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The quest for a sustainable industry: mining, path dependency and post-carbon regime in the European Arctic

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Abstract
The goal of the European Union's Green Deal industrial plan is to achieve an ecological transition over the next three decades. This transition includes the electrification of energy and transport systems. Achieving such a transformation requires access to critical raw materials for the technologies that will enable the post-carbon transition of European societies. In this context, the European Arctic (also referred to as the Barents region) is seen as a key asset that can contribute to the EU's green plan, in particular due to its high potential for mineral resources. Since the 19th century, Europe's northernmost regions have developed a long tradition of mining activities (e.g., Swedish iron ore, which has been mined by LKAB). Fennoscandia's mineral potential opens up new prospects for the industry. However, fundamental challenges lie ahead, such as the impact of climate change, pollution management, and social acceptability. Although the Nordic countries have based the economic development of their northern regions on sustainable principles, the concept of sustainable mining and its operational implementation have their shortcomings, such as sustained land use conflicts with the Sámi people. In addition, the possibility of missing some key governance linkages may lead to new path dependencies due to a lack of a systemic vision. Once these issues are addressed, the Nordic mining industry could spearhead this defining process for Europe's ecological transition.

Keywords Nordic countries · Sustainable mining · Critical raw materials · European Arctic · Post-carbon transition

Introduction

The use of raw materials has become more intensive and complex in recent decades and the growing demand continues to drive resource extraction projects around the world (Neslen 2024). Among the various active mining areas, the Arctic region is the most attractive in is the so-called *commodity frontier* (Rør 2018; Tolvanen et al. 2019). Since the 19th century, mineral resources have been exploited in the European Arctic (also referred to as the Barents region), such as iron ore in Sweden. The Nordic countries, namely Finland, Norway, and Sweden, remain important players in Arctic mining. For the past decade, these countries have backed a wide range of programmes to promote mining activities, while the energy transition requires metals and minerals for technological needs. The presence of critical raw materials (CRMs) deposits (such as cobalt (Co), copper (Cu), and nickel (Ni) brings a new light on the hypothetical expansion of mining operations in the polar region, given the specific interest coming from the European Union (EU). In order to stand out in the global competition for critical resources, the EU relies on the potential mineral resources in the northernmost territories to contribute to the socio-technical system transformation (European Commission 2023; European Union 2020b; European Union 2023b).

However, the nature and scale of mining operations draw the debate back to the unsustainable features of socio-technical systems built since the industrialisation process, manifested in persistent problems and the inability of social structures to address them (Loorbach 2007). Yet sustainability appears to be a central element in defining and investigating the stakes of a new mining era on the European continent. As such, transitioning towards a free-carbon socio-technical regime involves overcoming carbon lock-in. As defined by Unruh, this condition is created by 'a combination of systematic forces that perpetuate fossil fuel-based

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infrastructures' driven by technological and institutional features (2000:817). In other words, the termo-industrial civilisation, defined as a complex and interdependent socio-technical system based on the use of fossil fuel resources, needs to address this shortcoming in order to succeed in the shift into a new socio-technical regime.

While several countries, such as Germany, Poland and Spain, have longstanding mining experience, the debate among the Nordic countries is the most advanced due to the significant geological potential in the Barents region (Boyd et al. 2016). In this respect, these territories have several CRM deposits enabling the EU to produce a relevant amount of minerals and gain further strategic industrial and economic autonomy in the face of massive geopolitical changes. Given this fact, the development of extractive activities is the only way to provide the materials needed for the transformation of the energy system model (wind power, solar power, electrification of transport, etc.) as the critical materials recycling loop remains a long-term perspective (Gregoir and van Acker 2022; Vidal 2022). Growing demand for critical metals means opening up new mining frontiers and expanding mining operations geographically, while such activities can dramatically alter landscapes and impact local environments and communities (Tang and Werner 2023).

Based on a green industrial policy, the EU envisions a practical implementation of the industrial ecology, defined as a *flexible*, *proactive*, *designed-in* and *encompassing* system (Jelinski et al. 1992). But the 'green' turn that is being promoted is limited by two constraints: the need to avoid financial losses, since the main interest of industrial ecology is to link ecology to utility; and the need to limit as far as possible the impact of extractive activities on the natural ecosystem. From this perspective, the concept of a sustainable mine is subject to this double limitation, which the Nordic countries are trying to overcome. While this article aims to assess the concept of sustainable mining as a policy instrument, it also highlights research questions regarding the ability of these countries to address its implementation in the Arctic context. For instance, which obstacles might hinder increased mining activities in the European Arctic? Could the Nordic countries succeed in breaking out of carbon lock-in and shifting to a new socio-technical regime?

With these questions in mind, the article is structured as follows. The first two sections deal with preliminary theoretical background and methodology. The third section turns to a comprehensive analysis of the mining policy in the European Arctic and related issues for applying a sustainable mining governance model. The discussion section highlights the current limitations and blind spots of the concept of sustainable mining, while suggesting new directions to explore.

Theorical background

Sustainable mining: literature review

As Orr (2002) recalls, the concept of sustainability originally came to the public through Wes Jackson's research on agriculture in the late 1970s. Subsequently, this concept gained popularity among academics until its inception in 1987 by the Brundtland Commission. The Brundtland Report introduced the broadest definition of sustainable development, including a flexible dimension in the following terms,

"The sustainable development is not a fixed state of harmony, but rather a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development, and institutional change are made consistent with future as well as present needs." (Brundtland 1987).

In light of this definition, the Commission made sustainability a central feature to enable the maintenance of the needs to present generations without compromising the ability of future generations to enjoy similar opportunities (Orr 2002). In other words, sustainable development aims to meet the basic needs of humanity in respectful and equitable conditions, without jeopardising the balance of life on Earth (Kemp and Martens 2007). Sustainability remains a key issue for international organisations and industrial powers when it comes to implementing a socio-economic model capable of safeguarding humanity's future. Meanwhile, the flexibility of the definition of sustainable development has led to an expanding academic debate over the last three decades. As such, the concept is open to alternative interpretations depending on the context in which it is used, such as the mining sector (Endl et al. 2021). The mining sector has not been spared from these discussions, where the issues of a normative application of a sustainable mine have become central. According to Reis Montero et al. (2019), mining activities are in line with the Sustainable Development Goals (SDGs) promoted by the United Nations (UN) since 2015. Extractive operations should therefore consider the use of clean technologies, which includes the energy system and infrastructure used (Aznar-Sánchez et al. 2019). Thus, the mining industry plays a central role in SDG 12 "Ensure sustainable consumption and production patterns", especially considering the current discussions on the implementation of the circular economy in Europe (Endl et al. 2021). This is the purpose of the EU's ambition to transform its socio-technical system in the coming decades (European Union 2019; European Union 2020a).

As noted by Hodgkinson and Smith (2021), a successful path towards a sustainable mine would require the ability to provide needed the metals and minerals needed to support decarbonisation without significantly increasing greenhouse

gas emissions. The sustainability debate also extends to the water, energy, and raw materials used, which are necessary inputs for mining processing (Ranängen et al. 2017). In other words, the mining industry must address the functioning of its operations and the management of the resources required to ensure the extraction of minerals. Similarly, mining operations generate waste and pollution that need to be addressed, while permits and legislation aim to curb their impact on surrounding areas. Social issues are another facet of what involves sustainability issues in the mining sector. As reminded by Ranängen and colleagues (2017), the social dimension in the industry includes education, job opportunities, and participation of local communities. In summary, the mining industry has to actively engage in the search for balance required by sustainable development goals.

A perspective from social sciences

As mentioned above, the concept of sustainability is open to a variety of interpretations, but there is a risk of being locked into silo thinking or one-dimensional approaches (Endl et al. 2021). In this context, the mining sector may maintain a self-centred approach, ignoring the broader impacts that it contributes to current socio-technical systems. Given the uncertainties and non-linear conditions, mining stakeholders as organisations are obliged to take a systemic approach to the management of their extractive operations in order to be consistent with a socio-environmental perspective (Wilkinson and Hill 2001).

Similarly, the emergence of the concept of sustainability and its popular use is generating debate about the tangible implications for its nature and application. However, the stated aim of the sustainability concept is an attempt to promote the transformation of socio-technical systems. From this perspective, the deeper meaning of sustainability lies in the ability to predict the future and handle uncertainty (Dresner 2008). The concept's essence is also a victim of its success: its overuse makes all stakeholders conform to defined normative principles (Caradonna 2014; Baldassare and Campo 2016). The excessive use of sustainability has become a gamble, with companies overusing the language of sustainability to market their products (Caradonna 2014). Obviously, this extensive practice of sustainability language based on green-related terms that cropped up in an extensive way ("green shift", "green technology", "green industry", "green finance", "green evangelist", etc.). It is therefore an effective marketing tool for companies to bolster their communication campaign. Nonetheless, critiques have emerged that question, for example, the nature of some energy transition projects, which have been labelled 'green colonialism' (Normann 2021).

As a result, extractive industry actors expose themselves to the risk of greenwashing their discourse in order to comply with commitments in line with the United Nations' SDGs. To move beyond the rhetoric and language constructed around sustainability, progress requires a clear definition of the concept and its key dimensions, including a more integrated approach (Giovannoni and Fabietti 2013). To enable the development of such an approach, it is, therefore, crucial to conduct comprehensive assessments in order to have a complete overview of all factors for a successful sustainable policy (Turnheim et al. 2015). In this context, the mining sector may be forced to adopt guiding principles that combine social, environmental, ethical, and financial dimensions to effectively move towards the fulfilment of integrated sustainability. The main challenge is to avoid bottlenecks related to these different aspectsthat may arise between stakeholders, such as industrial groups and local communities. In the end, it is not necessarily a matter of solving these tensions, but rather of managing them (Giovannoni and Fabietti 2013).

Path-dependency and sustainability governance: the risk of the carbon lock-in trap

Path dependency theory provides a coherent analytical framework to capture the complexity of this definition. From this point of view, it highlights the rigidity of the socio-technical systems of which the mining industry is part. As Mahoney and Schensul (2006) remind us, the definition of path dependence remains open to debate, as scholars have developed several perspectives. While economic historians such as David (1985) and Arthur (1989) gave birth to the concept, it has spread to other disciplines due to its plasticity and the theoretical renewal it offers. For instance, path dependence theory holds a significant value in institutional studies (Andrews-Speed 2023). Despite the various theoretical ramifications that this concept introduces among scholars, it demonstrates its relevance within the framework of studies on the transition to sustainability. To disentangle the critical knot of socio-technical systems, Apajalahti and Kungl (2022) argue that the central idea of path dependency lies in the self-reinforcing mechanisms that are inherent in them. Put another way, the emergence of a decarbonised industrial sector should not be achieved from a technical, legal, social or ethical perspective, but rather through a combination of all these approaches. As Bornemann and Strassheim (2019) stress, the adoption of sustainability as a political concept expresses a willingness to respond to the carbon lock-in, which is the result of past choices that have persisted over time.

Ensuring sustainable governance entails contemporary societies to go beyond themselves and address complex,

multidimensional and multi-stakeholder obstacles (Barile et al. 2018). Due to the trajectory of scientific and technological development, the thermo-industrial civilisation will have to cope with the new state of the Earth. Despite these planetary changes, human ingenuity may be overwhelmed by the complexity and triggering of non-linear dynamics (Homer-Dixon 2000). Applied to the mining industry, this calls for the consideration of several factors that worsen its governance capacity. Due to the relevance of this economic sector, it is a crucial pillar of the ecological transition. More specifically, this sector is at the beginning of a complex industrial value chain, that operated throughout the entire ecosystem of contemporary societies.

Given this expected outcome, extractive activities highlight the difficulty of managing economic drivers and ecological conditions (Vidal 2022). A solution to break out of the path-dependent, fossil fuel-based socio-technical system could come from a more reflexive governance system (Clark and Harley 2019). The Earth's changing conditions bring with them a high degree of uncertainty that human history has never experienced during the Holocene epoch, which began around 12,000 years ago. Implementing sustainability governance in the mining sector requires the ability to address growing threats (biodiversity loss, extreme weather events, changes in biogeochemical cycles, etc.) that would structurally lead to unsustainable trajectories for current socio-technical systems (Clark and Harley 2019; Raudsepp-Hearne et al. 2020).

Method and empirical study

The empirical study is based on the three countries that are part of the Barents region, namely Finland, Norway, and Sweden. To perform this research, the article draws on both primary and secondary sources gathered from European and Nordic mining policies and other related and relevant documents in the context of the energy system transformation. This empirical study combines two complementary perspectives on mining policy in this Arctic region. First, it approaches the issue from a European and national perspective by analysing their respective strategic considerations regarding extractive activities. Second, it addresses critical issues related to the implementation of a sustainable mining model in the European Arctic. Finally, the final discussion highlights the main blind spots in the concept of sustainable mining and options for improving the concept in the future.

The Arctic deposits: a geological perspective

The European Arctic is remarkable from a geological point of view, as the area lies on the Fennoscandian Shield, which contains some of the oldest rocks in Europe (Henderson et al. 2015). The mining potential is the largest known on the European continent. Since the turn of the millennium, there has been renewed interest in developing critical mineral deposits in the region due to increasing global demand (Jürisoo and Nilsson, 2015; Van Dam et al. 2014). This demand trend is driving the mining outlook and has a direct impact on the Nordic economies. During the second half of the 20th century, mining activities in Fennoscandia have been declining or, at best, stable. Nonetheless, the mineral potential of the Barents region is significant enough to provide part of the EU's needed CRMs. Finland, Norway, and Sweden have significant mineral resources, that could be exploited in the light of the net carbon reduction targets to be achieved by 2050.

In the region, Sweden remains the metals giant, producing over 90% of the EU's iron ore (Liljenstolpe et al. 2023). In addition, Finland and Sweden account for over half of the EU's metals production and have active exploration industries to develop future mine sites (Boyd et al. 2016). Due to geological developments, all three Nordic countries have significant copper (Cu) and nickel (Ni) reserves (Bortnikov et al. 2015). With regard to nickel, the latter is an essential component for the electric vehicle batteries and renewable energy infrastructure. Due to its unique properties, copper remains an indispensable element for the electrification of the infrastructure of modern societies. For example, the Nussir copper deposit in Finnmark, northern Norway, located in the inner Repparfjord, is the largest known in the country, with an estimated reserve amounts of 74 million tonnes of ore (Rør 2018). In addition, Finland has nickel-copper deposits, formed during the Archean Eon (4,000–2,500 Ma) that could be exploited. The exploitation of the Talvivaara nickel deposit (2008) and the Kevista copper-nickel deposit (2012) are some examples of a new milestone in Finnish mining history (Boyd et al. 2016). Although these reserves are still insufficient to meet demand, the European Arctic is home to significant mineral potential on a European scale.

Analysis: the European Arctic at the nexus of mining systemic challenges

The mining industry era in the ecological transition

A European mining strategy: a geopolitical dimension

The ambitious European industrial strategy– combining green and digital transitions– requires an overall assessment as a starting point for its completion. While the industrial backwardness is due to a lack of production capacity, the weakened position of the EU is due to a compelling manufacturing and technological dependence on third countries, in particular China (European Commission 2023). This systemic dependence can be seen at every stage of the value chain. To counter this dependency, the European Commission intends to reduce this geopolitical dependence and strengthen its industrial and technological independence. Among the strategic axes supported by the EU, the Raw Materials Initiative of 2008 focused primarily on securing access to the raw materials needed by European manufacturing industries (European Commission 2019). CRMs are essential enablers for all strategic sectors of the EU economy, including aerospace, renewable energy, electric transport and defence (European Commission 2020a). Based on the European Green Deal, a cornerstone document, the EU aims to transform its economy and society towards a more sustainable path (European Union, 2019; see also European Commission 2021). This goal also supports a geopolitical ambition to become a post-carbon power. For this reason, the EU aims to establish itself as a model for the completion of systemic climate and environmental measures. The European Union expects to implement a long-term strategy allowing complete decarbonisation of its energy sector, in line with the 2015 Paris Agreement goals of limiting the global average temperature increase to 1.5 °C above pre-industrial levels.

In order to achieve such an ambition, a comprehensive reduction of carbon emissions is necessary and urgent. This decarbonisation principle is to be framed by a policy of reindustrialisation. Therefore, the EU aims to implement an industrial value chain to recover CRMs from extraction to the intermediate product, using refining processes to supply electronics, automotive and battery manufacturing companies (European Commission 2020a). That said, the aim is to create a complex and holistic ecosystem. Reindustrialisation is also part of the implementation of a fossil-free energy model, moving away from material flows based on fossil fuels.

From this perspective, the EU aims to improve its position in the geopolitics of energy, while ensuring security and autonomy in strategic economic sectors (European Commission 2023). To support this ambition, the EU needs to build strong and resilient partnerships with countries to secure the long-term supply of the required CRM for zero-carbon technologies (European Union 2020b). Norway thus appears as a critical partner for the EU and the completion of this geopolitical empowerment strategy. To this end, the establishment of a Green Alliance implies the integration of the Nordic country into a broader geopolitical vision that includes working together to maintain and develop green technologies and to ensure access to CRMs (European Commission 2024; Norwegian Office of Prime Minister 2023). This close relationship leads to a growing EU dependence on Norway. However, this partnership is part of a coherent pattern in which the Nordic countries represent a strategic area for the European mining industry. These countries are part of the European transition policy and compete with major industrial powers such as China, the United States, and Japan. These countries are working to secure their supply chain, diversify sources of supply for CRMs, and develop their domestic value chains (European Commission 2020b).

The EU plans to exploit critical raw materials on European soil in order to ensure its independence with regard to CRMs. In response to this new path, the EU supports funding programmes to assess the feasibility of exploiting critical mineral deposits on the European continent (Regueiro and Alonso-Jimenez 2021). The European Commission has set a target of approaching or reaching at least 10% of domestic demand for CRMs (European Union 2023b). Although the European continent has a long mining tradition, it is the only geographical area where mining production has been in decline since the beginning of the 21st century (Umbach 2022). This is due to the political decision to voluntarily reduce production capacity, which has been applied for several decades, reflecting concerns about the conservation of resources and biodiversity (Martins 2021). In other words, factors that have slowed down the development of mining in the EU in recent decades include the lack of investment in the exploration and exploitation of critical minerals, the diversity and slowness of national authorisation procedures, and low levels of public acceptance (European Commission 2020b). As a result, the EU is experiencing a critical setback while other industrial and mining powers are gaining economic and technological advantages in the global post-carbon transition. Due to its geological potential, the European Arctic is an asset to unlock critical mineral deposits and initiate a European industrial reorientation in the context of global change.

Nordic mining policy: a socio-economic dimension

The development of the Arctic region is a common priority for the three Nordic countries. To this end, they intend to promote economically, socially, and environmentally sustainable development in the polar region (Government Offices of Sweden 2020; Finnish Government 2021; Norwegian Ministry of Foreign Affairs 2021). Within this long-standing public policy framework, these countries are committed to drastically reducing carbon emissions and investing in carbon-free solutions. Their respective Arctic strategies fit into a global framework that includes the United Nations' SDGs and the EU's climate and energy policies (Littleboy et al. 2019).

Beyond these public policies, which consist of general orientations without specific financial and material application of the stated goals, there are structural differences between the three Nordic countries. This situation logically leads to different gradients in the size of the mining industry in the region, as well as different levels of expertise and investment. Historically, Sweden and Finland have been more economically dependent on Arctic mining activities, while Norway has lagged behind in an economy dominated by maritime activities.

(1) Sweden aims to develop mining activities in the northern areas, while increasing labour supply, improving infrastructure and ensuring an effective permitting process are elements to achieve these goals over time (Government Offices of Sweden 2011, 2020). The Swedish mining strategy published in 2013 supported the need for growth in the mining sector, but with a strong emphasis on sustainability (Government Offices of Sweden 2013). Interestingly, the 2013 Swedish mining strategy does not evaluate Arctic mining per se, but identifies the north as a prominent region for the mining sector with remarkable natural and cultural values (Tiainen et al. 2015). Swedish public policy emphasises coordination and dialogue between different stakeholders, including the Sami people, in order to successfully implement sustainable mining. While the Swedish government has described the Arctic as an area of innovation and international exchange, progress has yet to be made towards a more integrated stakeholder trust system (Haikola and Anshelm 2016). To this end, the regions of Norbotten and Västerbotten rely on competitive and groundbreaking research institutes and universities that are connected to companies and the business community (Vidal 2022). With its long-standing expertise, the country has a solid industrial ecosystem in the mining sector and is building on this foundation.

(2) Finland aims to promote mining as a key pillar of the national economy and to become a world leader in sustainable mining by 2050. Finland's mining strategy focuses primarily on the industrial development of mining and responsible mining. To this end, Finland relies on an active multi-stakeholder collaborative approach to successfully implement Canada's Toward Sustainable Mining (TSM) programme (Lesser 2021). The three main objectives of the policy are to maintain domestic growth and prosperity, solve global challenges in the mineral value chain, and mitigate environmental impacts (Tiainen et al. 2015). In addition, Finland has improved its mining regulations to ensure that there are sustainability goals for the mining industry (Tiainen et al. 2015). Among other things, the Finnish Mining Act of 2011 was amended in 2023 to specifically address local concerns and provide opportunities to influence the consultation process (Similä and Wallen 2023). Meanwhile, mining is being promoted by local authorities as part of their economic development programmes, which in turn attract investors to the region, such as the Sakatti copper and nickel mine in Sodankylä, Finland (Poikela et al. 2023; Vidal 2022).

(3) Norway relies on the fishing and hydrocarbon sectors, which have historically shaped its economic model. From this perspective, Norway is not a mining powerhouse, unlike its two neighbours. Despite this, Norway has shown a commitment to strengthening the mining industry in the country, particularly in northern Norway. As recalled by Rør (2018), Norway has not opened any new mines for metallic minerals in Norway for several decades. The self-reinforcement of the hydrocarbon industry, which cannibalises investment, dampens the rise of other more peripheral industrial sectors, including mining. Support for extractive activities in northern Norway is part of an industrial policy of maximum wealth creation, including full employment (Norwegian Ministry of Trade, Industry and Fisheries 2023). Norway has also paved the way for the long-term development of seabed mining on its continental shelf, including in the Arctic. (Norwegian Ministry of Energy 2024; Norwegian Offshore Directorate 2019). This decision is a further expression of the objectives of expanding an economic development model based on the exploitation of natural marine resources.

As the EU looks to reverse the carbon emissions model, raw materials are key to the deployment of carbon-free technologies. Finland (2) and Sweden (1) have a long history of mining, which qualifies them to be the pillars of European mining policy. Structurally, however, Norway (3) is the weakest link in the Nordic mining strategy, while the EU sees this non-EU country as a strategic partner. As the driving force, these countries are pursuing a long-term strategic policy in which their northern part reflects their economic ambitions. In addition to creating jobs for the local population, such national strategies would aim to support innovation and create favourable conditions for private actors in the Barents region.

Sustainable mining industry in the Barents region

The key differentiating factor for the Nordic mining industry remains the ability to create new standards in line with international environmental and energy commitments. In this case, the Nordic countries are working on certification schemes for metals that may enable them to increase their competitive advantages for sustainable battery production and green electrification (Government Offices of Sweden 2020). In other words, the Nordic policy orientation, which combines their vision of Arctic development and their commitment to implementing a sustainable post-carbon model, places the mining industry at the centre of this dual ambition. It is also the key enabler for strengthening the value chain in these countries. For example, Finland plans to develop its battery value chain upstream, but also in the field of recycling of batteries and battery materials (Ministry of Economics Affairs and Employment of Finland 2021).

Conversely, the growing demand for critical minerals has led to calls for increased investment into key infrastructure such as ports, railways and roads within the Barents region. These improvements also need to be sustainable to meet the industrial goals triggered by the development of mining projects. The modernisation of logistics and transport infrastructure is an integral part of the Barents region's integration into the European industrial programme. On the one hand, the geographical remoteness and the relatively small population in the northernmost region are the main obstacles to building appropriate infrastructure (Norwegian Ministry of Foreign Affairs 2021b). On the other hand, these infrastructures are expected to promote multimodal transport and create transport corridors across the northernmost region (Henderson et al. 2015). the issue of transport capacity is essential for the expansion of the mining industry and has led to further cooperation between Sweden and Finland (Tiainen et al. 2015). In other words, sustainable development commitments in the mining industry overlap with long-term transport solutions in the northernmost region. The Nordic countries are committed to providing sustainable and low-carbon systems for these transport infrastructures (Finnish Government 2021). They therefore prioritise this factor in their Arctic development strategy. However, as underlined in their Arctic policy, the Nordic countries see the strengthening of transport infrastructure as a precondition for the growth of local economies, which require better interconnectivity (Government Offices of Sweden 2020; Finnish Government 2021).

Complementary to future mining projects, the modernisation and construction of infrastructure should address socio-environmental issues to implement this systemic vision for sustainability. The EU supports a similar vision, as it has launched a key partnership with Norway on the prospect of developing 'sustainable land-based raw materials' (European Commission 2024). Whether at European or national level, the promotion of sustainable mining supports a discourse that addresses geopolitical and socio-economic objectives.

Spotlight on the Swedish mining company LKAB

The mining industry in the Swedish Arctic region dates back to the 19th century; Luossavaara-Kiirunavaara Aktiebolag (LKAB), founded in 1890, started operations in Kiruna in 1898. The Kiruna mine remains the largest underground iron ore mine in the world, while also being an important job provider in the area (Jürisoo and Nilsson 2015). In addition to this long-standing operation, LKAB plans to explore new mineral deposits in line with Sweden's green policy. In January 2023, LKAB (2023a) announced that it had identified the largest known deposit of rare earth elements (REE) on the European continent. The deposit is estimated to contain more than 1.3 million tonnes of in situ rare earth oxides (LKAB 2023c). The process from the identification of this deposit to its eventual exploitation could take at least 10 to 15 years. In total, the Swedish group estimates its mineral reserves at 5.7 billion tonnes, an increase of 43% compared to 2022 (LKAB 2024). This includes REE and phosphorus. To support increased mine production, LKAB is looking to invest in modernising its logistics infrastructure and has announced plans to invest in a brand new loading terminal at the Norwegian port of Narvik. Historically, iron ore from LKAB's mines has been transported by freight train via the Ore Railway to the ports of Luleå in Sweden and Narvik in Norway. Since then, this transport axis has remained strategic for the mining group. As an integral part of its production system, LKAB has an investment in the Duroc Rail group, a specialist in wheel maintenance for locomotives and wagons (LKAB 2023d). The activities of LKAB therefore play a part in shaping the development of the region.

In spite of a long industrial footprint in the Barents region and its negative social and environmental impacts, LKAB emphasises its commitment to sustainable mining, which is largely promoted through communication tools. The Swedish company develops a holistic vision of sustainability, including employment, ethics, responsible operations and resource-efficient production (Ranängen et al. 2017). Based on this comprehensive vision of sustainability, the mining company is investing to fully decarbonise its operations in the coming decades. To achieve this, LKAB has partnered with steelmaker SSAB and utility Vattenfall to develop the use of 100% renewable hydrogen-based direct reduced iron (DRI) (European Commission 2023). LKAB's long-standing role in Sweden's northern regions makes it an indispensable stakeholder in future mining operations.

The company's increased investment in infrastructure modernisation is a direct measure of the need to reduce carbon emissions in its mining operations. As a strategic blueprint, LKAB seeks to implement a carbon-free strategy from mining to ore processing, with the Norbotten region becoming the epicentre of a 'green industrial transformation' (LKAB 2020). As part of its sustainable vision, LKAB is committed to working according to the so-called mitigation hierarchy, which enables it to avoid or at least minimise, restore and ultimately compensate for the impacts of mining operations. To support this vision, LKAB emphasises that ecological landscape design will become a key tool to visualise what the industrial areas could look like after the end of operations and to anticipate the post-mining phase (LKAB 2023b).

Overall, the Swedish company is repositioning itself in the industrial mining landscape as a driver of the green industrial transition in the region, with the circular economy at its core. To this end, the creation of a circular industry park in Luleå is helping to establish a value chain. In addition, the Norwegian company REEtec will complete this industrial value chain by using innovative and sustainable technology to separate rare earth metals with the prospect of deep and intelligent mining (Bye 2022; Franceschini et al. 2019). At the European level, the establishment of an industrial complex using critical minerals throughout the Nordic region is an asset in order to cope with China's competitive advantages in the distant future.

Bottlenecks of sustainable mining in the European Arctic

Social issues

The social acceptability of mining operations remains a systemic cause of conflict that Nordic societies should also address. As Martins (2021) recalls, the mining industry faces hurdles due to a general lack of social acceptance in the EU for new mining operations and upcoming projects. In the Nordic mining strategies, the coexistence of mining with other land uses and livelihoods is an important issue, as there are various competing land use interests in their respective northern areas, such as tourism infrastructure, protected areas and reindeer husbandry (Government Offices of Sweden 2020; Finnish Government 2021). In Arctic mining areas, reconciling the interests of mining companies with the traditional livelihoods of local communities, such as reindeer herders and indigenous people's rights, is a dominant issue in mining development. (Tiainen et al. 2015). The presence of the Sámi people in Europe's northernmost region gives them leverage in negotiations with the mining industry, and encourages the latter to engage (National Audit Office of Finland 2021; Norwegian Ministry of Trade Industry and Fisheries, 2023).

Overall, the European Arctic is considered a politically and economically stable region, while the EU's interest in mineral exploitation has long remained isolated (Van Dam et al. 2014). However, the evolution of the EU's strategy over the past decade is undermining the fragile consensus among different stakeholders for competitive land use. De facto, the role of the EU is to help maintain equilibrium while acting as a transformative force. In practical terms, the EU may be called upon to implement regulations and standards that would overlap with national legislation and be more consistent across the region. Similarly, local communities expect positive outcomes from mining operations, including compliance with local regulations on environmental standards (Norwegian Ministry of Trade, Industry and Fisheries 2023). Beyond these regulations and administrative procedures, local acceptance of mining operations is a long interactive process of building and maintaining trust among stakeholders (National Audit Office of Finland 2021). In this respect, addressing the social dimension is critical to enable the fulfilment of an agreement that suits all parties by taking a systemic view of mining activities, including the post-mining future (Tolvanen et al. 2019).

Environmental issues

The environmental dimension is of particular concern when mining operations in a fragile ecological system such as the Arctic region. As for the European Arctic, these activities have long-term effects on the local ecosystem, and climate change has a faster and more widespread impact (Tolvanen et al. 2019). These uncertainties further complicate the expected impacts of mining activities. However, further research focuses on ways to mitigate these non-linear factors.

One of the key challenges with regard to the environmental dimension of mining activities related to the management of mine waste, while the problem continues to grow. As Mudd (2021) notes, mining operations continue to shift to lower grades to meet the demand for minerals and metals, which in turn consumes even more resources and expands the geographical areas of exploitation. In response to this, the Nordic countries apply various regulations. For example, Norway applies the Environmental Impact Assessment Directives, the Water Framework Directive and the Mining Waste Directive (Norwegian Ministry of Trade, Industry and Fisheries 2023), which require mining companies to use processes and technologies that are more environmentally friendly for the regional natural ecosystem.

The development of mining activities in the polar region implies the further use of resources needed for the mining

industry: energy, raw materials, and water (Ranängen et al. 2017). Among these resources, water is a critical factor of divergence between stakeholders. As seen in other mining areas, the high demand for water use triggers numerous conflicts between miners and local communities. To avoid this development in the European Arctic, it is necessary to prioritise efficient water use and minimise the amount of contaminated water discharged into the local hydrological system. Overall, mining activities have a negative impact on biodiversity, which can endanger flora and fauna species.

The long-term consequences associated with mining operations result in large-scale changes to the local ecosystem (Lassila 2021). For the Nordic countries, this means implementing measures to reduce tailings, dust, and other disturbances in future mining operations. The expansion of such socio-technical systems also leads to lock-in, which results in a patterned interaction with the natural environment. Beyond international commitments and national regulatory legislation, the European Arctic is a powerful example of this ontological conflict between a human activity that has continued to expand thanks to technological progress, and an environment that is subject to these increasing impacts.

Governance issues

Ethical, democratic, and institutional factors are part of the equation to be addressed when it comes to economic development in the European Arctic region. In light of these concerns, the European Commission recognises the importance of implementing an effective plan that includes measures that can facilitate public acceptance by focusing on stakeholders from an expanded civil society (European Union 2023a). In their respective strategies, the three Nordic countries emphasise the need to bring social and cultural benefits to the Sámi people. In fact, infrastructure projects have revealed a number of hurdles in the consultation process, especially with regard to Sámi participation(Vidal 2022). In the context of mining projects, the lack of participation of the various stakeholders in the advancement of such industrial projects persists.

In the Norwegian case, the national legislation appears to empower local communities and environmental agencies in decision-making processes (Fauchald 2014). However, economic projects in northern Norway face organised and experienced opposition that underlines the lack of long-term resolution of ethical and justice issues. For example, the Nussir project in Finnmark epitomises the growing governance dilemma between the commitment to protect the fragile Arctic ecosystem and the ambition to shift to a post-carbon socio-technical system. This discrepancy lies at the heart of the stalemate between different interest groups, resulting in protracted social and environmental conflict. In this case, the root of the conflict is the marginalisation of the Sámi community by the mining company Nussir ASA and the public authorities (Laros 2022). In particular, the mining project threatens the biodiversity and the hydrological balance of the Repparfjord, which is used by the Sámi for their fishing activities (Rør 2018; Buhman et al. 2021; Laros 2022). In August 2021, the German company Aurubis, Nussir's main customer, terminated the memorandum of understanding with its Norwegian partner, stating that 'certain social aspects of the project need to be given even greater consideration' (Aurubis 2021). As a result, local opposition succeeded in halting, at least temporarily, the start of mining operations (Datava and Hobi 2023; Norwegian Saami Association 2021). Overall, this mining project is a reminder of the complexity of overcoming the conflict between the green shift and its social, environmental, and ethical costs associated with extractive activities.

For their part, the Finnish authorities are committed to improving the participation of local communities in the decision-making process, stressing that this represents a guarantee for a sustainable future in the northernmost area (Tolvanen et al. 2019). Nonetheless, the quest for untapped mineral resources has led to resistance movements in their northernmost areas, such as the anti-mining movement in the village of Ohcejohka (Lassila 2018). In Sweden, the critical bottleneck hinges on the protracted land use conflict between mining development and the respect of Sámi rights (Raitio et al. 2020; Tarras-Wahlberg and Southalan 2022). Land use planning is a key component of managing mining projects in the region, a challenge shared by all three countries.

Discussions

In the European Arctic context, the challenge of developing a sustainable mining model is multifaceted. From local socio-environmental concerns to the geopolitical implications of Europe's industrial dependence, the mining sector has to make the transition in the face of these many considerations. In this context, mineral resources are part of the European guidelines that provide a framework for national public policies on mining. In other words, the correlation between the European reindustrialisation strategy under the umbrella of green policies and the economic, social, normative, and ethical application of sustainability places the European Arctic at the crux of this industrial challenge. The mining industry in the Nordic countries is therefore under pressure to make operational efforts to achieve sustainable mining. Responding to these imperatives raises fundamental contradictions about the nature of mining and its negative

impacts. The European Arctic is an example of this new dynamic that the Nordic countries have embraced, while the ongoing ecological transition will increase the pressure on land use (Avango et al. 2019; Coates and Holroyd 2020).

From a socio-technical systems perspective, the transition to a post-carbon model is an institutional, normative and technological issue (Wyborn et al. 2019). To achieve this, a number of hurdles need to be overcome in the search for a sustainable mining model. Although the Nordic countries may see themselves at the forefront of the mining industry, the design of their strategy should recognise a transparent commitment that enables them to define and steer new global mining standards.

However, the Nordic case highlights two fundamental hurdles about the nature of sustainable mining, both of which are blind spots for addressing the mining industry's carbon regime.

(1) Within the global industrial supply chain, the mining industry is one link in a vast, complex and interdependent network. However, this global network as a whole remains highly carbon intensive, which limits the decarbonisation dimension of mining.
(2) Mining generates negative environmental impacts (pollution, waste, consumption of water resource, etc.) that undermine the sustainability regime and its compatibility with natural ecosystems.

Therefore, these two pitfalls remain critical points in the current definition of the mining industry's sustainability regime. Addressing issues (1) and (2) is a particularly complex matter that goes beyond the mining sector and requires systemic coordination between actors in order to articulate the institutional, normative and technological regime towards a post-carbon socio-technical system. Overall, the Nordic countries envision such a post-carbon socio-technical system, as stated in their respective strategies. To get closer to this ambitious goal, the many stakeholders involved in this industrial transformation could consider better coordination of institutional and technical arrangements to overcome different time patterns (Bauer and Herder 2009). In addition, the inertia of administrative institutions remains an obstacle to rapid transformation in the context of climate change (Ekardt 2020). Beyond the technical adaptation of this industry, its stakeholders are called upon to become more involved in the governance structure.

Nonetheless, the adoption of such a socio-technical system design remains insufficient to overcome (1) and (2) targets and remains poorly addressed by the EU Green Industrial Plan and the Nordic mining strategies. Mining policy in these countries underlines the challenges of implementing a sustainable mining model beyond the environmental, social and governance (ESG) framework. As things stand, the sustainable mine described by the Nordic countries does not solve the path dependency in which this industry has expanded. In this respect the decoupling of the carbon regime is consistent with a bifurcation of *path dependency* towards *pathway reconfiguration* (Geels and Schot 2007).

An industrial transition, also called *industransition*, is a core concept that, beyond the decarbonisation of its production regime, integrates a break with the extractivist model deeply rooted in the industrialisation process. As such, it involves to ultimately preventing the risk of triggering a mineral lock-in. The latter, together with carbon lock-in, is a twin trap affecting the organisation of complex, interdependent global industrial supply chains. In other words, the *industransition* implies a paradigm shift in the interaction between resources and the functioning of the socio-technical systems that depend on their use. In the extractive industry, the development a symbiotic relationship between the mining process and the surrounding ecosystem is an essential step in addressing carbon and mineral lock-in. Based on bioprocesses, research into the use of fungi in mining processes could contribute to the emergence of a biomine, through niche innovation (Geels and Schot 2007; Hein et al. 2023; Jones and Bismarck 2024). Thus, the development of such socio-technical systems leads to a symbiotic lock-in, resulting in a patterned interaction with the natural environment, which enters into a transitioning path.

As mentioned earlier, the Swedish company LKAB has embarked on a technological transition to eliminate its carbon footprint and reduce the environmental impact of its activities. For example, the recovery of by-products from iron production opens up the prospect of bioleaching processes (Kinnunen and Hedrich 2023). Despite these efforts made, industrial and mining processes remain ontologically a socio-technical system that has emerged from the industrialisation era. The hypothesis of *industransition* is therefore a questionable horizon, highlighting above all that the current model of sustainable mining is still in a fragmented state.

Conclusion

Agricola's *De Re Metallica* (1556) was the first to draw attention to the rift in society as a result of mining activities. Since then, the ever-increasing metabolism of fossil fuel-based societies has exacerbated and complicated the conflicts around mining. In the wake of the material needs that a post-carbon social metabolism threatens to consume even more of, this trend is leading to the quest for new resources in even more distant corners of the planet. The current

debate about seabed mining, or even the speculative option of lunar resource exploitation, reflects a headlong rush into new territories to meet the needs of a socio-technical system that is consuming ever more resources. Against this background, the Arctic is at the forefront of this new mining era, heralding the future frontiers of resource extraction.

The resurgence of extractive activities in the European Arctic, in the light of the transformation of the energy model, is reigniting tensions within the social structures of the Nordic countries. This new drive is in line with a sustainable policy under the aegis of the EU's Green Deal industrial plan. Hence, the completion of a sustainable mining pathway in the Nordic countries is tied to the success of a European mining model in line with international standards defined by the UN SDGs. Based on this empirical study, the European Arctic is a powerful case of this systemic conflict between human activities, which have continued to expand thanks to technological progress, and an environment that is increasingly exposed to these impacts.

This research draws attention to the efforts in the Nordic countries to implement a sustainable mining model based on the environmental, social and governance aspects. But it has also highlighted the need to address the technological, normative and institutional questions. In other words, in order to achieve the expected post-carbon socio-technical systems, any long-term sustainable and systemic divestment must comprehensively address these challenges. Finally, further research is needed to improve and extend the avenues explored in this empirical study.

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