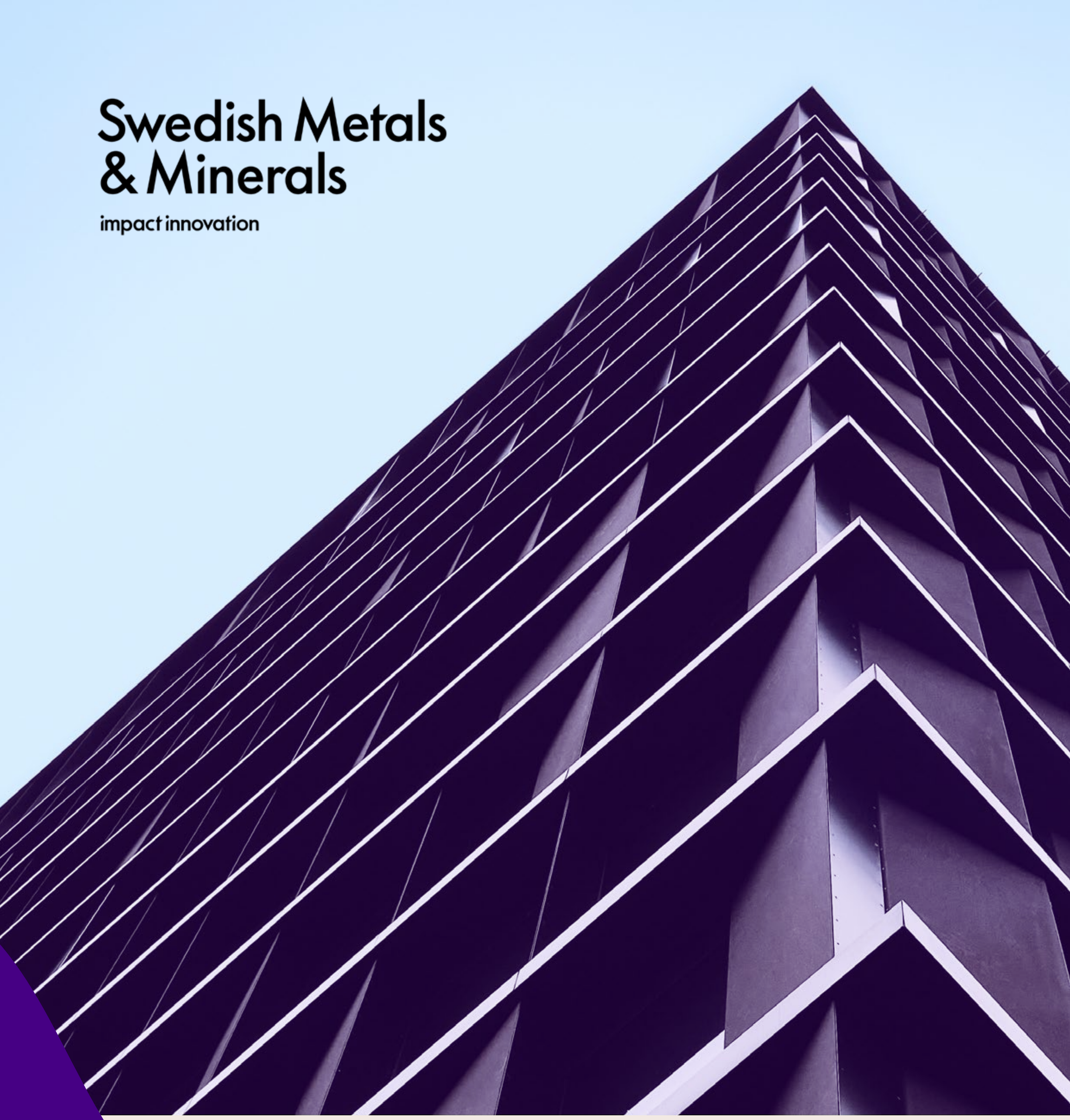
Swedish Metals & Minerals

impact innovation



ROADMAP

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ROADMAP **SWEDISH METALS & MINERALS**

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1. The Mission

Introduction

The program's mission is: *enabling a sustainable and resilient supply of metals and minerals for the societal transition*

The mission is broken down into the following key components required to achieve it:

Enabling: Ensuring that the entire process chain, from exploration to use and recycling, has the *knowledge* and *methods* required to achieve a sustainable and resilient supply of metals and minerals for the societal transition. The extent to which such a process chain can be realized depends on a number of factors external to the program, such as global trade flows, including geopolitical tensions, and political will. The program's goal is to make this complete system possible and ready for implementation when conditions allow.

Sustainable: An activity is sustainable if it can be carried out indefinitely without accumulating harmful effects on its surroundings, whether environmental or social, while simultaneously balancing investments, revenue, and cost in a way that enables economic growth. All human activity impacts its surroundings in a variety of ways, some of which are harmful. The key to sustainability is to ensure that harmful impacts do not accumulate.

Resilient: In the context of the mission, resilience means that the value chain, from exploration to metal products, should be able to withstand unforeseen events that could cause disruption, such as global unrest, supply chain disruptions, the bankruptcy of individual companies, or severe market disturbances. Thus, it should be free from fragile links, ensuring the robustness of the entire process chain.

Metals and minerals supply: Today, Sweden is Europe's leading producer of iron and produces several other metals and minerals, with a highly advanced metal production industry that is globally competitive. The mission is for Sweden to maintain and strengthen its established position, based on three key objectives:

1. Create the conditions needed to extract and utilise critical and strategic elements that are not currently being recovered.
2. Develop metals and minerals processing that is resource-efficient and minimises environmental impact.
3. Design materials that offer greater functionality and make more efficient use of available raw materials, in order to prevent shortages and strengthen resilience.

The societal transition: Moving from a society in which fossil fuels are a key energy source to one in which they are not.

Program and Roadmap

As one tool to achieve the mission, the industry was granted a program within the Impact Innovation initiative (see decision, The Swedish Energy Agency Ref. No. 2024-201554) This is a governmental initiative over ten years, with funding channelled through three authorities: The Swedish Energy Agency, Formas, and Vinnova.

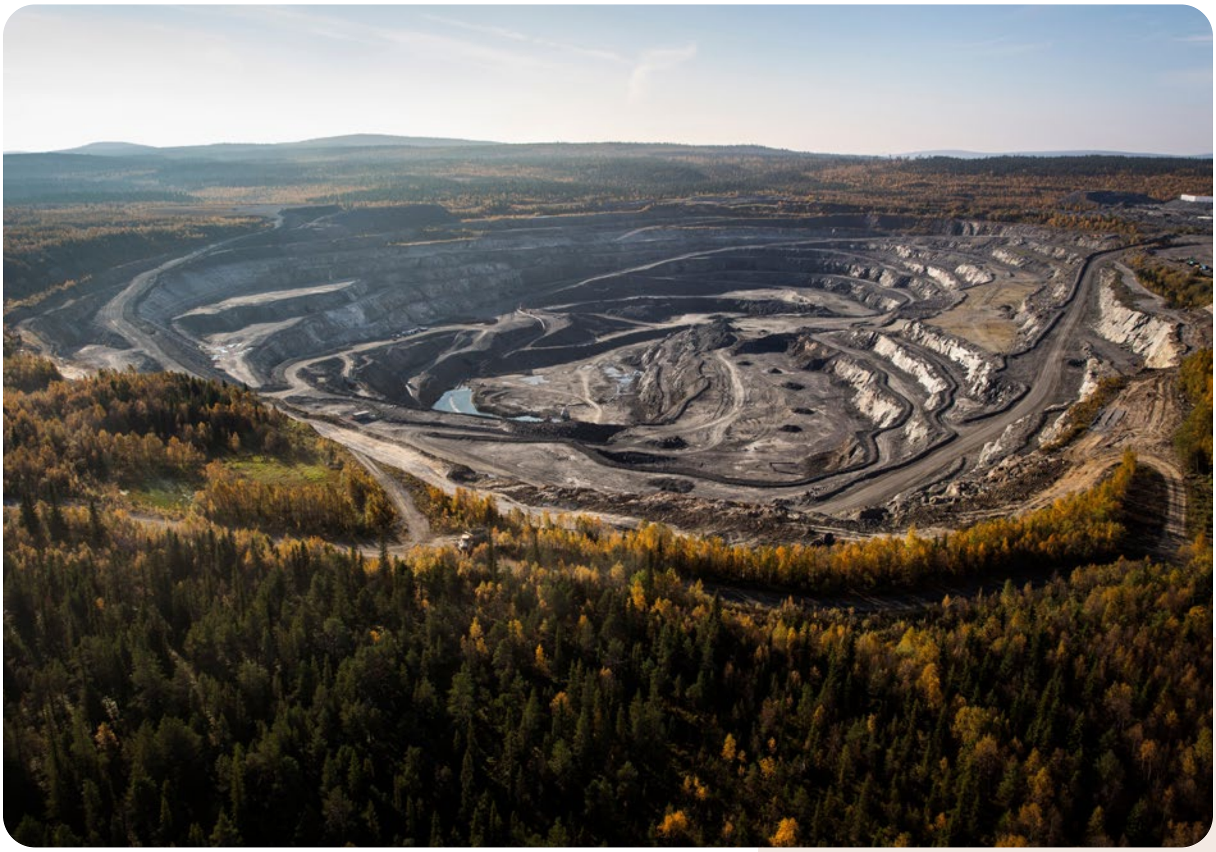
The program funds research and innovation initiatives through open calls, over which it exercises influence regarding content and thematic demarcation.

The program also includes a program office, funded equally by authorities and industry. In addition to analyzing, prioritizing and preparing calls and other interventions, the program office can fund conferences, seminars and other initiatives that complement and strengthen research and innovation efforts.

The program office has compiled this roadmap based on workshops and interviews with representatives from the above-mentioned sectors. The roadmap presents challenges in nine different areas that must be addressed in order to accomplish the mission. It also presents a "desired future state", indicating when the challenges in each area have been overcome.

Vision Statement

Sweden will deliver the critical raw materials and advanced metallic products needed for a modern, resilient and fossil-free society – and set a global benchmark for sustainable resource management.



2. The Minerals and Metals Value Chain in Transition

2.1 The Global and Societal Context

The driving forces behind the mission are fundamentally reshaping the conditions for the minerals and metals sector. Global climate targets, biodiversity commitments, circular economy policies, and increasing geopolitical tensions are redefining how raw materials are sourced, processed, and used.

Minerals and metals are indispensable for a modern, sustainable society. Electrification, fossil-free energy systems, battery technologies, advanced infrastructure, and digitalization all rely on secure and sustainable access to a wide range of raw materials. At the same time, extraction and processing of these materials must fit into such a sustainable society and therefore operate with negligible greenhouse gas emissions, minimal impacts on water, land, and biodiversity, and with strong social legitimacy.

Europe's ambition to strengthen strategic autonomy and secure resilient value chains puts additional emphasis on domestic capabilities in exploration, mining, mineral processing, and metallurgy. In this context, Sweden — with its long industrial tradition, strong innovation ecosystem and access to geological resources — plays a key role.

However, the sector operates within complex and evolving societal frameworks. Permitting processes, land-use conflicts, community engagement, and expectations of transparency and traceability have become central determinants of project feasibility, particularly in the exploration and mining sectors. While technological development has advanced rapidly, regulatory and societal challenges have persisted, requiring new approaches to integrate technical, environmental, and social dimensions from the outset. This roadmap should therefore be understood not merely as an industrial strategy, but as a contribution to a broader societal transformation.

2.2 The Mineral and Metal Process Chain

The minerals and metals process chain consists of a series of interdependent activities that transform geological resources into functional materials and products essential for modern society. These activities form a continuous system — from identifying mineral resources in the ground to producing advanced materials, manufacturing products, and ultimately recovering metals for reuse

Exploration and Resource Definition

Exploration is the process of identifying and evaluating mineral deposits in the Earth's crust. It includes geological mapping, geophysical measurements, drilling, sampling, and analysis to determine the size, quality, and economic viability of a resource.

At this stage, decisions are made about whether a deposit can be developed and how it should be extracted. The characteristics of the ore body — grade, mineral composition, depth, and geometry — significantly impact the subsequent processing methods, energy demand, environmental impact, and recyclability.

Mining and Extraction

Mining involves the physical extraction of ore from the ground, either through underground or open-pit operations. This stage involves extensive interventions in nature and substantial up-front investments, and therefore requires careful planning to ensure safety, resource efficiency, and minimal environmental disturbance.

Modern mining integrates automation, electrification, digital monitoring, and advanced ground control systems. The way a deposit is mined — including fragmentation methods, ore selectivity, and waste management — directly affects downstream processing efficiency, recovery rates, and environmental performance.

Mineral Processing and Beneficiation

Mineral processing separates valuable minerals from waste rock. This typically involves crushing, grinding, flotation, magnetic separation, or other physical and chemical techniques.

This stage is often energy- and water-intensive. Its efficiency determines how much of the valuable material can be recovered and how much becomes tailings. Processing choices influence water management, energy consumption, and the quality of feedstock delivered to metallurgical operations.

Metallurgical Processing and Refining

Metallurgy extracts and refines metals from mineral concentrates or recycled materials. This includes pyro- and hydrometallurgical processes, direct reduction, electrolysis, and other refining techniques.

Metallurgy determines the purity and chemical composition of the final metal and thus lays the foundation for its performance in use. It is also central to decarbonization, as metallurgical processes are typically heat- and energy-intensive. The transition to electrification, hydrogen-based reduction, and circular material flows is reshaping this stage of the process chain.

Material Development and Alloy Design

Once metals are refined, they are engineered into specific materials and alloys tailored for (often conflicting) performance requirements such as strength, hardness, ductility, corrosion resistance, conductivity, formability, weldability and heat conductivity.

Material development connects directly to product innovation. Design choices at this stage influence not only performance in use, but also manufacturing efficiency, durability, reparability, and recyclability.

Product Manufacturing and Integration

Metals and alloys are transformed into components and integrated into product assemblies such as vehicles, energy systems, infrastructure elements, electronics, and industrial equipment.

Manufacturing technologies, product design standards, and regulatory requirements increasingly shape upstream production. Requirements for a low carbon footprint, traceability, and circularity are now becoming material properties alongside traditional ones such as hardness, strength and durability, thus influencing material selection and processing routes.

Recycling and Secondary Resource Recovery

All the way from the mine through to manufacturing, metals ending up in side-streams and residuals can be recovered and reintroduced into the value chain. The same is true for products at the end of their life. Recycling reduces the need for primary extraction and could potentially reduce environmental impact, depending on collection, sorting, and processing systems.

Increasingly, recycling is not an isolated stage but integrated with primary metallurgy. The availability and quality of scrap influence alloy design, impurity levels, and raw material demand upstream.

System Interdependence Across the Value Chain

The different parts of the value chain are technologically, environmentally, and economically interconnected. In the broadest perspective, exploration results determine the material design space and thus the functionality of metal products. One obvious example is Rare Earth Elements, which are crucial for many electrical applications, but where global supply variations lead to cost fluctuations and even shortages of certain end products. Cost fluctuations and global trade distortions also affect elements with more mature markets such as copper, nickel, vanadium, lithium, and phosphorus.

Between the two ends, there are other interdependencies, such as exploration results determining mining methods and processing routes, mining practices influencing process efficiency and waste generation, and processing and metallurgy defining energy intensity, emissions, and material quality. Recycling practices obviously affect materials supply and are in turn dependent on material design and production.

Water and energy systems run through the entire chain. This means that water and energy efficiency cannot be addressed only in a single step but have to be viewed from a systems perspective. Access to fossil-free electricity, hydrogen infrastructure, efficient water management, and circular heat and material integration are decisive for achieving climate and sustainability goals.

Because of these interdependencies, no

single segment can achieve sustainability or competitiveness in isolation. If not systemically coordinated, improvements in one part of the chain may create bottlenecks or unintended consequences elsewhere, thus increasing system waste and jeopardizing the program mission.

Collaboration, partnerships and mutual understanding are thus important to optimizing value chain performance and are therefore a core priority for accomplishing the mission.

In fact, the mineral and metal value chain must be understood and developed as an integrated socio-technical system — linking geology, technology, industry, policy, environment, and society to provide solutions for a sustainable and resilient future.

2.3 Drivers and Challenges

Common and Overarching Perspectives

The metals and minerals sector faces a set of shared and overarching drivers:

- Climate neutrality and reduced greenhouse gas emissions
- Increased resource efficiency, including circularity
- Water management and reduced environmental impact
- Biodiversity protection and responsible land use
- Secure and resilient supply chains
- Digital transformation and automation
- Strengthened competitiveness and productivity

The drivers are, however, facing complex conditions:

- Geopolitical tensions leading to regionalized markets
- Global competition for strategic raw materials
- Rapid changes in demand and immature markets for many raw materials
- Rapidly evolving regulatory frameworks
- High capital intensity and long investment cycles
- Societal acceptance and competing land-use interests
- Increasingly complex metal and mineral sources lead to new demands for technology, process and product development

One key challenge is balancing accelerated deployment of new technologies with regulatory predictability and societal trust. Technological readiness alone is not sufficient; implementation depends on coherent policy frameworks, effective stakeholder dialogue and access to skills and infrastructure. The transformation required is systemic rather than incremental. It demands coordinated action across value chains and sectors.

Prerequisites and challenges beyond the roadmap

Certain local challenges lie beyond the direct scope of this roadmap but are decisive for its successful implementation.

Energy Systems and Power Infrastructure

Electrification, hydrogen-based processes, and digitalized operations increase demand for reliable fossil-free electricity. Access to grid capacity, competitive pricing, and predictable long-term energy policy are enabling conditions for fossil-free mining and metallurgy. Without timely expansion of generation and transmission infrastructure, the transition risks delay.

Transport and Logistics Infrastructure
Efficient rail, road, and port infrastructure is essential for competitive and sustainable minerals and metals production and distribution. Increased volumes of critical raw materials, deeper integration into European value chains, and expanding circular flows place new demands on logistics systems, particularly in northern Sweden.

Clarifying the Limitation

This roadmap focuses on research, innovation, collaboration, and systems development within the minerals and metals sector and beyond. It does, however, aim not to replace national infrastructure planning, energy policy, or transport strategies.

Nevertheless, achieving the desirable future states described in the following chapters requires alignment and adaptation between technological innovation and these broader societal framework conditions.

2.4 Research, Innovation and Collaboration

Research and innovation are decisive enablers of the transformation described in this roadmap. Achieving fossil-free production, strengthened raw material resilience, and circular value chains requires coordinated advances across the entire system — from exploration and mining to metallurgy, manufacturing, recycling, and skills development. Breakthroughs are required in following areas:

- Electrified and automated mining systems
- Fossil-free metallurgical processes, including hydrogen-based reduction and bio-carbon solutions
- Advanced mineral processing for complex and low-grade ores
- Recovery of critical and strategic raw materials from primary and secondary streams
- Materials combining advanced and complex property profiles with recyclability and high production efficiency
- Circular use and valorization of residues and by-products
- Digital twins, AI-assisted process control, and integrated system optimization
- Traceability and digital product passport systems spanning the entire process chain
- Multi-scale modelling of process–structure–property relationships across the entire process chain
- Sustainable water and environmental management

These priorities are closely aligned with the mission of ensuring a sustainable and resilient metals and minerals supply for the societal transition.

Industrial Research and Innovation in Practice

The transformation is not hypothetical; it is already underway through large-scale industrial research and demonstration efforts in Sweden.
Examples include:

- Development and industrial testing of fossil-free ironmaking routes based on hydrogen
- Electrification and automation of underground mining systems
- Large-scale investments in scrap-based and direct-reduced steel production
- Integration of digitalization and AI into mineral processing and metallurgical control systems

- Innovative development and use of mineral and metal products, strengthening raw material availability and resilience
- Industrial symbiosis initiatives for utilization of slag, tailings, and process residues
- Carbon capture and utilization concepts for hard-to-abate emissions

Swedish companies are investing heavily in pilot plants, demonstration facilities, digital infrastructure, and competence development. Publicly funded research plays a crucial role in de-risking these investments and accelerating scale-up.

Companies are responsible for the majority of R&D investment in the sector, but public co-funding enables long-term research, high-risk innovation, and system integration — particularly in areas such as hydrometallurgy, CRM refining, circular material flows and advanced process modelling.

The Role of the Program

The program complements industrial investment and sectoral initiatives by providing:

- A mission-oriented coordination platform
- A system integrator across value chain stages
- A catalyst for cross-sector collaboration
- A bridge between research, policy, and industrial implementation

By combining technological, environmental, social, and policy perspectives, the program ensures that innovative efforts are aligned with long-term sustainability goals rather than optimized in isolation. Through its activities, calls and projects, system-level analysis and targeted interventions, the program

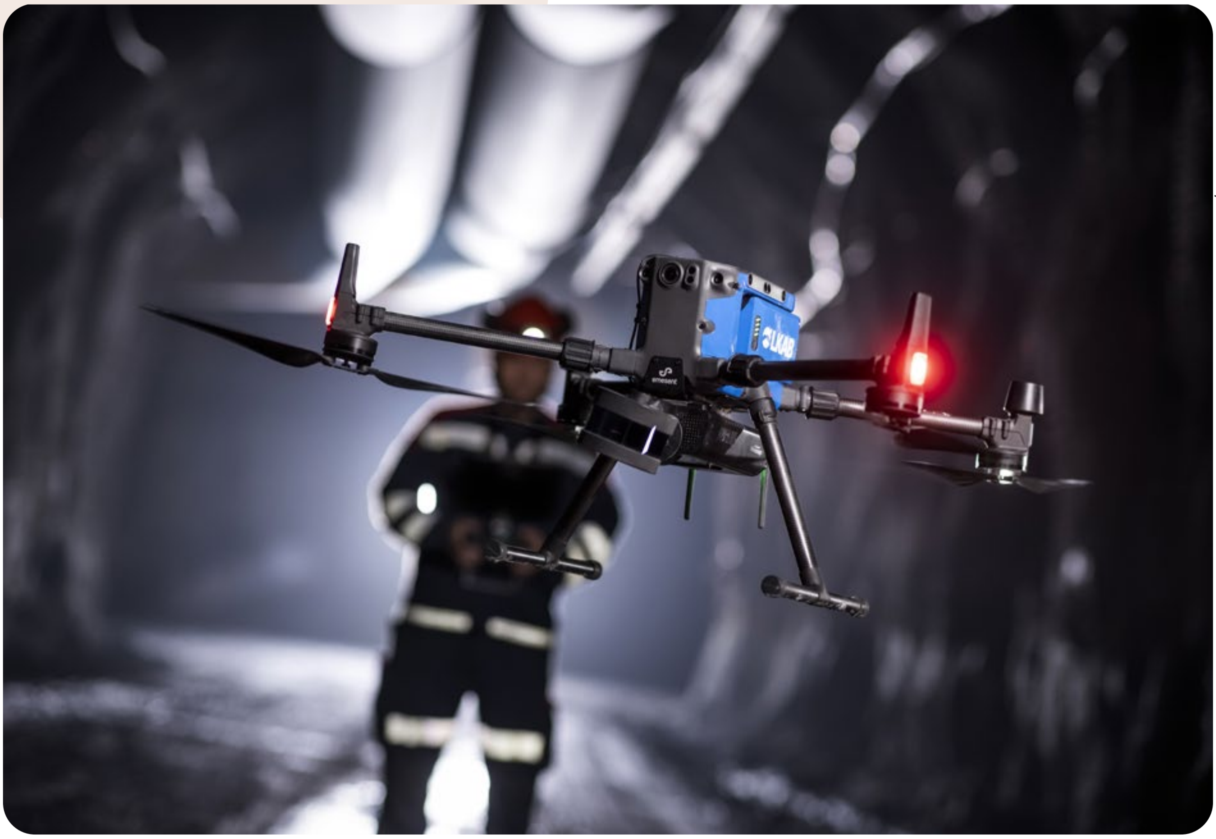


FOTO: FREDRIC ALM, LKAB

helps identify bottlenecks, avoid duplication, and strengthen synergies across initiatives.

National Collaboration Landscape

The program operates within a broad national innovation ecosystem.
Related Impact Innovation programs, such as **Net Zero Industry** (ref), and **Water Wise Societies** (ref), address adjacent systemic challenges including industrial decarbonization and sustainable water governance. Joint activities and coordinated calls can accelerate system integration where mineral and metal production intersects with energy and water systems.

Excellence clusters under development at Swedish universities will also contribute critical competence and research infrastructure. Existing and emerging centres in mining, metallurgy, materials science, digitalization, and environmental systems form an important knowledge base for the mission.

In addition, regional innovation environments and industrial clusters support SME participation, scaling of solutions and competence supply across the country.

European and International Dimension

At European level, the transformation of the mineral and metal value chain is closely linked to:

- The Critical Raw Materials Act (CRMA)
- The Green Deal and Climate Legislation
- Industrial decarbonisation partnerships
- Circular economy policies

The co-funded European partnership **RAMP (Raw Materials for the Green and Digital Transition)** shares many of the goals of Swedish Metals and Minerals and provides a platform for coordinated research, demonstration, and policy development across Europe.

The **Clean Steel Partnership** calls address decarbonization in the steel industry, particularly related to reduction processes. Through engagement in European technology platforms, partnerships and industrial alliances, Swedish actors both contribute to and benefit from international knowledge exchange, large-scale demonstration funding and harmonised standards development.

International cooperation can also strengthen supply security through strategic partnerships on critical raw materials, shared standards for sustainable production, and coordinated recycling systems.

FOTO: FREDRIC ALM, LKAB

3. Method

The following chapters describe the stages from exploration to product manufacturing and the three aspects of sustainability in relation to the mission.

Each chapter describes challenges that must be overcome to fulfil the mission.

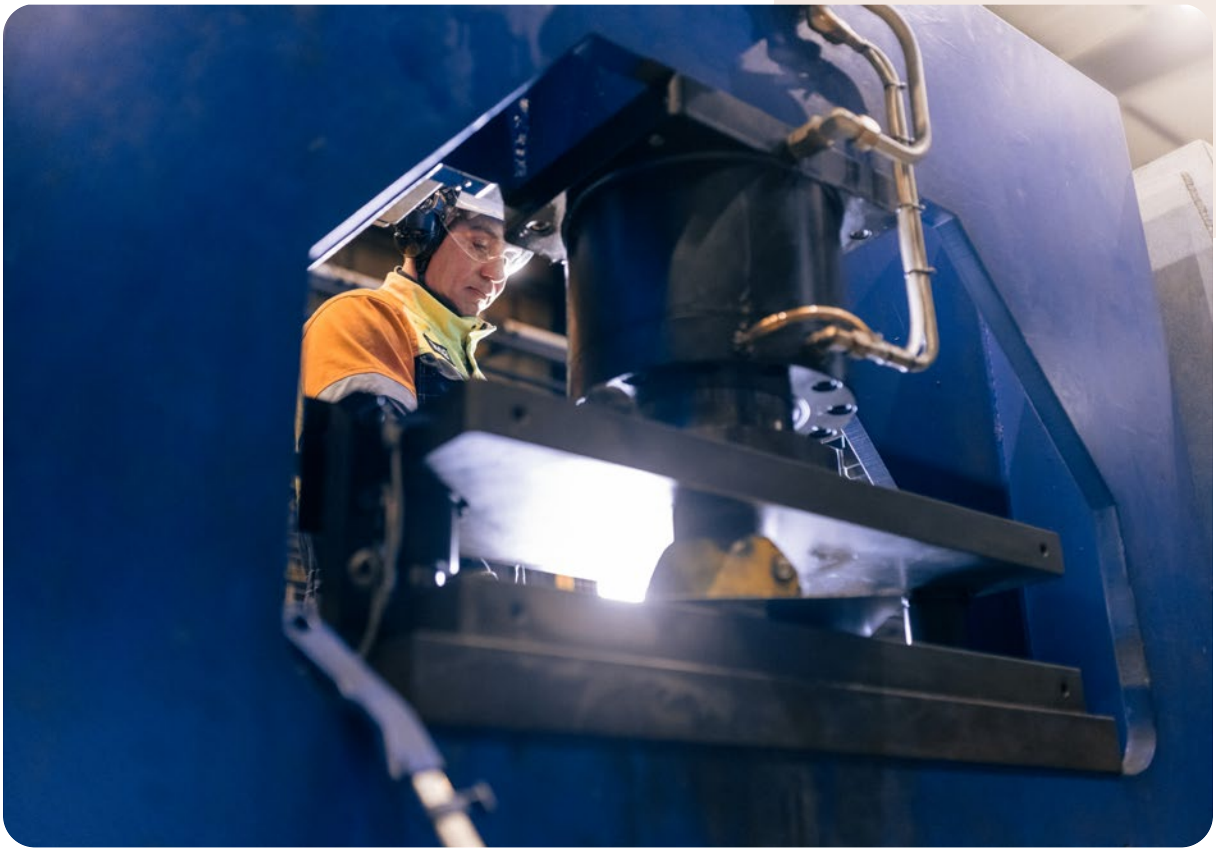
Each chapter also lays out a Desirable Future State, i.e. how the area would function when current challenges are overcome.

The idea is that the program directs its resources toward research and development efforts that address and resolve the challenges to the point where the desirable future state is within reach.

As mentioned in this document, there are also many other initiatives and efforts that address and may help resolve the challenges. Therefore, it is a key task for program management to prioritize which challenges are to be addressed when and by what means. To this end, the program will constantly review the status of the challenges and the work ongoing to address them against the gaps between the desired future states.

Here, program functions such as the advisory board Mission Control should ensure that the challenges are analyzed from all relevant program perspectives.

This roadmap was published in 2026 and describes challenges and desirable future states towards 2035–2045.



4. Focus areas

4.1 Exploration

Exploration forms the foundation of the entire mineral and metals value chain. Without continuous exploration, there can be no sustainable production of the raw materials essential for modern society and its transition. Sweden's bedrock holds significant potential for industrial minerals, iron, base, and precious metals, as well as critical raw materials (CRMs), but large areas remain under-explored — particularly at depth and beneath sedimentary cover.

To ensure a secure and responsible domestic supply of metals, future exploration in Sweden must combine scientific excellence, technological innovation, and societal acceptance. Efficient and low-impact exploration will rely on better geological understanding, advanced sensing, and analytical techniques, and integrated data workflows that connect early-stage exploration with ore characterization and processing potential. At the same time, exploration must adapt to new environmental and societal expectations, with transparent permitting and stronger collaboration among industry, academia, and authorities.

The coming decade represents a critical opportunity to renew Sweden's exploration capacity, combining digital transformation and environmental responsibility to uncover the resources needed for a sustainable and competitive mining industry.

EXPLORATION

CHALLENGES

Geoscience and Technology

- Detecting and exploring deep or concealed deposits remains a major technical and scientific challenge. Existing detection methods have limited resolution at depth and depend heavily on sparse legacy data.
- Although technical tools are rapidly evolving, the lack of robust geological models and mineral systems knowledge hinders meaningful interpretation.
- Re-exploration of historically mined areas offers significant potential but is hindered by legal, environmental, and practical challenges.
- Development of new and non-invasive methods (remote and airborne sensing, geochemical fingerprinting, and geophysical approaches) for data collection to reduce the environmental footprint.
- Long delay between identifying ore bodies and the start of mining, and high uncertainties contribute to increasing financial risk and environmental disturbance.

Data and Digital Transformation

- Limited integration of multidisciplinary data into dynamic 3D and 4D geological models.
- To ensure that scientific advances translate into operational value, new evaluation methods for existing datasets have to be developed, and research results should be linked with field implementation.
- Machine learning and AI-driven prospectivity modelling require uncertainty-aware and transparent approaches.
- Balancing automated integration, optimization, and validation of AI-generated solutions for mineral exploration while maintaining expert oversight and data quality control.
- Insufficient interoperable data infrastructures and lack of access to standardized, high-quality geoscientific data that is critical for both industry and public sector use.

Environmental and Social Frameworks

- Ensuring responsible land management and stakeholder trust.
- Access to land requires balanced solutions between competing land uses, national interests, and indigenous rights.

- Shorter exploration seasons due to climate change reduce opportunities for winter drilling.
- Insufficient knowledge levels about exploration and mining among public authorities, including municipalities, county administrations, and national agencies, lead to uninformed and inconsistent decision-making.

Knowledge and Infrastructure Development

- Establishing a broad and deep competence base covering mineral systems, geoscientific modelling, sensing technology, AI, and Arctic field logistics.
- Ensuring stable access to infrastructure such as drilling capacity, laboratories, and data platforms is crucial for competitiveness.

EXPLORATION

DESIRABLE FUTURE STATE

Technical and Scientific Excellence

- High-resolution imaging and predictive targeting beneath cover and at depth are routine, supported by advanced sensing technologies and robust geological models.
- New exploration technologies are fully operational, enabling resource discovery in previously inaccessible areas.
- Integrated geoscience workflows link early-stage exploration with ore characterization and processing potential, ensuring efficient resource development.
- Efficient, low-impact drilling and real-time assays are implemented for cost-effective and environmentally responsible exploration at depth.
- Climate-adaptive operational models ensure resilience to shorter exploration seasons and extreme weather conditions.

Digital Transformation and Data Integration

- Dynamic 3D and 4D geological models are standard, powered by interoperable, high-quality geoscientific data platforms accessible to industry, academia, and authorities.
- AI and machine learning are seamlessly embedded in prospectivity analysis, real-time drilling analytics and decision support systems, with transparent, un-

certainty-aware algorithms and "human-in-the-loop" oversight.
- Continuous feedback loops between digital tools, geoscientists, and field operations ensure rapid translation of research into operational value.

Environmental Responsibility and Attractiveness

- Exploration operates with a minimal land, water, and CO_2 footprint, supported by non-invasive sensing and low-impact drilling technologies.
- A robust competence pipeline exists, with revitalized geoscience education programs aligned to industry needs and incorporating digital, AI, and sustainability competencies.
- Continuous professional development programs maintain a highly skilled workforce across geoscience, data science, and Arctic logistics.

Infrastructure and Logistics

- Stable access to critical infrastructure — including drilling capacity, laboratories, and data platforms—is guaranteed through strategic investments and shared-use models.
- Arctic and remote region logistics are fully supported by advanced technologies and coordinated supply chains, enabling year-round exploration activities.

Governance and Institutional Capacity

- Public authorities at all levels possess deep knowledge of exploration and mining processes, ensuring informed, consistent, and timely decision-making.
- Institutionalized collaboration frameworks between government, industry, and academia drive innovation and policy alignment.
- Economic and financial mechanisms, including incentives and risk-sharing models, sustain long-term investment in exploration and technology development.

Vision Statement

Sweden is recognized for its exploration ecosystem, which has evolved into a model of sustainability, innovation, and resilience. Resources can be discovered also in previously inaccessible areas, including ore characterization and processing potential, thus ensuring efficient resource development.

4.2 Mining

Mining is becoming an increasingly complex process. Ore deposits are more often located at greater depths, while environmental requirements for mining operations continue to tighten. These factors pose several challenges both for mining operations and the industry's ambitions for achieving sustainability.

To meet these challenges and strengthen competitiveness, the working environment must be safeguarded and energy efficiency and productivity improved, while simultaneously reducing environmental impact.

Safety-driven innovation—through automation, improved ground control, and reduced human exposure to hazardous environments—has been a central motivation for the development of new mining methods and remotely controlled and autonomous equipment. In addition, the extraction process must achieve higher energy efficiency and be integrated with downstream processes. Furthermore, to ensure sustainable mining processes, an extensive reduction in emissions is needed without reducing economic sustainability. Potential new products from waste materials, including waste rock and tailings, could also affect the mining operation, which requires new solutions across the whole mining chain.

To achieve safe and sustainable mining, new innovations and technical solutions must be developed and implemented. These are dependent on reliable monitoring and communications within a mine. Therefore, data-driven decision-making is a requirement for future mining.

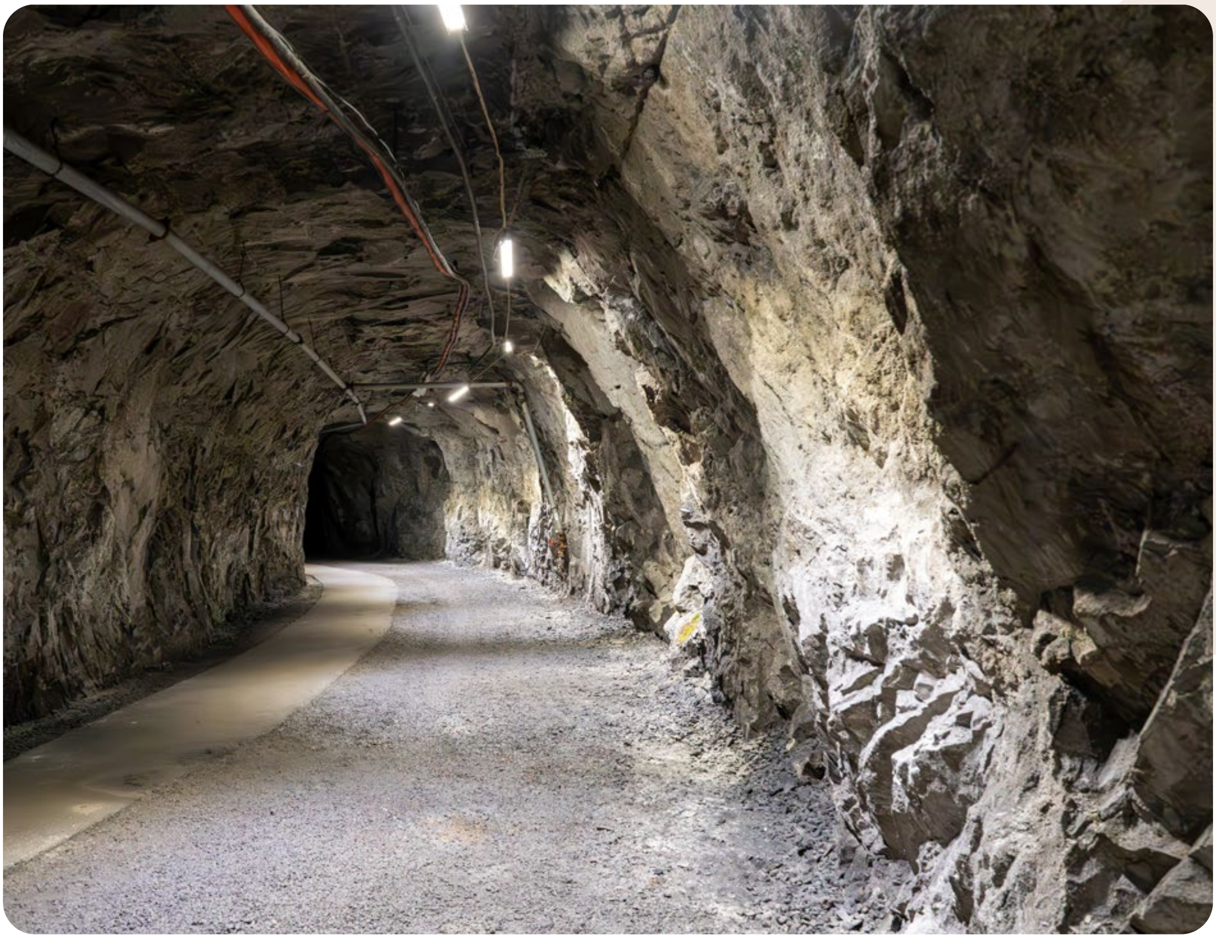


FOTO: ADOBE STOCK

MINING

CHALLENGES

System and Strategy

- Treat mining as a complete system — from resource definition to processing, waste management, and closure — integrating sustainability, safety, and productivity goals.
- Adapt management and operational strategies to rapid technological change, spanning research, development, and production across the mining value chain.
- Address the growing geopolitical challenges and price volatility for critical raw materials through selective, flexible mining of low-grade ores and CRMs.
- Establish predictable and transparent permitting frameworks for mining operations to support long-term investment and innovation.
- Strengthen strategic foresight and scenario planning to align national interests, industrial competitiveness, and climate objectives.
- Keep pace with the rapid evolution of digitalization, automation, and electrification technologies to meet the demands of deep, complex, and fossil-free mining operations.

Depth, Complexity, and Productivity

- Tackle the increasing geotechnical and operational complexity of mining, where high rock stresses, seismic risks, and limited access demand new methods, equipment, and support systems.
- Develop safe, efficient, and economically viable mining solutions, including adaptive mine design and predictive ground control.
- Maintain productivity and competitiveness despite lower ore grades. Advance continuous excavation and adaptive mine planning, including preconditioning techniques to manage stress and enhance reliability.
- Implement KPI-based performance metrics — such as energy per ton, CO_2 per ton, and resource recovery — to benchmark and accelerate sustainability.

Technology, Automation, and Safety

- Deploy autonomous, continuous, and fossil-free mining systems supported by real-time process control and predictive maintenance.
- Enable safe integration of hybrid operations, where manual, semi-autonomous, and autonomous machines interact seamlessly under unified standards.
- Ensure real-time data exchange and analytics capabilities across mining

systems, while addressing cybersecurity, data infrastructure and data governance challenges.
- Develop sustainability-driven products and systems by designing equipment that meets stringent environmental standards, including energy efficiency, emissions reduction, and circularity in materials and manufacturing.
- Expand the use of AI, advanced analytics, and digital twins to connect geological models, production systems, and maintenance strategies, enabling proactive and data-driven decision-making.
- Improve ground control, monitoring, and sensor-based risk management to prevent incidents and increase operational safety.
- Reduce human exposure to hazards through automation and remote-controlled systems, supported by robust communication and localization networks with full coverage.
- Enhance ventilation, air quality, and climate control for healthier underground environments, ensuring well-being and safety for all personnel.

MINING

DESIRABLE FUTURE STATE

Operational Excellence and Sustainability

- Mining is fossil-free, powered by electricity, hydrogen, and other CO_2-neutral energy sources.
- Continuous excavation is standard practice, reducing downtime, energy use and material losses.
- Adaptive mine planning is routinely applied, minimizing waste and maximizing resource recovery.
- All equipment is designed for circularity, with modular components, recyclable materials, and embedded lifecycle tracking for reuse, re-manufacturing, and minimal waste.
- Energy, water, and CO_2 intensity per ton of ore have decreased dramatically, supported by KPI-driven performance metrics for transparency and benchmarking.
- Circular mining models are increasingly implemented: waste rock and tailings are valorized, and for example nitrogen, phosphorus, sulphur, and CO_2 are recovered and reused.
- Mine closure and post-mining land use are integrated from the start, ensuring minimal ecological footprint.

Technology and Automation

- Fully interoperable and modular systems, with equipment and digital platforms that enable plug-and-play integration across mixed fleets and mining environments, supported by international standards.
- Autonomous and remote-controlled systems dominate production, operating under ISO-certified mixed-traffic protocols for seamless interaction between manual and automated equipment.
- AI-driven analytics, digital twins, and predictive maintenance ensure data-driven decision-making, optimizing safety, productivity, and sustainability.
- Robust cybersecurity and data governance frameworks safeguard digital infrastructure and operational continuity.

Safety and Attractiveness

- A strong safety culture contributes to attractive workplaces, where trust, competence development, and employee involvement are central, and where safety is seen as an enabler of productivity, innovation, and long-term competitiveness.
- Human exposure to hazardous areas is virtually eliminated through automation and remote operations.
- Underground environments feature advanced ventilation, air quality control, and climate systems, ensuring health and well-being.
- The sector attracts and retains leading competence in mining engineering as well as automation, electrification, sustainability, and digitalization.

Vision Statement

Sweden is recognized as a global leader in safe, sustainable, and digitally integrated mining and mining technology — pioneering fossil-free operations, circular resource models, and data-driven innovation that set the benchmark for productivity, environmental stewardship, and social responsibility.

4.3 Mineral Processing and Metallurgy

Mineral processing and metallurgy together form the critical bridge between mining and the metals and materials that enable the societal transition. They determine how efficiently, responsibly, and resiliently mineral resources are transformed into products on which society depends. While mineral processing liberates and concentrates valuable minerals from ore, metallurgy extracts, refines, and recycles metals from both primary and secondary sources. As such, these stages are central to the sustainability, resilience, and competitiveness of the Swedish mining and metals value chain.

Sweden has long combined advanced technology, fossil-free electricity, and innovation to achieve world-leading productivity with low emissions. However, the coming decade presents significant challenges: new and increasingly complex raw materials, lower ore grades, growing volumes of scrap, and the urgent need to decarbonize energy- and heat-intensive processing and smelting. Both mineral processing and metallurgy are highly energy- and water-intensive, and future operations must therefore be fossil-free, resource-efficient, and circular. This requires new methods to recover critical raw materials, manage by-products, and close material loops through recycling and side-stream valorization.

In parallel, fundamental shifts in metallurgical routes — driven by climate targets — are reshaping material flows and process requirements. The transition towards increased use of secondary raw materials, direct reduction, and fossil-free energy carriers such as hydrogen is altering demand for raw material qualities, process flexibility, and system integration across mineral processing, metallurgy, and recycling. At the same time, several process steps remain hard to abate, reinforcing the need for coordinated technological, infrastructural, and value-chain solutions.

Meeting these challenges demands an integrated transformation across the entire process chain—from crushing and flotation to smelting, refining, and recycling — supported by digitalization, real-time data, and system-level optimization. Efficient water and waste management must be aligned with clear regulatory frameworks and harmonized sustainability metrics. At the same time, Sweden must continue to strengthen its research and innovation capacity, pilot and demonstration facilities, and competence base to secure long-term global leadership in sustainable mineral processing and metallurgy.

FOTO: SSAB

MINERAL PROCESSING AND METALLURGY

CHALLENGES

Complex and Variable Raw Materials

- Lower ore grades, increasing mineralogical complexity, and polymetallic or secondary feedstocks require advanced and often hybrid mineral and metallurgical separation methods.
- Limited refining capacity for critical raw materials (CRMs) in Sweden and Europe constrains value creation and supply security.
- Knowledge gaps regarding how trace elements affect product purity, recovery rates, and process economics.
- The global move from blast furnace to the electric arc furnace (EAF) increases demand for removing scrap impurities.
- A need for holistic, cross-disciplinary solutions that integrate mineral processing, hydrometallurgy, and pyrometallurgy to handle complex inputs efficiently.
- Ensuring robust and operable mineral processing and metallurgical processes that can handle increasing variability in raw materials, energy supply, and operating conditions without compromising safety, quality, or efficiency.
- Refining gases and inclusions in steel produced in EAFs using new combinations of iron sources, alloys, and slag formers.

Circularity and Valorization of Residuals

- Valorization of by-products is limited by technical, legal, and economic barriers.
- The detailed content of residuals and circular streams is not known well enough to avoid inadvertent mixing and other cost-driving risks.
- The lack of systematic recovery of critical and strategic elements from ores, slags, dusts, and residues remains a significant challenge.
- Residuals from other industrial processes and even post-consumer waste contain potentially valuable raw materials for the metals-producing industry.
- Recycling of falling oxide fractions.
- Finding suitable and sustainable uses for increased volumes of slag from different metallurgical operations.
- Lack of holistic approaches and business models that combine industrial, environmental, geopolitical, and economic perspectives on circularity options.
- Insufficient integration between primary metallurgy and large-scale recycling of batteries, electronics, alloys, and incineration residues limits resource efficiency and value creation.

Energy and Decarbonization

- Reducing the high energy intensity of comminution and smelting requires substantial efficiency gains across all stages of beneficiation, refining, and metallurgical processing.
- Transitioning to fossil-free energy sources while maintaining process stability, operational flexibility, and product quality in energy-intensive metallurgical operations.
- Decarbonizing metallurgical energy needs through large-scale electrification and hydrogen-based reduction, including enabling fossil-free electrical heating across the full temperature range required in metals production.
- Ensuring cost-efficient, reliable access to fossil-free electricity and hydrogen at scale, including integration with local and regional energy systems to support grid stability, flexibility, and industrial demand.
- Scaling up hydrogen infrastructure—including electrolysis capacity, storage, and logistics—while addressing material compatibility, safety, and embrittlement risks in metallurgical environments.
- Developing sustainable and resilient supply and value chains for fossil-free reductants and electrodes, including bio-carbon with consistent quality and integrity, and fossil-free electrode materials for both self-baked and pre-baked technologies.
- Improving system-level energy integration by efficiently utilizing process spillovers such as excess heat and oxygen to enhance overall resource and energy efficiency.

Water and Environmental Management

- High water demand in mineral processing requires new and improved water management and minimized discharge.
- Water protection regulations require improved purification technologies that avoid creating additional complex residues.
- Development of sustainable and circular water systems coordinated with environmental legislation.
- Greater understanding of water quality effects on processing and metallurgy, including interactions with reagents and emissions.

Digitalization and Process Integration

- Optimizing entire process chains requires real-time sensing, geo-metallurgy, and predictive models.
- Robust sensors and reliable data are required to improve yield, reduce waste, and increase energy efficiency through AI-assisted process control.

- Digital twins are needed to enable proactive optimization from geological models to metallurgical outputs.
- Interoperability and benchmarking require data standardization and integration across units and companies.

Infrastructure and Research Capacity

- Insufficient pilot and demonstration facilities exist to test and scale new metallurgical and recycling processes.
- Declining student enrollment and skill shortages limit long-term capacity.

Legal, Regulatory, and Standardization Barriers

- Lack of coherence between legal requirements and sustainable solutions, especially regarding emissions to water, waste handling, and by-product use.
- Inconsistent definitions of "waste" reduce circularity and prevent resource recovery.
- The absence of harmonized standards for measuring sustainability performance and emissions.
- Regulatory gaps for industrial minerals, slags, and CRM refining limit industrial flexibility.
- Slow permitting processes and uncertainty in environmental approvals delay innovation and investment.

MINERAL PROCESSING AND METALLURGY

DESIRABLE FUTURE STATE

Resource Efficiency and Circular Material Flows

- Energy-saving comminution, bulk sorting, and advanced flotation are standard, significantly reducing energy use and improving upstream material quality for metallurgical processing.
- Holistic, cross-disciplinary solutions integrate mineral processing, hydrometallurgy, and pyrometallurgy, enabling efficient handling of complex primary and secondary raw materials.
- Methods for extracting valuable elements — including critical and strategic materials — from residuals and waste streams are so cost-effective that all significant material streams are valorised.
- Tailings, slags, dusts, and other residues are transformed into usable raw ma-

terials with suitable functional properties and are integrated into new value chains, for example as inputs for cement clinker and supplementary cementitious materials (SCMs).

- Scrap collection, sorting, and utilisation are highly developed, making steel scrap and other secondary materials fully viable feedstocks on par with virgin raw materials.
- Large-scale recycling of batteries, electronics, alloys, and incineration residues is seamlessly integrated with primary metallurgical operations.

Fossil-Free Energy and Process Transformation

- Hydrogen- and electrified metallurgical processes are fully operational, with sustainable bio-carbon used where relevant.
- Handling of hydrogen is as straightforward and safe as that of other fuels and reduction agents, making its application a routine business decision rather than a technical constraint.
- Heating processes are emission-free and can seamlessly switch between multiple technologies — such as induction, resistance heating, hydrocarbons, hydrogen, and electricity — to optimise availability, loads, and costs.
- Specifications for metallurgical-grade bio-carbon are well established, with mature and transparent markets enabling reliable sourcing and trade.
- Sustainable, fossil-free electrodes are available through resilient European value chains, supporting both pre-baked and self-baked technologies.
- For hard-to-abate process emissions, suitable and cost-effective carbon capture technologies are available and implemented where required.
- Metallurgical processes exist for removal of all types of tramp elements.

Water and Environmental Performance

- The effects of water quality on mineral processing and metallurgy — including interactions with reagents, emissions, and product quality — are well understood and systematically managed.
- Sustainable water treatment and water management systems are fully implemented and aligned with environmental legislation, enabling closed-loop operation and minimal environmental impact.

Digitalisation, Process Control, and Integration

- Real-time sensing, metallurgical and geometallurgical models, and digital twins are integrated across plants and value chains.
- AI-assisted process control ensures optimised, stable, and environmentally friendly operations, improving yield, energy efficiency, and resource utilisation.

- Strong integration and industrial symbiosis between upstream and downstream industries and surrounding communities reduce the overall environmental footprint and enhance system efficiency.

Industrial Capacity, Competence, and Global Leadership

- Refining capacity in Sweden and Europe is established for key critical raw materials, strengthening supply security and value creation.
- A strong competence base is secured through close collaboration between industry, academia, and research institutes, supported by continuing education and skills development.
- Sweden is recognised internationally as a global benchmark for fossil-free, resource-efficient mineral processing and metallurgy, setting the standard for sustainable metals production.

Vision Statement

Sweden is recognised as a global leader in fossil-free, resource-efficient mineral processing and metallurgy, delivering resilient, circular, and digitally integrated process chains that enable sustainable metals production, industrial competitiveness, and the societal transition.

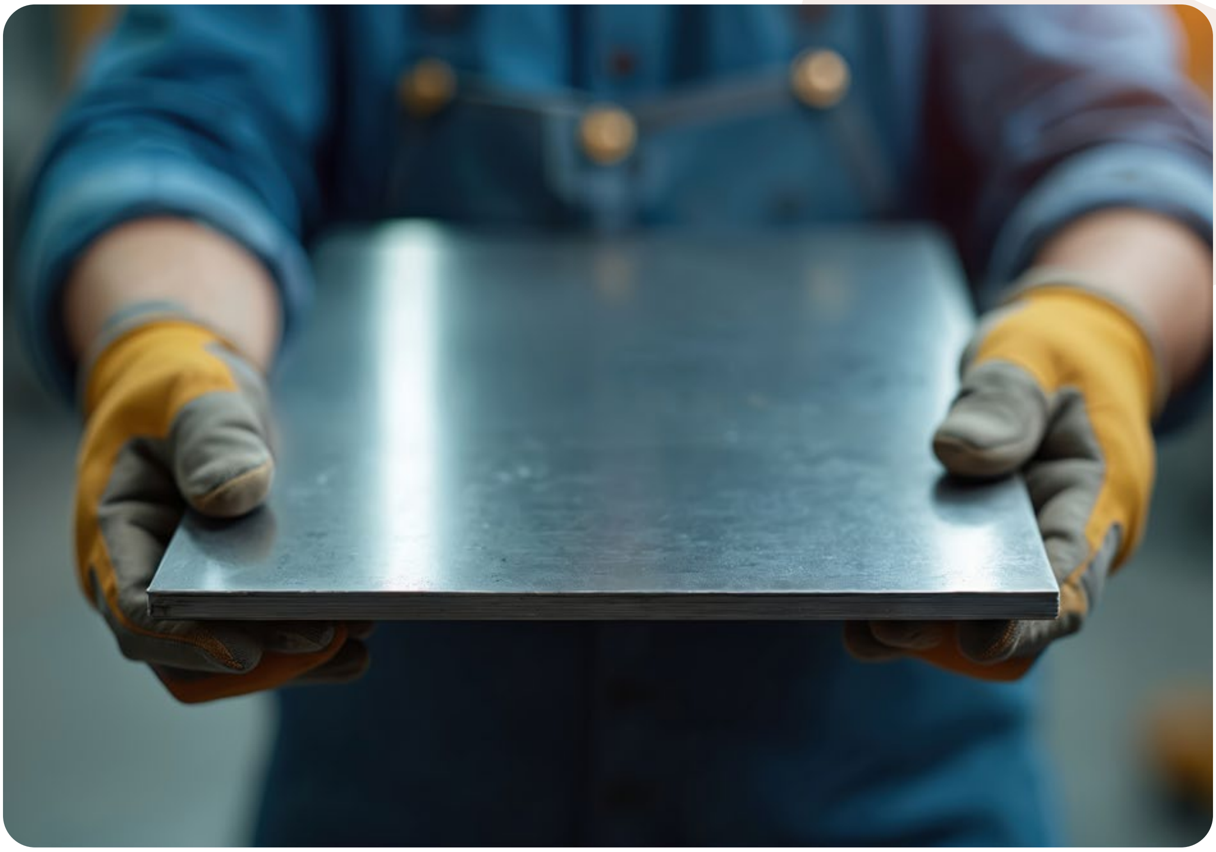


FOTO: ADOBE STOCK

4.4 Metals production

The sole purpose of producing metals is to fulfil one or more useful functions in society. The less material that is needed to fulfil a certain function, the more functionality and thus societal benefit can be achieved from available amounts of raw materials.

More advanced, higher-performance materials could increase efficiency in current applications and enable future, more efficient technologies to accomplish the desired function, thus reducing the amount of material in circulation.

The properties of metallic materials are achieved through chemical, mechanical, and thermal processing of metals. Making materials more advanced inevitably means pushing the limits of current practices. This means that materials development and process/production development are inseparable.

There are analytical tools to predict microstructure and material properties based on chemical composition and mechanical and thermal processing. However, physical processing is limited by available technology and can vary greatly depending on the shape and form of the final product, which means there are many adjustments to be done before a theoretical recipe manifests itself in actual physical products that can be produced at a competitive cost.

The models are also limited to areas of known properties and relationships. Developing new materials with more radical properties requires extensive experimentation, both for defining compositions and suitable process routes.

Competition from applications in energy generation and storage, electronics, and transportation may cause price volatility and supply shortages of alloying elements such as cobalt, vanadium, and nickel. This calls for more flexible alloying concepts to achieve a certain property profile.

To meet increasing demands for a low environmental footprint and enable optimal material selections, models also need to factor environmental performance into property profiles.

One particular field of materials development is powder metallurgy. Hot Isostatic Pressing (HIP) and sintering routes have enabled many new materials solutions and have yet much unexploited potential.

Additive manufacturing has advantages in terms of short production times, near net shape, and lightweight construction. The more conventional production routes, such as casting and stamping, are currently enabling larger parts with maintained, or better performance.

The coming years should take advantage of modern digitalization tools to integrate the full process chain, from crushing and flotation to smelting, refining, casting, metalworking, and recycling, as well as to optimize design and preparation for production and efficient circularity of parts and materials.

Efficient waste and emission management should be coupled with clear legal frameworks and harmonized sustainability metrics.

METALS PRODUCTION

CHALLENGES

Materials development

- Knowledge gaps as to real-life load exposure, including corrosion, fatigue, hydrogen degradation, wear, elevated service temperatures, and others.
- Increasing batch sizes for efficiency requires thermomechanical processes that can change properties late in the process.
- A number of critical alloying elements are only available outside of Europe.
- Long lead times from a desired property profile to market.
- Lack of robust and cost-effective routes for fabrication and decommissioning of complex products, including wrought, cast, and powder-metallurgical alloys.
- Tramp elements in circulated materials limit composition options.
- Alloying strategies depend on critical raw materials.
- Including environmental footprints in property profiles.
- Insufficient purity levels of end-of-life scrap.

Melting

- All types of melting furnaces display losses of both heat and material.
- Reactions between metal and its surroundings decrease the yield of alloying elements and cause inclusions or other internal defects after solidification.

- An energy and resource intensive process step, resource efficiency and quality are particularly important for melting, not least for cast parts as they have little room for adjustments downstream.

Casting

- Hardness and strength of metals influence the risk of cracks and other surface or internal defects.
- Low degree of automation in component foundries requires advanced quality control.
- Cast parts are getting both larger and more geometrically complex and prediction and control of local properties are of increasing importance.

Metal working

- Forming advanced cast metal into bar, plate, pipe, wire, and more complex shapes involves a risk of cracking and other defects.
- The introduction of continuous rolling from casting to finished plate or coil puts more strenuous requirements on temperature control and other process parameters.

Heating/cooling

- Replacing fossil-fuel-fired furnaces with electrical heating requires a better understanding of the consequences of electrification in the heating processes. How parameters like furnace design, thermal efficiency, temperature uniformity, atmosphere, and durability affect electrified heating processes needs to be investigated.
- Cooling to achieve optimal product properties requires extreme control of flow of air and cooling media.

Quality control

- Automating manual inspection to improve quality and productivity.
- Replacing destructive testing for quality control of microstructure and mechanical properties.
- Replacing empirical models with analytical ones for optimizing surface morphologies and chemistries and facilitating surface treatment.

Systems integration

- There are no systems or procedures in place to connect data between sections, either for the analysis of large data sets nor for controlling processes in real time.

METALS PRODUCTION

DESIRABLE FUTURE STATE

Materials Development

- Desired material property profiles are based on real-world data from relevant applications, integrated with results from standardized testing.
- Materials selection models are available for complex property profiles in combination with regulatory requirements.
- The time required to qualify a defined property profile in production is halved compared to 2025.
- Alloying concepts and process routes are so versatile that key properties can be sufficiently achieved even if certain alloying elements are in short supply.
- Cast, wrought, and powder metallurgical materials can be readily integrated, formed, and joined in components and also separated and re-used or recycled at the end of service life.
- Strategies to handle an increased share of recycled content are so well established that secondary alloys are equally applicable.
- Material structures and properties can be seamlessly modelled from atomistic to component levels. Models are available both at the specialist and engineering-generalist levels, and are sufficiently rapid to allow direct application within production.
- AI and Machine Learning (ML) are used to accelerate materials development, and PIML (Physics-informed Machine Learning) is fully established.
- The time for integration of new materials in standards has been halved.
- New materials are developed and implemented for energy, infrastructure, medical, transport, and communications solutions, integrating sensors and facilitating circular business models.
- The foundations for LCA and definitions of environmental performance are agreed, accessible, and realizable.

Materials Processing

- Methods, processes, and technology for efficient and virtually error-free casting, metalworking, and heating/cooling are available for an increasing number of grades.
- Industrial heating furnaces cause no harmful emissions and can seamlessly switch between multiple heating technologies (induction, resistance, hydrocarbons, hydrogen, etc.) to handle variations in availability and optimize loads and costs.
- High-quality regulation and control systems are in place that can predict product quality after heating.

- Existing processes are optimized for energy efficiency. Optimization models for selecting fuel type and energy-efficient heating are available.
- Technologies for recovering low-grade energy are in place.
- Material loss to oxide scale formation is reduced by flexible heat treatment processes and oxide removal through mechanical and chemical methods is efficient.
- Sensors, modelling, and AI/ML analysis are used in real time, enabling process feedback loops and optimization across the process chain.
- Microstructure and property evolution can be modelled and predicted over the process chain.
- Process chemicals, including binders, lubricants, degreasers, and pickling solutions, are used in an efficient and circular manner with minimum environmental impact.
- Predictive maintenance of equipment is fully implemented, and there is no unexpected downtime due to failures or other reasons.
- Manual process steps that involve risks of personal injury or loss of quality have been fully automated.
- There is full traceability in process chains, traceable down to individual items.
- Quality inspection is fully automated, and there are standardized definitions of surface attributes which are applicable to all product types.

Vision Statement

Sweden is recognised as a global leader in fossil-free, resource-efficient metals production, delivering metal products with advanced property profiles that fulfill high demands for long service life and low cost of ownership.

4.5 Product manufacturing and use

By virtue of their extreme versatility and affordability, products and components made of metal are found everywhere in society. Huge pieces of metal provide stability for buildings and railways, and microscopic pieces add key functions to medical instruments and electronics.

Transforming metals into their final, operational shape and form is accomplished via techniques and procedures that also affect and alter the metal's properties, something which must be considered when selecting materials and procedures for a given application and, consequently, when developing materials for certain applications.

In the perspective of the mission, it is essential that products are made of materials that provide the desired functionality at low weight and for a long time, as this reduces material consumption and thus makes available supply last longer.

In addition, the ongoing transition has added sustainability criteria such as climate footprint and recyclability to other functional criteria such as durability, appearance, and weight. Making optimal materials selections thus means mastering complex combinations of traditional performance criteria and sustainability criteria.

Materials development and technology therefore go hand in hand with product development all the way until a final product or component is ready for production. In this work, the load patterns experienced by the components are key guidelines. This means that the application of modern sensor and data handling technology to metals production should also involve the product manufacturing and user steps.

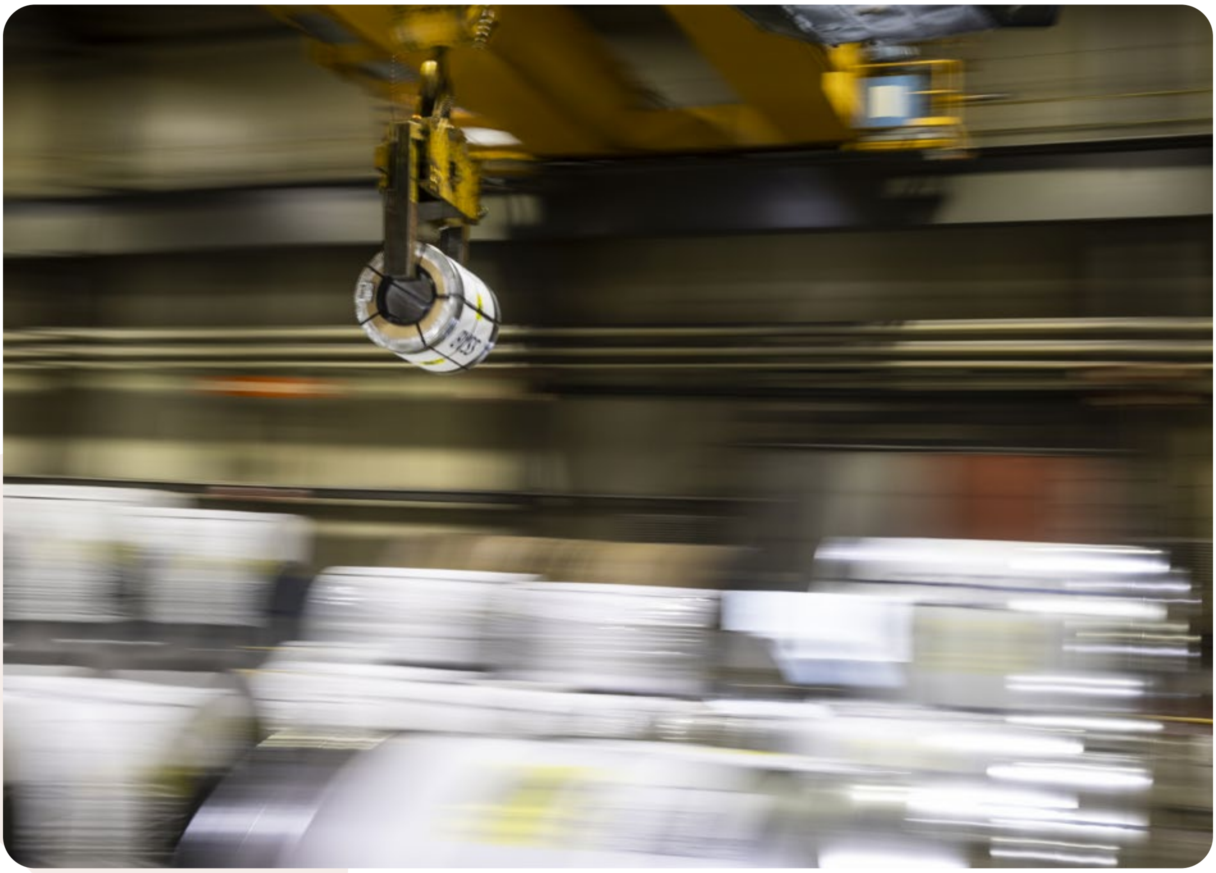


FOTO: SSAB

PRODUCT MANUFACTURING AND USE

CHALLENGES

Materials Development

- Monitoring load profiles and materials degradation during real use is associated with measuring and data ownership issues.
- Certain desired properties are conflicting, such as durability and recyclability.
- Desired property profiles often require critical elements.

Process Development and Selection

- The connection between chemistry, mechanical, and thermal processing, and the final properties of a metal product is not fully known.
- Modeling that links microstructure evolution during processing to long-term component performance and service life has limited predictive power.
- Efficient and reliable forming, joining, and coating techniques need to be developed in parallel with materials development.
- Production customization conflicts with productivity and low cost.
- The use of near-net-shape manufacturing techniques, such as component casting and forging, is limited due to knowledge gaps.
- Additive manufacturing has low process effectiveness and is insufficiently integrated with powder production.

Materials Selection

- Identifying optimal property profiles for a certain application is very complex.
- Standardization of new materials is slow, leading to advanced materials being undervalued for long periods of time.
- Quantifying sustainability criteria is hampered by insufficient LCA models and practices.
- Materials selection is frequently based on tradition and ad-hoc data.

Materials Introduction and Use

- When applying new, more advanced materials, the whole process chain has to upgrade its capabilities to handle them.
- Design for recycling, reuse, remanufacturing, and reduction is still at an early development stage.
- Tools for machining advanced, high-strength materials require potentially harmful elements such as cobalt.
- Vaporized lubricants and other process chemicals, welding fumes, and other emissions from processing advanced materials could pose health risks.

PRODUCT MANUFACTURING AND USE

DESIRABLE FUTURE STATE

Materials Development

- New materials are developed and implemented to enable improved technologies for energy, infrastructure, medical, transport, and communications solutions, while saving critical raw materials.
- Material properties can be predicted all the way from melting to finished product.
- Integrated and thoroughly verified databases are available for prediction of complex material properties such as fatigue, corrosion, wear, hydrogen resistance, creep, oxidation and embrittlement risk.
- AI and machine learning are integrated tools for modelling of material behavior.

Process Development and Selection

- The connection between chemistry, processing, and final properties for a particular application is so well known that material and process selection are made together.
- Load patterns from real applications are key guidelines for choice of production method.
- Remanufacturing is well-established, increasing resilience in manufacturing value chains.

Materials Selection

- Reliable and user-friendly “Material selector” helps material users select the optimal material for their needs, balancing performance, environmental friendliness, and market penetration.
- The foundations for LCA and definitions of environmental performance are agreed, accessible, and realizable.
- New materials are easily introduced in standards.
- The concept of Reduce-Reuse-Recycle underpins all applications of metallic materials and product demanufacturing is well established.

Materials Introduction and Use

- Different types of metallic materials can be combined in an optimal manner in components while allowing separation and reuse or reycling at the end of life.
- Alloy-to-alloy recycling is fully implemented so steel scrap used has the same composition as the alloy to be produced.
- Machining and joining techniques are resource-efficient and have no negative environmental consequences.
- Joining techniques enable quick disassembly and thus enable sorting and recovery with minimal metal degradation.

- Potentially harmful chemicals in the process chain are securely handled.
- Digital product passports are in place for all products affected by the EU's Ecodesign for Sustainable Products Regulation (ESPR).
- Manufacturing chains are so integrated knowledge-wise that advances in materials can rapidly manifest themselves in improved product performance.
- Flexible and generic substitution strategies minimise the use of hazardous and critical raw materials as alloying elements.

Vision Statement

Sweden is recognized as a global leader in developing high-quality metallic materials with enhanced fuctionality and recyclability which can facilitate the development of new and improved technologies for applications including power production, transport, infrastructure, food production and domestic use.

4.6 Competence supply

For any business to be run well, it needs access to competent people.

The mining and minerals and metals producing industries in Sweden have been around for centuries and have a core workforce with a strong local connection, high degree of loyalty and familiarity with the working environment.

In times of change, though, even the most experienced workforce has to upgrade its skills and knowledge, and retirees and career changers have to be replaced.

In addition, the metals and minerals sectors need new skills to handle modern tools such as artificial Intelligence and other digital technologies.

These new technologies not only require new skills, but they also alter the skill requirements of other roles in the organizations. Thus, automated systems may perform tasks previously performed by operators, whereas operators must perform tasks that require different skills and knowledge.

Up- and re-skilling existing workforces and educating new generations both require well-functioning education and training systems.

New technologies and skills are also available through partners and suppliers. In fact, connecting with new partners is the fastest and therefore often the first step for an organization when new challenges lie ahead. The ability to identify and form the right partnerships is thus an important part of mastering change.

Ensuring that the mining and minerals and metals producing industries in Sweden have the required skills and knowledge, therefore, involves systems and strategies for basic and advanced education, academic as well as vocational. It also requires that the industries can offer attractive jobs and work environments, and that the places where they operate can attract and satisfy an array of people and lifestyles. Last but not least, it requires being ready to find and form new partnerships with all that entails in terms of curiosity, risk management, and genuine mutuality.

COMPETENCE SUPPLY

CHALLENGES

Attractiveness and Recognition

- Mining and minerals and metals producing industries are typically located in communities that are not well known nationally.
- Maintaining a qualified workforce and logistical capacity in Arctic and remote regions remains a key condition for sustainable exploration in Sweden.
- Young people have little knowledge of mining and minerals and metals producing industries.
- Interest in STEM among young people is decreasing.
- Too few young people choose vocational programs, not least because they are perceived to have a lower status compared to academic programs.
- Specialists in digitalization and similar tools do not recognize potential careers in mining and metals production.

Education

- Engineering programs within mining, minerals, and materials attract few students, which puts them under constant threat to be cancelled.
- Frequent name changes and content modifications of engineering programs confuse both students and recruiters.
- Newly graduated engineers generally have firm theoretical knowledge but often lack laboratory skills.
- Declining student enrolment in geoscience and an imbalance between educational programs and sector needs threaten long-term capacity. Innovative, cost-efficient models are required to strengthen geoscience education while maintaining disciplinary depth.
- There is a mismatch between technology taught in educational programs and technology used in industry.

Partnership

- Academic institutions have few incentives for collaboration with industry, jeopardizing research and the relevance of education.
- Key technologies and competencies are available only in other, often distant, countries such as North America and China.
- Interoperability, benchmarking, and access to geoscientific data require data standardization and integration across companies and countries.

COMPETENCE SUPPLY

DESIRABLE FUTURE STATE

Attractiveness and Recognition

- Careers in mining and metals production are viewed as interesting and attractive, and young people look for paths into and opportunities in the industries

Education

- Relevant engineering and vocational programs are available, prioritized by educational institutions and of high quality.
- A robust competence pipeline exists, with revitalized geoscience education programs aligned to industry needs and incorporating digital, AI, and sustainability competencies.
- Vocational and academic programs have equal status and are selected based on individuals' interests, aptitude, and future prospects.
- Employees have the right set of skills and view further education and upskilling as a natural part of the job.
- Education and upskilling are available for all industrial positions, including operators, and adapted to actual working conditions and educational levels.
- Collaborative training initiatives between industry, academia, and government ensure knowledge transfer and innovation.
- Visiting students are actively encouraged to develop connections to Swedish industry and to seek employment there.

Partnership

- Active cooperation within and between Swedish industry and academia is well established.
- Swedish players are well connected to European and international arenas and have widespread networks.
- Required technologies and competencies are available within the European minerals and metals ecosystem.
- Data formats and interfaces are standardized, ensuring interoperability within and across the industry.

Vision Statement

Sweden is recognized for interesting and attractive jobs in the mining, minerals and metals producing sectors, where suitable training and education are available on all levels from high school to re- and upskilling of employees, and for well-established networks with international partners ensure access to relevant knowledge.

4.7 Social Sustainability

For metals and minerals supply to be sustainable, it also has to be socially sustainable.

Thus, mining and metals production should ensure safe, equal, and inclusive living conditions enabling people to live good lives. In a wider perspective, modern mining, minerals and metals producing industry operates in a complex social landscape: communities expect transparency, fairness, and environmental responsibility; local inhabitants, including indigenous people and landowners demand recognition of rights and participation; and green interest groups look for proof that the operations support the transition in a just and equitable way. All of this is expressed in society's laws and regulations and permit processes, which can therefore be seen as the quintessence of social sustainability.

At the same time, the sector continues to face persistent permitting challenges. Despite significant technological development, improved environmental performance, and increased possibilities to adapt operations to societal and environmental goals, permitting processes have remained largely unchanged over time. Lengthy, unpredictable, and fragmented permitting frameworks risk becoming bottlenecks for both sustainability transitions and strategic investments. This highlights the need for permitting systems that are transparent, science-based, and aligned with today's technical capabilities, societal priorities, and long-term sustainability objectives.

The attractiveness of industrial companies as employers in smaller towns and the attractiveness of the communities themselves are virtually inseparable. It is therefore important that the industry takes an active part in creating attractive, welcoming, and socially sustainable communities and places where people want to live.

Social sustainability thus touches upon many topics, such as governance, equality, diversity, equity, and regional development, that must be addressed to ensure that Sweden's mining and metals sector fulfils its mission to enable sustainable and resilient metals and minerals supply for the societal transition.

FOTO: ADOBE STOCK

SOCIAL SUSTAINABILITY

CHALLENGES

Permitting, Supervising and Legislation

- Weak alignment within EU legislation, including the Critical Raw Materials Act and other directives, jeopardizes supply and competitiveness.
- Weak alignment between EU and national legislation leads to extra work and jeopardizes the attainment of national and European goals.
- Sudden changes in legislation and policy hinder long-term predictability and thus erode investor confidence.
- Lengthy, unpredictable, and inconsistent permitting and supervision processes deter investment and slow down project realization.
- Permitting decisions are not aligned with national priorities such as supply security and defense preparedness.
- Navigating complex and evolving international standards and certification requirements for safety, emissions, and digital systems.

Land-Use Conflicts

- Competing land uses — including mineral deposit extraction, reindeer herding, forestry, recreation, food supply, energy generation, and nature conservation — are not harmonized nationally, leading to constant local conflicts.
- Lack of codes of conduct and best-practice models for engagement of affected communities risks making consultation processes irrelevant, disrespectful, and less useful for stakeholders.
- Processes for protection of indigenous people lack frameworks for early and constructive consultation.

Organizational

- Keeping workplaces and work environments safe and sound.
- Translating broader social ambitions into practical activities.
- Ensuring functioning collaboration between labor market parts.

Community Acceptance

- Major interventions in nature create public uncertainty and resistance.
- Growing polarization in media and public debate leaves little room for informed discussion about mining and metals production.
- Increasing consolidation and specialization widen the social gap between industrial sites and their surroundings.
- Lack of knowledge as to exploration and mining processes hampers effective collaboration and balanced governance.

- The spread of misinformation and disinformation in media and public discourse complicates constructive dialogue, reinforces polarization, and reduces trust.
- Social science analyses of the above points are largely missing.

Attractiveness

- Mining and metals producing industries and their potential career paths are not well known, particularly among younger individuals.
- Work safety issues are of extra importance due to the nature and image of working conditions.
- Small industrial communities do not match the needs and wishes of people at the age (25–30) when they are most likely to move.
- Traditional recruitment processes and expectations risk missing opportunities for competence supply.
- Build flexible, diverse, and attractive workplaces that combine high safety standards, remote work possibilities, and continuous learning.
- Strengthen strategic and managerial competence to ensure effective technology adoption and organizational agility.
- Attract and retain highly skilled professionals with expertise in core competences such as mining or metals production, but also digitalization, automation, electrification, safety, and sustainable operations.

Regional Development

- Weak and unclear links between risk and potential benefits for local communities regarding establishment or expansion of industries.

SOCIAL SUSTAINABILITY

DESIRABLE FUTURE STATE

By 2035–2040, the Swedish mining, minerals and metals sector operates with strong social legitimacy, underpinned by transparent governance, predictable permitting, and meaningful engagement with communities and stakeholders. Social sustainability is integrated across decision-making, enabling long-term investments, societal trust, and resilient regions while supporting the societal transition.

Permitting, Supervision, Governance, and Trust

- Permitting and subsequent supervision processes are transparent, efficient, predictable, and science-based, aligned with EU frameworks and national priorities.
- National permitting frameworks balance resource security, environmental protection, indigenous rights, biodiversity, forestry, food supply, total defense, and other societal interests in a coherent and coordinated manner.
- Regulatory processes reflect technological development and improved environmental performance, enabling rather than constraining sustainable transformation.
- Strategic foresight and scenario planning enable resilience against geopolitical risks and raw material price volatility.

Community Engagement and Acceptance

- Early, continuous, and meaningful engagement with communities and stakeholders is standard practice throughout the mine life cycle.
- Consultation processes are based on mutual respect, transparency, and shared understanding, strengthening trust and local acceptance.
- Public dialogue is informed by accessible, fact-based information, counteracting polarization and misinformation.
- Mining and metals production are broadly understood and recognized as enablers of a resilient and modern society and the industry is recognized as a trusted partner in climate action and regional development, fostering long-term social acceptance

Land Use, Rights, and Coexistence

- National frameworks enable coexistence between mining, reindeer herding, forestry, energy production, nature conservation, recreation, and other land uses.
- Indigenous rights and interests are addressed through early, structured, and

constructive consultation, supported by clear guidance and best practices.
- Land-use planning is guided by long-term societal value creation, fairness, and transparency.

Attractive Workplaces

- Mining and metals production offer modern, safe, meaningful, and attractive jobs, drawing a diverse and highly skilled workforce.
- Gender equality, equity, and diversity are fully integrated into organizational cultures, leadership, and career pathways.
- The sector is recognized as an attractive employer among younger generations and professionals with a wide range of competencies.
- Collaboration between labor market parts is well functioning

Regional Development and Shared Value

- Mining and metals producing regions are resilient and attractive, combining industrial activity with education, services, and quality of life.
- Clear and fair mechanisms ensure that local communities benefit from value creation, strengthening long-term support and regional development.
- Collaboration between industry, municipalities, academia, and other sectors supports sustainable growth beyond the mine itself.


FOTO: ADOBE STOCK

4.8 Environmental Sustainability

Mining, minerals and metals production inherently interact with land, water, and ecosystems. Among these, water is a defining factor for environmental sustainability, influencing everything from process efficiency and emissions to biodiversity, waste stability, and social acceptance.

In Sweden, access to clean water and robust water governance has long enabled responsible mining and metals production. However, increasingly complex ores, stricter environmental requirements, climate change, and new processing technologies place growing demands on how water is managed, treated, reused, and protected throughout the entire mine life cycle — from exploration to post-closure.

Environmental sustainability therefore defines the long-term viability of the mining and metals sector. To lead globally in responsible resource production, Sweden should ensure that water management, emissions, waste handling, and land use are addressed in an integrated and science-based manner. This includes minimizing environmental impact, safeguarding ecosystems, and enabling circular water use adapted to Nordic and Arctic conditions.

Building on Sweden's world-leading environmental performance, the focus should be put on further reducing climate impact, improving water stewardship, and strengthening resource efficiency. Doing so is essential not only for environmental protection, but also for maintaining trust, regulatory robustness, and global competitiveness in the mining and metals value chain.

At the same time, reducing greenhouse gas emissions remains a central environmental priority. While Swedish production is already among the least carbon-intensive globally, mineral processing and metallurgical operations are still energy- and heat-intensive, and further emission reductions are required to meet national and EU climate targets. Achieving fossil-free operations will require electrification, hydrogen-based processes, sustainable bio-carbon, and improved energy efficiency, implemented in close interaction with water, waste, and material management to avoid burden shifting between environmental objectives.

ENVIRONMENTAL SUSTAINABILITY

CHALLENGES

Climate Impact and Energy Transition

- High-temperature operations remain difficult to decarbonize through electrification, hydrogen-based reduction, and bio-based fuels.
- Achieve significant reductions in CO_2, nitrogen, and other emissions, advancing towards fully fossil-free mining operations.
- Access to fossil-free electricity varies, and altering pricing and taxation systems increases risk.
- Access to sustainable biomass is not secured.
- Combustion and thermal processes yield NO_x and particulate emissions.

Water and Environmental Management

- The EU Water Framework Directive sets limits on water processing conditions that are a) not directly related to the process and b) sometimes questionable from an environmental protection standpoint.
- New processing technologies may introduce changing effluent compositions.
- Preventing contamination and optimizing water use is particularly challenging in Arctic climates due to low water temperatures and sensitive ecosystems.
- There are data and knowledge gaps as to how current legal and technical measures influence overall environmental outcomes.

Waste, Tailings, and Material Valorization

- Mining generates huge volumes of tailings and waste rock that require large areas for storage.
- Significant differences in reuse potential exist between tailings, waste rock, and slags.
- Use of metallurgical slags and other industrial residues must meet stricter standards than the use of primary materials, thus limiting the possibility to reduce waste and demand for primary raw materials.

- Carbon mineralization and enhanced weathering in waste materials potentially offer new opportunities for CO_2 sequestration but are currently hindered by lack of research, regulation, and validation methods.
- Inherent challenges in ensuring long-term stability connected to technical reliability and economic feasibility in remediation and closure technologies due to the long time perspective.

Biodiversity and Land Use

- Mining and processing alter landscapes and thereby risk affecting biodiversity and ecosystem functions during and after use.
- Integrating ecological benefits and biodiversity goals with industrial and energy planning.
- Ecological compensation and rehabilitation are not always designed to deliver measurable outcomes that enhance nature values in active and legacy sites.

Governance, Data, and Regulatory Alignment

- Stricter EU and national environmental requirements on emissions, water, and waste without balancing value chain optimization.
- Permitting frameworks do not harmonize with measurable environmental benefits.
- Robust measurement and reporting standards for carbon capture, water quality, and waste valorization performance are lacking.

ENVIRONMENTAL SUSTAINABILITY

DESIRABLE FUTURE STATE

By 2035–2045, the Swedish mining, minerals and metals producing industry operates within planetary boundaries, with environmental performance integrated across the entire value chain. Environmental sustainability is addressed through holistic, science-based management of water, climate impact, waste, land use, and biodiversity, ensuring long-term safety, regulatory robustness, and social acceptance.

Climate Impact and Energy Transition

- Mining (2035), mineral processing, and metallurgical operations (2045) are fossil-free, with negligible emissions of CO_2, NO_x, and particulates.

Water and Environmental Management

- Water is managed throughout the mine life cycle, with minimal freshwater intake, high reuse rates, and no harmful releases to receiving waters.
- Water treatment technologies are adapted to process chemistry, climate conditions, and evolving effluent compositions, including cold and Arctic environments.
- Water and biodiversity management are strengthened and proactive monitoring and adaptive approaches to minimize ecological impact are applied.
- Environmental protection measures (for example waste prevention and reclamation) are integrated in the mine design to ensure that closure and post-mining land use are considered from the start, reducing long-term risk, costs, and remediation needs.

Waste, Tailings, and Resource Use

- Circular mining models that transform waste into value — recovering and reusing nitrogen, phosphorus, sulphur, and CO_2, and valorizing waste rock and tailings, thus reducing storage volumes and enabling circular material flows.
- Tailings, waste rock, and metallurgical residues are safely managed in long-term stable facilities, supported by monitoring, predictive modelling, and risk-based design.
- Carbon mineralization, enhanced weathering, and other CO_2-binding solutions are implemented where scientifically validated and environmentally beneficial.
- Remediation and closure technologies are cost-efficient, low-carbon, and reliable over long time horizons, ensuring post-closure safety and ecological recovery.

Biodiversity, Land Use, and Ecosystems

- Exploration operates with a minimal land, water, and CO_2 footprint, supported by non-invasive sensing and low-impact drilling technologies.
- Climate-adaptive operational models ensure resilience to shorter exploration seasons and extreme weather conditions.
- Biodiversity protection, restoration, and ecological compensation are standard practice, delivering measurable and verifiable net positive outcomes.
- Post-mining landscapes including water bodies, soils, and habitats, are designed to support long-term ecosystem functions and societal value.
- Land-use planning balances mining, energy infrastructure, biodiversity, and societal needs through transparent, science-based decision frameworks.

Governance, Data, and Decision Support

- Environmental performance is measured through transparent, harmonized indicators, aligned with global LCA, traceability, and reporting standards.
- Digital monitoring, modelling, and data integration support real-time environmental control and long-term impact assessment.
- Regulatory frameworks enable innovation, circularity, and environmental benefit while maintaining high levels of protection.
- Modernized legislation and relevant standards for waste management, tailings, and by-products enable innovation and circular solutions are in place.
- Transparency and communication regarding sustainability performance are improved and industry practices are aligned with public expectations and regulatory requirements, and transparent sustainability reporting aligns with global standards and public expectations, reinforcing trust and accountability.
- A holistic decision framework guides prioritization between climate, water, biodiversity, and land use to maximize overall sustainability gains.


FOTO: ADOBE STOCK

4.9 Economic Sustainability

For metals and minerals supply to be sustainable, it also has to be economically sustainable. Thus, mining and metals production must ensure stable, competitive, and resilient economic conditions enabling companies to run the business through global shifts, market cycles, legal demands, and the demands of the societal transition.

Without economic sustainability, the industry is not able to invest, innovate, or maintain the competence and competitiveness required to fulfil the program mission.

The modern mining, minerals and metals producing industry operates in a complex economic landscape with fierce global competition and lurking geoeconomic attempts to disturb markets for political gains. All of this has to be considered and handled to achieve and maintain economic sustainability.

The competitiveness of the companies is also tied to the economic vitality of the regions in which they operate. It is therefore important that regional economies are capable of supporting long-term investment, industrial transformation, and labor attraction.

Also, the aims of the mission involve bringing materials to market that currently are used in small quantities compared to potential production and expected demand. This makes future supply-demand relationships and thus pricing very difficult to predict, which adds substantial uncertainty to investment decisions.

Economic sustainability thus touches upon many topics, such as investment climate, competitors' and countries' actions, productivity, circularity, secure and competitive access to raw materials including scrap and other secondary raw materials, regulatory frameworks and their proportionality, and regional development. All these topics have to be addressed to ensure that Sweden's mining and metals sector fulfils its mission to enable sustainable and resilient metals and minerals supply for the societal transition.

ECONOMIC SUSTAINABILITY

CHALLENGES

Investment Climate

- Upfront capital requirements for extraction, processing, electrification, and circularity are large with long payback times.
- Lengthy, unpredictable, and inconsistent permitting processes increase financial risk, delay capital deployment, and weaken competitiveness.
- Market development uncertainty, not least in terms of future market prices, hampers investments in the production of materials currently used in small volumes such as REEs.
- Political fluctuations and shifting policy signals prevent longterm predictability which erodes investor confidence.
- Uneven distribution of costs, risks, and benefits along value chains weakens investment incentives for initiatives with obvious system benefits.
- Small and medium-sized enterprises face disproportionate challenges in accessing capital and managing regulatory and market risks, which may limit their ability to invest in modernization and transformation.

Market Conditions and Supply Security

- Global cyclical demand patterns and geoeconomic interventions increase uncertainty in business and investment planning.
- Underdeveloped circular value chains and insufficient domestic recycling capacity, including limited access to high-quality scrap, limit resilience and increase exposure to global market shifts.

Productivity and Competitiveness

- Maintaining international competitiveness requires continuous modernization of processes, equipment, and digital capabilities.
- Regulatory requirements not sufficiently aligned with system-level outcomes increase operational costs and reduce competitiveness without achieving intended sustainability impacts.
- Skills shortages and demographic challenges limit productivity growth and raise operational costs.
- Uncertain access to reliable, competitively priced electricity, including sufficient grid capacity and power availability, jeopardizes competitiveness and electrification of processes.

Marketing and Sales Strategies

- Limited market awareness and structured demand mechanisms for advanced

and tailor-made material solutions constrain market uptake.
- Cost-benefit calculations for more advanced, costly materials are complex and require insight into final applications.
- Desired property profiles for a certain application may vary from customer to customer.
- Fragmented and non-harmonized qualification and certification processes create barriers to market entry and scaling.

Infrastructure and Regional Capacity

- Smaller industrial communities struggle to provide the necessary infrastructure to support both existing operations and future expansions.
- Regional disparities in economic capacity and risk sharing risk slowing the pace of industrial transformation.

Recycling

- Business models for circularity, scrap use, and closed-loop systems are not yet fully developed or economically viable in all segments.
- Lack of traceability and standardized data on material composition complicates efficient recycling and market integration.
- Lack of coordination across the value chain limits high-value recirculation of materials.

ECONOMIC SUSTAINABILITY

DESIRABLE FUTURE STATE

By 2035–2045, the Swedish mining, mineral and metal producing industry is known for low investment risks thanks to regulatory stability and predictability, and low operational risks thanks to well-functioning infrastructure with access to input goods, transport opportunities, expertise and suitable R&D facilities.

- Stable and long-term-oriented regulatory frameworks attract investment through lower risk premiums.
- A resilient and diversified raw materials base combining domestic extraction with secure and competitive access to scrap and other secondary raw materials through highvalue recycling and circular flows minimizes import dependencies and the risk of disturbances.
- Well-developed markets with low market risks for the production of strategic elements.
- Modern, fossilfree, digitalized operations enable high productivity and efficiency.
- Economically viable mining and metals regions offer innovative ecosystems, infrastructure, and living environments that attract talent and support long-term industrial development.
- Value creation from mining and metals production contributes to strong regional economies that benefit local communities and the national industrial system.

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