

Accepted Manuscript

Earth Science, Systems and Society

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DOI: <https://doi.org/10.1144/esss2025-007>

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Received 6 June 2025

Revised 29 September 2025

Accepted 9 October 2025

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Supplementary material at <https://doi.org/10.6084/m9.figshare.c.8092902.v1>

Manuscript version: Accepted Manuscript

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Assessing ESG and economic challenges for cobalt supply from new mining projects in Europe

Abbreviated Title: ESG challenges for European cobalt projects

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Abstract

Despite abundant cobalt resources in Europe, only Finland and Turkey currently extract the 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. 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 license to operate.

Supplemental material: I. Additional description on methods, results and limitations of the multicriteria analysis; II: Ranking sheets for conducting the multicriteria analysis. Available at <https://doi.org/10.6084/m9.figshare.30373047>

Introduction

Cobalt is an essential raw material for the decarbonisation transition due to its use in batteries for electric vehicles (EV). 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 these deposits 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 license 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 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 shorter, 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 are produced 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, 2022).

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 is 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

In order 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 multi-criteria approach. Multi-criteria analysis is a useful tool for assessing and comparing different projects or options in order 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 qualitatively assessed, while economic figures like 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, these include: 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 (Figure 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, processing technologies, and are in two diverse European regions. Table 1 lists the selected deposits and features.

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 normalised 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 includes 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 SI-I and II.

The political and legal aspects are 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 is for the year 2020 (Kaufmann and Kraay, 2022).

The environmental domain assesses five indicators summarised 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 2km 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 implicated by the exploration company (Table 2).

Lastly, we include an approximate economic assessment of the project, which evaluates the net smelter return, 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). On the contrary, 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 impacts 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 are well-studied and several mines across the globe recover cobalt as a by-product of nickel and copper extraction. The 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). The 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, 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 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 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, utilised 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 likely involve cyanide leaching to recover gold and further geometallurgical extraction of cobalt (Mudd et al. 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 (Figure 2). This section highlights key similarities and differences among the exploration projects and the rationale behind the respective ranking.

Political and legal aspects

The ranking of the political and legal aspects shows a clear picture with similar rankings over the six indicators for each country. All 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 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, 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 this region.

Our analysis shows that the Sakatti project has the highest environmental impact on land use (Figure 3). Twenty-five percent of the exploration permit area with buffer is in a wetland known as the Viiankiaapa mire that results 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 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 is in a wetland, and the designated reindeer herding area. Eight percent of the area also overlaps with protected areas. The two highest ranking projects are Çaldağ and Gördes in Turkey, mainly due to a lack of conflict with protected areas. However, land use conflicts due to project development taking place within protected areas are not common in Turkey, as only seven per cent of Turkey's terrestrial land and inland waters are designated 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, 2021b), 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, 2021a) and new mining projects will likely 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 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 higher 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 have also 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 of public perception and existing disputes are variable. The highest ranking is given to the LK project, Espedalen and Kevitsa as no existing disputes with the local communities or other rightsholders are known and negative public perception towards mining is small or directed towards specific Sami-inhabited regions. Çaldağ ranks lowest as the project has seen strong opposition since 2008 (EJAtlas and Mutlu OE, 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 stakeholder 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). On the contrary, 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 the local stakeholders, good ESG policies, and transparent online appearance (Anglo American, 2022a; b; Mawson Oy, 2022a; 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 are limited for these projects and their website is clearly targeted towards investors and include limited relevant information for local citizens.

Economic aspects

Results of the net smelter return (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) (Figure 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. It should be noted 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 likely 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 is 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 (less than 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 on 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, which are Çaldağ, Gördes, and Kiskamavaara, due to their commodities, cobalt and nickel. Cobalt has the highest price volatility, which has a large share in the current assets of Kiskamavaara. Nickel is the major asset at Çaldağ and Gördes, which has the highest price volatility of all non-ferrous base metals (Cu, Zn, Pb, Al, Ni) (DERA, 2022a).

The gross metal value share of cobalt is low in most projects (Figure 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-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. Ninety-four per cent 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 in 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 both for local communities and exploration companies (Yıldız, 2021). Nevertheless, the example of the Gördes mine shows, that mine development is possible by prioritising community engagement and participation to gain the social license to operate. Meta Nickel has made efforts to consult the 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 have 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 OE, 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 legislations 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 an 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 like 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 Sámi 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 Sámi 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 Sámi (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 is 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 underneath a Natura 2000 site, which affects its rank in the land use sub indicators “protected areas” and ecosystem service value. Wetlands like the here affected Viiankiaapa Mire are deemed to have one of the highest ecosystem service values and is therefore particularly important for conservation. Current plans by the operating company Anglo American are to minimise 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 to apply 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 stakeholder to minimise the impact on reindeer herders and improve the community’s trust. The Kevitsa mine has also developed in proximity to Natura Habitat site and reindeer herding. 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 farmer’s crops. However, the example of Gördes shows that mine development and gaining community approval in the Manisa province is possible.

In other regions, it is more difficult to gain a social license 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 their environmental permit approved (Guzik et al., 2021; Eerola, 2022). Nevertheless, the company has made an effort to gain social acceptance and 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, deleterious elements, and 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 PGEs (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 gross metal value (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 like 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 maximise 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, high-pressure acid leaching plants (HPAL) 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 additional costs through extended ramp-up times and technical issues and may therefore be unrealistic.

Compared to HPAL, atmospheric pressure tank leaching (AL) has lower investment costs, 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 are from acid neutralisation with lime or limestone; a factor that 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 minimising acid consumption.

Gold-cobalt projects like Rajapalot and Kuusamo could provide a new promising source of cobalt. Their cobalt share in the gross metal value 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 (Figure 5). The reason for this is that 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 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 is based on a process simulation by Rinne et al. (2021) whereas the energy consumption data from nickel deposits was collected from currently operating mines.

The Kiskamavaara project is the only project where cobalt has the highest GMV share after copper, meaning that the company has a greater interest in maximising cobalt recovery. However, our analysis also showed that the net smelter return 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 here developed multicriteria analysis 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 summarised below. Further details regarding limitations and uncertainties of the analysis are described in 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 prioritise 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. The volatility varies depending on the time period and commodity that is 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 here analysed metal markets and their price volatilities 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 like 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 than conventional mineral deposits.
6. The proposed method, based on multi-criteria 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 World Governance Indicators and the Environmental Performance Index. 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:

- 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 environmental performance indicator (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 Sàmi indigenous 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 to 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 to 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 production start 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 that 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 priorities actions for tackling economic, social, and environmental risks. However, the analysis only represents a snapshot in time and uncertainties in the future project developments should be considered when interpreting the data. Simple adaptations 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.

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 that were interviewed for the participation in this study as well as Jonathan Naden and Frances Wall for fruitful discussions and initial reviewing.

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Figure captions

Figure 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.

Figure 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 rank. 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.

Figure 3: Land use maps of selected projects, showing different biomes within the exploration permit area with a 2km buffer as well as overlaps with protected areas. (A) Sakatti, Finland. (B) Espedalen, Norway. (C) Rajapalot, Finland. (D) Çaldağ, Turkey. Data from Costanza et al. (2014); UNEP-WCMC and IUCN (2021).

Figure 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). The NSR/t includes a factor, that takes concentrate content, treatment charges, treatment losses and refining charges into account.

Figure 5: Share of gross metal value per commodity based on total resource estimates and the average metal prices from August 2021 - July 2022 (DERA, 2022b).

Tables

Table 1 Selection of cobalt-bearing deposits in Europe for further assessment based on data from Horn et al. (2021) and company reports. Target commodities are ordered by importance for each project. g/t, gram per tonne, IOCG, Iron-oxide copper gold deposit; Mt, million tonnes; UNFC, United Nations Framework Classification.

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 & Haukiahö)	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
Kiskamavara	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
Gördest†	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

* The current resource estimate does not include any gold grades and resources, but it will most likely be an important commodity at this deposit (Talga Resources Ltd, 2019).

† Gördest and Kevitsa are operating mines that produce cobalt and are included for comparison. Mineral resources estimates and metal grades are pre-mining figures.

Table 2 Description of the individual indicators of the environmental, social and economic domain. For a more detailed explanation, see SI-I.

Environment	
Environmental performance index (EPI)	The country's efforts to protect environmental implementing sustainability goals
Environmental hazard potential (EHP)	Pollution risk & natural hazards, direct impacts on ecosystems, and competition in water usage, using site-specific geological, geographic and technical parameters
Land use (LU)	Impact of current land use, using spatial data on ecosystem service values and proximity to nature 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 to 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 to 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 projects 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

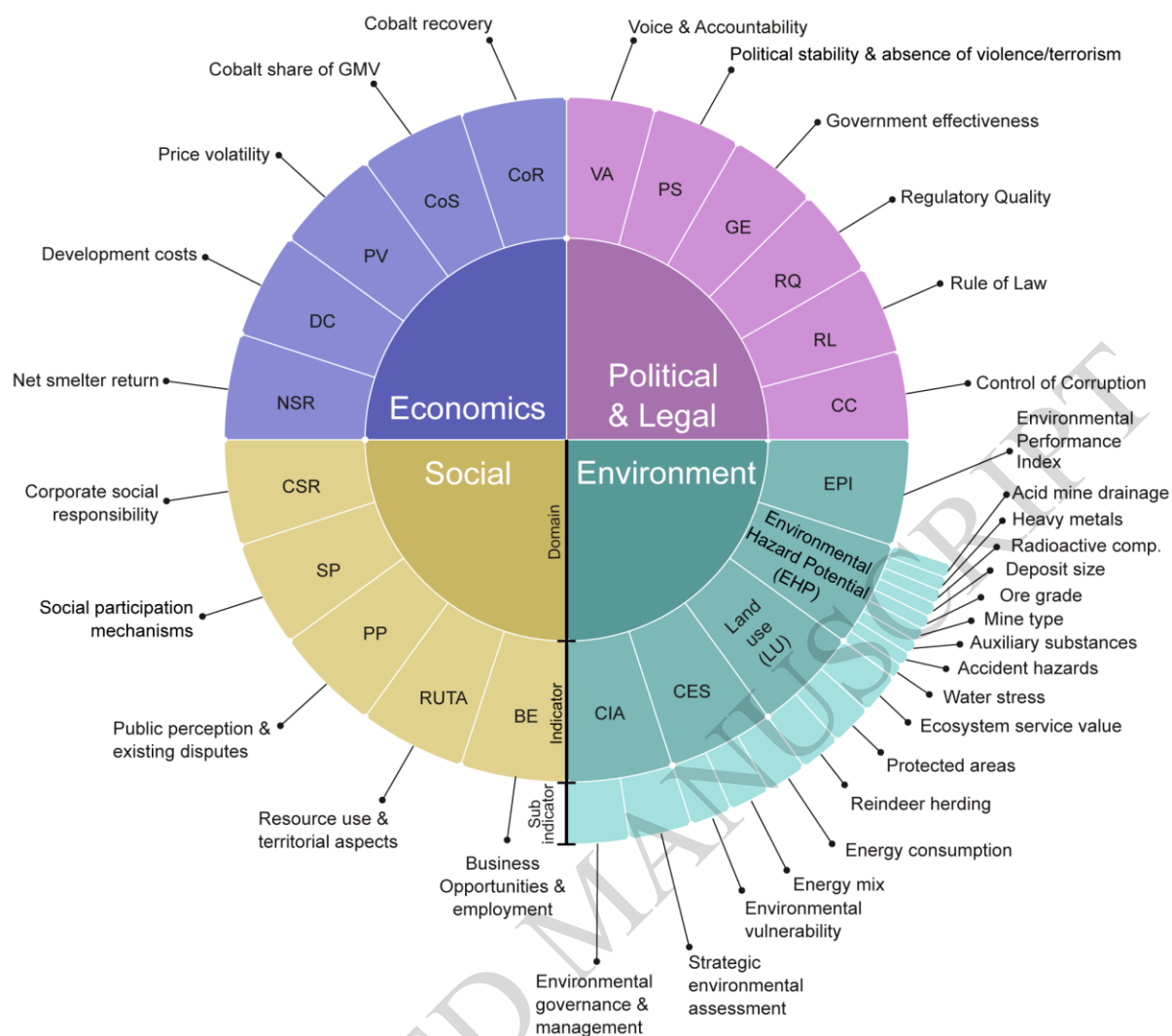


Figure 1

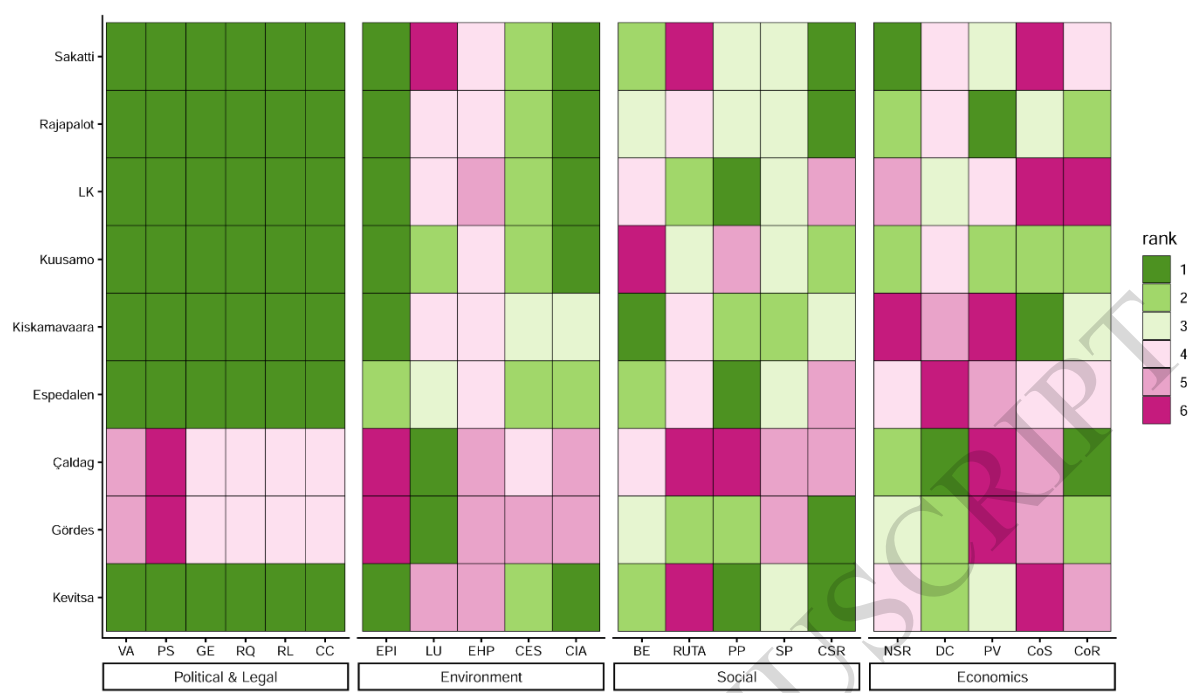


Figure 2

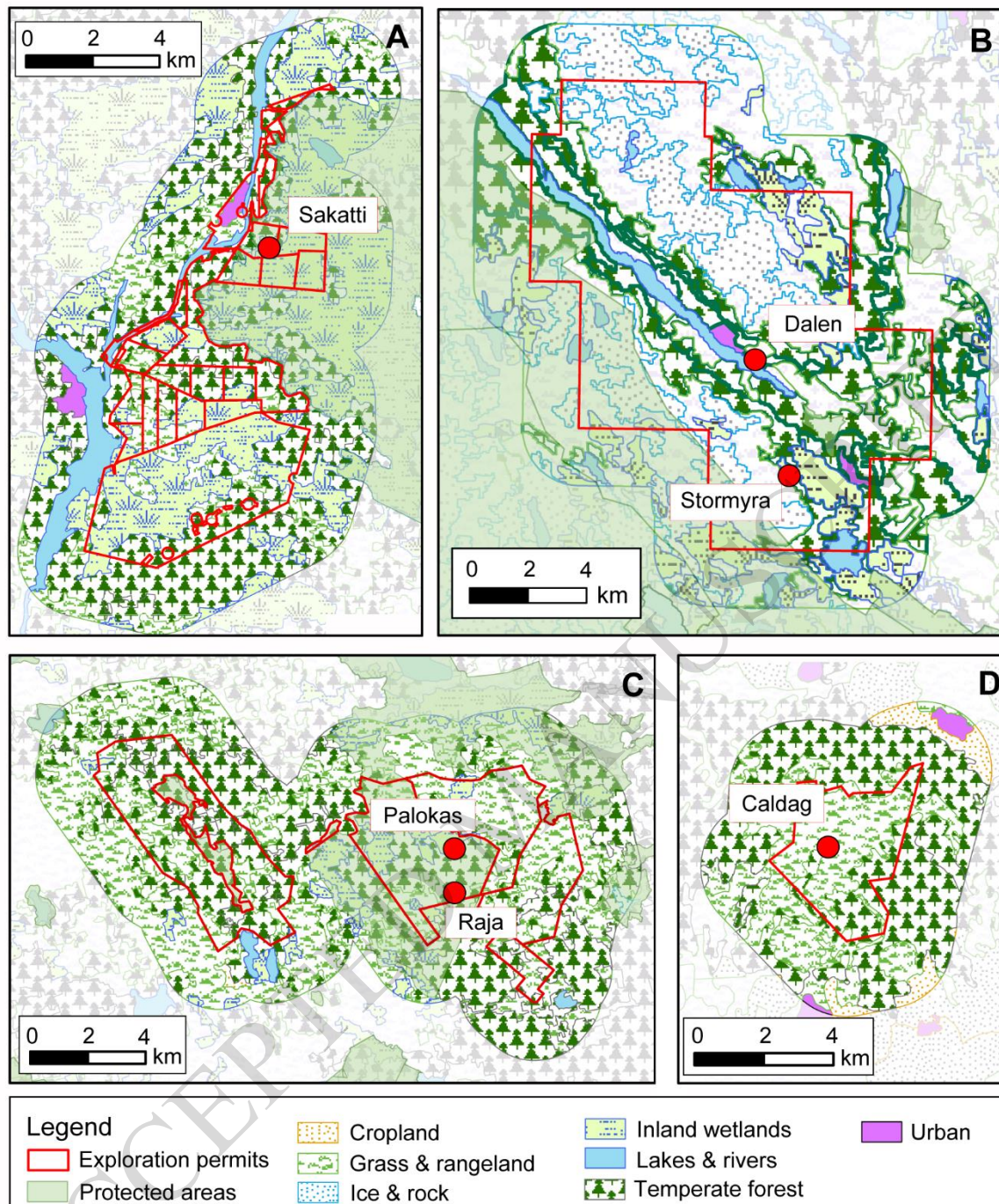


Figure 3

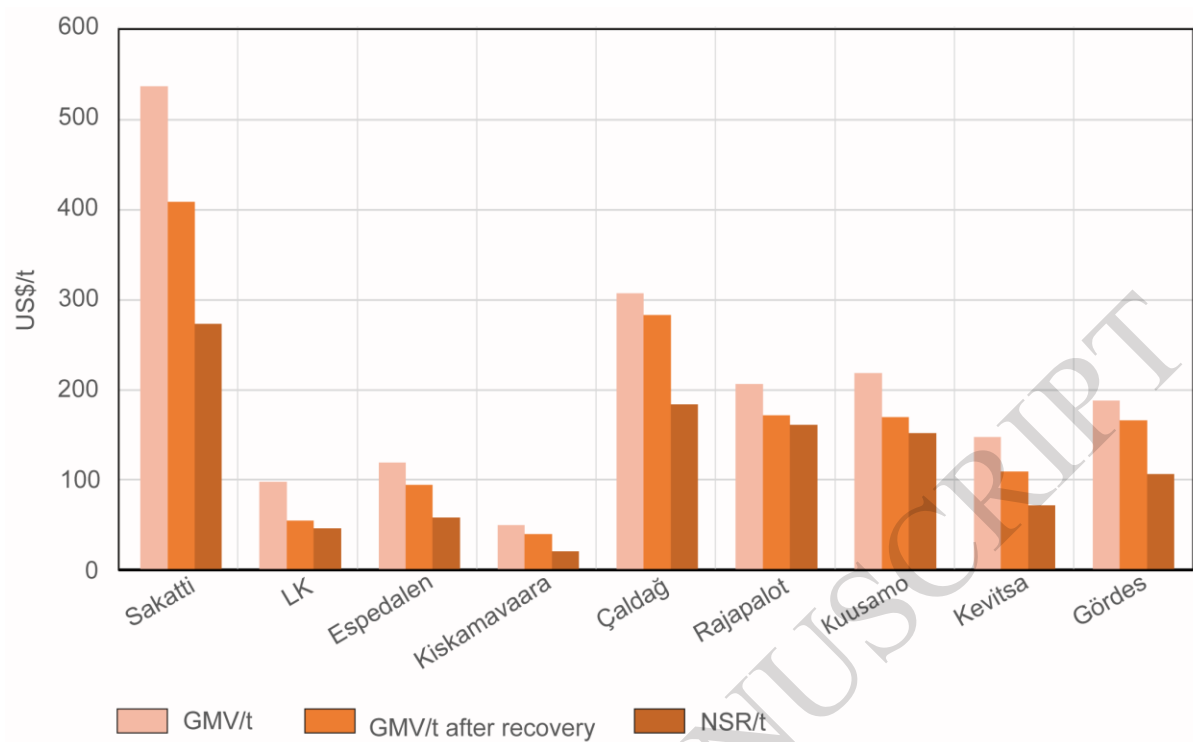


Figure 4

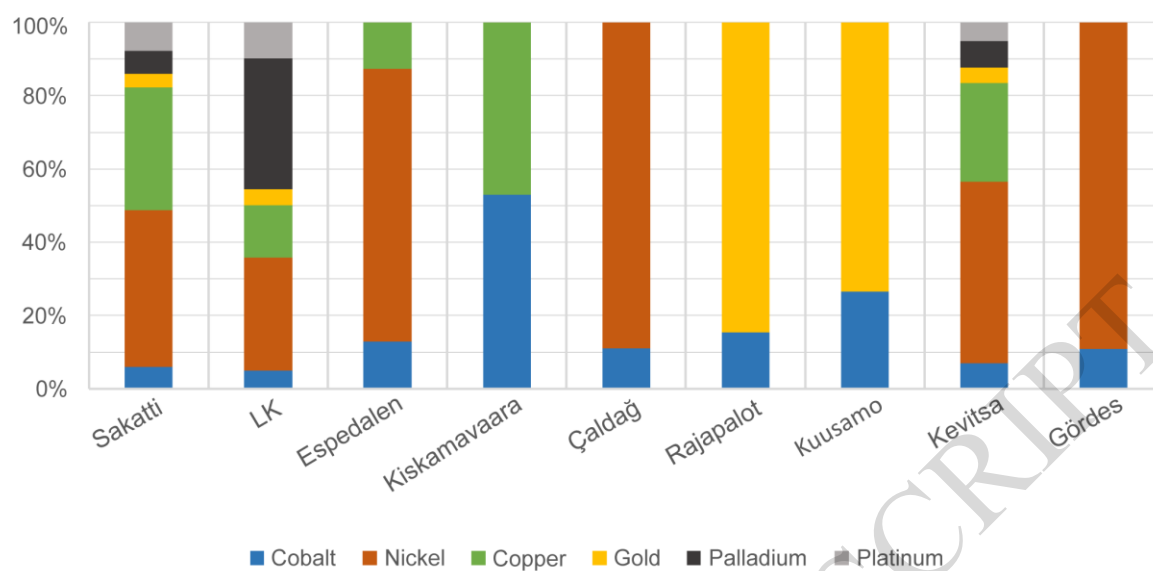


Figure 5