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Mining and extraction in the Arctic – a nordic perspective on sustainability and near-term challenges

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Abstract
This paper addresses mining and extraction in the Arctic with examples fetched from the Identified Geographic Areas in the Euro-Asian Arctic region. The overall Arctic region is undergoing significant changes in land and sea use, fishing, forestry, transportation, freshwater diversion, urbanisation, and more. The Arctic, covering 6 percent of the earth's surface, is a nursery of the planet food chains and migratory wildlife important to Earth and ecosystem survival. It houses 25 percent of the world's Large Marine Ecosystems, substantial amounts of energy resources including oil, gas, and critically required materials. The region, with a mere 0.1 percent of the global human population, has generated considerable material wealth for the eight Arctic states surrounding it and the global north. The region is facing unprecedented changes and opportunities. The Arctic has warmed up four times faster than the rest of the planet and an intensive exploitation of its mineral wealth, fish stocks and strategic military location has resulted in 3,000 hazardous hotspots areas to remedy. Key challenges and opportunities for sustainability of the Arctic resources relate to the mining and extractive sector and associated infrastructure. The issues include on-shore and off-shore exploitation such as intentions to mine sea- and riverbeds in sensitive eco-systems. Action-wise, in the regulatory and incentives spheres, the European Union and the Nordics countries are moving forward to embrace the world leading initiative on a Green Deal. Similarly, Canada, Russia and the US have amended or are adjusting their regulatory framework to tackle the rapidly changing arena. For the wellbeing of Arctic, organisations such as the Arctic Council, its permanent participants of Indigenous peoples, and observers, including countries like China, Japan, India, Germany, the Netherlands, have engaged constructively and aspiring to continue doing so to access a fair share of the Arctic Wealth.

Keywords Mining · Extraction · Remediation · Sustainability · Cross-media · Pathways

Introduction

The Arctic has several delineations (AMAP 1998). This paper addresses the mining and extraction sector in the Euro-Arctic region. The focus is on sustainability and near-term challenges based on cases in the "Identified Geographic Areas," Fig. 1, described in Annex 1 of the Agreement on Enhancing International Arctic Scientific Cooperation (US Dept. State 2017; Arctic Council 2017).

The Arctic spans about 6 percent of the Earth's surface and has been populated for thousands of years. The Indigenous population of the Arctic is approximately one million of the total population of about ten million (Wang and Roto 2019; Glomsrød et al. 2021). Eight countries – Canada, Denmark, Finland, Iceland, Sweden, Norway, the Russian Federation (RF) and the United States (US) are considered as Arctic states. The circumpolar Arctic covers 14.8 million square kilometres of land and 13 million square kilometres of ocean. The Arctic has an extensive infrastructure contributing significantly to the regional and global economies. With 0.1 per cent of the world population, the region's Gross Regional Product (GRP) 2018 was about USD 615 billion equivalent to 0.7 per cent of the global gross domestic product (GDP) (Glomsrød and Wei 2021). Russia has the largest surface area covering more than half of the Arctic and its population share of the Arctic is 69 per cent. In 2018 the Russian Arctic's income was 73 percent of the total Arctic GRP. Canada has the second largest Arctic surface area (29 per cent) while its population and share of the 2018 Arctic

This paper provides examples of efforts to harness sustainable development in the Arctic and possible pathways forward.

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Fig. 1 Approximate extent of the Arctic Identified Geographic Areas as described in Annex 1 of the Agreement on Enhancing International Arctic Scientific Cooperation (US Dept. of State, 2017)

GRP is about 1.3 and 1.7 per cent, respectively. The second largest economy, Alaska, contributed 8.9 per cent to the 2018 Arctic GRP. The Arctic Ocean is the smallest and the shallowest of the five major oceans and mostly surrounded by Eurasia and North America. This area is classified as a high sea (Rosen and Thuringer 2017; Hossain and Roncero 2023). Its shallow depth has enabled the Arctic coastal countries to claim a continental shelf greater than 200 nautical miles. Hence broad margins of the continental shelf, most of the Ocean's seabed, and water column belong to single states. Legally and territorially, only 15 percent of the Arctic, approximately 3 million square kilometres (an area the size of India), may be considered as being part of the "global commons" or "international waters" and outside the jurisdiction of any of the eight coastal states (Rosen and Thuringer 2017). Three major rivers, the Yenisei, Ob, and Lena drain large regions of the Russian Federation and one, the Mackenzie River, drains from Canada and flow onto the world's largest continental shelf to intermingle with Arctic waters, Fig. 2 (Macdonald et al. 2005). The four rivers provide a total of 3,300 cubic kilometres of freshwater annually to the Arctic Ocean. The combined discharge from these rivers is nearly 10 per cent of the river discharge to the world oceans (Environment Canada et al. 2008). The circumpolar region houses 17 of a total of the planet's 67 Large Marine Ecosystems (LME) and several priority areas for conservation of wildlife (PAME 2009; WWF 2023).

Impacts from unprecedented human activity and changes in recent times are significantly altering the global environment on a large scale (Steffen et al. 2004). Science is signalling that around 1 million animal and plant species are now threatened with extinction, many within decades. The abundance of native species in most major land-based habitats has fallen by at least 20 percent since 1900. More than 40 percent of amphibian species and almost 33 percent of all marine mammals are threatened. Of the nine planetary boundaries considered critical for maintaining a habitable Earth, stratospheric ozone depletion is one of only three that have not already been transgressed (Richardson et al. 2023). The five direct drivers of change, in descending order, are identified to be: (1) changes in land and sea use; (2) direct exploitation of organisms; (3) climate change; (4) pollution and (5) invasive alien species (Díaz et al. 2019; Brondizio et al. 2019).

Human activity and planetary change are having a substantially greater amplification in the Arctic. The region has warmed nearly four times faster than the rest of the globe since 1979 (Rantanen et al. 2022) and is experiencing increasing sea ice melts, Fig. 3 (Corell et al. 2013). In addition, there are cross-media aspects to address, such as short-lived climate pollutants (SLCP) (Vygon 2018; ACAP 2019; Vorobev and Shchesnyak 2019; AMAP 2021a), release of hazardous substances, like mercury (AMAP 2011, 2021b), persistent organic pollutants (POPs) (AMAP 2021c), radioactivity (AMAP 1995b), and chemicals of emerging concerns such as per- and polyfluoroalkyl substances (PFAS) (UNEP-AMAP 2011). The Arctic's vulnerability needs substantial effort to harness a sustainable future (SDWG 2021).

Globally and regionally, parties have established several binding instruments to help deal with the planetary and sustainability challenges such as the globally successful Montreal Protocol for protection of the global stratospheric ozone layer (UNEP 2024a, b), the Convention on Biological Diversity and the Kunming-Montreal Global Biodiversity Framework (UNEP 2013), the Sustainable Development Goals (United Nations 2023a), UN Convention on the Law of the Sea (IMO 2019), the UN Framework Convention on Climate Change and its processes (United Nations 2024c); the Minamata Convention (UNEP 2021), the Convention on Long-Range Transboundary Air Pollution (UNECE 1979), the Convention on Environmental Impact Assessment (UNECE 1991), the Declaration on the Protection of the Arctic Environment (Arctic Portal 1991).

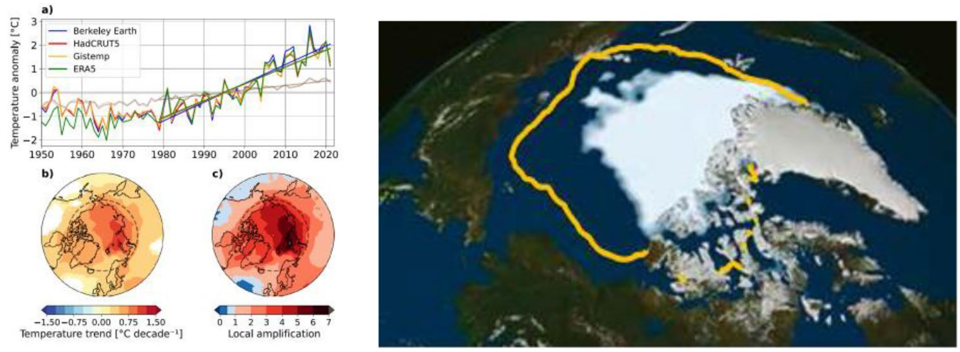
An important initiative relevant to the Euro-Arctic is the European Union's (EU) "Green Deal" package (EC 2023a, 2024a). The Deal is based on a plethora of legislation, financial stimulus and governance including the EU Action Plan towards "Zero Pollution for Air, Water and Soils." The Green Deal's "Fit for 55" package aims to reduce net greenhouse gases (GHG) emissions by at least 55 percent by 2030 compared to 1990 and achieve "net zero" emissions of GHG by 2050. An objective is to decouple economic growth from resource use leaving "no person or place" behind. The "zero pollution vision" for 2050 envisages air, water, and soil pollution to be reduced to levels no longer considered harmful to health and natural ecosystems, to respect the boundaries with which our planet can cope, thereby creating a toxic-free environment. The legislation package involves all sectors of the economy, inter alia fuels (maritime; aviation; alternative fuels); standards for vehicles; energy (energy efficiency; renewable energy, energy performance of buildings); Critical Raw Materials (CRM) (EC 2023b; EU Reg. 2024), land use, forestry and agriculture; effort sharing; emissions trading system (ETS); carbon border adjustment mechanism; social climate fund; cohesion of the Industrial Emissions Directive (IED) and its "Seville Process" for information exchange to regulate the European industrial operations including the use of best available techniques and practices (BAT-BEP) (EC 2018, 2019a, 2023c, 2024b), ETS; taxation policies; and application of the fluorinated-GHG directive (EU Dir. 2024).

The fora addressing the Euro-Arctic region include the Arctic-, Barents- and the Nordic Councils (Arctic Council 2024a; Barents Euro-Arctic Council 2024; Nordic Council and Nordic Ministers 2024), the Oslo-Paris Commission (OSPAR 2024), and the Helsinki Commission (HELCOM 1999, 2020, 2024). Parties to the fora rank among the world's most developed economies. Restrictions during 2020–2023 due to the corona pandemic, and the impasse since 2022 due to conflict between Russian and Ukraine have, however, affected cooperation in the Arctic. All Arctic cooperation was put on hold in 2022. While a decision taken by the Arctic Council (AC), in February 2024, calls for a gradual resumption of official Working Group

Fig. 2 The major physical pathways (wind, ocean currents and rivers) that drain and transport contaminants to the Arctic (Macdonald et al. 2005)

meetings in a virtual format, to enable project-level work to advance (Artic Council 2024b), the Barents Euro Arctic Council (BEAC) cooperation with the Russian Federation has ceased (Edvardsen 2023). The key circumpolar platform has been the Arctic Council working through six Working Groups, including Indigenous peoples, to address science, governance, strengthening of sustainable development, capacity building, environmental protection, removal of hotspots, financing of projects and implementation. In response to the Inari Declaration (Arctic Council 2002), the

Fig. 3 **a** The Arctic has warmed nearly four times faster than the globe since 1979 (Rantanen et al. 2022); **b** Arctic Sea ice melts down to its minimum in mid-September, before colder weather rebuilds the ice cover. The figure shows the 2012 minimum (recorded on 16 September), compared with the average minimum extent between 1979 and 2010 (yellow line). (Corell et al. 2013)



(a) **(b)**

AC Project Support Instrument (PSI) was operationalised in 2014 by the Nordic Environment Finance Corporation (NEFCO) to fund projects and removal of hotspots (AMAP 1995a, 1995b, 2003). The PSI contributors, Finland, Iceland, Norway, Russia, Sweden, the US, Sámi Parliament, and NEFCO, decide on a consensus basis and have co-financed AC projects (Arctic Council 2021a). Progress on the projects is tracked annually through the AC "Amarok" documents (Arctic Council 2015; Arctic Council 2019; Arctic Council 2021b). The scale, time spans, lessons learnt and opportunities relevant to the extractive sector are highlighted by a number of the Arctic Contaminants Action Programme (ACAP) and Conservation of the Arctic Flora and Fauna Working Group (CAFF) projects dealing with the oil and gas facilities, introduction of BAT-BEP (for instance, to the mining and metallurgical sector), modernisation of energy supply in off-grid communities, fisheries, protection of Arctic migratory bird pathways, shipping, and waste management (Arctic Council 2021a; ACAP 2024). The Arctic cooperation has also resulted in several legally binding Agreements including use of the precautionary principle (Hossain 2023; Tanaka and Romera 2020) in the Arctic, as highlighted by:

- The Central Arctic Ocean Fisheries Agreement (US. Dept. State 2021; Canada Govt. 2018). Canada, PR China, Denmark, EU, Iceland, Japan, Norway, Korea (ROK), RF, and the US cooperate to prevent unregulated fishing, facilitate scientific research, and monitor the central Arctic Ocean. It is the first multilateral agreement of its kind to take a legally binding, precautionary approach to protect an area before an activity has started.
- The Arctic Science Agreement addresses access by scientists of the Arctic States to the Arctic "Identified Geographic Areas," movement of persons, equipment, materials, use of research infrastructure, and capacity building (US. Dept. State 2017).
- The International Code for Ships Operating in Polar Waters (Polar Code) The International Maritime Organisation's (IMO) Polar Code deals with the full range of design, construction, equipment, operations, training, search and rescue, and environmental protection relevant to marine transportation and ships (IMO 2017).
- The Arctic Marine Oil Pollution Preparedness and Response Agreement (Arctic Council 2013) deals with oil pollution preparedness and response in the region to protect the fragile ecosystems.
- Arctic Search and Rescue (SAR) Agreement (Arctic Council 2011) coordinates life-saving maritime and aeronautical SAR response in an Arctic area to incidents regardless of the nationality or status of persons needing help.

The Barents Euro-Arctic Council (BEAC) addresses sustainable development, climate change, loss of biodiversity, and pollution (BEAC 2024a, b). The BEAC priorities include the extractive sector, removal of hotspots (Bambulyak et al. 2013; Mikaelsson et al. 2020), waste management, environmental efficiency plans and implementation of BAT-BEP. There have been several information exchanges on the EU and Russian best reference (BREF) guidance documents for industrial activities like the extensive BAT-BEP programme in Russia conducted with BEAC, AC and Swedish bilateral cooperation (Swedish EPA 2020). In 2014 Russia passed an amendment, Federal Act No. 219-FZ as part of the Federal Act No. 7-FZ, to enable an integrated permitting system promoting BAT-BEP (Mikaelsson et al.; EC 2024b). The regulation entered into force in 2019 replacing the old licensing system that relied on maximum allowed concentrations of pollutants' release. Russia aims to have 300 of the largest operators apply for an Integrated Environmental Permit (IEP). The BREF guidances for the IEP are developed through the RF BAT Bureau (RF Bureau 2024). Several BEAC projects have been co-financed by the Barents Hot Spots Facility set up by the Nordics to finance technical assistance, addressing of environmental hot spots and similar issues (Forsström 2008). Despite adversity caused by Russia's leaving the BEAC in 2023, its integrated legislation is a major stride towards harmonisation with the OECD and EU frameworks.

The Arctic's economy is dominated by the extractive sector, public administration, defence, and the transportation infrastructure (Duhaime et al. 2021). Activities in the extractive sector cover existing "brown-field" operations, new "green-field" investments, and legacy issues. Ores in the region were first discovered in the 1660s and mining companies started as early as in 1890 (SGU 2023). Recently several large projects have been launched. LKAB is aiming to invest in hydrogen-based iron and steel production (LKAB 2023); Boliden has expanded its operations at the Aitik Copper mine and the Rönnskär Smelter; the Alaska Native Corporation owned Red Dog mine has been operating one of the world's largest lead, zinc and silver mines (Kreel 2024) since 1989; the Nornickel Group is consolidating in Murmansk and Krasnoyarsk. In Canada, the large Mary River iron mine is being brought on stream in Nunavut. While some Alaskan Arctic offshore activities, for oil and gas exploitation in the Willow (US Dept. Interior 2023) and Liberty fields (US Dept. Interior 2022; Rosen 2023), are receiving mixed signals for operations in a sensitive environment, Norway plans to continue investments in the Arctic offshore sector. This is demonstrated by the offering of blocks and licenses in the Barents Sea and Svalbard area for oil, gas, and storage of CO_2, commissioning of the Goliat off-shore oil platform at the Norwegian Sea-Barents Sea interface in 2016, and the start-up of production from the Johan Castberg platform in 2024 (Lindholt and Glomsrød 2021). Goliat is the second off-shore oil platform established in the Euro-Asian Arctic after the Prirazlomnoye platform. The Prirazlomnoye field in the Russian Pechora Sea was discovered in 1989 and the world's first Arctic-class ice-resistant oil platform, at 20 m depth, was commissioned in December 2013. New developments in the Arctic include decision by Norway to proceed with offshore seabed exploitation of minerals in the LME areas between Svalbard and Iceland despite concerns by experts (Norway Govt. 2024; Nåmdal et al. 2023; WWF Norway 2024). Seabed mining aims to extract lithium from deep-sea brine reservoirs, mine polymetallic nodules containing copper, manganese, nickel, and cobalt on the sea floor at depths of around 3,500–6,000m.

Conservation and use of marine biological diversity, beyond national jurisdictions, is increasingly attracting global scrutiny. While scientific information is insufficient, ongoing research is revealing a rich and vulnerable biodiversity and emerging issues of concerns. It is estimated that up to 30 percent of the world's undiscovered natural gas and 70 percent of undiscovered oil is in the Arctic (Corell et al. 2013; Rosen and Thuringer 2017). Most (84 percent) of the undiscovered oil and gas in the Arctic occurs offshore in the LMEs and sensitive areas (WWF 2023). The area north of the Arctic Circle is estimated to have recoverable reserves of 90 billion barrels of oil, 47 000 billion cubic meters (BCM) of natural gas, and 44 billion barrels of liquid natural gas. Greenland is estimated to have the world's largest deposits of rare earths (Corell et al. 2013; Rosen and Thuringer 2017). Annual production of oil (2016) in the Russian Arctic zone (RAZ), Fig. 4, is about 66 Mt of oil and 21 BCM of Associated Petroleum Gas (APG) containing about 83 vol. percent methane (CH_4) and up to 22 vol. percent Non-methane Volatile Organic Compounds (NMVOC) (Vygon 2018).

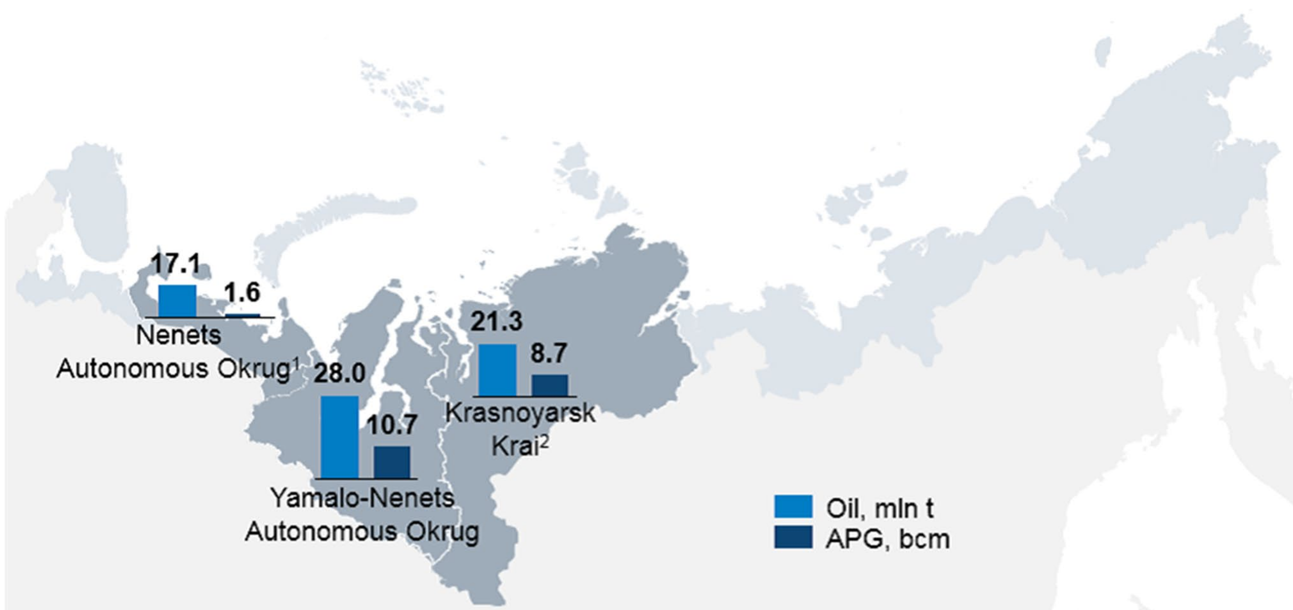


Fig. 4 Oil and APG production in Russian Arctic Zone in 2016 (Vygon 2018)

Investments in the extractive sector require a substantial infrastructure including construction, activity dealing with licensing, exploration, drilling, energy and water supply, food supply, housing, transportation, tele-communications, waste and chemical management, security (military) activities. A decade ago, the Arctic was expecting investments worth USD 10 -100 billion (Chatham House 2012) by 2023, mostly in the extractive sector. Others (Rosen and Thuringer 2017) estimate that between 2005-2017, China alone invested over USD 1.4 trillion in the economies of the Arctic states of which about USD 89 billion has been invested in infrastructure, assets, and projects located in the Arctic.

The tremendous growth in global resource use, in the past 60, years, has resulted in increasing environmental pressures with associated transboundary impacts (Jungsberg 2019). As the ice and snow recede and access to new areas becomes easier, the Arctic is expected to play an expanded role in the supply of resources (Corell et al. 2013). Extraction and supply of minerals are considered necessary for a low-carbon footprint and decarbonisation of the technosphere to achieve a sustainable lifestyle (Linghede 2024; Byman 2024; Teseletso and Adachi 2023). Supply of electricity from renewables, globally in 2016, was about 147 TW corresponding to 14 percent of the total demand. To achieve a global temperature below 2 Celsius by 2100, requires that 70 percent of electricity be generated from renewable sources by 2050 (Teseletso and Adachi 2023). However, low-carbon economy and energy systems rely heavily on CRM such as copper, nickel, silver, lithium, cobalt; and iron and steel (Watari et al. 2019). Extracting such metals leaves a large ecological footprint impacting air, water, land and requires management of chemicals and vast amounts of waste including mine-rock, tailings, day- and mine-water. Total material requirement for a transition to a low carbon economy, for the period 2015 to 2050, is forecast to increase by up to 900 percent for the electricity sector; and up to 700 percent for the transport sector. The increase in mine waste over the coming decades is among the most significant ecological and social development challenges we face in coping with the global energy transition and cater to the expected urbanisation and industrialisation (Owen et al. 2024). There is growing apprehension about the massive transition of energy systems from fossil fuels to renewables, the daunting amounts of raw materials and finances needed, and whether a green growth is possible (ETC 2023; McKinsey 2022; Hickel and Kallis 2019; Merz et al. 2023). The argument is that an energy transition addresses only a single symptom of ecological overshoot and worsen other symptoms significantly in the process. **If a transition is not managed appropriately by the stakeholders, there are significant environmental impacts, and social liabilities, associated with the mining and extractive sector.** For sustainability, a reduction in the use of fossil fuels and material consumption between 40 and 90 percent has been suggested with a corresponding adjustment of lifestyles (Akenji et al. 2019).

Sustainability must address land and water use, biodiversity, climate change, and environmental protection with respect to production and consumption. The concept of 'sustainability,' 'sustainable development,' 'anthropogenic ecological overshoot' is vast (Burns 2015; Steffen et al. 2004, 2015; Griggs et al. 2013; UNGA 2015; Merz et al. 2023). The definitions from the International Standard Organisation (ISO) are as follows (ISO 2019):

- Sustainability—state of the global system, including environmental, social and economic aspects, in which the needs of the present are met without compromising the ability of future generations to meet their own needs; noting (i) that the environmental, social and economic aspects interact, are interdependent and are often referred to as the three dimensions of sustainability. (ii) Sustainability is the goal of sustainable development
- Sustainable Development: development that meets the environmental, social, and economic needs of the present without compromising the ability of future generations to meet their own needs; noting that the definition is derived [from the] (Brundtland Report 1987)

In efforts to pursue sustainable development, nations have adopted 17 Sustainable Development Goals (SDG) with specific targets for implementation by 2030 (United Nations 2024a; Sveriges Miljömål 2024). However, at the midpoint to 2030, the SDGs are in trouble (United Nations 2023b). An assessment of the 139 targets shows only 15 percent are progressing as expected to be achieved by 2030. Nearly half (49 percent) exhibit moderate to severe deviations from the desired trajectory. 17 percent of the targets have stagnated, and 19 percent have regressed below the 2015 baseline levels (United Nations 2024b). Similarly, progress on health-related SDGs is not encouraging. Of the 32 health-related SDG global targets, none have yet been achieved, and none are on track under current trends (WHO 2024). Correspondingly in Sweden, evaluation of sixteen environmental quality goals shows that only one – that of "a Protective Ozone Layer" has been reached (Swedish EPA 2023). Three environmental targets, for "Clean Air," "Non-Toxic Environment," and "Safe Radiation," may be attained fully or partially by 2030. The other twelve environmental quality goals and the generational objective are not expected to be reached in Sweden by 2030.

The extractive sector must tackle spatial, temporal, social and governance challenges. The 'Domestic Material Consumption' (DMC) metric covers raw materials (biomass, minerals, metals, and fossil fuels) associated with production processes and provides a production- (rather than a consumption-) based perspective. Materials or energy embodied in the moved goods are not traced by the metric, hence the burdens associated with the production for export cannot be allocated to final consumption (Hickel and Kalis 2019). Between 2000 and 2019 the global DMC increased by 66 per cent—tripling since the 1970s – to reach 95.9 Giga tonnes (United Nations 2023c). The DMC for the 8 Arctic states was about 13 billion tonnes (2017) (UNECE 2024) – 14 percent of the global total. High tonnage commodities such as iron and steel, aluminium, copper nickel, oil, and gas have throughputs in the range of million tonnes per annum and market prices of the commodities are typically below a couple of hundreds of USD per tonne (Szekely 1994). Speciality materials, including metal composites, CRMs (Australian Govt. 2023; EC 2023b), have production rates in thousands of tonnes per annum or less and prices of an order of thousands of USD per kilogram. Operations in the oil and gas sector tend to span over 20–40 years, while mining and extractive operations span 100 years or more (Ottenhof 2023). Prevailing conditions influence extraction efficiencies especially regarding exploitation of coupled resources i.e. more than one metal or resource value, such as sulphur, gets extracted by the operator as by- or co-products from ore, concentrates, tailing, slag, and waste. There are accordingly opportunities at hand, subject to techno-economic feasibility assessments, innovative technologies, and incentives, to exploit minute concentrations. Realisation of projects draw upon several factors such as demand, prices, taxes, capital cost, innovation, access to BAT-BEP, regulatory, and contractual agreements with the rights- and stakeholders on sharing of the revenues, and sustainability aspects. In practice a wide mechanisms, monitoring, verification range of sophisticated tax reliefs, royalties, security, and reporting (MVR) help harness incentives (AusIMM 2020; Canada Govt. 2023; Jamieson 2013; Tarras-Wahlberg 2023). Considering incentives involved, including those dealing with legacy and emerging issues, makes the taxpayer and rights holders among the most important stakeholders for investments. For example, the requirement from the Green Deal for quick access to resources, has drawn calls from the rights holders (Sámediggi 2023) for a better engagement of the Euro-Arctic Indigenous people and communities. The calls demand an active partnership in the Green Deal transformation; participation in profit-making elements of downshifting and increased recirculation; respect for the Indigenous people right to lands, waters, seas and safeguarding of their culture, livelihoods, and lifestyle; application of a coherent approach to protected areas also across borders; delivering on the Agenda 2030 goals that promote protection, restoring and a sustainable use of land-, [and water] based ecosystems including forest management.

There is thus much to gain from clarity on how resources are exploited, and benefits shared in practice (Tysiachniouk 2020; Tysiachniouk et al. 2020). Benefit sharing can cover extraction, land and water usage, transportation (pipelines, railway, formal and informal roads, river, coastal, air transportation), housing, use of infrastructure, capacity building. Success depends upon efficacy of frameworks such as corporate social responsibility standards used by extractive industries; benefit sharing in line with international and national legislation; implementing legislation that supports indigenous and local interests; methodologies for assessing compensation to Indigenous communities from extractive industries. Payments take the form of compensation, investment, charity, or a combination of the three. Global trends are favouring greater state and or rights-holder involvement with clauses reflecting equity investment contracts (OECD 2020).

Improving efficiency and downshifting on production and consumption can take advantage from several pathways. A major consumer of energy and materials is the housing sector responsible for 37 percent of global GHG emissions (UNEP 2023). Better governance, design, and construction with help of standards, certification, such as the Building Research Establishment Environmental Assessment Method (BREEAM), Leadership in Energy and Environmental Design (LEED), Zero Emissions Buildings, servicing, offer substantial energy efficiencies, e.g. from levels of 100–500 kWh/m^2-y to ca 15 kWh/m^2-y or less. Added opportunities are offered by choice of urban – peri urban planning, choice of building materials (steel, concrete, wood, adobe), waste management hierarchy of prevention, reuse-recycling-circularity, and disposal. Recent practices include reuse of mine waste as pastes for backfilling of underground infrastructures (Rankine et al. 2007; Sharghi and Jeong 2024; Darlington 2024). The ISO 59000 family of standards also offer a guidance on circular mechanisms (ISO 2024). In 2005, the global economy processed about 62 Gt of materials. While end of life waste flow available for reuse was up to 13 Gt/y (Haas et al. 2015), just 30 percent of this waste flow – 4 Gt/y (6 percent of total processed material) – was recycled. Total ore extraction was approximately 5 Gt/y containing about 1 Gt of metals of which 75 percent ended up as stocks. For metals such as copper, the end-of-life recycling rates are 45–60 percent while iron and lead get recycled by up to 90 percent. For speciality materials with a wide range of metals and metalloids the current recycling rates are around 1 percent (e.g. lithium). They face challenges since they are used in small quantities (nanomaterial technologies and microelectronics), in complex alloys, composite materials, and individual products can contain dozens of different metals. Recycling of such metals becomes demanding, costly, and cross-contaminations risk material properties (e.g. copper impurity in steels). There is room for improving material recovery rates with innovation, using BAT-BEP (Simas et al. 2022) such as in the cases of Cu, by up to 95–100 percent, and lithium recovery can be improved to 80 percent. Circularity may have a better potential in high income countries where large valuable stocks are an accumulation of wealth and logistically available in relative proximity to processing facilities. Copper in-use stock in the global north doubled from the 1960s to about 180 -200 kg per capita by 2015 and is expected to redouble by 2050 (Löf 2024). The global average is around 50 kg per capita (Watari et al. 2022). With growing demand, and declining ore grades, GHG emissions for copper alone are forecasted to increase to about 2.7 percent of total emissions by 2050. The "remaining carbon budget" (RCB) for restricting global warming to 1.5 C is estimated to be about 250 Gt $CO_{2\text{-e}}$ (Lamboll et al. 2023). Global emissions in 2023 were approximately 40 Gt $CO_{2\text{-e}}$ and the rate will consume the RCB by 2029. The extractive sector needs to respond to the RCB, and the impacts posed by population growth, land and water use, and pollution (Seal et al. 2017). Figure 5 depicts the urgency for action about climate change. Pledges from the Nationally Determined Contributions (NDC) will reduce GHG by about 35 Gt $CO_{2\text{-e}}$ annually by 2030. There is still a large gap, of nearly 40 G t $CO_{2\text{-e}}$ annually, to mitigate within 7 years to reach 20 Gt $CO_{2\text{-e}}$ annual target for the 1.5 Celsius goal (Black et al. 2023a, b). The mitigation task is further complicated by the steadily increasing total fossil fuel subsidies globally that amounted to USD 7 trillion in 2022, equivalent to nearly 7.1 percent of the global GDP, and projected to reach USD about USD 8.1 trillion by 2030 (Black et al. 2023a).

Extensive exploitation of Arctic resources has also rendered numerous "hotspots" requiring mitigation of pollutant release and management of hazardous substances. Presently it is estimated that there are more than 3,000 hotspots in the circumpolar region (Robin des Bois 2009; Environment Canada 2008; ACOPS 1995; AMAP 2003, BEAC 2020, Huuska and Forsius 2002; HELCOM 2020; PAME 2009). The scale of remediation varies widely as illustrated by mine closures implemented by Norway in Svalbard (Erikstad and Hagen 2023); decommissioning of the oil- and gas infrastructure in the North Sea and the Norwegian Arctic (Espeland and Reksnes 2023); and the cases presented below. The former Svea Mine area, situated in the inner Van Mijenfjorden in the Svalbard archipelago, had been a coal mining settlement since 1917. Store Norske Spitsbergen Grubekompani (SNSG), with the Norwegian State as its largest owner (Flyen et al. 2022), started mining at Svea in the 1930s. The main impacts have been (Granberg et al. 2017) air pollution; fire hazards; ground deformation; soil and water pollution; and water resource depletion. The contamination was spread over a large area (Fig. 6) releasing HM (Fe, Cu, Mn, Cd, As, Ni, Hg); Polycyclic Aromatic Hydrocarbons (PAH); acid run-off; nutrients (from blasting); chemicals, e.g. PCB, PFC, PFAS; fuels and petroleum products. In 2018 the Norwegian Parliament decided to end mining in Svea and to restore the area to its natural state in line with the Svalbard Environmental Act (Norway Govt. 2001). Triage required improved knowledge about risk assessments, fate, and effects of contaminants in the Arctic ecosystems and SNSG engaged a team of geological, social-cultural, biological diversity,

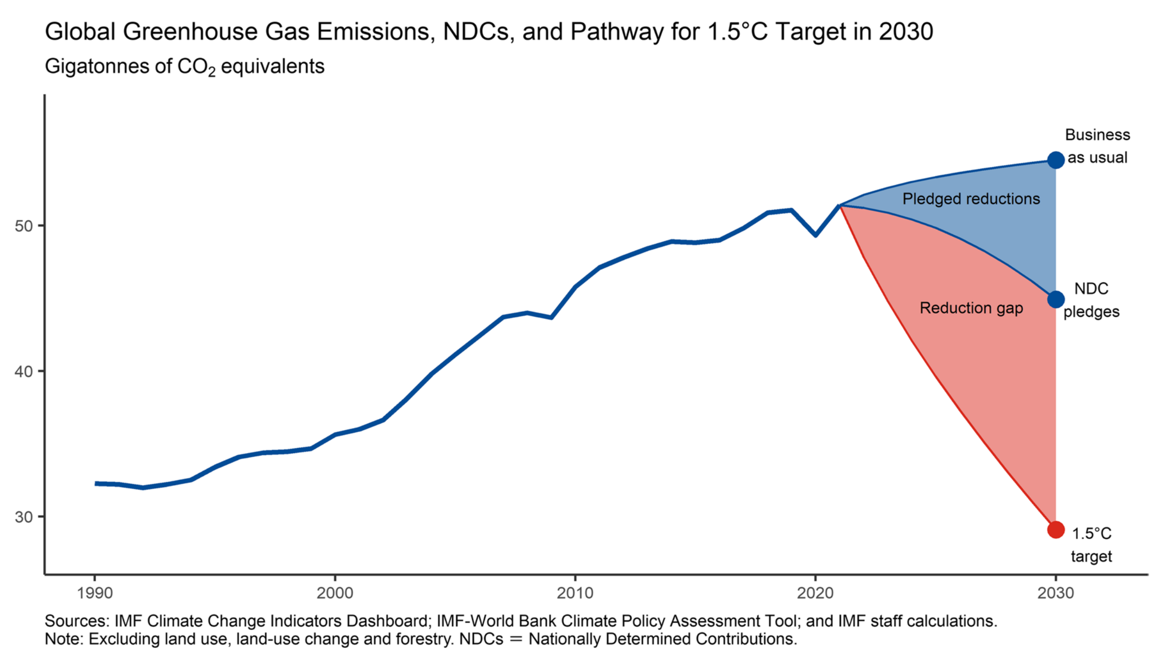


Fig. 5 Global Greenhous Gas Emissions, NDCs, and Pathway for 1.5 Celsius target in 2030 (Black et al. 2023b)

Fig. 6 Map of Svea showing reported contaminated sites as coloured circles, Legend: Red: Serious contamination, remediation needed; Yellow: Use with restriction; Green: Unrestricted use. (Granberg et al. 2017)

ecosystems, and landscape experts to help plan and implement the restoration and closure (Erikstad et al. 2023).

Today little remains of more than 100 buildings that once stood on the site except for the heritage structures. The area is part of the newly established Van Mijen National Park. Seven other mines in Longyearbyen have ceased operations and the last coal mine is due to close in 2025. Figure 7 depicts one site. The Svea-project is one of the largest restoration projects ever conducted in the Norwegian Arctic at a cost of about 2 billion Norwegian kroner (Euronews-AFP 2023; AF-Gruppen 2021) (EUR 142M; USD 160M).

Another large-scale remediation underway is the decommissioning of the offshore oil and gas infrastructure in the North Sea. There are about 27,000 oil wells, 615 platforms

Fig. 7 The entrance to the Nord Svea mine situated on the Höganäs glacier, during the mining operation, left picture 2008, and after restoration—right picture 2019 (Erikstad and Hagen 2023)

and 43,000 km of submersed pipelines in the North Sea area alone (Espeland and Reksnes 2033), Fig. 8. Nearly 10 percent of all platforms, 20 percent of the pipelines and 70 percent of the wells are redundant and impacting the marine and coastal zone (Herbert-Read et al. 2022). OSPAR Decision 98/3 (OSPAR 1998) prohibits abandoning platforms and infrastructure in the sea after production has ended unless operators have been granted exemptions. Decommissioning costs are notoriously difficult to calculate due to many unknowns and central issues include who bears the liability. Ownership of assets tend to transfer during the life of a field and occurs, typically, 10 and 20 years after commissioning when income from production start to diminish and the risk profile begin to increase (Jamieson 2013). According to OSPAR, ultimate responsibility stays with the owner and any remaining liability in perpetuity.

In the case of Norway, Frigg and Ekofisk, Fig. 9, are the largest fields where the operator considers the remediation has been done. Shutdown and clean-up on the Norwegian shelf are expected to cost around EUR 5 billion during 2020–2027. The clean-up cost of the entire North Sea, 2020–2030, will cost around EUR 30 billion. A major part of

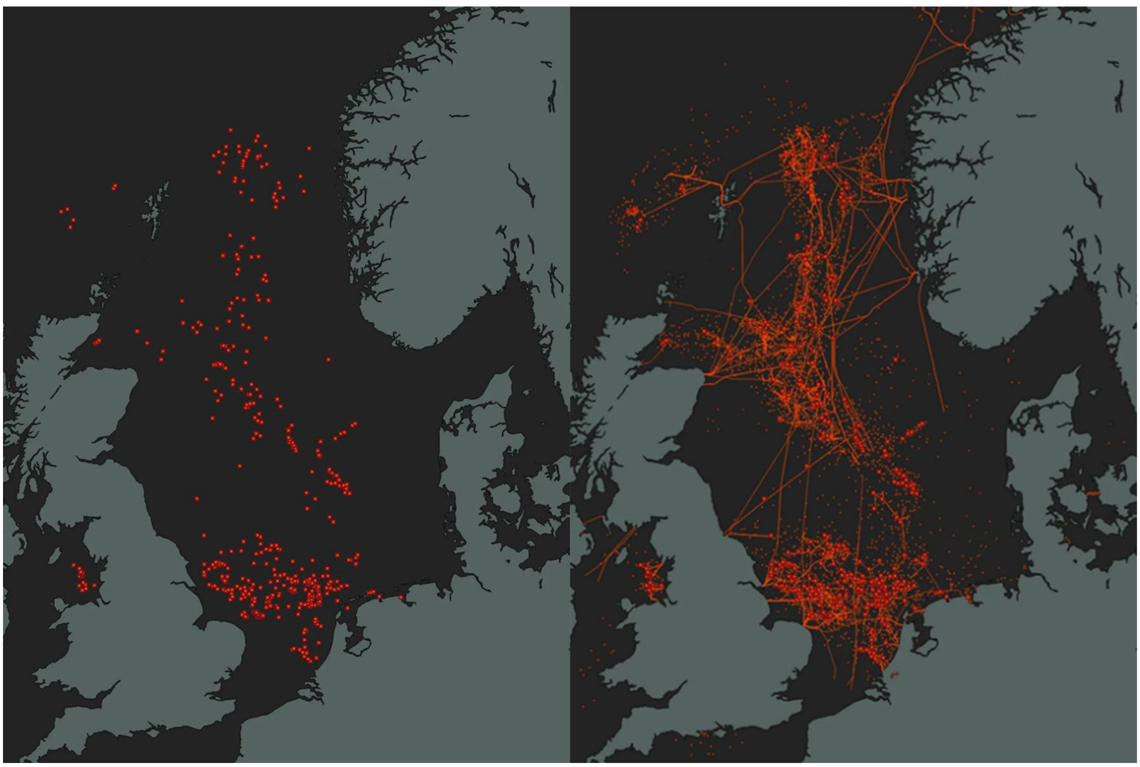


Fig. 8 Map of the North Sea and sub-Arctic depicting platforms, wells, and pipeline network (Espeland and Reksnes 2023)

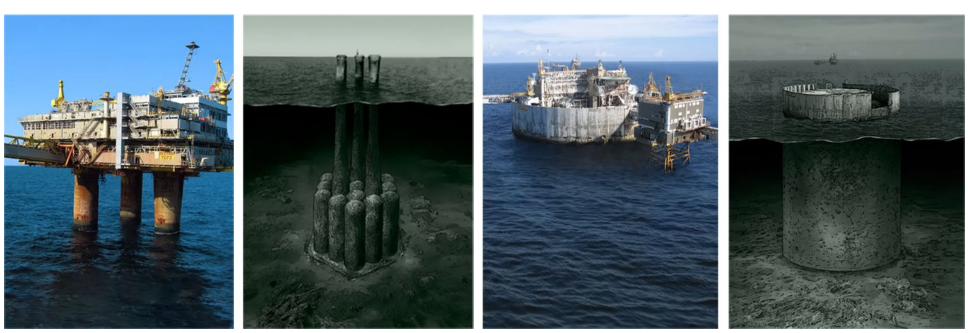


Fig. 9 Frigg TCP2 pre- and post- decommissioning and close-down in 2004. Principal owner Total Energies is responsible for monitoring Frigg. They ensure that the signal-lights and radar are working and check the condition every four years. Further south, the Ekofisk structure stands unused next to several platforms that are in operation. Much remains to be implemented (Espeland and Reksnes 2023)

decommissioning is well plugging. Average plugging costs in the North Sea are about USD 3 million per well taking an average of 30 days to complete (Jamieson 2013). For the 160 wells in the Brent Field, typically at 2,800m to 3,000m depth, it is estimated that it could take over 13 years to plug the wells at a cost of USD 550 million. For all of the North Sea, Espeland and Reksnes (2023) report SINTEF estimates of EUR 80 billion just for plugging the wells by 2050.

Waste and chemical management is a priority area of Arctic cooperation (Arctic Council 2019) and the pioneering remediation of the Sillamäe radioactive tailings dam (Jaaksoo et al. 2012; Barnekow et al. 2002) is an example taken-up below. EU has recently established guidelines on handling of waste from extractive industries, and on securing financial guarantees relevant to the extractive sector (EU Directive 2006; EC 2018, 2019b 2021). The Russian Federation (RF Bureau 2024) guidance is similar and takes into consideration the local circumstances.

Emerging issues include the ubiquitous release of PFAS that have broad applications and release from the oil and gas, mining, extractive industries, firefighting, sewage systems, and landfills (Barfoot et al. 2022; Keyte et al. 2021; Glüge et al. 2020). PFAS are increasing in the Arctic (Butt et al. 2010; Hartz et al. 2023). Ideally, the most cost-effective countermeasures are use of the precautionary principle to curtail use, followed by countermeasures closest to the source of pollution, and harnessing of the liability costs. The Nordic Council estimates that healthcare costs from exposure to PFAS in Europe alone range between EUR 52 to EUR 84 billion annually (Goldenman et al. 2019; Kärrman et al. 2019). To purify PFAS contaminated water is estimated to cost EUR 238 billion for the EU and remediation of soils, globally, is estimated to cost over EUR 2 trillion. Extrapolation of remediation costs of PFAS contamination globally gives a staggering estimate of EUR 16 trillion per year—nearly 15 percent of the entire global economy of 2019. The estimate excludes damages to animals or reduction of property value. In comparison the global market size for the PFAS producers in 2022 was just over EUR 28 billion (Chemsec 2023).

Contemporary pressures are bringing substantial modifications to regulations and economic stimuli in Canada, the US, EU, and the Nordic states to address "green growth" (Canada Govt. 2019; Mining Association of Canada 2022; White House 2023; CEQ (2023); NEPA.GOV 2023; Seal et al. 2017). The consequences are yet unclear. Near term challenges here can learn from the post-war successes and failures of complex mega systems (Hughes 1998) where successful developers were those who were able to respond to the demands of ethnic, environmental, cultural, and other interest groups since the modus operandi includes rather than excludes political and social factors, i.e. an open rather than a closed system. One tool for a structured follow-up of complex systems is that of Maritime Spatial Planning (MSP). The MSP is based on a phased approach with regular revisions and adjustments in a 2050 perspective. MSP is currently work-in-progress in the EU, Sweden, and globally (EU Directive 2014; Hav 2022; MSP 2021).

Methods

The paper focuses on progress spanning 3–5 decades and draws upon experience accumulated from cooperation, agreements, assessments, permitting processes, and implementations – locally, regionally, and globally. The information is fetched from accessible platforms, databases, and includes interactions between bi-lateral and multilateral Nordic engagements; regional, and global multilateral agreements.

The extractive sector faces complex issues often applying triage in addressing development, economics, and sustainability. A few field cases from the Arctic region are presented reflecting decades of multifaceted efforts to address resource efficiency, sustainable development, and remediation.

The engagement of the Indigenous and local communities draws upon the research reported from the field on impacts and benefits sharing that the sector has strived to address. Each case has intrinsic features and limitations due to location, legislative framework, economic incentives, time frames and the engaged stakeholders.

Case studies and results

The cases in this paper address operations undergoing modernisation, or closure, subject to agreements and legislation in place or in development. Technology and operations wise, the projects benefit from several guidances. The EU has 38 BREF documents of which 25 are relevant to the extractive sector including ancillaries. There are also horizontal "REFs" in the EU Package dealing with cross-cutting matters such as economics and cross-media effects, energy efficiency, industrial cooling systems, releases from storages, and monitoring of emissions to air and water from installations under the IED. Similarly, the Russian Federation has established 50 BREF documents of which 41 BREF can be relevant to the extractive sector and ancillaries. Guidances regarding EIAs, remediation, are in addition.

The Rönnskär Smelter

The Rönnskär Smelter, Fig. 10, is a complex non-ferrous metals operations situated in northern Sweden. Construction started in 1928 and the smelter was commissioned in 1930. Its infrastructure includes seaport, road, and railway

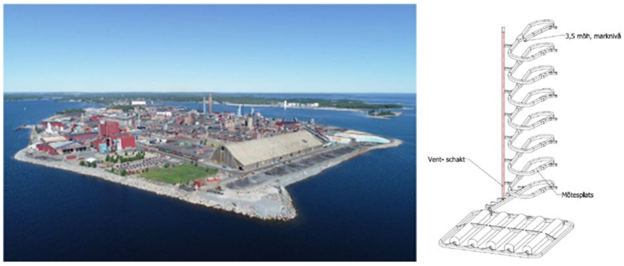


Fig. 10 The Rönnskär smelter (Hedlund et al. 2022)

facilities. The smelter is the largest operations in the region and ranks among the world´s foremost recyclers of materials, Fig. 11. It treats, recycles, and refines metals from concentrates and secondary materials.

Figures 11, 12, 13, 14 and 15 depict mitigation of pollutants' release to air and water, improved resource and energy effectivity, management of hazardous chemicals and wastes while increasing production (Lindeström et al. 2009). The smelter was taken off the HELCOM Hotspot list in 2003 (HELCOM 2002; HELCOM 2020) acknowledging the significant improvements in its performance, over a 93-year period (1930–2023), and responding to improving regulations and introduction of BAT-BEP. In 2012 the smelter expanded its production, from 75,000 t/y to 120,000 t/y with further energy efficiency and reduction in the release of pollutants. The improvements, costing SEK 1.3 billion (USD 150 M), leveraged scrap recycling using the Kaldo rotary technology and the flash-smelting process to treat the sulphidic copper concentrates. The extractive sector in Sweden enjoys a conducive fiscal and tax regime (Tarras-Wahlberg 2023) and the smelter improvement provided a payback of costs within four years. The smelter produced 270,000 t of copper, lead, zinc, gold, and silver in 2022, Table 1, and is among the best performers regarding sulphur controls in the region (Sundqvist 2010).

The operator's management of waste has also been innovative. A deep rock repository, beneath the smelter, was commissioned in 2022 for permanent storage of treated

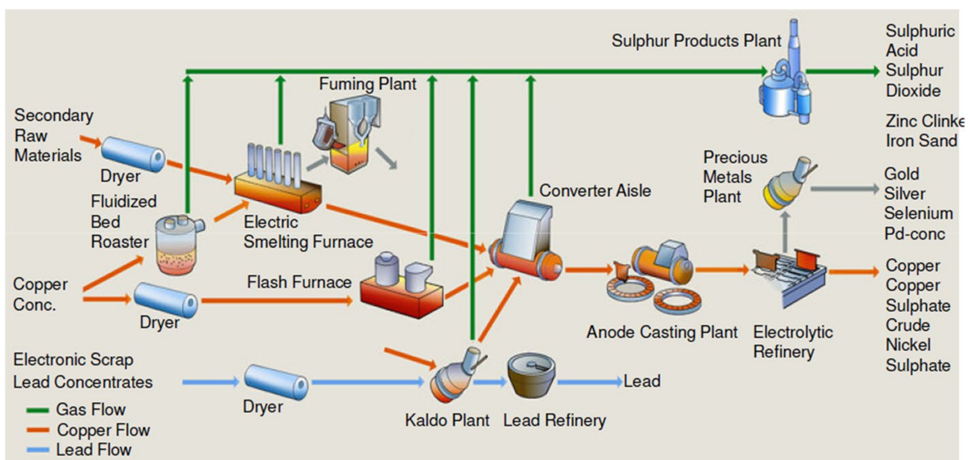


Fig. 11 Process flowsheet, Rönnskär Smelter (Sundqvist 2010)

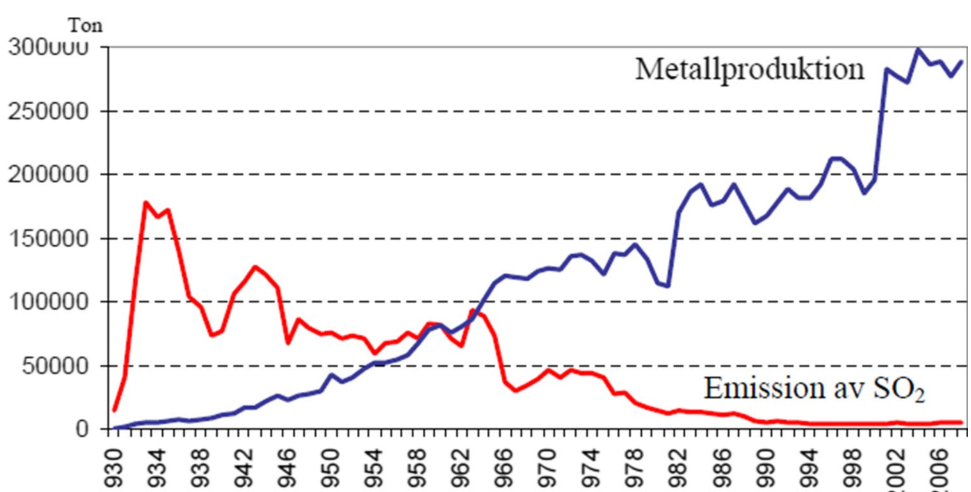


Fig. 12 Metal production (copper, lead, and zinc clinker) and sulphur dioxide emissions from the Rönnskär Smelter since commissioning in 1930

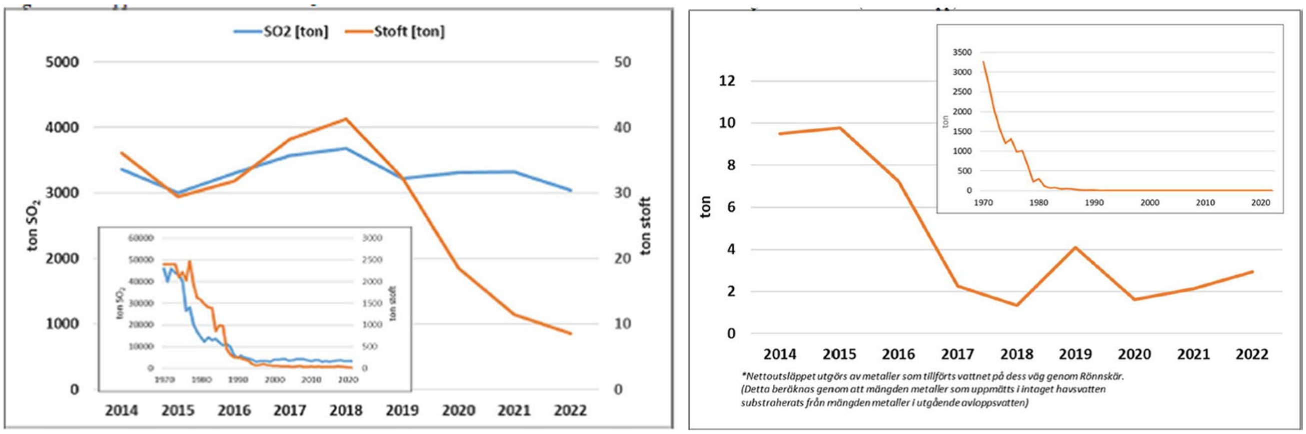
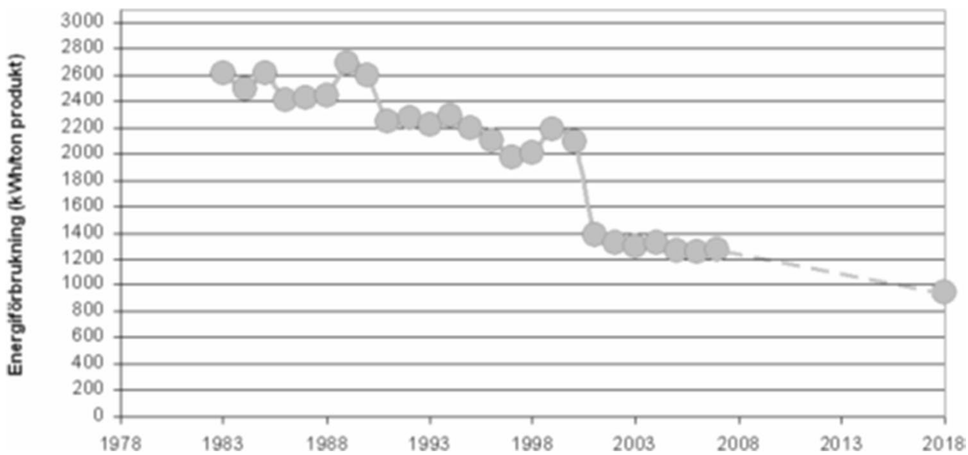


Fig. 13 Reductions of emissions to air and water from the Rönnskär Smelter, period 1970–2009 (Sundqvist 2010)

Fig. 14 Energy consumption of electricity in terms of kWh per tonne products (copper + lead + zinc clinker). The decline in 2000 is due to use of new flash-smelting unit utilising the energy contained in the sulphidic concentrates



waste with hazardous substances such as mercury, arsenic, and cadmium. The capacity of the deposit is about 400,000 tonnes and cost about USD 20 M. The design criteria for leakage from the deposit, upon closure, are maximum of 1 kg/y for cadmium, and maximum 1 g/y for mercury. The maximum limiting values of leakage for Cd is 10 kg/y and 10 g/y for Hg.

The Rönnskär Smelter operations over the decades reflects a successful response by its management team to harmonise with developing regulation, technology, and capacity building, to deliver a high performance in severe Arctic conditions (Bergquist 2007; Bergquist and Lindmark 2016). Material efficiencies have improved several folds and releases to the environment have been reduced to background levels for several toxins. The result has been removal of the smelter from the HELCOM hotspot list. It is among global leaders regarding recycling of non-ferrous metals and effective waste management. Complex smelter operations undergo continuous modifications requiring regular studies and regulation. The operator is currently investigating release of additional toxic substances from the complex and an "end-of-operations" exit. As a provisional measure, a security of about USD 75 M has been deposited for post-closure restoration measures.

Nikel-Pechenga-Zapolyarny Mining and Smelting Operations – "Pechenga Nikel Smelter"

One of the issues at the Finnish-Norwegian-Russian border has been the trans-boundary pollution from the Pechenga mining and ancillary operations at Nikel and Zapolyarny in the Murmansk Oblast (Fig. 16). The Pechenga-Nikel Combine (PNC) is operated by the Kola Mining and Metallurgical Company (KMMC), a subsidiary of Nornickel (Norilsk Nickel). The smelter was constructed in 1938 and started operations in 1942. Post- World War II restart of operations in November 1946 produced 5 tonnes of high-grade Cu-Ni matte. The operations utilised the electric furnace – converter technology. A sulphuric acid plant (SAP) was added in the 1970s. By 1992 the PNC was among the largest

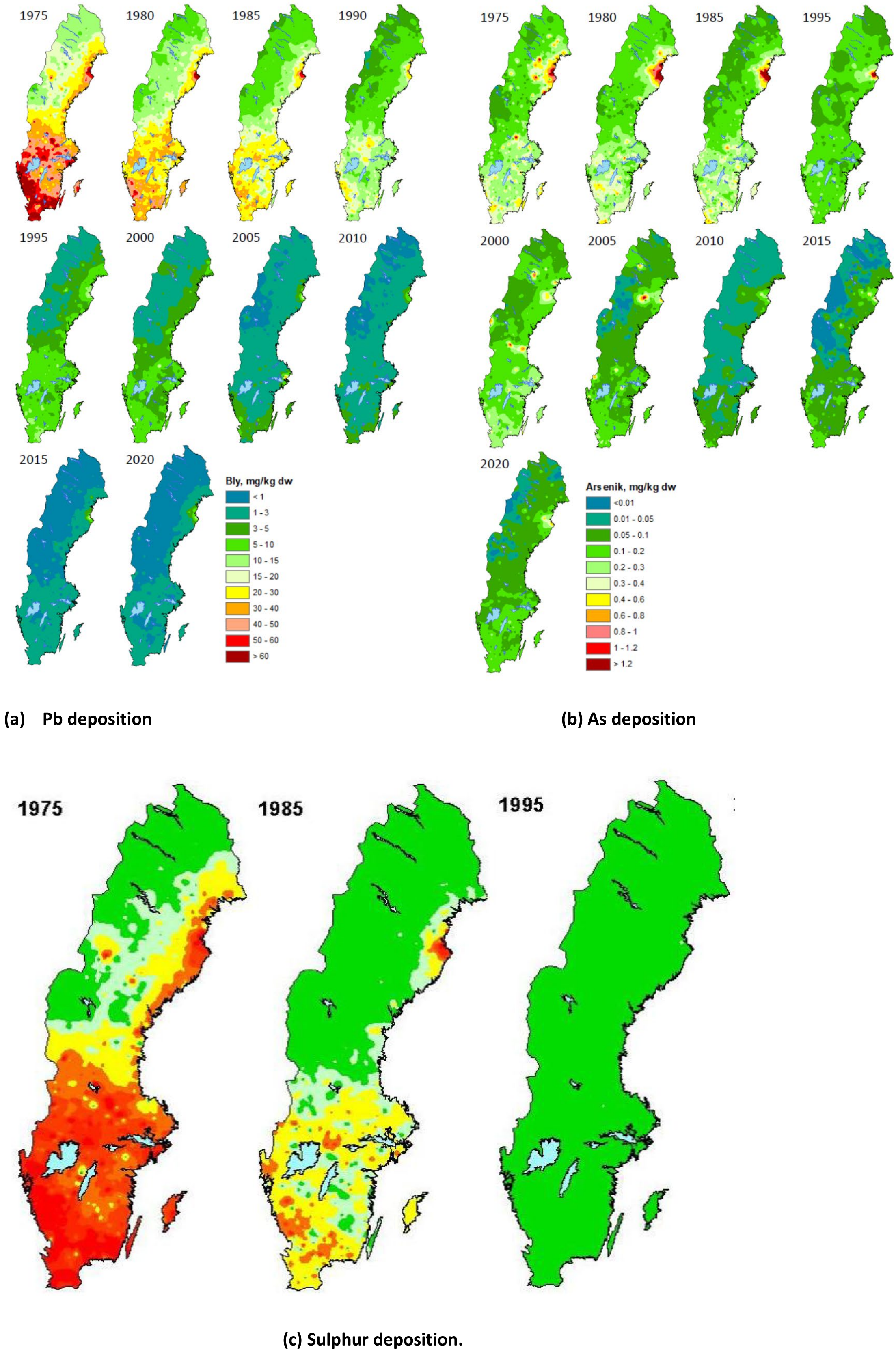


Fig. 15 Improvement in the deposition over Sweden since 1975 of (**a**) Lead, **b** Arsenic and (**c**) Sulphur (Karlsson et al. 2021)

Table 1 Reduction of emissions and increase of production between 1970 and 2022 at the Rönnskär Smelter

Ref. Milörapp. 2008—2022	Emissions			Production
	SO2, t/y	Dust, t/y	Water, t/y	Production, t/y
Period 1970	43800	2340	1999	125000
Period 2022	3037	8,6	3	270000
Reduction/Increase, %	***93,1***	***99,6***	***99,85***	116

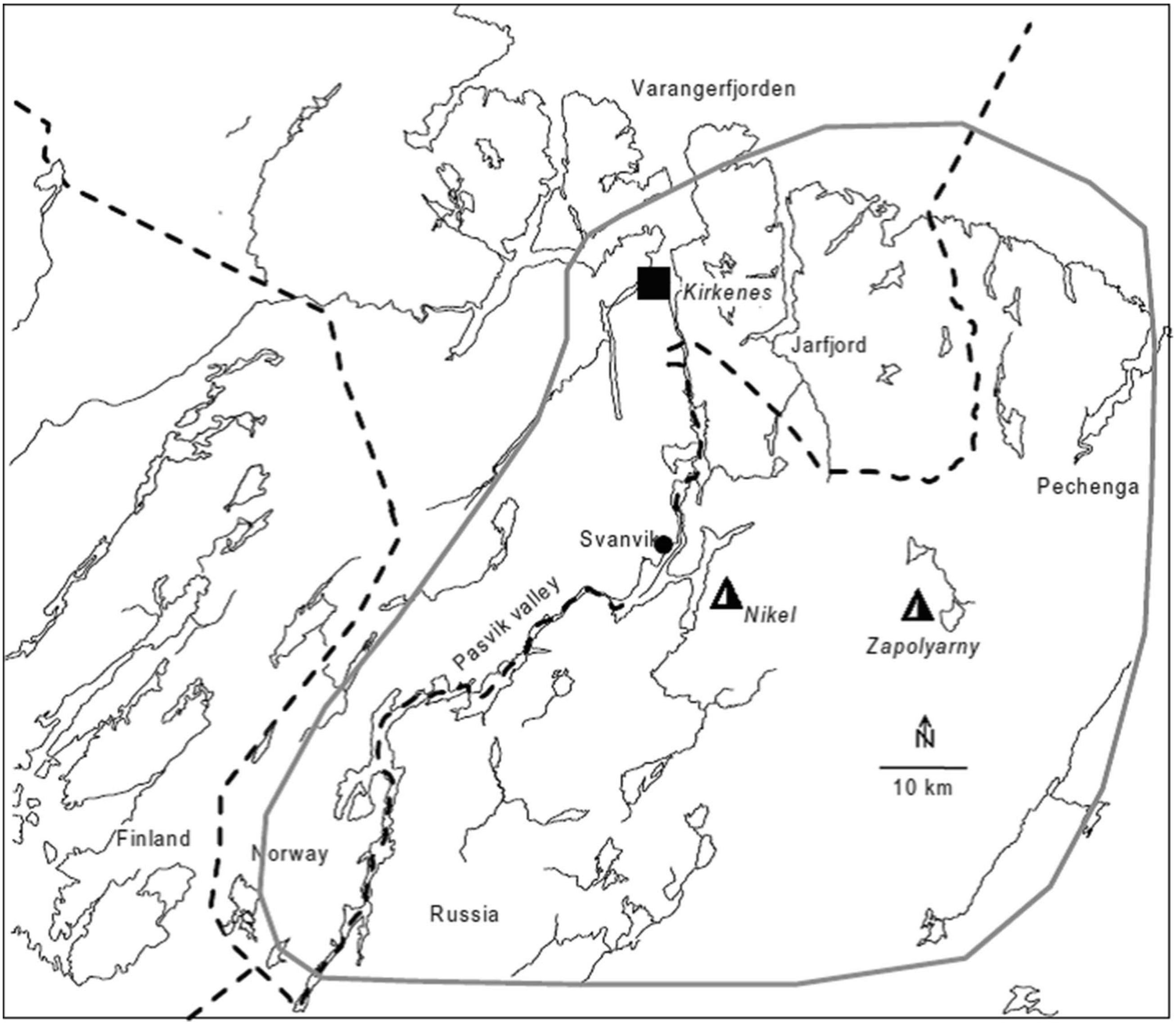


Fig. 16 Map of area of interest (outlined) in the border region between Finland, Norway, and Russia (SFT 2002)

industrial operators producing about 120 000 tonnes of high-grade Cu-Ni matte with 13 000 employees.

PNC has two underground and two open pit mines (Michelsen 1994). The Concentrator Plant No 1 and the pellet roasting plant are in Zapolyarny. The Kola-Kotsel-vaara underground mine, Concentrator No 2, the smelter, and the SAP, are in Nikel. The total output of the four mines was about 8 M tonnes per year (t/y) (ENMOP 1992). The beneficiation plants produced about 570,000 t/y of concentrates and the roaster, about 400,000 t/y of pellets. Unabated emissions of sulphur dioxide (SO_2) and heavy metal (HM) laden toxic dust were huge. Emissions

Table 2 Emissions of Sulphur dioxide (SO_2) and Dust including Heavy Metals (Nickel (Ni), Copper (Cu) and Cobalt (Co)) at the Kola Mining and Metallurgical Company's operations in Nikel and Zapolyarny, Murmansk (ENMOP 1992)

Emission to atmosphere	Zapolyarny, t/y		Nikel, t/y		Total, t/y	
	1990	1991	1990	1991	1990	1991
SO2	67 200	67 500	190 100	189 800	257 300	257 300
Dust	4 070	4 050	3 880	3 870	7 950	7 920
Ni	147	164	165	131	312	295
Cu	80	88	92	88	174	176
Co	8	6	5	5	13	11

ENMOP (1992)

from the Zapolyarny (1991) operations were about 68,000 tonnes SO_2 and 4,000 tonnes of HM dust. Emissions from the smelter operations in Nikel (1991) were approximately 190 000 t/y of SO_2 and 3900 t/y of HM dust, Table 2 (ENMOP 1992). The smelter also treated about 1 M t/y of high sulphur content Cu-Ni ore shipped from Norilsk. Total energy requirement of the pyro-metallurgical processing at the PNC was of about 220 MW. The SAP capacity was about 150,000 t/y of sulphuric acid. More than 1 M tonnes of waste was generated from the slag cleaning operations. The PNC's total emissions of SO_2 and dust, including from the power plant, were about 260,000 tonnes and 8,000 tonnes, respectively, in 1991—compared to 400,000 tonnes of SO_2 emitted in 1979.

Emissions from the PNC were the largest point source of pollution in Northern Europe with serious impacts on the environment and human health. The most severe effects were in Nikel and Zapolyarny towns with a population of about 50,000. Distinct impacts were also observed in Norway and Finland. Soils, water, flora, and fauna over an area of about 2750 hectares (ha) were seriously affected by the acidic precipitation and HM contamination. A large area was laid barren, and the regeneration ability of the ecosystem had been lost. The total area of the impacted ecosystem in the Kola region was estimated at 93,000 ha (930 square km) and increasing at a rate of 800 ha annually (ENMOP 1992).

In response to agreements such as the Convention on Long Range Convention on Long-range Transboundary, the Convention on Environmental Impact Assessment, the Declaration on the Protection of the Arctic Environment, Finland, Norway, and Russia discussed the severe pollution and mitigation of impacts in the Arctic whereby Outokumpu and Elkem submitted an offer, in 1991, to Norilsk Nickel for modernisation of the PNC. The proposal, costing approximately USD 600 M, would reduce SO_2 emissions from 257 300 t/y to 14 500 t/y. The proposal got rejected as too expensive. In September 1992, the Ministers of Environment of the Nordic countries and Russia decided that further alternatives for modernisation of PNC should be elaborated where upon an international tender was floated by the Russian Tendering Committee (RTC) in July 1993 for response by 15 Nov. 1993. Three qualifying tenders were assessed with help from NEFCO. On 5 January 1994, the RTC declared that the proposal of the Scandinavian Consortium of Elkem, Kværner Engineering (Norway) and Boliden Contech (Sweden) as the most appropriate (Lukyanchikov 1994).

The Scandinavian Consortium 1993 proposal was to cost up to USD 310 M using electric furnaces and converter technology for matte production. An additional SAP, to the two existing plants, would mitigate SO_2 emissions to less than 10,000 t/y. Dust emissions were to be reduced in the range 300 t/y to 2000 t/y depending on the option chosen. Financing of the Modernisation Initiative for the PNC (MIP) was based on OECD export financing (OECD 2024) with guarantees from the national institutes corresponding to standard ratios for the sector i.e. 85 percent credit, 15 percent equity. Norway allocated up to NOK 300 million (USD 40.5 M) for the MIP's environmental measures in accordance with the bilateral agreement between Norway and Russia. The Nordic Investment Bank (NIB) could provide the required long-term credit financing based on federal guarantees.

Norilsk Nickel engaged NIB as financial and technical adviser in 1997 resulting in the 2001 Agreement to finance a restructured MIP (NIB 2001). The Project was to be implemented by Norilsk Nickel-KMMC with Boliden Contech as the Nordic partner. The restructured MIP was to cost approximately USD 90–100 M and emissions were to reduce to 12,000 t/y of SO_2 and 300 t/y HM dust. The production of matte would increase from 120,000 t/y to about 145,000 t/y. Reduction in emissions were to be achieved by replacing pellet roasting with cold briquetting; switching 5 electric furnaces and eight converters to a single, compact, state-of-art double-zone Vanyukov Furnace technology (Tarasov and Bystrov 1993; Bystrov et al. 1996; Keskinkelic 2019); upgrading the slag cleaning furnace; construction of a new oxygen plant and an additional SAP. Financing of the MIP was based upon a NIB credit of USD 30 M, Norwegian and Swedish grants of up to USD 40 M with Norilsk Nickel covering the remaining amount. The work on the MIP started in 2002 aiming for a completion by 2006 (NIB 2002). However, due to delays and a revised strategy, regarding changing environmental and sustainability priorities of the country, a decision was taken by Norilsk Nickel, in 2016, to close the Nikel Smelter and dismantle the plant (Nornickel 2016). The Nikel smelter ceased operation on 23 December 2020.

Independent Norwegian monitoring reports that the levels of pollutants are now low (2021). The air quality in the Norwegian area has improved (Berglen et al. 2022) and in compliance with the threshold values for SO_2. Target values for Ni, As and Cd in the air are complying also. The Finnish monitoring of the border environment also reports improvement regarding air pollutants (Grekelä 2023) and the water quality of some lakes that are naturally sensitive to acidification. A recovery in the fish populations of some lakes has also been confirmed. Terrestrial lichen species have started to return ten kilometres west of the smelter, and signs of the recovery have been noted on the trunks and branches of trees 70 kms west of the smelter. However, HM values in the border area have not seen a reduction at all. Monitoring indicates, on the contrary, that Ni deposition has increased over the past few years. Elevated HM concentrations are evident in the sediments of lakes and rivers, soils, and plants even up to 50 kms from the smelter. Accumulation of HM in mosses and pine needles has increased over the past 20 years. Regarding HM, the problem of pollution is worse since toxicity remains in the cycle and transfers through the food chain to accumulate in larger predators. In summary, despite protracted efforts, the case of MIP has delivered mixed results and requires following up.

The MIP Project highlights the importance of Arctic cooperation and leveraging of trans-boundary pollution preventive agreements. Dialogue could harness a triage of costs, pollution mitigation, innovative technology, guarantees, and expert management. It took nearly 30 years of negotiations to reduced costs from USD 600 M to about USD 100 M. Contributing factors included transparent tendering, use of a compact autogenous smelting technology, full financing, superior environmental performance, and a robust MVR regime. Further rationalisation by the owners through consolidation of the Kola operations has led to smelter closure and elimination of pollution at Nikel. Emissions from the heat power plant in Nikel remain, however, and the status of emissions from Zapolyarny are not known. Waste and water management, and releases from ancillary facilities still need follow-up.

Remediation of the Radioactive Sillamäe Tailing Pond; An Agenda 21 showcase

The Sillamäe Tailing Pond (STP) is located northeast Estonia 30–50 m from the shoreline of the Baltic Sea—Gulf of Finland (Mirotvortsev 2001). The STP was a legacy issue of co-deposition of wastes from uranium, coal shale and rare-earth processing during the period 1948–1990. Depositing of rare-earth wastes continued up to 2003. The size of the STP area is approx. 50 ha (1 × 0.5 km), the height of the containment dam is up to 25 m and the thickness of the tailing's massif is approx. 20 m. The STP contains up to 8 M m^3 (12 M tonnes) of hazardous uranium mill tailings; oil shale and power-plant ash wastes; loparite (titanium, niobium, tantalum, and other rare earths elements) wastes. The main issue with the STP was the design and instability of the containing slopes facing the seaside that risked a dam failure and a release of massive quantities of radioactive tailings into the Baltic Sea—Gulf of Finland. Furthermore, contaminants were continuously being released to the environment through three pathways: (i) Precipitation and hinterland water seepage through the mass of tailings releasing nutrients, acids and toxic substances (e.g. uranium, thorium, barium, strontium) to the sea; (ii) During summers the surface of the STP would dry-up resulting in erosion and dust dissipation from the depository to the surroundings and the town of Sillamäe about 1.5 km away; (iii) Leakage of radioactive gas, radon, which impacted the town as well.

The remediation project started in 1999. A financing agreement between Estonia, the European Commission (EC) was signed, and a EUR 20 M budget was established. Financing was to be provided by Denmark, Estonia, the EC, Finland, Norway, Sweden, and NEFCO. The design targets included a structural stability in a 1,000-year perspective and use of natural materials instead of artificial materials such as PVC, geotextiles. Main measures focused on:

- Reinforcement of the dam; building wave-breaks on the shorefront and reinforcing the dam structure by driving stabilising piles between dam and the shoreline
- Collecting and diverting the waters from the hinterland by use of a diaphragm wall 580 m long and 18 m deep using a bentonite-cement formula and channels
- Contouring the surface of the depository, re-enforcing with a root-resistant multilayer coverage including low permeability fine clay and waterproof cover.

Feasibility studies for the STP were prepared during 1998 – 2000 and remediation was achieved during 2000 – 2009 (Figs. 17 and 18). The total cost for project, preparation of detailed design and construction works, was about EUR 21 M. The final covered deposit is shaped like a hill (Fig. 18). It is covered with vegetation to prevent erosion and dust emissions. The cover layer includes measures to prevent penetration by vegetation roots. The STP MVR uses lysimeters, stability and slope monitoring. While radon is still being emitted from the tailings deposit, it decays before getting to the surface. Half-time of radon is approximately 4 days. The key feature of the remediation is the innovative use of a cost-effective diaphragm wall – 580 m long,

(a) 1999

(b) 2001-2003

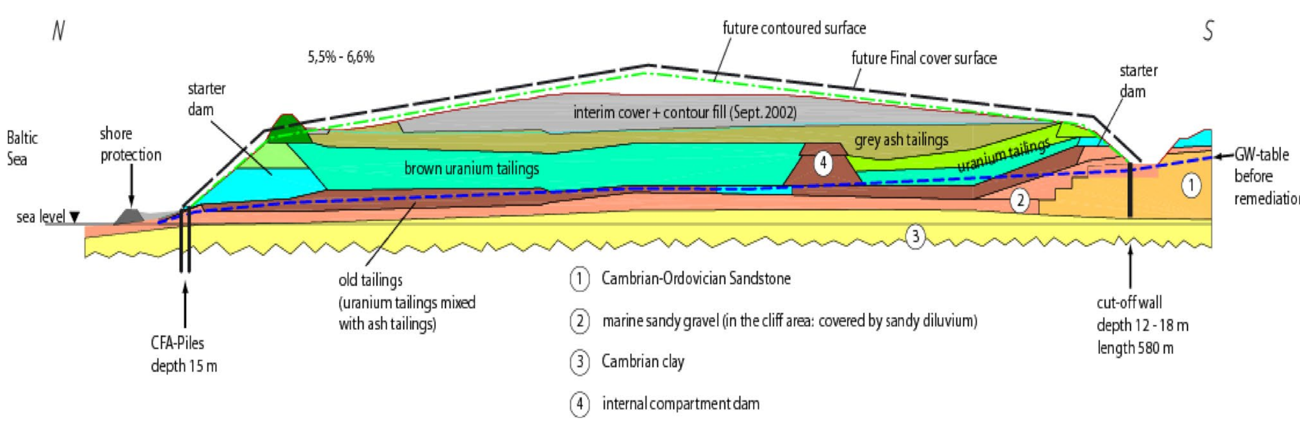


Fig. 17 Sillamäe radioactive tailing pond (STP) at start of remediation programme (1999) and during the remediation phase 2001–2003. The cross-section depiction of the STP shows key measures deployed (Jaaksoo et al. 2012). Note: Cross section of the Sillamäe Tailing Pond. Area: approximately 50 ha. Volume: 8Mm3. Amount hazardous waste: about 12 M tonnes. Dam height: up to 25 m. Dam length: 2.7 km. Thickness of tailings deposit: approx. 20m

Fig. 18 Sillamäe Tailing Pond and Sillamäe Port, Spring 2012, Three years after completion of remediation. An Industrial Zone and transportation hub for road, sea, and railway. Remediation Detail Design and construction cost approximately EUR 21 million

12–18 m deep using bentonite-cement materials. The wall together with drainage trenches limit inflow of water from the hinterland that ranged up to 220,000 m3/y to below 30,000 m3/y (after pond coverage).

The STP has not only become the first environmentally remediated depository of uranium tailings in the whole of Eastern and Central Europe, but it is also now part of a port, logistics, and industrial complex with a vibrant economy for the Sillamäe town population and the region.

Conclusion

The Arctic region is undergoing profound transformations from resource exploitation, regional, and global transboundary impacts. With a mere 0.1 percent of the global human population, the region generates considerable material wealth for the eight Arctic states surrounding it and the global north. The extractive sector is the largest contributor to the Arctic economy. For the near future, the sector will continue expanding subject to conducive techno-economic, pecuniary, and risk feasibilities regarding investments. The sector's significant contribution to the functioning of complex global systems requires broad competency and triage to enable sustainable development. The illustrative cases presented in this paper including smelter operations in Sweden, mining, beneficiation, and smelting operations in Russia, and remediation of a radioactive tailing deposit in Estonia, underscore the importance of accessing best practices towards sustainable goals with help of robust knowledge, good governance, dedicated open dialogue, prioritising of sustainability aspects with financing, and follow up.

Management of Arctic activity must systemise and integrate land and sea use; biodiversity; climate change; pollution, security, including the traditional values of the rightholders. Further actions in the sector need to respond to the reality that midway to 2030, the Sustainable Development Goal targets have delivered meagre or no results except in the case of protection of the stratospheric ozone layer. There is even reversal for some goals while emerging pollutants like PFAS are becoming ubiquitous and require containment. In parallel, vastly detrimental, fossil fuel subsidies continue to increase. The Arctic already has 3,000 hazardous hotspots that require remediation but face mounting geo-political tensions that have introduced a hiatus in circumpolar cooperation and further multidimensional risks, including economic sanctions, and political uncertainty. Non-Arctic actors, such as China, India, Japan, Korea, Germany, France, United Kingdom, are demanding greater participation in decision making and access to the Arctic's resources while the Indigenous peoples and communities are concerned about their rights, sustainability, and benefit sharing.

On the positive note, circumpolar cooperation has instruments and proven practices, at hand, to leverage and allow for a harmonised co-existence in the Arctic. Use of the precautionary approach; polluter pays principle; respecting the common heritage of humankind principles; fair and equitable sharing of benefits; integrated assessments, licensing, that restores ecosystem integrity; application of best available science, practice, and innovation, together with inculcating the traditional knowledge of indigenous peoples and local communities are powerful and tried tools to harness a sustainable extractive sector. Improving efficiency and downshifting on production and consumption can use pathways that synergise superior techniques, standards and certifications, settlement planning, choice of building materials, waste management hierarchy of prevention, reuse-recycling-circularity, and disposal. There is much to gain from Maritime Spatial Planning in obtaining clarity on the most sustainable pathway regarding the land and sea interface, from a holistic perspective, including expected impacts and mitigation from the related activities.

The paper emphasises the role of governance, strong institutional capacity, harnessing of cross media impacts, access to technology and knowhow, internalising of costs, and start and strengthening efforts. Integrated approaches are already part of the Arctic countries' regulatory frameworks. Currently several key regulations are under modification, to encourage a quicker transformation. However, their impact is unclear and may take decades beyond 2030 -2050 to monitor, verify and remedy. In cases of uncertain impacts, costs, and liabilities, with demands for burden-sharing associated with the cradle-to- the-grave approach, there is merit to consider that an apparent high value of an exploitation in challenging Arctic conditions may not automatically translate into important contributions to national economy. Exploitation of extractive resources may not bring the expected wellbeing as illustrated by many examples from around the globe. In such case(s) investors might be well advised to hold back, or go slow, on exploiting certain reserves despite the inevitable pressures from vested interests to ramp up exploitation and production as fast as possible.

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Consent for publication Sole author—consent is granted.

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