Research article

ES3
Earth Science, Systems and Society

https://doi.org/10.1144/esss2025-007 | Vol. 5 | 2025 | esss2025-007

Assessing environmental, social, political and legal, and economic challenges for cobalt supply from new mining projects in Europe

Stefan Horn*, **Evi Petavratzi and Richard A. Shaw**

British Geological Survey, Nicker Hill, Keyworth, Nottingham NG12 5GG, UK
SH, 0000-0001-8234-7419; EP, 0000-0003-0528-8237; RAS, 0000-0002-7691-4568
* Correspondence: stefanhorn630@gmail.com

Abstract: Despite abundant cobalt resources in Europe, only Finland and Turkey currently extract this metal. This study examines challenges to new cobalt supply by comparing seven exploration projects and two operating mines in Finland, Norway, Sweden and Turkey. A multicriteria analysis framework was developed to assess four domains, environmental (E), social (S), political and legal (G), and economic (EC), each with five to six indicators. The results highlight complex interactions between indicators on national and local scales. While Nordic countries have strong mineral governance and thus rank highly in the political and legal domain, challenges persist, amplified by low rankings in land use and territorial aspects for some projects, particularly Sakatti, due to its vicinity to protected areas, reindeer herding and indigenous people. Furthermore, economic conflicts of interest with tourism result in low rankings for Kuusamo in two social indicators. The arctic region is also particularly vulnerable to climate change, exacerbated by anthropogenic activity. Turkey's Çaldağ project ranks highest for cobalt recovery, but it ranks low in all but one environmental indicator, due to high energy consumption and weak environmental governance in Turkey. Many mining conflicts could be mitigated by earlier community engagement to gain a social licence to operate.

Keywords: Cobalt; ESG; sustainable mining; exploration; Europe; multicriteria analysis; social acceptance; environment; mineral governance

Supplementary material: Additional description of the methods, results and limitations of the multicriteria analysis, and ranking sheets for conducting the multicriteria analysis are available at https://doi.org/10.6084/m9.figshare.c.8092902.v1

Thematic collection: This article is part of the Geoscience for a Sustainable Society collection available at: https://www.lyellcollection.org/topic/collections/geoscience-for-a-sustainable-society

Received 6 June 2025; **revised** 29 September 2025; **accepted** 9 October 2025

Cobalt is an essential raw material for the decarbonization transition due to its use in batteries for electric vehicles (EVs). Although Europe is one of the fastest growing EV markets in the world, progress in building up an independent EV supply chain is slow and overseas competition affects the domestic market (IEA 2024). Cobalt mine production in Europe is particularly small, accounting for only 1% of global cobalt mine production in 2022 (BGS 2024), despite a diverse range of cobalt-bearing deposits across Europe (Horn *et al.* 2021). However, many of these deposits are small and data are sparse for most of them and their resources. Given that the EU imports 81% of cobalt ores and concentrates (SCRREEN 2023), it is vital to increase our knowledge of domestic cobalt resources and identify opportunities for potential supply to EVs in Europe. Investment into European mining projects is minor compared to other continents (S&P Global 2024). Most exploration projects in Europe commonly face land-use conflicts, legislative hurdles, as well as social opposition to mining due to the potential for negative effects on the environment and local communities (Lewicka *et al.* 2021). A prominent example is Rio Tinto's Jadar lithium project in Serbia, where large protests against its development led to the government's decision to revoke its licence due to concerns over environmental impacts. The project is still not operational after more than 20 years in the exploration phase (Vivoda and Loginova 2025). Public acceptance of mining and trust in the extractive industry is very low in Europe (Mancini and Sala 2018) and as it is a very densely populated continent, exploration and mine planning are more difficult to achieve. Involvement from a large pool of stakeholders is required to find the best solution for all affected parties, making the development in many cases lengthy and complicated. In Europe the distance of communities to a mine is likely to be less, and therefore the impact on these communities is possibly perceived as more significant.

In addition, environmental, social and governance (ESG) factors play an important part in the modern extractive industry. The expectation is that the provision of raw materials required for a green and sustainable future is done in a responsible and sustainable way (Laurence 2011; Wall *et al.* 2017; Herrington 2021). Mining can have various environmental and social impacts that affect the livelihood of the ecosystem and local stakeholders. The government has an important role in tackling these challenges, as it can set a robust political and legal framework that citizens can trust (Respect International 2016; MAC 2021; Erdmann and Franken 2022). All these factors can also cause delays or the failure of mining projects. Exploration projects can take up to 20 years before production can commence, in many cases due to ESG-related and economic issues (Jowitt *et al.* 2020; Petavratzi and Gunn 2023).

Safeguarding Europe's goal to have a secure supply of cobalt while also ensuring responsible sourcing of these materials requires a better understanding of the bottlenecks in domestic cobalt supply and the challenges facing mineral exploration and mine development. Voluntary sustainability and ESG auditing schemes and life cycle assessment have become important tools for mining companies to prove good governance to their shareholders, but these often lack a holistic approach (e.g. looking at issues beyond a specific process, project or country) or are not focused on the raw material exploration and production stages.

This study evaluates the opportunities and challenges of selected European mining projects, specifically related to cobalt-bearing deposits and the main challenges that may cause delays or failure of an exploration project. Case studies of cobalt-producing mines and their development history are compared to current European exploration projects to identify incentives that could improve their success rate and speed of development. This aims to improve our understanding of the challenges of mineral exploration and cobalt production in Europe.

Methods

To identify the main challenges associated with prospective mine supply of cobalt in Europe, seven exploration projects, identified as potentially economic, were assessed and compared using a newly developed, semi-quantitative multicriteria approach. Multicriteria analysis is a useful tool for assessing and comparing different projects or options to aid decision-making. One important aspect is that criteria can be based on quantitative and qualitative data. For example, the public perception of mining in a country can only be assessed qualitatively, while economic figures such as the cobalt value of the deposit can be estimated quantitatively. By ranking these indicators on the same scale, it is possible to compare the different underlying datasets with each other (Nautiyal and Goel 2021).

There are four overarching analysis domains used to assess potential issues that could delay or even impede the success of each exploration project: environmental considerations (E), social conditions (S), political and legal conditions (G), and economic considerations (EC). Each domain comprises a matrix of indicators that contribute to the assessment (Fig. 1). The political and legal domain is based on world governance indicators published by the World Bank (Kaufmann *et al.* 2010). Indicators in the other domains were specifically chosen to develop a tailored assessment framework.

The selection of exploration projects was based on the following criteria:

- include the most advanced exploration projects in Europe;
- include a variety of deposit types; and
- include various geographical regions.

Two operating mines that produce cobalt (i.e. Kevitsa and Gördes) have been added to the analysis for comparison. They were chosen as they represent different deposit types and processing technologies, and are in two diverse European regions. Table 1 lists the selected deposits and features.

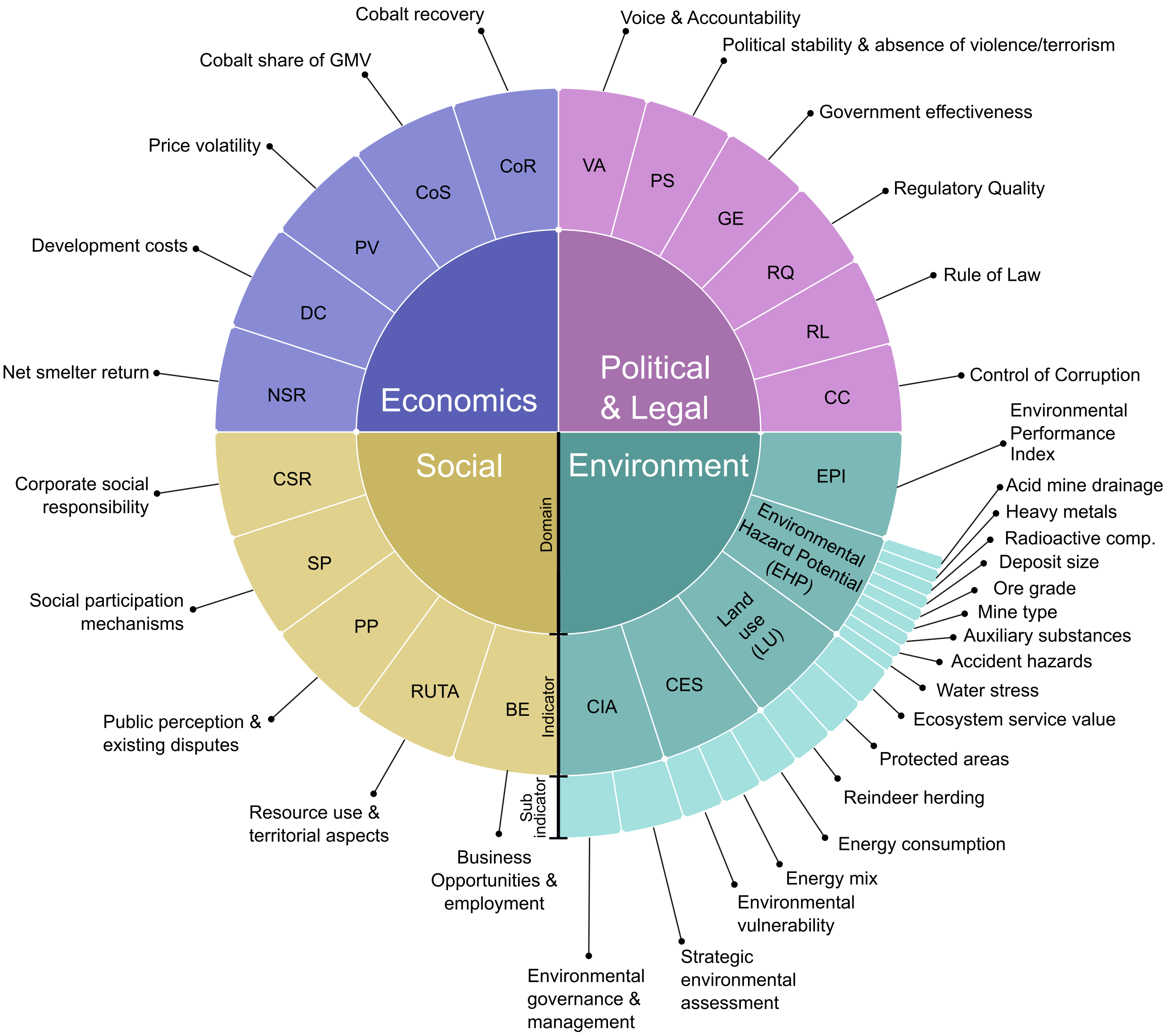

Fig. 1. Illustration of the domains, indicators and sub-indicators for the multicriteria analysis. Acronyms: CES, climate and environmental stress; CIA, cumulative impact assessment; GMV, gross metal value; Comp, components. See Table 2 for indicator abbreviations.

Table 1. Selection of cobalt-bearing deposits in Europe for further assessment based on data from Horn et al. (2021) and company reports

Name	Country	Deposit type	Target commodities	Total resources and combined metal grades	Planned mining method	UNFC class
Sakatti	Finland	Magmatic sulfide deposit	Copper, nickel, palladium, platinum, gold, cobalt	44.4 Mt @ 0.96% Ni, 1.9% Cu, 0.05% Co, 3.3 g/t Au, 4.9 g/t Pd, 6.4 g/t Pt	Underground	222
Rajapalot	Finland	Metasediment-hosted deposit	Gold, cobalt	9.8 Mt @ 28 g/t Au, 0.04% Co	Underground	223
Läntinen Koillismaa (LK) project (Kaukua & Haukiaho)	Finland	Magmatic sulfide deposit	Palladium, nickel, copper, platinum, gold, cobalt	87.9 Mt @ 5.1 g/t Pd, 1.9 g/t Pt, 1 g/t Au, 0.13% Ni, 0.15% Cu, 0.01% Co	Open pit	222
Kuusamo project (Juomasuo)	Finland	Metasediment-hosted deposit	Gold, cobalt	5.8 Mt @ 27 g/t Au, 0.09% Co	Underground	222
Kiskamavaara	Sweden	IOCG-style deposit	Copper, gold*, cobalt	7.6 Mt @ 0.25% Cu, 0.04% Co	Open pit	223
Espedalen (Dalen & Stormyra	Norway	Magmatic sulfide deposit	Nickel, copper, cobalt	9 Mt @ 0.37% Ni, 0.16% Cu, 0.02% Co	Open pit & underground in separate locations	223
Çaldağ	Turkey	Laterite deposit (oxide type)	Nickel, cobalt	37.9 Mt @ 1.14% Ni, 0.05% Co	Open pit	222
Gördes†	Turkey	Laterite deposit (oxide type)	Nickel, cobalt	50.9 Mt @ 0.7% Ni, 0.03% Co	Open pit	111
Kevitsa†	Finland	Magmatic sulfide deposit	Nickel, copper, platinum, palladium, gold, cobalt	208 Mt @ 0.31% Ni, 0.42% Cu, 2 g/t Pt, 1.5 g/t Pd, 1 g/t Au, 0.01% Co	Open pit	111

Target commodities are ordered by importance for each project. Abbreviations: g/t, grammes per tonne; IOCG, iron oxide–copper–gold deposit; Mt, million tonnes; UNFC, United Nations Framework Classification.
*The current resource estimate does not include any gold grades or resources, but it will probably be an important commodity at this deposit (Talga Resources Ltd. 2019).
†Gördes and Kevitsa are operating mines that produce cobalt and are included for comparison. Mineral resource estimates and metal grades are pre-mining figures.

The scoring framework consists of six distinct classes that are illustrated on a colour scale ranging from dark green (1) as the highest rank to dark pink (6) as the lowest rank. All underpinning indicator values are normalized and converted to this ranking system.

Various data sources were analysed and used during the assessment to ensure that indicators are comparable across all selected deposits. This included research articles, company reports, reports from government agencies, international authorities, industry associations and deliverables from research projects. In addition, five semi-structured interviews were undertaken with relevant stakeholders to get a better understanding of the benefits and challenges of exploration and mining in these countries and to acquire further information (e.g. grey literature) and insights from experts in the field. This included experts from the Geological Surveys of Finland and Sweden, a mineral exploration industry expert from Turkey, representatives of the Reindeer Herding Association in Finland and the Sàmi Parliament of Sweden. The conducted analysis and detailed results for each domain are also provided in supplementary material SI-I and II.

The political and legal aspects were assessed by using indicators of the World Governance Index (WGI) that consists of six separate indicators: (1) Voice and accountability (VA), (2) Political stability and absence of violence/terrorism (PS), (3) Government effectiveness (GV), (4) Regulatory quality (RQ), (5) Rule of law (RL) and (6) Control of corruption (CC) (World Bank 2022). The used WGI data are for the year 2020 (Kaufmann and Kraay 2022).

The environmental domain assesses five indicators summarized in Table 2. The first two use the existing assessment framework of the Environmental Performance Index (EPI) for a country-wide perspective (Wolf *et al.* 2022) and a modified version of the Environmental Hazard Potential index (EHP) (Dehoust *et al.* 2017; Manhart *et al.* 2019). The third indicator looks at impacts on land use, by analysing spatial data on each project's exploration permit area with a 2-km buffer. This includes the ecosystem service value of the area, proximity to protected areas and reindeer herding areas. Climate and environmental stress analysis is used to quantify the estimated energy consumption of the proposed project, the energy mix in the country and environmental vulnerability, while the cumulative impact assessment evaluates the strategic environmental assessment frameworks and environmental governance of the country.

The social domain is a semiquantitative assessment of five indicators based on qualitative data. These are business opportunities and employment, resource use and territorial aspects, public perception and existing disputes, social participation mechanisms by the government, and corporate social responsibility strategies implemented by the exploration company (Table 2).

Lastly, we include an approximate economic assessment of the project, which evaluates the net smelter return (NSR), estimated development costs and price volatility (Table 2). In addition, the economic indicator determines the cobalt share of the gross metal value in the resource and estimated cobalt recovery based on the planned processing technology to assess how likely it is that cobalt is efficiently recovered at the project.

Geological, economic and technological factors influence the viability and sustainability of an exploration project and the cobalt recovery. Hence, the multicriteria analysis considers ore deposit geology, the planned mining method as well as processing technology in its rankings. Key concepts are briefly described here. Given the right geological conditions, open pit mines tend to be more cost-effective than underground mining, which can triple the cost of an operation (Scott and Whateley 2010). However, an underground operation is preferable for many environmental reasons, due to a reduction in land use, noise and dust pollution as well as waste accumulation (Dudka and Adriano 1997; Nelson 2011). Nevertheless, underground mining may cause other negative impacts that should be considered, including higher safety risks for workers and surface subsidence above underground workings (Sahu *et al.* 2015). Ore deposit geology and mineralogy also affect possible processing methods, which in turn impact economic feasibility and cobalt recovery. The selected projects include magmatic Ni–Cu sulfide deposits, nickel laterite deposits as well as three deposits with gold as the main asset. Magmatic Ni–Cu deposits have been well studied and several mines across the globe recover cobalt as a by-product of nickel and copper extraction. The

Table 2. Description of the individual indicators of the environmental, social and economic domain

Description	
Environment	
Environmental performance index (EPI)	The country's efforts to protect environmental implementing sustainability goals
Environmental hazard potential (EHP)	Pollution risk and natural hazards, direct impacts on ecosystems, and competition in water usage, using site-specific geological, geographical and technical parameters
Land use (LU)	Impact of current land use, using spatial data on ecosystem service values and proximity to natural protected areas and reindeer herding areas of the exploration permit area
Climate and environmental stress (CES)	Estimated energy consumption during mine operation, country's renewable energy share and environmental vulnerability of local vegetation
Cumulative impact assessment (CIA)	Implementation of strategic impact assessments, environmental governance and monitoring
Social	
Business opportunities & employment (BE)	Positive and negative effects of a new mine development on the local economy of the affected region based on existing industries, employment and local infrastructure
Resource use & territorial aspects (RUTA)	Conflict with other industries and stakeholders on land and natural resources. Open pit mining is considered more disturbing than underground mining. The size of the exploration permit area is also considered
Public perception & existing disputes (PP)	Public perception towards mining in the country or sub-region and existing disputes with local stakeholders
Social participation mechanisms (SP)	Procedures available that ensure legal and procedural fairness during a new mine development, including requirements of stakeholder engagement and mechanisms for complaints and appeals
Corporate social responsibility (CSR)	Voluntary actions by the exploration company to engage with and support the local community by analysing their environmental, social and governance policies and information shared on their website
Economics	
Net smelter return (NSR)	Estimated financial return on sales based on the gross metal value of current total resource estimate and deductions for metal recovery losses and treatment and processing costs
Development costs (DC)	Estimated capital expenditure of the project based on comparisons with available costs for similar successful projects
Price volatility (PV)	Influence of price fluctuations on the exploration projects based on their target commodities. Higher price fluctuations leads to increased investment risk
Cobalt share of gross metal value (CoS)	Cobalt's contribution to the project's profit based on its price and tonnage, which may influence decisions on cobalt recovery routes
Cobalt recovery (CoR)	Typical cobalt recovery based on the planned processing route of the project or, if not available, the most common processing route for this deposit type

For a more detailed explanation, see supplementary material SI-I.

ore is typically processed via froth flotation to produce both nickel–cobalt and copper concentrates before it is shipped to a smelter (Dehaine *et al.* 2021). Cobalt recovery via this processing route is, however, relatively low (Crundwell *et al.* 2011; Dehaine *et al.* 2021). In contrast, cobalt extraction from laterite deposits only recently became a dominant part of the cobalt supply chain since the development of several new high-pressure acid leaching (HPAL) projects from the 1990s onwards (Peek *et al.* 2009; Mudd 2010). Atmospheric pressure tank leaching (AL) is an even newer laterite processing technology with lower investment costs and slightly higher metal recovery rates, and it can be used to process both laterite ore types (limonitic and saprolitic ore), while HPAL plants can only handle limonitic ore (Stanković *et al.* 2020). However, the leaching time to reach maximum recovery for AL is longer and the process requires higher acid consumption, which increases operational costs and raises the risks of environmental damage in case of a leak (Stanković *et al.* 2020). The AL technology also carries a greater risk as it has not been used on a commercial scale before. There are several other hydrometallurgical technologies used for laterite ores, but we focus on HPAL, utilized at the Gördes mine, and AL, planned to be used at Çaldağ. Gold–cobalt projects could be an important future source of cobalt for Europe. There are two similar American projects that plan to start production soon (NICO project, Canada, and Blackbird, USA) (Fortune Minerals Inc. 2022; Jervois Mining Ltd. 2022). Processing of these ores will probably involve cyanide leaching to recover gold and further geometallurgical extraction of cobalt (Mudd 2007; Rinne *et al.* 2021) The affiliation with gold gives these projects the advantage of a stable commodity market and low price volatility.

Results

The results of this study are consolidated into a single matrix, encompassing all indicators used across domains and the ranking of each exploration project (Fig. 2). This section highlights key similarities and differences among the exploration projects and the rationale behind the respective ranking.

Political and legal aspects

Ranking of the political and legal aspects shows a clear picture with similar rankings over the six indicators for each country. The Fennoscandian countries (i.e. Finland, Norway and Sweden) have the highest rank in all indicators. Furthermore, their WGI ranking is higher than most high-income countries within the Organisation for Economic Co-operation and Development (OECD) (Kaufmann and Kraay 2022). Turkey, however, is positioned in the lower ranks of all European countries and central Asia and ranks especially low in 'Voice and accountability' and 'Political stability and absence of violence/terrorism'. One reason for this ranking is the attempted political coup in 2016, and constitutional changes to the presidential system away from a parliamentary democracy in 2017 (Freedomhouse 2021), leading to a reduction in public participation in governance.

Environmental aspects

The environmental indicators present a complex picture across the selected projects. The EPI results align with the WGI indicators in

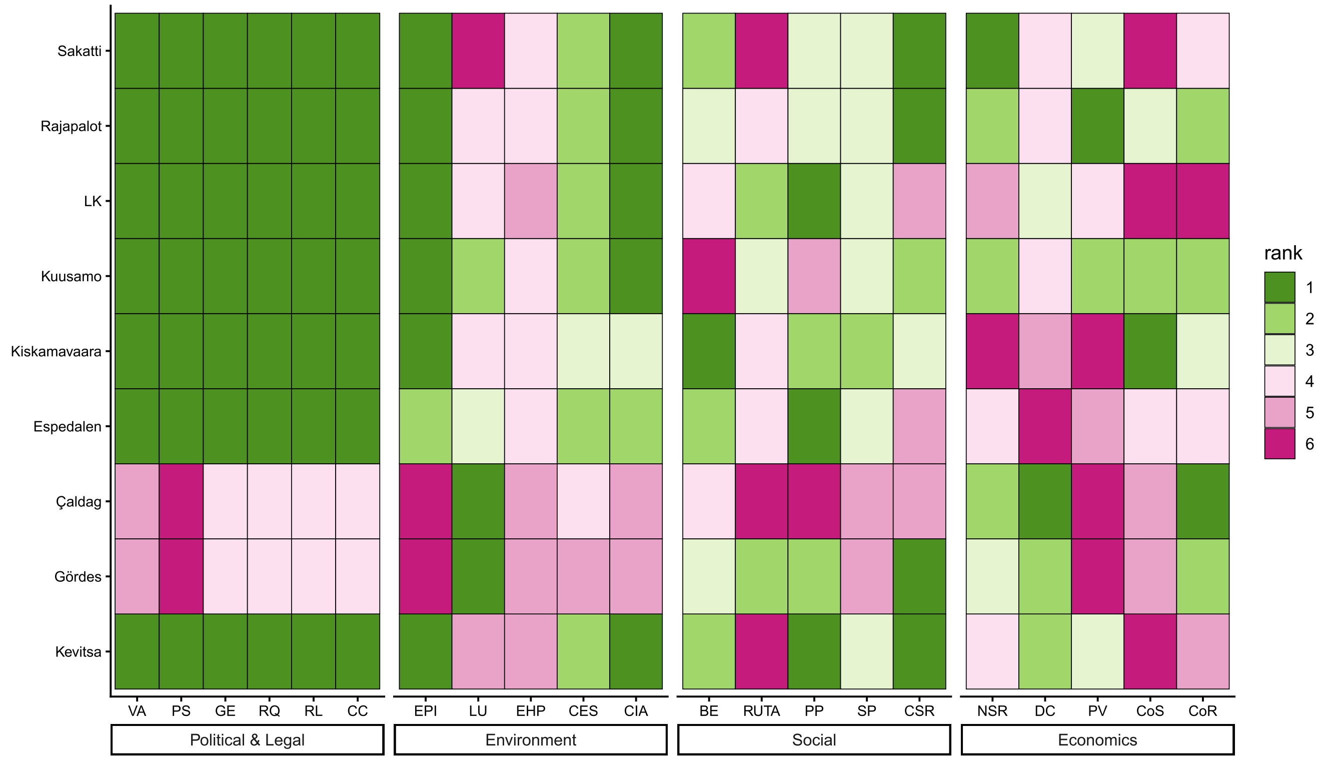

Fig. 2. Score matrix for four domains and their indicators. Rank 1 (dark green) is the highest rank and rank 6 (dark pink) is the lowest. Acronyms from left to right: VA, Voice & accountability; PS, Political stability & absence of violence; GE, Government effectiveness; RQ, Regulatory quality; RL, Rule of law; CC, Control of corruption; EPI, Environmental performance index; LU, Land use; EHP, Environmental hazard potential; CES, Climate and environmental stress; CIA, Cumulative impact assessment; BE, Business opportunities & employment; RUTA, Resource use and territorial aspects; PP, Public perception on mining and existing disputes; SP, Social participation mechanisms; CSR, Corporate social responsibility; NSR, Net smelter return; DC, Development costs; PV, Price volatility; CoS, Cobalt share of gross metal value; CoR, Cobalt recovery.

the political and legal domain, with Fennoscandian countries ranking significantly higher than Turkey. Turkey scores below the EPI average, reflecting poor performance in conservation efforts and lack of measures to mitigate greenhouse gas emissions (Wolf *et al.* 2022).

The aggregated EHP ranks range between 4 and 5 across all projects, with each showing high hazard potential in at least one sub-indicator. Pollution risk is high in all projects due to heavy metals in ores, and hence acid mine drainage is a common risk. The water stress index is low for most Fennoscandian projects, while the projects in Turkey show a high threat as water is scarce in the region.

Our analysis shows that the Sakatti project has the highest environmental impact on land use (Fig. 3). In total, 25% of the exploration permit area with buffer is in a wetland known as the Viiankiaapa mire, resulting in the highest ecosystem service value of all selected projects. The mire is also a Natura 2000 habitat and Sakatti's potential negative impact on this protected area leads to a rank of 6 for the project. Natura 2000 is the EU's network of nature areas that member states are obliged to maintain and restore the conservation status of valuable and threatened species (EEA 2023). In addition, Sakatti lies within a designated area for reindeer herding. The Kevitsa mine has also a low rank as large parts of the permit area are in a wetland, and the designated reindeer herding area. Eight per cent of the area also overlaps with protected areas. The two highest ranking projects are Çaldağ and Gördes in Turkey, mainly due to no conflict with protected areas. However, land use conflicts due to project development taking place within protected areas are not common in Turkey, as only 7% of Turkey's terrestrial land and inland waters are designated with this status (UNEP-WCMC 2022).

Climate and environmental stress is a combined indicator of energy consumption, energy mix and environmental vulnerability. The projects in Finland and Norway rank highest in this category with a high renewable energy share (rank of 2), while the Turkish laterite deposits have a higher energy consumption in laterite processing combined with a low energy share ranking due to a renewable energy share of only 16%. Therefore, Çaldağ and Gördes have a ranking of 4 and 5, respectively. It should be noted that the operator may decide to power the plant with renewable energy, which would reduce its environmental footprint substantially. However, this is not considered in our methodology, as this is not currently taking place.

Finland has a robust system in place for strategic environmental assessment (SEA) and strong environmental governance (OECD 2021*b*), which results in a high score for cumulative impact assessment. In contrast, Turkey has the lowest rank as SEA is not part of a regular process in any government plans and programmes. Environmental governance and monitoring are missing, as are effective legal frameworks and environmental democracy (OECD 2019). However, there are efforts in some areas such as EIA and water management processes to align environmental practices with international and EU standards.

Social aspects

Evaluation of business opportunities and employment across the projects is variable depending on the local situation at the project level. Kiskamavaara has the highest rank of 1 as its location in the rural area of Upper Norrland in northern Sweden has a well-established mining region that contributes 19% to the regional gross domestic product (OECD 2021*a*) and new mining projects will probably benefit existing businesses in the region. In contrast, the Kuusamo project in Finland ranks lowest as it is situated in an attractive tourist region with nature conservation areas, leisure

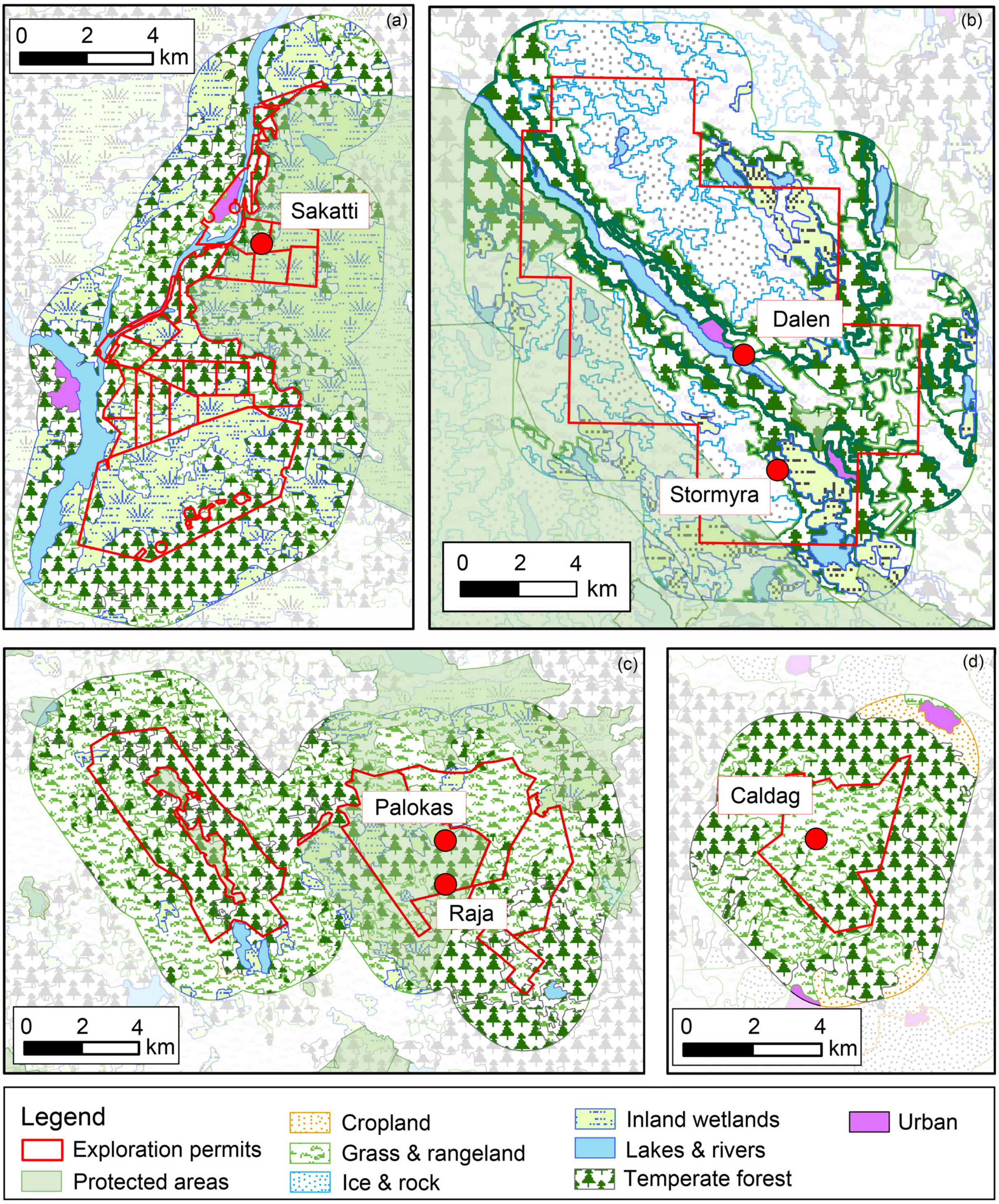

Fig. 3. Land use maps of selected projects, showing different biomes within the exploration permit area with a 2-km buffer as well as overlaps with protected areas. (**a**) Sakatti, Finland; (**b**) Espedalen, Norway; (**c**) Rajapalot, Finland; (**d**) Çaldağ, Turkey. Source: data from Costanza *et al.* (2014) and UNEP-WCMC and IUCN (2021).

centres and local businesses that depend on tourism and would therefore mostly experience negative impacts from mining (Guzik *et al.* 2021; Eerola 2022). For other projects, the economic sectors are more variable, and therefore introducing a new mine could elicit new challenges but also opportunities for the regions.

Resource use and territorial aspects (RUTA) are an issue in all projects to various degrees. The Läntinen Koillismaa (LK) project in Finland and the Gördes mine in Turkey have shown no clear conflicts of territories with other rightsholders, but they are and will be operated as open pit mines, which will generally have a greater impact on local land and water resources and therefore have a rank of 2. Despite Çaldağ being in the same province as Gördes, it ranks in the lowest class of 6 because of a clear conflict with the agricultural industry in the Gediz river plain, which is one of the most important agricultural regions in Turkey (Elçi *et al.* 2015). An open pit mine will not only have an impact on land use but will also require access to water resources creating a conflict of interest with the agricultural sector for a scarce resource in the region (Agartan and Yazicigil 2012; World Resources Institute 2019). Kevitsa and Sakatti also have a low rank of 6 as both projects impact grazing land and migration routes of reindeer herding as well as recreational nature conservation areas that are within the wider exploration permit area (Reindeer Herder's Association of Finland 2014; Saariniemi 2018).

The results regarding public perception and existing disputes are variable. The highest ranking is given to the LK project, Espedalen and Kevitsa as no existing disputes with local communities or other rightsholders are known and negative public perception towards mining is low or directed towards specific Sami-inhabited regions. Çaldağ ranks lowest as the project has seen strong opposition since 2008 (EJAtlas and Mutlu 2014; Birgün 2019) and public perception towards mining in Turkey is largely negative (Yaylaci 2005; Özen and Özen 2013). The Kuusamo project in Finland has a rank of 5 due to several conflicts with other land uses and the tourist sector over time (Eerola 2022).

The indicator 'social participation' shows a clear difference between the Nordic countries and Turkey. In Sweden, consultation with stakeholders (including the Sàmi parliament and reindeer herding cooperatives) must be done before any exploration work can commence, but there is room for improvement (rank of 2). In Finland and Norway, relevant stakeholders and land users need to be consulted before exploration can begin, but private agreements between exploration companies and landowners are possible, leading to exclusion of other land users (Fauchald 2014; Hojem 2015). By contrast, Turkish law does not include any regulations or guidelines for stakeholder engagement (Somay *et al.* 2021). The EIA process includes a social impact assessment, but does not involve stakeholder consultation (Yıldız 2021). The Turkish deposits therefore have a rank of 5.

The highest rank in corporate social responsibility (CSR) was reached by four of the deposits. Two of these are the operating mines, where generally more information is available on CSR activity along the development stages. Sakatti and Rajapalot have a good rank due to active engagement with local stakeholders, good ESG policies and transparent online appearance (Anglo American 2022*a*, *b*; Mawson Oy 2022*a*, *b*). The LK project, Espedalen and Çaldağ only reach a rank of 4 due to little visible engagement with communities through the companies' websites, which are only in English (Kendrick Resources Plc 2022; Palladium One Mining Inc. 2022). Community engagement can include announcements and public events to inform local communities about current activities and identify any conflicts of interest. Public information about such events is limited for these projects and their websites are clearly targeted towards investors and include limited relevant information for local citizens.

Economic aspects

Results of the NSR estimate show that the most advanced exploration project, Sakatti, has the highest rank with an estimated 272 US $/tonne, followed by Çaldağ with 183 US$/tonne (rank 2) (Fig. 4). Both projects have a higher NSR estimate than their neighbouring working mines Kevitsa and Gördes. This could mean that the NSR is overestimated for these deposits. The lowest ranking deposit is the Kiskamavaara deposit with only 21 US$/tonne. Note that Kiskamavaara is an early exploration project and the NSR estimate is based on current inferred resources. These do not include a gold grade, which will probably be an important asset in this project. Figure 4 also displays the gross metal value (GMV) and the GMV after recovery losses during ore processing. Magmatic Ni–Cu sulfide deposits with processing via flotation have a large monetary loss from low metal recoveries, while recoveries of hydrometallurgical processing of laterite deposits are high. The main asset of Rajapalot and the Kuusamo project is gold, which has good metal recovery and only minor losses through further treatments and charges.

The operating Kevitsa and Gördes mines, as well as the Çaldağ project have the lowest development cost (DC) estimate and have therefore the highest rank in this indicator. The projects with smaller resource estimates (<30 million tonnes of ore) all have higher development costs at this point. They are all at an early exploration phase with only an inferred resource estimate indicating that more exploration work is needed to evaluate the economic feasibility of these projects.

The highest rank and lowest price volatility is given to Rajapalot, closely followed by the Kuusamo project at rank 2. They both have gold as their main asset, which has a much lower price volatility than any of the other metals in these projects. Three projects have the lowest rank, namely Çaldağ, Gördes and Kiskamavaara, due to their commodities, cobalt and nickel. Cobalt has the highest price volatility, and has a large share in the current assets of Kiskamavaara. Nickel is the major asset at Çaldağ and Gördes, and has the highest price volatility of all non-ferrous base metals (Cu, Zn, Pb, Al, Ni) (DERA 2022*a*).

The gross metal value share of cobalt is low in most projects (Fig. 5). Kiskamavaara is the exception and has the highest rank with a cobalt share of 53%, making it the dominant asset in this project. All other projects have much lower cobalt shares ranging from 26% in the Kuusamo project (rank 2) down to 5% in the LK project (rank 6). This results in cobalt being produced as a by-

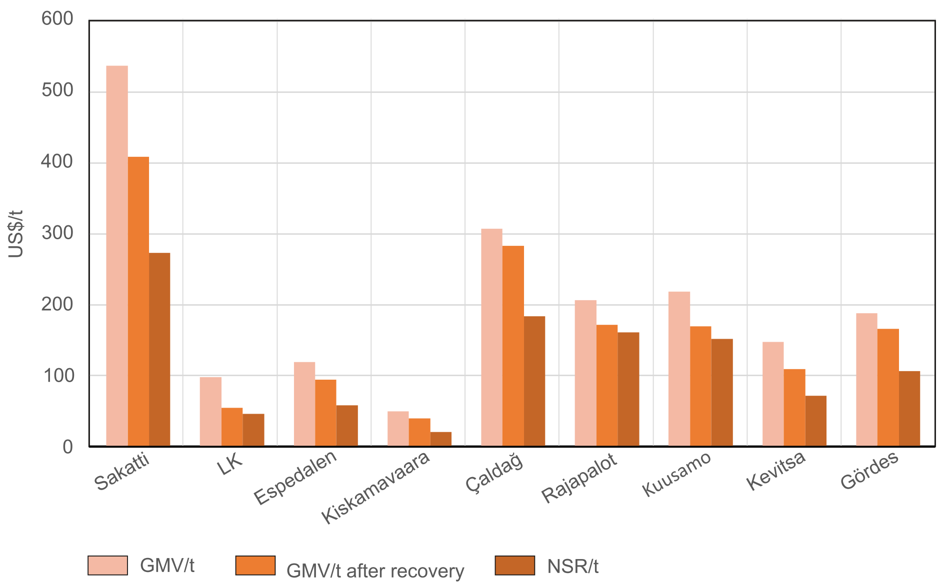

Fig. 4. Comparison of the selected economic indicators gross metal value per tonne (GMV/t), GMV/t after recovery losses from processing, and the net smelter return per tonne (NSR/t). NSR/t includes a factor that takes concentrate content, treatment charges, treatment losses and refining charges into account. LK, Läntinen Koillismaa.

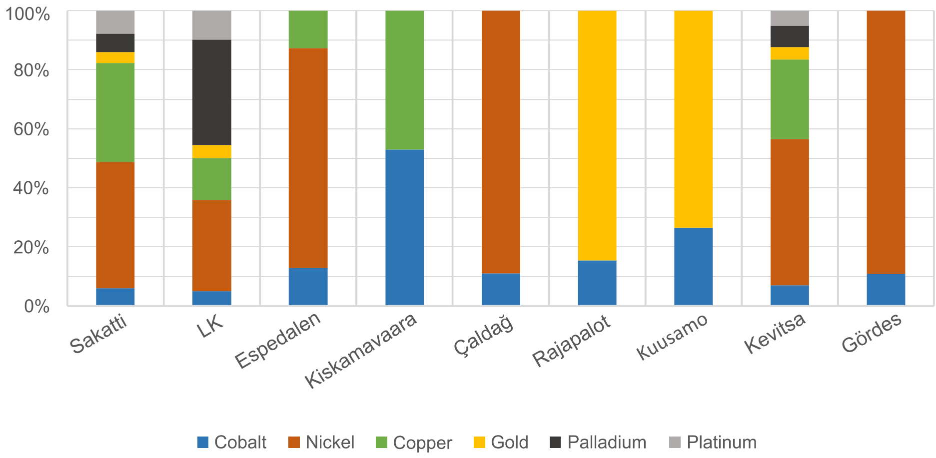

Fig. 5. Share of gross metal value per commodity based on total resource estimates and the average metal prices from August 2021 to July 2022 (DERA 2022*b*). LK, Läntinen Koillismaa.

product. The cobalt recovery potential is largely dependent on the deposit type and processing technology used to extract the metals. The highest cobalt recoveries are reached through hydrometallurgical processing of the laterite deposits. In total, 94% recovery is achieved with atmospheric leaching at Çaldağ (rank 1) and 89% cobalt recovery with high-pressure acid leaching at Gördes (rank 2). Nevertheless, the second rank is shared with the gold projects Rajapalot and Kuusamo, which have an estimated 88% cobalt recovery through a flotation process to produce a cobalt concentrate. Even though Kiskamavaara has the highest GMV/t of all projects, cobalt recovery through flotation during metallurgical testing reached a recovery of 77%, slightly lower than at Rajapalot. The lowest recovery of cobalt is at the LK project with only 19%, ranking lowest in this category.

Discussion

The multicriteria analysis shows that there are a variety of challenges that can impede the development of an exploration project with cobalt resources. The projects are influenced by multiple factors, including national normative rules, cultural aspects specific to a country or region, as well as geological and technological factors and target commodities.

Country-scale challenges in Fennoscandia and Turkey

The results reveal significant differences influenced by geographical location, particularly between the Fennoscandian countries and Turkey. Turkey ranks much lower in the political and legal domain. This leads to a lack of societal trust in the government's ability to regulate the mining industry and address the social and environmental impacts of exploration and mining. Since the Turkish Government allowed foreign investment into the country in 1985, various exploration companies started to explore predominantly for gold (Özen and Özen 2013). Local opposition to new projects increased in the 1990s due to concerns surrounding landownership, environmental impacts, and the lack of benefits or value-addition to local communities. The government disregarded these concerns and instead amended mineral and environmental laws in 2004 to make exploration and mineral extraction easier and expropriated landowners to enable mine development. As a result, violent protests developed locally and in larger cities, which led to a deep mistrust with mining authorities and a negative perception towards mining. Social participation mechanisms introduced by the government are generally inadequate; for example, there are no specific guidelines for stakeholder engagement at the exploration stage. The only element of social participation is during the development of the environmental impact assessment, where stakeholders can comment on mining plans. Overall, the permitting process is described as difficult and long-winded, which creates a challenging environment for mine development for both local communities and exploration companies (Yıldız 2021). Nevertheless, the example of the Gördes mine shows that mine development is possible by prioritizing community engagement and participation to gain the social licence to operate. Meta Nickel has made efforts to consult local communities with their mine plans and held regular meetings with local leaders of surrounding villages (Meta Nikel Kobalt A.S. 2022). In contrast, the Çaldağ project has not had a similar development trajectory. The previous permit holder of Çaldağ, European Nickel, did not engage sufficiently with the community, leading to local opposition and, ultimately, the company's divestment in the project (EJAtlas and Mutlu 2014).

Environmental performance on climate change mitigation and protection of important ecosystems in Turkey is also poor. As conservation efforts in the form of protected areas are small, there is a lack of data on vulnerable species and habitats in the country that may be threatened by industrial development programmes. This lack of data leads to a limited ability for environmental management and monitoring as shown in the indicator 'cumulative impact assessment' (CIA). There are efforts to align environmental legislation with international and EU practices, but there is still room for improvement, which may be reached by more regular strategic environmental assessments and better horizontal coordination between different government bodies.

In contrast, Finland, Norway and Sweden all have a good ranking in the political and legal domain. They are also frontrunners in many aspects of environmental protection and management, despite uneven implementation of environmental regulations in Sweden and Norway. This, combined with bedrock geology favourable for metal deposits, makes Fennoscandia a key region for mining in Europe. All countries have a minerals strategy that supports the development of new mineral extraction sites, including critical metals such as cobalt, and invest in research in the field of sustainable mining (Nurmi *et al.* 2010; Norwegian Ministry of Trade and Industry 2013; Swedish Ministry of Enterprise and Innovation 2015). However, it is also the only European region inhabited by indigenous people, the Sàmi people. The 'UN Declaration on the Rights of Indigenous Peoples' protects their livelihoods, most importantly the practice of reindeer herding. Despite their protected status as well as their right to use privately and state-owned land, reindeer pastures are gradually declining (Pape and Löffler 2012; Landauer *et al.* 2021), and industrial projects (e.g. wind power farms or mines) reduce the grazing area for reindeer herding and affect their migration. As many of these new projects are developed to support the energy transition with renewable energy projects and mining for green technology metals, it is perceived that the Sàmi are paying the price for Europe's green energy transition (McVeigh and Thymann 2022; Bidgood and Hall 2024). Furthermore, the Arctic has warmed three times faster than other global ecoregions in the last 50 years, making it one of the most vulnerable ecoregions in Europe affected by climate change (Seddon *et al.* 2016; Bednar-Friedl *et al.* 2022). This has led to various impacts on reindeer herders, such as rapidly changing weather conditions and the expansion of shrubs on grazing land that puts additional pressure onto the traditional livelihoods of the Sàmi (Rasmus *et al.* 2020; Landauer *et al.* 2021). While mining in the Arctic does not directly intensify climate change effects more than in other regions, it can increase the impacts on this ecoregion and the communities, which are already more vulnerable to this global event. While the Nordic countries are among the frontrunners in sustainable cobalt mining, multiple challenges remain – particularly concerning land use, indigenous communities and climate change impacts – before supply from new mines can be expanded.

Local factors that affect mine development

While governments can set the right legal framework to ensure best practice in the management of environmental and social impacts in their country, in principle each project is unique due to its local setting, and therefore any subsequent impacts on other land uses and resources in the region are influenced by it. Many projects are in close vicinity to protected areas, where regulations are stricter and mine development needs to ensure that the affected site remains unharmed. This can lead to higher development costs and delays, which can make a mine unprofitable. For example, at Sakatti, the ore body lies beneath a Natura 2000 site, which affects its rank in the land use sub-indicators 'protected areas' and ecosystem service value. Wetlands such as Viiankiaapa Mire affected here are deemed to have one of the highest ecosystem service values and are therefore particularly important for conservation. Current plans by the operating company Anglo American are to minimize its environmental impact by building most facilities underground or outside of the protected area. The environmental impact assessment was approved and the company is in the process of applying for a mining permit (Anglo American 2024). The project is also situated in a designated reindeer herding area, but Anglo American actively engages with local stakeholders to minimize the impact on reindeer herders and improve the community's trust. The Kevitsa mine has also developed in proximity to a Natura Habitat site and reindeer herding area. It is a good example of challenging land use conflicts being resolved by early engagement with stakeholders and committing to higher environmental performance levels to build additional trust (Luodes 2019).

Other common regional issues of mine development are conflicts with other established industries in the region such as agriculture and forestry, as in the example of Çaldağ, Turkey. Here the issue is focused on a conflict of water use in an area of high water stress and concerns about water contamination that can affect farmers' crops. However, the example of Gördes shows that mine development and gaining community approval in Manisa province is possible.

In other regions, it is more difficult to gain a social licence to operate, as in the example of the Kuusamo project, Finland. Despite a country-wide positive perception of mining, the project ranks low in the indicator 'public perception and existing disputes' (PP). The Kuusamo municipality has seen various disputes since the 1950s from forestry, fishery and hydropower to uranium exploration and mining that have emerged in the last 20 years (Eerola 2017; Guzik *et al.* 2021). Many people are concerned about the effects on the well-established tourist sector, but statistics have shown that tourism was not affected by exploration activities despite largely negative media coverage of the dispute. In the case of the Kuusamo project, the current permit holder Latitude 66 Cobalt Oy inherited the dispute from the former permit holder that was unsuccessful in getting its environmental permit approved (Guzik *et al.* 2021; Eerola 2022). Nevertheless, the company has made an effort to gain social acceptance and has considered tourism in their planning. Such conflicts have previously been described as the 'Not in my leisure area' (NIMLA) phenomenon (Eerola 2017) and can be related to the 'Not in my backyard' (NIMBY) phenomenon that is known to be a common issue with mining projects in Europe (Badera 2015).

Influence of geological and technological factors

Geological factors have an influence on many different aspects of primary supply of cobalt. Cobalt occurs in various mineral deposit types that are associated with different minerals, commodities of interest and deleterious elements, and that vary in size and metal grade. Each deposit is hosted in different country rocks at varying depths that influence technological factors such as the mining method or mineral processing. All these factors have different impacts on economic feasibility, the environment and society.

In our selection of deposits, the majority will be operated as an open pit, which in economic terms is the preferred method compared to underground mining (Scott and Whateley 2010). In contrast, an underground operation is preferable for many environmental reasons. This is why Sakatti and Rajapalot are planning underground mining to enable mining beneath a protected area.

The magmatic Ni–Cu sulfide deposits (Sakatti, LK project, Espedalen and Kevitsa) assessed in this study are well positioned in Fennoscandia with a well-established upstream supply chain. There is currently one nickel smelter in Hajarvalta, Finland, that could be supplied with concentrate. The smelter is operated by New Boliden and is currently supplied by the Kevitsa mine for processing of nickel, copper, cobalt and platinum group elements (New Boliden 2022). In addition, there are Finnish refineries in Hajarvalta and Kokkola that can process smelter matte to produce cobalt intermediate products (Nornickel 2022; Umicore 2022). The price volatility of magmatic sulfide deposits is moderate to high mainly because nickel has seen significant price fluctuations in past years. Nevertheless, nickel, as well as copper and cobalt are essential raw materials for the envisioned energy transition and their demand is forecasted to grow in the future, which makes these projects attractive to investors (IEA 2021). A disadvantage of this deposit type is that cobalt recovery via this processing route is relatively low. Average recoveries during flotation are about 72%, but most cobalt is lost at the smelter stage with around $50 \pm 20\%$ recovery (Crundwell *et al.* 2011; Dehaine *et al.* 2021). Research into improved cobalt recoveries from these deposit types is needed. Nevertheless, recoveries can differ for copper smelters or other processing technologies. The LK project is also a magmatic Ni–Cu sulfide deposit, but its focus is palladium, while the cobalt GMV share is only 5%. Metallurgical test work at the mine site resulted in a cobalt recovery of only 19%, the lowest of all compared deposits (SLR Consulting Ltd. 2022). By-products such as cobalt do not commonly reach the same recoveries as the main commodity (palladium recovery is at 74% at LK), because they may not be associated with the same mineralogy as the target commodity. Furthermore, the metallurgical process is designed to maximize recovery for the target commodity, while recovery of other commodities is of secondary importance. Enhancement in recovery processes for by-products requires additional investment, which should be justified by demand dynamics and potential return-on-investment.

Our analysis of the laterite deposits shows that the development costs at Gördes are some of the lowest compared to other projects. However, HPAL plants are often very capital-intensive. Expensive titanium-lined autoclaves are needed to prevent corrosion. In addition, many previous HPAL developments struggled with technical failures and long production ramp-up times that increased development costs (Gabb 2018; Stanković *et al.* 2020). One explanation for these divergent results is that our analysis does not consider these additional costs and may therefore be unrealistic.

Compared to HPAL, AL has lower investment costs and slightly higher metal recovery rates, can be used for low-grade ores and can process both laterite ore types (limonitic and saprolitic ore), while HPAL plants can only handle limonitic ore (Stanković *et al.* 2020). However, the leaching time to reach maximum recovery for AL is longer and the process has a higher acid consumption, which increases operational costs and raises the risks of environmental damage in case of a leak (Stanković *et al.* 2020). The AL technology also carries a greater risk because it has not been used on a commercial scale before. Whilst HPAL is better established as a processing technology for laterite deposits, atmospheric pressure tank leaching offers several advantages such as lower investment costs and higher cobalt recovery. It is evident that choosing the most cost-effective and sustainable laterite processing route is challenging. When comparing laterite deposits to other deposit types, the HPAL and AL process have the advantage of high cobalt and nickel recoveries. In contrast, the energy consumption of the two are the highest compared to processing routes of a sulfide ore (considering energy consumption from flotation–smelting–refining). This combined with the low renewable energy share in Turkey could lead to higher fossil fuel consumption and greenhouse gas emissions than the projects in Fennoscandia. In addition, a large amount of greenhouse gas emissions from hydrometallurgical processes come from acid neutralization with lime or limestone; this factor is not considered in our analysis (Norgate and Jahanshahi 2011). The use of large amounts of acid in areas with increased risk of natural hazards, such as earthquakes or landslides, adds to the environmental concerns about these two projects. Hydrometallurgical laterite processing is considered as a new promising source to produce high-grade nickel and cobalt for the EV industry, but the additional environmental stress that is caused by these processes is a challenge. Future research should focus on improving their energy efficiency and minimizing acid consumption.

Gold–cobalt projects such as Rajapalot and Kuusamo could provide a new promising source of cobalt. Their cobalt share in the GMV is relatively high, which may influence the company's decision on improved cobalt recoveries. Exploration companies Mawson Gold (Rajapalot) and Latitude 66 Cobalt OY (Kuusamo) are clearly presenting cobalt as an important asset in their project, even though gold is undoubtedly the main asset (Fig. 5). This is because cobalt resources outside of the Democratic Republic of the Congo are very attractive to investors due to the criticality of cobalt and increasing demand for conflict-free cobalt. The environmental footprint of gold mining is significantly higher than for most other metals (Norgate and Haque 2012). This is dominantly due to low ore grades, high waste to ore ratios and cyanide-leaching that poses a significant threat of environmental pollution (Mudd 2007). The energy consumption in our analysis is relatively low compared to other processing routes. However, these results should be interpreted with caution as there is currently no practical experience of producing cobalt and gold from such a deposit type. The data are based on a process simulation by Rinne *et al.* (2021) whereas the energy consumption data from nickel deposits were collected from currently operating mines.

The Kiskamavaara project is the only one where cobalt has the highest GMV share after copper, meaning that the company has a greater interest in maximizing cobalt recovery. However, our analysis also showed that the NSR estimate is lowest compared to all other projects. Gold, which is also present in the deposit, could improve the economics of the project (Martinsson 2011). However, gold resources have not been systematically assessed and are not part of the current resource estimate, which are only inferred resources at the time of analysis (Talga Resources Ltd. 2019). Further drilling and exploration work is required to prove the economic viability of Kiskamavaara. The permit holder, Talga Resources, is focusing on the production of battery anode material and graphite mining and therefore exploration efforts at Kiskamavaara seem to be slower than in other projects such as Rajapalot.

Strength and weaknesses of the multicriteria analysis

The multicriteria analysis developed here can be used to assess exploration projects for cobalt and may be adapted for other commodities. During the analysis, it became clear that the method has both strengths and weaknesses that should be considered in future applications. These are summarized below. Further details regarding limitations and uncertainties of the analysis are described in supplementary material SI-I.

Strengths:

- The analysis is a useful tool to compare different factors that influence the development of a mining project on one simplified ranking system.
- It accounts for not only the development of the project, but also the likelihood of cobalt production as a by-product, which can be applied to other by-product metals in future work.
- The analysis can compare a diverse range of projects, i.e. different deposit types and countries, and give policy-makers an early opportunity to identify challenges and prioritize the most important issues to address.
- The analysis can be applied to early exploration projects, where there is commonly little information about project economics or environmental and social aspects.

Weaknesses:

- The analysis can only assess the project at a certain point in time, but several indicators are very dynamic and change relatively quickly (e.g. commodity prices). This adds uncertainty to the analysis.
- Many of the ESG-related criteria are based on qualitative data, making an objective ranking difficult.
- Several indicators are based on assumptions on the project's future development, leading to considerable uncertainties.
- The ranking system is designed to compare the selected projects against each other, and other projects cannot be directly assessed with the same scoring system.

The use of the indicator price volatility should be critically reviewed as it is influenced by various factors and differs for each commodity. Volatility varies depending on the time period and commodity being analysed. A higher price volatility does not always necessarily indicate a high-risk market and it will be difficult to use the indicator for a wide range of commodities, as exemplified by Josso *et al.* (2023). Nevertheless, the metal markets and their price volatilities analysed here seem to reflect their markets relatively well. Gold has low volatility, representing a stable market with low investment risk, whereas cobalt has the highest price volatility, indicating a less established higher risk market.

Recommendations to increase cobalt supply from Europe

Although previous work has shown that cobalt is available in several different deposits across Europe (Horn *et al.* 2021), the multicriteria analysis presented here shows that the most advanced exploration projects of these deposits all have different challenges to overcome before cobalt supply can commence from these resources. The following points should be considered to improve domestic cobalt supply from European sources:

(1) A country's governance should provide a robust legal framework for exploration and mine development to streamline the project-permitting process, facilitate the coordination of government agencies participating in the process and provide guidance on social participation mechanisms.
(2) Environmental management regulations should be clear about the responsibilities of national and local government and different government agencies. Furthermore, a comprehensive knowledge base of a country's most important and threatened ecosystems is needed to ensure their full protection.
(3) Exploration and mining companies have the responsibility to engage with local stakeholders to understand their needs and should adjust their project plans accordingly. Corporate social responsibility practices can help to gain societal trust and acceptance of the local community, if these are not only implemented to please investors (Ranängen and Lindman 2018).
(4) A better understanding of cobalt mineralogy and geometallurgy is needed to achieve better recoveries and increase cobalt production from new and existing operations. Many mines with minor metal assays such as cobalt report substantial losses from these by-products due to their low value.
(5) Other potential future resources for cobalt could be supplied from secondary resources such as mine and processing waste. Although there are many abandoned mine sites with potential secondary resources for cobalt in Europe (Horn *et al.* 2021), information about their characteristics, resource tonnages and metal grades is almost non-existent and these sites will face similar environmental, social and economic challenges to conventional mineral deposits.
(6) The proposed method, based on multicriteria analysis principles, is a versatile and robust tool for evaluating the ESG and economic challenges of exploration projects across diverse geological and geographical settings. This framework can be adapted to assess various commodities, including co-products and by-products, through a quantitative approach. However, many indicators, particularly those related to social aspects, remain difficult to quantify due to limited data availability. To enhance the framework's effectiveness and facilitate broader adoption, more data should be collected or made accessible, similarly to well-established metrics such as the WGI and the EPI. Regularly reviewing and updating indicators based on newly available metrics is essential to ensure the framework remains accurate and relevant.

Conclusions

Increasing European cobalt supply from new mine development faces many challenges. Our multicriteria analysis assessed seven exploration projects and two mines by ranking them between 1 (High) and 6 (Low) in 21 indicators that cover political and legal, environmental, social, and economic aspects. The assessment includes country-wide and project-specific indicators using quantitative and qualitative data from various literature sources and expert interviews. The study has shown that each mining project is defined by country governance frameworks, geology, local environment, market dynamics and social aspects, which all impact the success of a project and whether cobalt is recovered. The main conclusions of this study are as follows.

A robust and holistic national regulatory framework should ensure a sustainable path for new mine development and can facilitate exploration. However, finding the balance between attracting new investment and creating and maintaining societal trust can be difficult.

Finland, Norway and Sweden have well-established mineral governance and all mine projects have the highest rank in the political and legal indicators. They also rank high in environmental governance with the ranks of 1 and 2 in the EPI as well as in cumulative impact assessment. These countries are also rich in cobalt-bearing deposits, including magmatic Ni–Cu sulfide deposits (Sakatti, LK, Espedalen) and Cu–Co–Au deposits (Rajapalot, Kuusamo, Kiskamavaara). However, the Arctic is one of the most vulnerable European regions to climate change and increasing anthropogenic influence such as mining activity in this area can cause additional stress and increase the vulnerability of this region and the indigenous Sàmi people. Sakatti has the lowest rank in land use impact due to its location within a nature protected area and a reindeer zone.

The Çaldağ nickel–cobalt laterite deposit in Turkey could bring additional cobalt supply into the European market, and the Gördes mine demonstrates the feasibility of a mine with a hydrometallurgical processing route in Turkey. The two laterite deposits have the highest ranking in cobalt recovery of 1 and 2, compared to the pyrometallurgical processing routes likely to be used at the magmatic sulfide deposits with ranks of 4–6. However, the environmental footprint in hydrometallurgical processing is higher, as shown in the low rank of Çaldağ and Gördes in the climate and environmental stress indicator. Moreover, Turkey ranks very low in the political and legal indicators (rank 4–6) and environmental performance (EPI) (rank 6). This makes sustainable and responsible mine development in Turkey difficult and was partly the reason for previous issues with the start of production at Çaldağ.

Improvement of cobalt recovery for maximum resource efficiency and reduced waste accumulation should be an important part in future research to help reduce the overall impact on the environment and the people who live in it.

The multicriteria analysis used in this study serves as a tool to identify the main strengths and challenges of different deposits and can be used to prioritize actions for tackling economic, social and environmental risks. However, the analysis represents only a snapshot in time and uncertainties in the future project developments should be considered when interpreting the data. Simple adaptions to the framework should enable its use on other mining projects and different target commodities than cobalt. The analysis can be a useful tool for investors to perform due diligence and risk assessment or it can be used to develop better strategies for domestic mineral supply in the future by policy-makers.

Scientific editing by Hannah Hughes

Acknowledgements This work was supported by the Natural Environment Research Council [NE/L002434/1]; The British Geological Survey (BGS); University of Exeter; and the Cobalt Institute. The copyright of the paper is jointly owned by the BGS and the University of Exeter and published by permission of the Executive Director, BGS (UKRI). BGS Reference: OAE24/327. This research was originally submitted as part of a PhD thesis at the University of Exeter in November 2023 (Horn 2023). The authors would like to thank all experts who were interviewed for the participation in this study as well as Jonathan Naden and Frances Wall for fruitful discussions and initial reviewing.

Author contributions **SH**: conceptualization (lead), data curation (lead), methodology (lead), visualization (lead), writing – original draft (lead);

EP: funding acquisition (lead), supervision (lead), writing – review & editing (equal); **RAS**: supervision (supporting), writing – review & editing (supporting)

Funding This work was funded by the Natural Environment Research Council (NE/L002434/1) with additional funding from the British Geological Survey and the Cobalt Institute.

Competing interests 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.

Data availability All data generated or analysed during this study are included in this published article and the supplementary material SI-I and SI-II.

References

Agartan, E. and Yazicigil, H. 2012. Assessment of water supply impacts for a mine site in Western Turkey. *Mine Water and the Environment*, **31**, 112–128, https://doi.org/10.1007/s10230-011-0167-z

Anglo American 2022*a*. A calculationt of Sakatti's ecological compensation in the Inari collective forest is published – Media release, https://finland.angloamerican.com/en/media/press-releases/a-calculation-of-sakattis-ecological-compensation-in-the-inari-collective-forest-is-published [last accessed 24 October 2022].

Anglo American 2022*b*. Community, https://finland.angloamerican.com/en/community [last accessed 24 October 2022].

Anglo American 2024. About Sakatti, https://finland.angloamerican.com/en/about-sakatti [last accessed 13 June 2024].

Badera, J. 2015. Problems of the social non-acceptance of mining projects with particular emphasis on the European Union – a literature review. *Environmental & Socio-Economic Studies*, **2**, 27–34, https://doi.org/10.1515/environ-2015-0029

Bednar-Friedl, B., Biesbroek, R. *et al.* 2022. Europe. *In:* Pörtner, H.-O., Roberts, D.C. *et al.* (eds) *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, 1817–1927, https://doi.org/10.1017/9781009325844.015

BGS 2024. *World Mineral Statistics Data*. British Geological Survey (BGS), https://www.bgs.ac.uk/mineralsuk/statistics/world-mineral-statistics/world-mineral-statistics-data-download/ [last accessed 3 January 2025].

Bidgood, A.K. and Hall, J. 2024. We need to talk about mining in the Arctic. *Earth Science, Systems and Society*, **4**, 10117, https://doi.org/10.3389/esss.2024.10117

Birgün 2019. *An Application was Made to the ECtHR for the Cancellation of the Turgutlu Çaldağı Mining Project; Turgutlu Çaldağı maden projesinin iptali için AİHM'e başvuruldu* (in Turkish). Birgün, https://www.birgun.net/haber/turgutlu-caldagi-maden-projesinin-iptali-icin-aihm-e-basvuruldu-279370 [last accessed 23 October 2022].

Costanza, R., de Groot, R. *et al.* 2014. Changes in the global value of ecosystem services. *Global Environmental Change*, **26**, 152–158, https://doi.org/10.1016/j.gloenvcha.2014.04.002

Crundwell, F., Moats, M.S., Ramachandran, V., Robinson, T.G. and Davenport, W.G. 2011. *Extractive Metallurgy of Nickel, Cobalt and Platinum Group Metals*. Elsevier, Amsterdam.

Dehaine, Q., Tijsseling, L.T., Glass, H.J., Törmänen, T. and Butcher, A.R. 2021. Geometallurgy of cobalt ores: a review. *Minerals Engineering*, **160**, 106656, https://doi.org/10.1016/j.mineng.2020.106656

Dehoust, G., Manhart, A. *et al.* 2017. *Discussion of the Environmental Limits of Primary Raw Material Extraction and Development of a Method for Assessing the Environmental Availability of Raw Materials to Further Develop the Criticality Concept (ÖkoRess I). A Method for a Site-Related Approach*. Oekoinstitut e.V., Dessau-Roßlau, https://www.umweltbundesamt.de/publikationen/discussion-of-the-environmental-limits-of-primary [last accessed 16 September 2022].

DERA 2022*a*. *Volatilitaetsmonitor April 2022*. Deutsche Rohstoffagentur (DERA), https://www.bgr.bund.de/DE/Themen/Min_rohstoffe/Produkte/Volatilitaetsmonitor/vm_22_04.pdf;jsessionid=E7C9F9843F2CCAF710274694B5EA0A64.2_cid321?__blob=publicationFile&v=3 [last accessed 14 February 2025].

DERA 2022*b*. *Preismonitor Juli 2022*. Deutsche Rohstoffagentur (DERA), Berlin, https://www.bgr.bund.de/EN/Themen/Min_rohstoffe/Produkte/produkte_node_en.html?tab=Commodity+prices [last accessed 18 September 2022].

Dudka, S. and Adriano, D.C. 1997. Environmental impacts of metal ore mining and processing: a review. *Journal of Environmental Quality*, **26**, 590–602, https://doi.org/10.2134/jeq1997.00472425002600030003x

EEA 2023. *The Natura 2000 Protected Areas Network*. European Environment Agency (EEA), https://www.eea.europa.eu/themes/biodiversity/natura-2000/the-natura-2000-protected-areas-network [last accessed 16 September 2025].

Eerola, T. 2017. *Corporate Social Responsibility in Mineral Exploration – The Importance of Communication and Stakeholder Engagement in Earning and Maintaining the Social License to Operate*. Report of Investigation. Geological Survey of Finland (GTK), Espoo, https://tupa.gtk.fi/julkaisu/tutkimusraportti/tr_233.pdf [last accessed 6 July 2021].

Eerola, T. 2022. Corporate conduct, commodity and place: ongoing mining and mineral exploration disputes in Finland and their implications for the social license to operate. *Resources Policy*, **76**, 102568, https://doi.org/10.1016/j.resourpol.2022.102568

EJAtlas and Mutlu, O.E. 2014. *Caldag Nickel Mine, Turkey*. Atlas of Envrionmental Justice (EJAtlas), https://ejatlas.org/conflict/caldag-nickel-mine-turkey [last accessed 23 October 2022].

Elçi, A., Simsek, C. *et al.* 2015. Simulation of groundwater flow in the Gediz River Basin. 9th EWRA World Congress Istanbul, Istanbul, https://doi.org/10.13140/RG.2.1.4694.6404

Erdmann, M. and Franken, G. 2022. *Sustainability Standard Systems for Mineral Resources – A Comparative Overview – 2022*. Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Hannover, https://www.bgr.bund.de/DE/Themen/Min_rohstoffe/Downloads/studie_sustainability_standard_systems_2022.pdf?__blob=publicationFile&v=7 [last accessed 14 February 2025].

Fauchald, O.K. 2014. Regulating environmental impacts of mining in Norway. *Nordic Environmental Law Journal*, **1**, 53–65, https://www.nordiskmiljoratt.se/onewebmedia/Fauchald%20NMT%202014-1.pdf

Fortune Minerals Inc. 2022. Status, https://www.fortuneminerals.com/assets/nico/nico-status/default.aspx [last accessed 28 October 2022].

Freedomhouse 2021. Freedom in the World 2021 – Turkey, https://freedomhouse.org/country/turkey/freedom-world/2021 [last accessed 5 January 2023].

Gabb, J. 2018. *HPAL: Upping the Pressure – Global Mining Research Presentation*. Global Mining Research, https://gigametals.com/site/assets/files/4861/2018-03-19-hpal.pdf [last accessed 17 November 2022].

Guzik, K., Galos, K. *et al.* 2021. Potential benefits and constraints of development of critical raw materials' production in the EU: analysis of selected case studies. *Resources*, **10**, https://doi.org/10.3390/resources10070067

Herrington, R. 2021. Mining our green future. *Nature Reviews Materials*, **6**, 456–458, https://doi.org/10.1038/s41578-021-00325-9

Hojem, P. 2015. *Mining in the Nordic Countries – A Comparative Review of Legislation and Taxation*. TemaNord 2015:542. Nordic Council of Ministers, Copenhagen, https://doi.org/10.6027/TN2015-542 [last accessed 24 October 2022].

Horn, S. 2023. *Europe's Cobalt Supply Potential for Low-Carbon Vehicles*. PhD Geology, Camborne School of Mines, University of Exeter and the British Geological Survey, http://hdl.handle.net/10871/134832 [last accessed 14 February 2025].

Horn, S., Gunn, A. *et al.* 2021. Cobalt resources in Europe and the potential for new discoveries. *Ore Geology Reviews*, **130**, 103915, https://doi.org/10.1016/j.oregeorev.2020.103915

IEA 2021. *The Role of Critical Minerals in Clean Energy Transitions – World Energy Outlook Special Report*. International Energy Agency, https://iea.blob.core.windows.net/assets/24d5dfbb-a77a-4647-abcc-667867207f74/TheRoleofCriticalMineralsinCleanEnergyTransitions.pdf [last accessed 14 February 2025].

IEA 2024. *Global EV Outlook 2024 – Moving Towards Increased Affordability*. International Energy Agency, Paris, https://www.iea.org/reports/global-ev-outlook-2024 [last accessed 30 September 2024].

Jervois Mining Ltd. 2022. Idaho Cobalt Operations, https://jervoisglobal.com/projects/idaho-cobalt-operations/ [last accessed 28 November 2022].

Josso, P., Lusty, P.A.J. *et al.* 2023. *Review and Development of the Methodology and Data Used to Produce the UK Criticality Assessment of Technology-Critical Minerals OR/23/044*. British Geological Survey, https://ukcmic.org/downloads/reports/ukcmic-review-and-development-of-the-methodology-and-data-used-to-produce-the-uk-criticality-assessment-of-technology-critical-minerals.pdf [last accessed 20 December 2023].

Jowitt, S.M., Mudd, G.M. and Thompson, J.F.H. 2020. Future availability of non-renewable metal resources and the influence of environmental, social, and governance conflicts on metal production. *Communications Earth & Environment*, **1**, 13, https://doi.org/10.1038/s43247-020-0011-0

Kaufmann, D. and Kraay, A. 2022. *The Worldwide Governance Indicators, 2022 Update*. The World Bank Group, https://info.worldbank.org/governance/wgi/ [last accessed 19 October 2022].

Kaufmann, D., Kraay, A. and Mastruzzi, M. 2010. *The Worldwide Governance Indicators – Methodology and Analytical Issues*. Policy Research Working Paper. The World Bank Group, https://ssrn.com/abstract=1682130 [last accessed 14 February 2025].

Kendrick Resources Plc 2022. Kendrick Resources Plc – turn-key energy metals portfolio, https://www.kendrickresources.com/ [last accessed 24 October 2022].

Landauer, M., Rasmus, S. and Forbes, B.C. 2021. What drives reindeer management in Finland towards social and ecological tipping points? *Regional Environmental Change*, **21**, 32, https://doi.org/10.1007/s10113-021-01757-3

Laurence, D. 2011. Establishing a sustainable mining operation: an overview. *Journal of Cleaner Production*, **19**, 278–284, https://doi.org/10.1016/j.jclepro.2010.08.019

Lewicka, E., Guzik, K. and Galos, K. 2021. On the possibilities of critical raw materials production from the EU's primary sources. *Resources*, **10**, 50, https://doi.org/10.3390/resources10050050

Luodes, N. 2019. *Case 8: Kevitsa Mine: A Case of Integrated Land Use Planning, Environmental Commitment and SLO – MinLand Project*. D6.2. Geological Survey of Finland, MinLand project, https://www.minland.eu/project-results/good-practice-guidelines/ [last accessed 07 November 2022].

MAC 2021. *Towards Sustainable Mining 101: A Primer*. Mining Association of Canada, https://mining.ca/wp-content/uploads/2021/10/TSM-Primer-English.pdf [last accessed 10 December 2021].

Mancini, L. and Sala, S. 2018. Social impact assessment in the mining sector: review and comparison of indicators frameworks. *Resources Policy*, **57**, 98–111, https://doi.org/10.1016/j.resourpol.2018.02.002

Manhart, A., Vogt, R. *et al.* 2019. The environmental criticality of primary raw materials – a new methodology to assess global environmental hazard potentials of minerals and metals from mining. *Mineral Economics*, **32**, 91–107, https://doi.org/10.1007/s13563-018-0160-0

Martinsson, O. 2011. Kiskamavaara a shear zone hosted IOCG-style of Cu-Co-Au deposit in Northern Norrbotten, Sweden. The 11th Biennial Meeting of the SGA. SGA, Antofagasta, https://www.diva-portal.org/smash/get/diva2:1004527/FULLTEXT01.pdf [last accessed 11 November 2022].

Mawson Oy 2022*a*. Borderland mining project – Rajapalojen Kaivashanke (in Finnish), https://rajapalot.fi/ [last accessed 24 October 2022].

Mawson Oy 2022*b*. Environmental, Health and Safety Policy, https://mawsongold.com/environment/environmental-health-and-safety-policy/ [last accessed 14 February 2025].

McVeigh, K. and Thymann, K. 2022. 'We Borrow Our Lands from Our Children': Sami Say They are Paying for Sweden Going Green. *The Guardian*, http://theguardian.org, https://www.theguardian.com/global-development/2022/aug/10/indigenous-sami-reindeer-herders-sweden-green-transition [last accessed 4 October 2022].

Meta Nikel Kobalt A.S. 2022. Social Responsibility, http://www.metanikel.com.tr/en/social-responsibility/ [last accessed 28 November 2022].

Mudd, G.M. 2007. Global trends in gold mining: towards quantifying environmental and resource sustainability. *Resources Policy*, **32**, 42–56, https://doi.org/10.1016/j.resourpol.2007.05.002

Mudd, G.M. 2010. Global trends and environmental issues in nickel mining: sulfides versus laterites. *Ore Geology Reviews*, **38**, 9–26, https://doi.org/10.1016/j.oregeorev.2010.05.003

Nautiyal, H. and Goel, V. 2021. Sustainability assessment: metrics and methods. *In:* Ren, J. (ed.) *Methods in Sustainability Science*. Elsevier, 27–46, https://doi.org/10.1016/B978-0-12-823987-2.00017-9

Nelson, M.G. 2011. Evaluation of mining methods and systems. *In:* Darling, P. (ed.) *SME Mining Engineering Handbook*. Society for Mining Metallurgy and Exploration, 341–348.

New Boliden 2022. *Annual and Sustainability Report 2021 – Care, Courage and Reponsibility*. New Boliden, https://www.boliden.com/investor-relations/reports-and-presentations/annual-reports [last accessed 8 November 2022].

Norgate, T. and Haque, N. 2012. Using life cycle assessment to evaluate some environmental impacts of gold production. *Journal of Cleaner Production*, **29–30**, 53–63, https://doi.org/10.1016/j.jclepro.2012.01.042

Norgate, T. and Jahanshahi, S. 2011. Assessing the energy and greenhouse gas footprints of nickel laterite processing. *Minerals Engineering*, **24**, 698–707, https://doi.org/10.1016/j.mineng.2010.10.002

Nornickel 2022. Kola Division (Finland), https://www.nornickel.com/business/assets/kola-division-finland/ [last accessed 9 January 2023].

Norwegian Ministry of Trade and Industry 2013. *Strategy for the Mineral Industry*. K-0725 E. Ministry of Trade and Industry, https://www.regjeringen.no/en/dokumenter/strategy-for-the-mineral-industry/id717109/ [last accessed 5 November 2022].

Nurmi, P.A., Lahtinen, R. and Vuori, S. 2010. *Finland's Minerals Strategy*. Geological Survey of Finland & The Ministry of Employment and the Economy, Espoo, http://projects.gtk.fi/minerals_strategy/index.html [last accessed 05 November 2022].

OECD 2019. *OECD Environmental Performance Reviews: Turkey 2019*. OECD Publishing, Paris, https://doi.org/10.1787/9789264309753-en

OECD 2021*a*. *Mining Regions and Cities Case of Västerbotten and Norrbotten, Sweden, OECD Rural Studies*. OECD Publishing, Paris, https://doi.org/10.1787/802087e2-en

OECD 2021*b*. *OECD Environmental Performance Reviews: Finland 2021*. OECD Publishing, Paris, https://doi.org/10.1787/d73547b7-en

Özen, H. and Özen, S. 2013. What makes locals protestors? A comparative study of the struggles between local communities and gold-mining MNCs in Turkey. 8th International Conference in Critical Management Studies, Manchester, https://www.escholar.manchester.ac.uk/api/datastream?publicationPid=uk-ac-man-scw:199553&datastreamId=FULL-TEXT.PDF [last accessed 23 October 2022].

Palladium One Mining Inc. 2022. Welcome to Palladium One Mining Inc, https://palladiumoneinc.com/ [last accessed 24 October 2022].

Pape, R. and Löffler, J. 2012. Climate change, land use conflicts, predation and ecological degradation as challenges for reindeer husbandry in Northern Europe: what do we really know after half a century of research? *Ambio*, **41**, 421–434, https://doi.org/10.1007/s13280-012-0257-6

Peek, E., Åkre, T. and Asselin, E. 2009. Technical and business considerations of cobalt hydrometallurgy. *JOM*, **61**, 43, https://doi.org/10.1007/s11837-009-0151-2

Petavratzi, E. and Gunn, G. 2023. Decarbonising the automotive sector: a primary raw material perspective on targets and timescales. *Mineral Economics*, **36**, 545–561, https://doi.org/10.1007/s13563-022-00334-2

Ranängen, H. and Lindman, Å. 2018. Exploring corporate social responsibility practice versus stakeholder interests in Nordic mining. *Journal of Cleaner Production*, **197**, 668–677, https://doi.org/10.1016/j.jclepro.2018.06.159

Rasmus, S., Turunen, M., Luomaranta, A., Kivinen, S., Jylhä, K. and Räihä, J. 2020. Climate change and reindeer management in Finland: co-analysis of practitioner knowledge and meteorological data for better adaptation. *Science of the Total Environment*, **710**, 136229, https://doi.org/10.1016/j.scitotenv.2019.136229

Reindeer Herder's Association of Finland 2014. *Guide to Examining Reindeer Husbandry in Land Use Projects*. Regional Council of Lapland, Rovaniemi, https://paliskunnat.fi/poroyva/PoroYVA_2014_EN_web.pdf [last accessed 14 February 2025].

Respect International 2016. *Responsible Cobalt Initiative (RCI)*. Chinese Chamber of Commerce for Metals, Minerals & Chemicals (CCCMC) Importers & Exporters and the Organisation for Economic Co-operation and Development (OECD), https://respect.international/responsible-cobalt-initiative-rci/ [last accessed 14 February 2025].

Rinne, M., Elomaa, H. and Lundström, M. 2021. Life cycle assessment and process simulation of prospective battery-grade cobalt sulfate production from Co-Au ores in Finland. *International Journal of Life Cycle Assessment*, **26**, 2127–2142, https://doi.org/10.1007/s11367-021-01965-3

Saariniemi, J. 2018. *Experienced Impacts of Mining in Sodankylä: Follow-Up Study. Regional Innovation in the Nordic Arctic and Scotland with a Special Focus on Regions with Large-Scale Projects (REGINA)*. University of Lapland, Rovaniemi, https://lauda.ulapland.fi/bitstream/handle/10024/63422/Saariniemi.Johanna.pdf?sequence=1 [last accessed 3 October 2022].

Sahu, H.B., Prakash, N. and Jayanthu, S. 2015. Underground mining for meeting environmental concerns – a strategic approach for sustainable mining in future. *Procedia Earth and Planetary Science*, **11**, 232–241, https://doi.org/10.1016/j.proeps.2015.06.030

Scott, B.C. and Whateley, M.K. 2010. Project evaluation. *In:* Moon, C.J., Whateley, E. and Evans, A.M. (eds) *Introduction to Mineral Exploration*. Blackwell Publishing, 253–277.

SCRREEN 2023. *Factsheets Updates Based on the EU Facsheet 2020 – Cobalt. Solutions for Critical Raw Materials – A European Expert Network (SCRREEN)*. French Geological Survey (BRGM), https://scrreen.eu/wp-content/uploads/2023/08/SCRREEN2_factsheets_COBALT-1.pdf [last accessed 14 February 2025].

Seddon, A.W.R., Macias-Fauriam, M., Longm, P.R., Benzm, D. and Willis, K.J. 2016. Sensitivity of global terrestrial ecosystems to climate variability. *Nature*, **531**, 229–232, https://doi.org/10.1038/nature16986

SLR Consulting Ltd. 2022. *Technical Report on the Läntinen Koillismaa Project, Finland*. Report for NI 43-101. SLR Consulting Ltd. on behalf of Palladium One Plc., Toronto, https://www.palladiumoneinc.com/projects/technical-reports [last accessed 3 September 2021].

Somay, S., Samlı, Z., Dağlı, S. and Kaya, S. 2021. *Mining in Turkey: Overview*. Thomson Reuters Practical Law, https://uk.practicallaw.thomsonreuters.com/4-616-5262?transitionType=Default&contextData=(sc.Default)&firstPage=true [last accessed 24 October 2022].

S&P Global 2024. *World Exploration Trends 2024*. S&P Global Market Intelligence, https://www.spglobal.com/market-intelligence/en/news-insights/research/world-exploration-trends-2024 [last accessed 3 January 2025].

Stanković, S., Stopić, S., Sokić, M., Marković, B. and Friedrich, B. 2020. Review of the past, present, and future of the hydrometallurgical production of nickel and cobalt from lateritic ores. *Metallurgical and Materials Engineering*, **26**, 199–208, https://doi.org/10.30544/513

Swedish Ministry of Enterprise and Innovation 2015. *Sweden's Minerals Strategy – For Sustainable Use of Sweden's Mineral Resources That Creates Growth Throughout the Country*. N2013.06, https://www.government.se/reports/2013/06/swedens-minerals-strategy-for-sustainable-use-of-swedens-mineral-resources-that-creates-growth-throughout-the-country/ [last accessed 5 November 2022].

Talga Resources Ltd. 2019. *ASX Release 21 August 2019; Maiden Cobalt Resource Estimate for Talga at Kiskama, North Sweden*. ASX:TLG, http://www.talgagroup.com/irm/PDF/85ddf263-46c5-46e0-8fab-8b84e1fbad28/MaidenCobaltResourceEstimateforTalgaatKiskama [last accessed 22 July 2020].

Umicore 2022. Rechargeable Battery Materials – Operations, https://rbm.umicore.com/en/operations/ [last accessed 9 January 2023].

UNEP-WCMC 2022. Supplementary material for 'Protected Area Profile for Turkey from the World Database on Protected Areas', https://www.protectedplanet.net/country/TUR [last accessed 20 October 2022].

UNEP-WCMC and IUCN 2021. *Protected Planet: The World Database on Protected Areas (WDPA)*. UNEP-WCMC and IUCN, Cambridge, UK, https://www.protectedplanet.net [last accessed 8 March 2021].

Vivoda, V. and Loginova, J. 2025. Lithium at the crossroads: geopolitical, economic, and socio-environmental complexities of the Jadar project in Serbia. *Mineral Economics*, **38**, 665–681, https://doi.org/10.1007/s13563-025-00517-7

Wall, F., Rollat, A. and Pell, R.S. 2017. Responsible sourcing of critical metals. *Elements*, **13**, 313–318, https://doi.org/10.2138/gselements.13.5.313

Wolf, M.J., Emerson, J.W., Esty, D.C., de Sherbinn, A. and Wendlin, Z.A. 2022. *2022 Environmental Performance Index*. Yale Center for Environmental Law

& Policy, New Haven, https://epi.yale.edu/downloads [last accessed 13 September 2022].

World Bank 2022. *Worldwide Governance Indicators – Documentation*. World Bank, http://info.worldbank.org/governance/wgi/Home/Documents [last accessed 6 October 2022].

World Resources Institute 2019. *Aqueduct Global Maps 3.0 Data*. World Resources Institute, https://www.wri.org/data/aqueduct-global-maps-30-data [last accessed 16 September 2022].

Yaylaci, E. 2005. Mining industry and SEA – an example in Turkey. *In:* Schmidt, M., João, E. and Albrecht, E. (eds) *Implementing Strategic Environmental Assessment*. Springer, Berlin, 631–645, https://doi.org/10.1007/3-540-27134-1_43

Yıldız, T.D. 2021. How can the effects of EIA procedures and legislation foreseen for the mining operation activities to mining change positively in Turkey? *Resources Policy*, **72**, 102018, https://doi.org/10.1016/j.resourpol.2021.102018