high flow velocities in the well. High flow velocities can be achieved by reducing the borehole radius and increasing the flow rate. If necessary, production tubing can be extended below the submersible pump down to the formation. Wellbore skin due to electrochemical reactions can be avoided by application of a proper, highly alloyed well completion material. Degassing of the produced fluid can be reduced by a lower pressure drawdown during production. Furthermore, the reduced pressure drawdown will prolong the mechanical sustainability of the (fractured) formation.

4.2.2. *Calculations for sustainable CRM co-extraction*

The approximate amount of CRM (m_{RM}) such as Cu or Li that can be produced during geothermal operation can be estimated using the following formula:

$$m_{RM} = \int_{t=0}^{production\ \ end} \xi \dot{V} c_{RM} dt,$$

here, ξ is the technical extraction coefficient, $\dot{V}$ is the volumetric flow rate, c_{RM} is the concentration of the raw material, and t is the production time.

All these parameters change over time and depend on technical capabilities. For sustainable extraction of CRM, it is necessary to avoid reduction in volume flow and in raw material concentration. The production rate is directly linked to the productivity index (*PI*) of the well. For a doublet system, with a distance *d* between the wells, the following formula can be applied if radial flow behavior and homogeneous reservoir conditions can be assumed (Lee, 1982):

$$PI = \frac{\dot{V}}{p_0 - p_t} = \frac{2\pi T}{\mu} \frac{1}{ln\left(\frac{d}{r_w}\right) + s},$$

Where T is the transmissivity of the formation, μ the fluid viscosity, p_0 and p_t is the pressure before and during production, respectively, r_w is the well radius and s is the "skin", which quantifies the additional pressure drop or gain near the wellbore.

An example of an application of this framework is given for the Groß Schönebeck site. For a sustainable productivity, the transmissivity of the

Table 2
Qualitative evaluation of key parameters affecting DLE using inorganic sorbents LMO, LTO, and LiAl-LDH ranging from very good (++) to low/critical (–).

	LMO	**LTO**	**LiAl-LDH**
Li adsorption capacity	++	++	o
Li Selectivity	++	+	o
Optimal pH	10–12	10–12	6–8
Additives necessary for pH stabilisation	yes *KH_2PO_4, $C_2H_3NaO_2$	Yes *Carbonate, $C_2H_3NaO_2$	no
Desorption solution	HCl	HCl / $C_6H_8O_7$	H_2O
	+	+(+)	++
Physical/chemical sorbent stability	-	++	+
Commercial availability	–	++	++

formation must be preserved, and any wellbore damage leading to the development of a positive skin should be avoided.

In addition to these operational considerations, it is important to recognize that successful co-production requires not only a reservoir with high permeability, high porosity, suitable temperatures, and elevated Li/CRM concentrations, but also the presence of sufficient local heat demand - whether municipal, agricultural or industrial - unless the reservoir temperatures are high enough for electricity production.

5. Metal extraction from geothermal brine

A major challenge for Li/CRM exploitation from geothermal brines is to quickly and selectively separate the Li ions (or other CRMs) from the fluid phase. Ideally, the CRM extraction does not interfere with the heat extraction process. So, careful considerations are needed to decide, where in the geothermal plant the metal extraction is located (e.g., before or after the heat exchanger). This operational link between heat and CRM extraction depends on the respective extraction technologies as well as on the properties of the fluid (flow, temperature, pressure conditions). In the following major extraction technologies for Li and Cu are summarized together with their respective advantages and disadvantages.

5.1. Direct lithium extraction (DLE) methods

The general DLE process consists of two recurring stages: (i) a selective Li-uptake step, during which Li^+ is extracted from the feed solution into a structured phase, and (ii) a Li-recovery or -desorption step, during which Li^+ is released into a separate eluate for downstream concentration and purification. Key performance criteria for DLE systems include Li-capacity (e.g., mg/g), separation factor (e.g., Li/Mg), regeneration efficiency, cycle stability, and energy consumption. These criteria must be met in the presence of high salinity, variable pH, scaling-prone constituents, and elevated temperatures and pressure.

In the following recent literature and data on DLE are summarized, including the comprehensive reviews of Farahbakhsh et al. (2024), Goldberg et al. (2022a), Yu et al. (2022), and Reich et al. (2023). The DLE technologies addressed herein are currently all under scientific investigation or pilot application.

5.1.1. Inorganic metal-based adsorbents

Among DLE approaches, sorption using inorganic metal-based adsorbents ("Li ion-sieves" when they selectively take Li^+ up) has emerged as a promising route. Three major categories have been the focus of research: manganese-based spinel oxides, titanium-based ion-exchange materials, and aluminum-based layered double hydroxides. A comparison between the three methods is given in Table 2. Critical aspects remain to be resolved, including the shaping of these materials (e.g., pelletizing or other processing methods), their integration into extraction systems, and their durability under continuous Li-cycling.

Lithium manganese oxide (LMO) sorbents are among the most studied Li-selective adsorbents, owing to their spinel structure derived from $LiMn_2O_4$. Once activated by acid leaching, these materials become highly selective ion-sieves for Li-recovery in complex brines (Li et al., 2018). The adsorption mechanism is governed by both ion exchange and a coupled redox process. Upon contact with a Li-bearing solution, Li^+ replaces protons in the manganese oxide lattice, while redox reactions involving Mn^{3+} and Mn^{4+} enable further Li-uptake and charge compensation (Feng et al., 1992; Hunter, 1981). Following Li-adsorption, regeneration of the LMO is achieved by acid washing, commonly with dilute HCl.

One of the major advantages of LMO sorbents is their excellent selectivity for Li over competing ions. Due to their specific pore structure, Li^+ ions (radius ~0.76 Å) can diffuse into the narrow channels of the sorbent, while larger mono- and divalent cations (Na^+, K^+, Mg^{2+}, Ca^{2+}) are excluded either sterically or by higher hydration energy requirements.

Three main precursor compositions are commonly used to synthesize LMOs, each differing in Li-to-manganese (Li/Mn) molar ratio and affecting the theoretical adsorption capacity. Higher Li/Mn ratios lead to higher Li-capacities due to the greater number of Li exchange sites within the lattice (Yu et al., 2022; Orooji et al., 2022). However, high loading capacities often depend on the application of alkaline buffers (e.g., NaOH or Na_2CO_3), as Li-intercalation releases protons, causing pH drops that suppress further Li-uptake. The optimal working pH for LMOs typically lies between ten and twelve (Liu et al., 2019). The applicability of LMO sorbents thus requires careful consideration of pH buffering strategies. Since geothermal brines of the NGB are typically sodium-dominated with high TDS and low buffering capacity they are particularly susceptible to acidification during Li-uptake. In contrast, fluids from the URG are generally CO_2-dominated, have lower TDS levels, and benefit from carbonate buffering due to dissolved carbon species. This distinction implies that for NGB-type fluids, the use of alkaline additives or pH buffers (e.g., $C_2H_3NaO_2$, KH_2PO_4) will be essential to maintain an optimal pH range required for efficient Li-uptake. Process involving LMO sorbents must strike a careful balance between raising the pH to enable efficient Li uptake and avoiding excessive chemical alteration (e.g., precipitations) of the native brine composition.

Titanium-based Li adsorbents, commonly referred to as Li titanate ion-sieves (LTO), are derived from Li_2TiO_3 or spinel $Li_4Ti_5O_{12}$ structures (He et al., 2015). These materials exhibit strong Li-selectivity and high structural stability, making them promising candidates for Li-recovery from complex brines. The adsorbent is typically prepared by acid leaching of Li_2TiO_3, yielding H_2TiO_3, a hydrogen titanate with a lamellar structure that contains vacant Li^+ sites. Upon exposure to a Li-bearing fluid, Li^+ ions selectively occupy these vacant sites, displacing protons bound to the framework oxygen atoms. Titanate sorbents have high efficiency even in highly saline brines, with excess concentrations of Na^+, K^+, Mg^{2+}, and Ca^{2+} ions (Chitrakar et al., 2014). As Li^+ ions replace H^+ in the H_2TiO_3 lattice, protons are released into the solution, gradually lowering the pH. As with the manganese oxides, this acidification can significantly reduce adsorption efficiency without buffering (Chitrakar et al., 2014). Desorption of Li from titanate ion-sieves is typically achieved using dilute acids (Wang et al., 2019) which causes negligible framework degradation, enabling repeated cycling.

Lithium–aluminum layered double hydroxides (LiAl-LDHs), represent one of the most technologically mature sorbent classes. They are of lamellar structure with the general formula $LiCl{\cdot}2Al(OH)_3{\cdot}xH_2O$ (Farahbakhsh et al., 2024) that is described as positively charged gibbsite-like layers $[LiAl_2(OH)_6]^+$, with charge-balancing Cl^- anions residing in the interlayer space (Zhong et al., 2021). During activation, deionized water is used to partially leach Li (as LiCl) from the structure, yielding a protonated form, $(H_\gamma Li_{1-\gamma})Al_2(OH)_6Cl$. This transformation creates Li-exchange sites and enables the material to function as a selective Li ion exchanger. The Li-adsorption mechanism in LiAl-LDHs proceeds primarily via a solid-state ion exchange reaction, where, Li^+ from the solution displaces protons in the LDH lattice, resulting in a mild acidification of the treated solution (typically a 1–2 unit drop in pH) (Liu et al., 2019). The optimal working pH for LiAl-LDH is near-neutral (pH 6–8), distinguishing it from manganese- and titanium-based sorbents, which require strongly alkaline conditions for effective Li-uptake. This neutral pH compatibility minimizes the risk of scaling in brines rich in divalent cations (e.g., Ca^{2+}, Mg^{2+}) (Farahbakhsh et al., 2024; Yu et al., 2022).

One of the key structural requirements for effective performance is the retention of a residual Li-fraction in the lattice. Complete removal of structural Li^+ during activation results in topotactic collapse into amorphous $Al(OH)_3$, thereby destroying the sorption capability. In terms of Li-selectivity, LiAl-LDHs demonstrate moderate performance, typically favoring Li^+ over other monovalent cations such as Na^+ and K^+, based on ionic radius and charge density (Jiang et al., 2020a, 2020b). Regarding Li-uptake capacity, LiAl-LDHs generally exhibit lower values compared to manganese or titanium-based ion sieves (Farahbakhsh et al., 2024; Yu et al., 2022; Jiang et al., 2020b; Isupov et al., 1999; Stringfellow and Dobson, 2021).

A critical advantage of LiAl-LDH materials lies in their regeneration behavior. Desorption is accomplished through simple water rinsing, where Li is eluted as LiCl without requiring acids. This mild regeneration process preserves the structural integrity of the LDH and minimizes chemical consumption. However, efficient elution typically requires high water-to-sorbent ratios (~100:1), necessitating water recycling and downstream concentration technologies such as electrodialysis (Goldberg et al., 2022a).

5.1.2. Polymer-based Li-selective adsorbents: lithium ion-imprinted polymers (Li-IIPs)

Different membrane-based technologies have become of interest for Li extraction (Zavahir et al., 2024). In this context, polymer-based Li-selective adsorbents, particularly Li ion-imprinted polymers (Li-IIPs), represent an emerging class of sorption materials that rely on molecular recognition rather than lattice intercalation or purely electrostatic ion exchange. Within the broader framework of adsorption-driven DLE, Li-IIPs operate via selective binding sites that are structurally and chemically tailored to Li^+, enabling targeted uptake even in complex multi-ion matrices such as geothermal brines. Similar to inorganic ion sieves, these materials follow the cyclic DLE principle of selective Li-uptake from the feed solution and subsequent desorption into a concentrated eluate phase, allowing repeated regeneration and reuse (Zavahir et al., 2024; Zhi et al., 2024).

The functional principle of Li-IIPs is based on ion imprinting technology (IIT) (Zhi et al., 2024), in which Li^+ ions act as template species during polymer synthesis. Functional monomers with coordinating groups (e.g., oxygen- or nitrogen-containing ligands) form complexes with Li^+ prior to polymerization. After crosslinking and subsequent removal of the template ion, three-dimensional cavities remain within the polymer matrix that are complementary to Li^+ in terms of ionic radius, coordination environment, and charge distribution. These imprinted binding sites exhibit a high degree of recognition specificity and preferential rebinding of Li^+ over competing cations (Zavahir et al., 2024; Zhi et al., 2024).

The Li-adsorption mechanism in Li-IIPs is primarily governed by coordination-driven binding within the imprinted cavities. The imprinted sites reduce the energy barrier for Li^+ desolvation and facilitate preferential complexation relative to larger or more strongly hydrated ions. Consequently, Li-IIPs can maintain selective Li-uptake in solutions with high ionic strength and elevated Mg/Li ratios, which represent a key challenge for DLE from natural brines (Zavahir et al., 2024; Zhi et al., 2024; Hu et al., 2025).

Operationally, Li-IIPs are well suited for cyclic DLE processes due to their mild regeneration behavior and high stability. Desorption of Li^+ is commonly achieved by dilute acid or chelating eluents, which remove the bound Li^+ while preserving the structural integrity of the polymer matrix (Testa, 2025; Rezaei et al., 2022).

However, several limitations currently restrict the large-scale deployment of Li-IIPs in industrial DLE applications: Compared to inorganic ion sieves (e.g., LMO or LTO), Li-IIPs often exhibit lower absolute adsorption capacities and slower adsorption kinetics due to diffusion limitations within the polymer matrix (Zhi et al., 2024). Challenges also remain regarding polymer recovery, membrane regeneration and fouling, shaping into mechanically robust particles, and long-term stability under high-temperature and high-TDS brine conditions (Zavahir et al., 2024; Zhi et al., 2024).

5.1.3. Electrochemical lithium extraction technologies

Electrochemical Li extraction (e-DLE) comprises a class of emerging separation technologies that exploit redox-driven ion transport to selectively recover Li^+ from complex aqueous matrices. These systems rely on an applied electrical potential to drive Li-intercalation into or through solid-state electrodes or membranes, enabling cyclic uptake and release without the need for chemical reagents (Battistel et al., 2020; Wang et al., 2021). Electrochemical DLE systems are generally classified into three main categories: battery-type systems (electrosorption/intercalation), electro-membrane processes (e.g., bipolar membrane electrodialysis – BMED), and hybrid configurations combining Faradaic and capacitive mechanisms (Zhao et al., 2023; Luo et al., 2023b; Luo et al., 2023a).

In battery-type systems, Li is selectively inserted into redox-active electrode materials such as Li manganese oxide ($LiMn_2O_4$) or Li iron phosphate ($LiFePO_4$) during the charging phase, and subsequently released upon polarity reversal or electrolyte exchange. These intercalation-based processes offer high Li^+ selectivity due to the structural and redox compatibility of the host material with Li^+ over competing cations like Na^+ or Mg^{2+} (Wang et al., 2021). Capacitive deionization systems, particularly membrane capacitive deionization (MCDI), rely on electrostatic adsorption mechanisms and can be enhanced through the use of Li-selective electrode coatings or functionalized membranes (Xue et al., 2020).

Electro-membrane systems such as electrodialysis (ED), selective electrodialysis (SED), and bipolar membrane electrodialysis (BMED) employ ion-selective membranes to separate Li-ions based on charge, size, and mobility. In particular, SED with monovalent-selective cation exchange membranes has been shown to effectively separate Li^+ from divalent cations (Mg^{2+} and Ca^{2+}) (Guo et al., 2023). BMED systems allow for in situ pH modulation through the dissociation of water at the interface of bipolar membranes, enabling Li-separation and conversion processes without external acid or base addition (González et al., 2023).

5.1.4. Liquid–liquid extraction

Solvent-based Li-extraction, also known as liquid–liquid extraction (LLE), is a separation approach in which Li^+ is transferred from an aqueous brine into an immiscible organic phase containing specialized extractant molecules. The process is driven by selective complexation, whereby Li forms coordination complexes with the extractants and is subsequently separated from competing cations (e.g., Na^+, K^+, Mg^{2+}, and Ca^{2+}) (Farahbakhsh et al., 2024; Swain, 2016). Three general classes of extractants are commonly used: (i) Acidic extractants (e.g., di-(2-ethylhexyl)phosphoric acid, abbreviated D2EHPA) (Nguyen and Lee, 2018), (ii) Neutral extractants (e.g., tri-n-butyl phosphate, TBP) (Liu et al., 2019; Nguyen and Lee, 2018; Xiang et al., 2017; Xiang et al., 2016), and (iii) oonic or basic extractants (e.g., quaternary ammonium salts like Aliquat 336) (Xie et al., 2014). Neutral and synergistic extractant mixtures are particularly relevant for Li-recovery due to their ability to discriminate Li^+ from more strongly hydrated or larger ions, based on charge density and solvation energy differences (Goldberg et al., 2022a).

Other neutral extractants include phosphine oxides, which can be tuned for improved selectivity or solubility depending on brine composition and temperature (Nguyen and Lee, 2018). Advanced extractants under investigation include ionic liquids (salts that are liquid at room temperature) and crown ethers, which are cyclic organic molecules that selectively coordinate with Li based on ionic radius. These systems show promise due to their tunable properties and thermal stability but remain limited by high cost, viscosity, and environmental uncertainty under field conditions.

The solvent extraction process typically involves multiple extraction and stripping stages, where Li is first loaded into the organic phase and then recovered (stripped) into an aqueous eluate, commonly hydrochloric or sulfuric acid. This regeneration step releases the Li while restoring the extractant for reuse. However, issues such as solvent loss, emulsion formation, and organic contamination of the aqueous phase pose significant operational challenges, particularly under high-salinity and high-temperature conditions typical of geothermal brines (Goldberg et al., 2022a; Farahbakhsh et al., 2024).

5.2. Copper extraction from geothermal brines

High Cu content in geothermal brines from sedimentary basins represents both a risk and an opportunity for geothermal well operation: unmanaged, it threatens the well performance through scale formation clogging the well (e.g., in Groß Schönebeck); properly managed, Cu could become another co-produced CRM.

At present, no industrial techniques are available for extracting Cu^{2+} from geothermal fluids during well operation. In this section, we discuss the suitability of various Cu-extraction methods - at different stages of development, for this purpose. Several strategies can be considered for recovering Cu from geothermal fluids: ***Electrowinning***, a well-established industrial technique that recovers high-purity Cu by electroplating, is effective only in acidic sulfate solutions (pH 1–3), which is incompatible with the near-neutral pH (4.5–7.0) of most geothermal systems. Under these conditions, Cu may precipitate as hydroxide and cathodic efficiency drops sharply. Additionally, high salinity can increase conductivity but also accelerates corrosion and favors side reactions (Hannula et al., 2019). ***Capacitive deionization*** (CDI), is an electro-sorption technology for the desalination of seawater (Zhang et al., 2022). For the selective separation of specific ions - particular Cu^{2+}- this method has been further developed into ***flow-electrode capacitive deionization*** (FCDI). FCDI employs electrochemical cells with suspended carbon-based electrodes that circulate through the system, allowing continuous ion separation (Zhang et al., 2020) across all pH conditions. Repeated electrochemical regeneration of carbon electrodes has proven effective, and the associated low energy demand suggests that the method could be applied sustainably. The emerging method of ***electrochemical ion pumping*** uses redox-active materials such as Prussian Blue analogues (e.g., CuHCF) as electrodes, to selectively adsorb and release Cu^{2+} from saline solutions (Galleguillos et al., 2020). While both, the FCDI and the electrochemical ion pumping methods seem promising regarding high selectivity, enabling a modular operation and low chemical input, neither has thus far been tested in natural geothermal fluids and the stability of the electrode material in high Cl- environments remains to be proven.

In-well Cu extraction, leveraging natural redox gradients and galvanic deposition, may offer a passive, energy-free recovery option. Novel designs could include deploying removable or rotatable steel collectors or specially alloyed sacrificial surfaces within the wellbore, allowing in-situ plating and subsequent mechanical recovery of native Cu. However, this approach must balance recovery with system longevity and flow assurance.

Importantly, any materials used for Cu recovery, especially in open systems, must not compromise reinjection standards. For example, Prussian Blue analogues, while effective for ion-selective adsorption, require careful containment to prevent nanoparticle or ligand release into reinjected fluids. Risk assessments must therefore address chemical compatibility, leaching potential, and environmental safety, with emphasis on non-toxic, regenerable materials.

6. Material selection for increased life-time of a co-extraction system

The geothermal fluid, particularly in sedimentary basins, is usually highly saline and contains a complex mixture of components, including various gases, that are of corrosive nature (e.g., Cl, Cu^{2+}, CO_2, H_2S). During fluid circulation - from production to injection - the fluid is subject to strong temperature and pressure changes causing a challenge to all materials exposed to the geothermal fluid. Therefore, materials must be carefully selected for each part of the system prior their application (Klapper et al., 2012; Bhuvanendran Nair Jayakumari et al., 2023). For safe operation, the suitability of equipment materials is primarily determined by salinity and chemical composition (especially chloride), pH and temperature – all of which are influenced by the geological setting and anti-scaling treatment (e.g., acidification). These factors have long been recognized in discussions of suitable materials, particularly metallic ones (Phillips et al., 1977; Kukacka, 1992).

Lithium-handling components, whether involving Li chloride (LiCl), carbonate (Li_2CO_3), or hydroxide (LiOH), are generally less demanding in terms of corrosion resistance due to the relatively low temperatures (< 80 °C) involved (Disu et al., 2024; Pan et al., 2024). In such cases, non-metallic materials (e.g., glass-fiber-reinforced plastics for tubing or vessels) may offer a viable alternative (Zhao et al., 2017). If LiCl is handled in metallic components under acidic conditions (pH 1–4; (Choubey et al., 2017)), e.g., when acids are used for desorption, stainless steels with a pitting resistance equivalent number (PREN) greater than 35 are required (Cabrini et al., 2017). Unalloyed steels should generally not be used, and also Cr-Ni steels are not recommended due to their susceptibility to corrosion (DECHEMA Materials-Table 2025). Although under typical operating temperatures Li_2CO_3 carbonate and hydroxide are not corrosive (DECHEMA Materials-Table 2025), surface depositions such as $FeCO_3$ or $Fe(OH)_2/Fe(OH)_3$) may form, which require removal. Only for Li desorption processes at high very temperatures (> 500 °C) (Disu et al., 2024) (normally not the case in geothermal context) metallic materials commonly used in combustion systems or ceramics are necessary to ensure safe operation. With respect to the brine-handling components, pitting and crevice corrosion are critical issues. These require high-alloy materials and the prevention of crevice formation at the interface between metallic and non-metallic materials (Bäßler et al., 2015; Tayactac and Ang, 2021; Schorr et al., 2019; Faes et al., 2019; Iberl et al., 2015; Bender et al., 2022; Mundhenk et al., 2013).

Highly-performance corrosion-resistant alloys with a high PREN ($>$ 40) are typically also resistant to pitting (Cabrini et al., 2017; Iberl et al., 2015). In contrast, unalloyed steel develops magnetite layers that lead to unacceptable high corrosion rates (Owen et al., 2025; Bäßler et al., 2009). Avoiding the use of unalloyed (carbon) steel prevents precipitation of Cu (and/or Pb) on internal surfaces (Stoljarova et al., 2021). In some cases, various types of inhibitors are used to prevent scaling or corrosion (Helali et al., 2024). However, because a negative effect of such inhibitors on the extraction equipment cannot be excluded, their use is not recommended when considering extraction of Li or other CRM.

While this section does not address electrode-, filter-, or adsorber materials, it is important to ensure that these materials also meet corrosion resistance requirements appropriate to their application.

7. Environmental, social, governance (ESG) aspects and life cycle assessment

Traditional Li mining (e.g., by salars) can have significant environmental and social impacts on workers, local communities and ecosystems. The Atacama Desert in northern Chile is a prime example of this, with the mining industry's use of scarce water resources endangering the livelihoods of indigenous communities and local ecosystems (Prior et al., 2013). In contrast, the Li co-extraction from geothermal fluids requires minimal space, and is assumed to have a low carbon and environmental footprint.

While the co-production of heat and CRM represents a promising technology to contribute to current and future energy and raw material needs of many countries, it carries certain environmental risks that can affect public perception and acceptance (Moser and Stauffacher, 2015). Acceptance of Li and Cu extraction is directly tied to acceptance of new geothermal energy plants. Studies indicate that the Russian invasion of Ukraine and the subsequent realization of energy dependency and vulnerability have significantly shifted public opinion (Nakamura et al., 2024). Since then, energy system security and resilience have become key objectives for the population, alongside sustainability. Nonetheless, deep geothermal energy plants are often contested due to several concerns:

- *Induced seismicity:* Fluid injection, and in particular hydraulic stimulation, can alter stress regimes and activate pre-existing faults, leading to microseismic events or, in rare cases, felt earthquakes. In the URV, geothermal-induced events are regularly observed (Küperkoch et al., 2018). Seismic risk mitigation includes real-time seismic monitoring and adaptive injection protocols. Although typically small, those microseismic events can raise concerns in nearby communities, especially where seismic events are uncommon. In the NGB, induced seismicity is minor: even during massive hydraulic stimulation at Groß Schönebeck, only magnitudes between –1.8 and –1.0 have been observed (Kwiatek et al., 2010).
- *Surface Subsidence*: Long-term extraction without adequate reinjection may lead to ground settling or sinking, potentially damaging infrastructure. Balanced fluid management strategies are essential to prevent not only subsidence, but also a reduction of reservoir pressures and subsequent loss of performance.
- *Aquifer and groundwater contamination: The* risk of mixing groundwaters from different formations with geothermal fluids that may lead to contamination of drinking water aquifers is small. Drinking water is usually extracted from shallow aquifers (depths <300 m) (Bauer et al., 2005), whereas fluids for thermal utilization and especially Li extraction are typically extracted from depths of >2000 m (Sanjuan et al., 2022). Direct hydraulic connection across numerous rock units is therefore very unlikely. Major problems could arise from connecting water horizons through drillings. With application of robust well integrity standards, this risk is negligible since it can be properly managed through an appropriate well design and completion, and continuous monitoring.
- *Exposure to radioactivity:* Geothermal fluids of deep sedimentary basins are known to contain naturally occurring radioactive materials (NORM) (Regenspurg et al., 2014; Eggeling et al., 2013). For the site in Groß Schönebeck, the geothermal fluid showed up to 0.1 Bq/mL for ^{226}Ra, ^{210}Pb, and ^{228}Ra and increased up to 100 Bq/g in scaling minerals collected from the filter residues (Regenspurg et al., 2014). These scales form upon cooling of the geothermal fluid during the heat exchange process shifting the chemical equilibrium resulting in oversaturation of certain minerals (e.g., baryte) that precipitate and incorporate the NORM elements. The extraction of CRM after the heat extraction might increase the scaling risks, if the process further decreases the temperature. Depending on the extraction technology, NORM might also influence the extraction and adsorbents/ membranes / ion exchange materials might become contaminated with NORM (Kölbel et al., 2024). The effect of NORM on adsorption materials is currently investigated and mitigation strategies are being developed in several research projects.
- *Contamination by gas emissions:* Depending on the geological formation various amounts of gases (mainly CH_4, CO_2, N_2, H_2, and H_2S) can be released during fluid production (e.g., (Feldbusch et al., 2018; Seibt et al., 2000)). However, most systems would be pressurized and the gas of the geothermal fluids would stay in solution and be re-injected into the reservoir. This avoids any environmental impact from the gas phase. Equally, the extraction of Li, Cu or other raw materials would need to be conducted under pressure in closed systems, not only to avoid degassing, but also to prevent precipitation by oxidation.
- *Contamination by additives*: For geothermal operation and for CRM extraction potentially components that are not naturally occurring in the formation fluid might be released into the water (e.g., scaling inhibitors, lubricants for maintaining the pump, buffers or additives for extraction process). Here, careful monitoring and potentially a filtration step of the composition of the injected water is needed.

These environmental risks are interlinked with public acceptance and societal support. Different acceptance factors are relevant: changes to the landscape, fear of negative effects on the environment, nature or one's own health, and planning and approval procedures that are experienced as unfair or non-transparent (Batel, 2020). Communities often perceive seismicity and contamination risks as more severe than technical assessments suggest. Nonetheless, downplaying the perceived risks is not helpful, since trust deficits can arise if community perspectives are not adequately addressed and if risks are poorly communicated (Mitchell et al., 2025).

Also, the lack of understanding about geothermal processes contributes to resistance. The GECKO study shows that fostering a positive public perception of deep geothermal energy requires trust in project developers, transparent and honest communication about potential risks, involvement of independent experts to provide unbiased reviews, and support and facilitation of the planning process (Rösch et al., 2022). Affected municipalities, stakeholders and citizens should be involved, and their needs and expectations should be respected (Rohse et al., 2024). The balance between opportunities and risks must be considered. This includes sharing energy with nearby municipalities to support them in transitioning to climate-neutral district heating systems and guidelines to obtain and maintain a Social License to Operate (SLO) for combined heat and metal extraction projects (Mitchell et al., 2025).

The extraction of Li from geothermal water is considered as an environmentally friendly alternative to conventional extraction methods. However, to make this statement valid, comprehensive lifecycle assessments must be conducted. To date, there are very few published studies in this context (Huang et al., 2021; Vulcan Energy 2021), partly due to the paucity of information collected in technical facilities rather than due to lack of laboratory data. Since processes and process steps necessary to extract Li differ from site to site, potential uncertainties when comparing sites and regarding up-scaling need to be considered when assessing and interpreting the environmental impacts.

Schenker et al. (2024), evaluated the environmental (kg CO_2eq) and health impact of geothermal Li extraction including processes and influences starting with the drilling of the well to the final Li_2CO_3 product using different scenario assumptions. Generally, the environmental impact increases with decreasing Li concentration in the brine and/or lower yield of the extraction process. Also, impurities in the brine that require pretreatment steps have a considerable negative influence on the environmental impact, especially due to a large energy consumption. Further energy consuming and thus, steps with large influence on the CO_2 equivalents, are drilling operations and post-purification. To improve the efficiency of the precipitation process, the volume of the desorption solution is decreased to increase the Li concentration e.g., through reverse osmosis. The impact of high-energy process steps considerably increases when using conventional energy mixes instead of energy produced by the connected geothermal powerplant.

Different extraction processes for Li are currently under investigation. Each process has different requirements with regard to energy and chemical consumption (Goldberg et al., 2022a; Farahbakhsh et al., 2024; Reich et al., 2023). Furthermore, the conditions at each site with regard to fluid composition vary (e.g., (Munk et al., 2025; Sanjuan et al., 2022; Gourcerol et al., 2024)). Thus, available data and reported LCA results are always a snapshot of a specific point in time and location. For example, pretreatment of the brine via precipitation of elements or water used for desorption via osmosis when working with LiAl-LDS has a relatively large CO_2-equivalent (Schenker et al., 2024). Both processes will, however, not be necessary in the NGB or URG when working e.g., with LMO or LTO (Reich et al., 2023; Slunitschek et al., 2025). At these and comparable sites, it will be necessary to assure closed systems to avoid release of climate active gases or the precipitation of potentially problematic radionuclides (Nitschke et al., 2014; Haas-Nüesch et al., 2018; Fechner et al., 2022). Working with LMO or LTO does not require additional water, but data for the usage of HCl or other acids to desorb Li from LMO and LTI are lacking (e.g., (Farahbakhsh et al., 2024; Reich et al., 2023)). With regard to drilling, especially the drilling depth and the targeted amount of water to be pumped is relevant for the climate impact (Schenker and Pfister, 2025). Thus, the depth of the reservoir at each site and the volume of available water has to be implemented into the LCA. This also highlights that co-production of heat or electricity and Li is highly recommendable from the perspective of environmental impact (Schenker et al., 2024). The influence of postprocessing, e.g., removing impurities before Li_2CO_3 precipitation, depends primarily on the process selectivity with significant differences between the respective DLE techniques. In the laboratory, battery grade Li solutions can be reached, however, it is not clear yet if this is also possible on an industrial scale (Reich et al., 2024). Due to these numerous variables and the lack of good input data, the current LCA results vary considerably. E.g., the CO_2-equivalent varied between the considered scenarios by a factor of up to 10 in the study of Schenker et al. (2024).

Vulcan energy focused in their LCA on global warming potential, carbon footprint, and direct water use (Vulcan Energy 2021). They claim to have negative CO_2 emissions with regard to their defined scopes (e.g., direct and embodied emissions) resulting in a negative global warming potential. Despite a higher direct water use e.g., compared to Australian mining, the calculated water scarcity factor (AWARE) is very low. This however, is mainly related to the higher water availability in Germany. Huang et al. (2021) combined a life cycle- and techno-economic assessment (LCA and TEA, respectively) for a Li-aluminum-layered double hydroxide chloride (LDH) sorbent and forward osmosis. They assumed that the DLE is connected to a 50 MW geothermal power plant, but did not include the construction of the powerplant and drilling of the geothermal wells in the LCA. The approach was based on laboratory data and upscaling to industrial scale was done via stoichiometry and empirical formulas. The life cycle impact methodology used was TRACI 2.1, which considers the classical impact categories like ozone depletion, global warming, fossil fuel depletion or ecotoxicology. The comparison with traditional Li mining pathways (spodumene or salar mining) made with corresponding datasets (Ecoinvent v3.5 database) showed a significant but variable reduction of the environmental footprint (between 1 and 95 %). A more recent study, however, that based on currently available scenarios for geothermal Li extraction, showed that the environmental impact of DLE is still similar or even larger than the one from the traditional salar mining (Schenker et al., 2024). From these scarce and partly contradictive results, we conclude that more and sufficiently transparent data at an industry level are needed to assure a reliable, adequate and comparable assessment of environmental impacts in the future.

Table 3

Central questions on CRM- heat co-extraction from geothermal brines with related challenges, problem evaluation, and suggested measures for the approach in sedimentary basins.

Relevant question for co-extraction	Challenge/ Knowledge gap/ operational problem	Problem evaluation (e. g., economic, social, operational aspects)	Requirements/ Suggested measure
What is the origin of a CRM in a reservoir and how transfer CRMs from rock to brine during production? *Chapter 3*	• Uncertainties exist in geological source, WRI, and transport (flow) paths of the CRM • Complexity of geology and mineral transformation processes (lab experiments often not transferrable) → predictions are highly uncertain • Problem to get adequate samples (cores often belong to companies)	Significant for basic understanding, resource estimation and economic assessment	• More site information needed (rock and fluid analysis across the sedimentary basin) • Valid parameter needed for numeric models (high data quality) →need for long term/ experiments / field studies • Change of mining laws→ samples and data need to be given to research/public
How to achieve/ sustain long term permeability /production rates of the reservoir? *Chapter 4*	Deep reservoirs are often of low permeability in sedimentary basins (decrease of permeability with increase of T and Li content) and require EGS methods	Significant for economy & society but EGS is expensive and often even not allowed	More (research) EGS projects needed to demonstrate safety and feasibility
	• Different time scales of thermal and hydraulic/ chemical break-through → different strategies for heat and CRM extraction • Few 3D underground models	Significant for economics	• More data for modelling needed (e.g., hydraulic tracer tests) → demonstrator • 3 D seismic to develop good underground models
How to choose the best CRM extraction technology for geothermal brines? *Chapter 5*	Complex fluid composition and site-specific challenges: • Unknown interactions of multielement extraction • Unknown effect of additives on production and extraction • Unknown effect of temperature on adsorber materials • Costs and recyclability of materials • High quantities of sorption materials needed for upscaling from lab to field	Significant for operation and economics → costs of sorbents, recycling	• Long term/ multi cycle loading/ unloading experiments at different sites and conditions • Test/ developments of other/new materials • Optimization of regeneration ➔ Testing at real conditions

(*continued on next page*)

8. Conclusion

Unlike traditional mining, the extraction of CRMs from geothermal brines could be co-located with energy production, but faces several technical challenges which is mainly the development of low-impact, cost-efficient extraction technologies that must be adapted to high-salinity, multicomponent fluid systems characteristic for deep

Table 3 (*continued*)

Relevant question for co-extraction	Challenge/ Knowledge gap/ operational problem	Problem evaluation (e.g., economic, social, operational aspects)	Requirements/ Suggested measure
Which materials are needed to ensure corrosion resistance? *Chapter 6*	Often the material selection (e.g., C-steel casing) occurs before fluid production → Right materials for specific fluids	Significant for economy and environment: corrosion results in high costs and contamination	Select adequate materials and accept higher prices for high alloyed materials → Increased acceptance for industry to invest in materials
How to ensure low environmental impact? *Chapter 7*	• Wastes (potentially radioactive) of used adsorption materials • Induced seismicity • Prevent accidents /GW protection/ • Unknown Energy consumption	Significant ESG[a] and economic problem	Risks and measures are known (e.g., waste disposal, ensure well integrity, soft stimulation) → measures need to be correctly applied and monitored
Ho to achieve social acceptance? *Chapter 7*	Diffuse fear of geothermal projects	Significant for society: citizens can stop (fracking) projects	Obtain a SLO[b]; explain and provide advantages (taxes, cheap energy…)

[a] ESG: Environmental, social, governmental.

[b] SLO: Social license to operate.

geothermal reservoirs. Integration of CRM recovery with heat production offers a pathway to improve the sustainability and economic viability of geothermal projects. Furthermore, economic and technical feasibility is closely related to environmental aspects and societal acceptance, which requires the development of joint strategies to secure CRM and heat co-extraction in the most sustainable way possible.

This contribution takes a holistic and interdisciplinary approach to summarize the challenges, risks, and benefits of co-utilizing deep sedimentary brines for both heat and CRM (Li and Cu) production. Our aim is to highlight pathways for future research by identifying existing knowledge gaps and obstacles that must be overcome to fully exploit this underexplored resource of regional relevance. It has been shown that co-extraction is a highly complex process; simply attaching a Li extraction plant to an existing geothermal well is unlikely to succeed without a thorough understanding and integration of the underlying processes.

While neither CRM extraction, nor geothermal energy exploitation alone may be economically viable in many cases, their combination has the potential to improve profitability and contribute to greater independence in both CRM and energy supply. In general, the combined heat and metal production requires similar trade-offs between optimizing thermal output and CRM recovery (e.g., concerning high flow rates, SLO, waste production, and material selection). An exception are fractured reservoirs (either naturally fractured or hydraulically stimulated reservoirs) since the thermal break-through (the moment, when the cooled re-injected water arrives at the production well) will occur later as compared to the hydraulic break-through, which means that a Li-depleted bine will arrive rather early (relevant for metal extraction), whereas a heat depleted brine would arrive later (relevant for geothermal-only application) at the production site.

In the following (Table 3), we summarize the challenges related to the different aspects and suggest measures to eventually allow successful co-extraction projects.

If successfully implemented, geothermal Li/CRM projects could play a significant role in strengthening both national and European Li supply chains. However, to proof the concept of co-extraction of CRM and heat at realistic conditions the questions addressed (Table 3) need to be answered, which requires research at demonstrator sites. Ultimately, this would allow a complete long-term LCA considering all aspects of co-extraction from drilling to CO_2 consumption.

Given the projected surge in demand, the discussed unconventional CRM sources are unlikely to replace traditional mining in the near term (Schmidt et al., 2023; Goldberg et al., 2023). However, their integration into a broader supply strategy represents a step toward a more diversified and sustainable raw materials base.

CRediT authorship contribution statement

Simona Regenspurg: Writing – review & editing, Writing – original draft, Project administration, Funding acquisition, Conceptualization. **Elisabeth Eiche:** Writing – original draft, Conceptualization. **Katharina Alms:** Writing – original draft, Visualization. **Ralph Bäßler:** Writing – original draft. **Guido Blöcher:** Writing – original draft. **Valentin Goldberg:** Writing – original draft. **Hannes Hofmann:** Writing – original draft. **Katrin Kieling:** Writing – original draft. **Christine Rösch:** Writing – original draft. **Lars Rüpke:** Writing – original draft. **Sylvia Sander:** Writing – review & editing, Writing – original draft. **André Stechern:** Writing – original draft. **Katharina Sielemann:** Writing – review & editing, Project administration. **Philipp Weis:** Writing – original draft, Visualization.

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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Data availability

No data was used for the research described in the article.

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