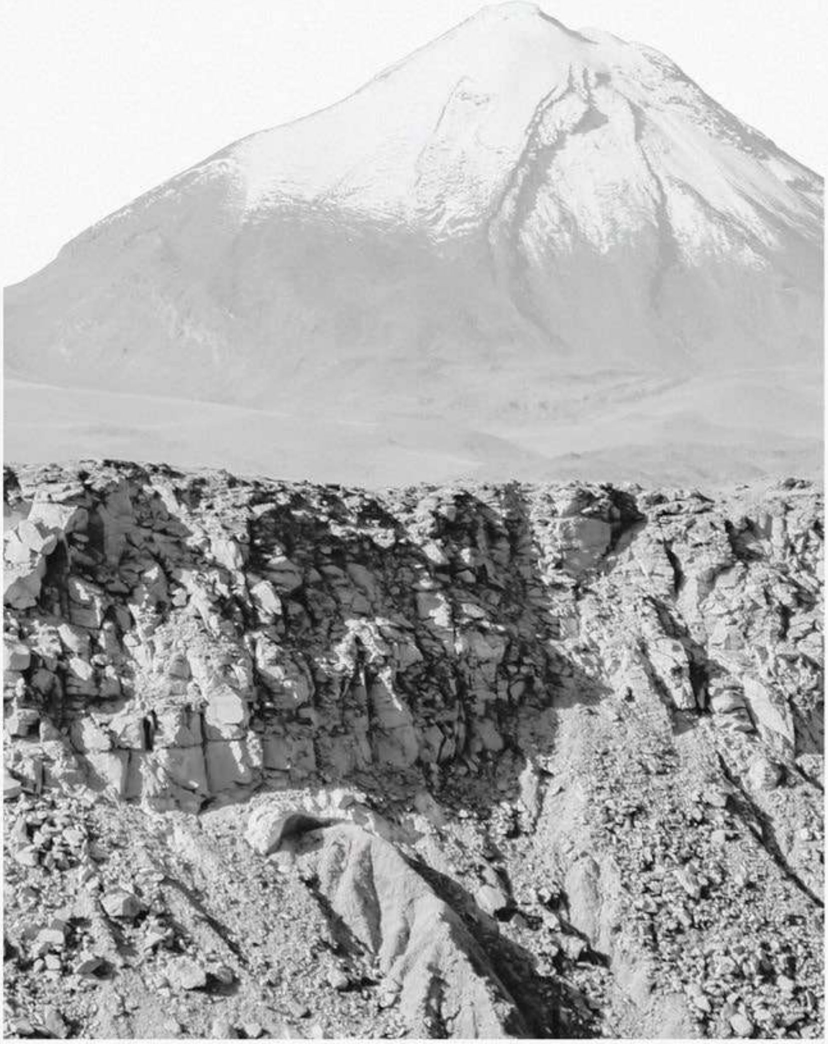
STATE OF THE CHILEAN MINING INDUSTRY

TECHNOLOGICAL CHALLENGES AND BUSINESS OPPORTUNITIES



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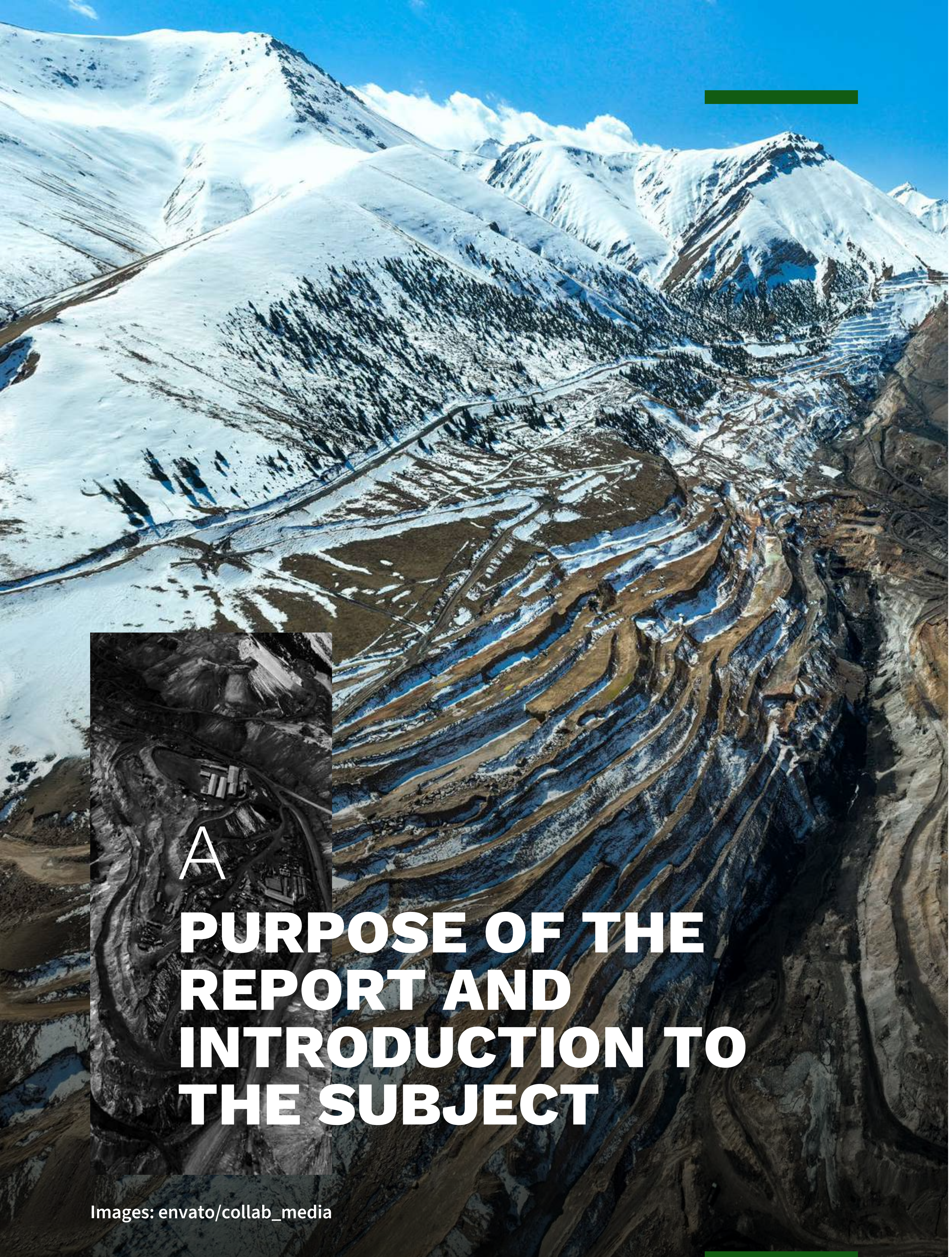


A

PURPOSE OF THE REPORT AND INTRODUCTION TO THE SUBJECT

Images: envato/collab_media

The following report was developed within the framework of the “Responsible Mining for Future Technologies” project, which is implemented by the Chilean-German Chamber of Commerce and Industry (AHK Chile) and financed by the German Federal Ministry for Economic Affairs and Energy. The purpose of this document is to systematically compile, structure, and assess publicly available information on business opportunities for German industry in the Chilean mining and raw-materials sector, with a particular emphasis on market trends, technological challenges, and structural transformation processes.

In addition to providing a concise overview of the Chilean mining sector, the report focuses on ongoing and anticipated structural changes in production techniques, operational methods, and technological standards.

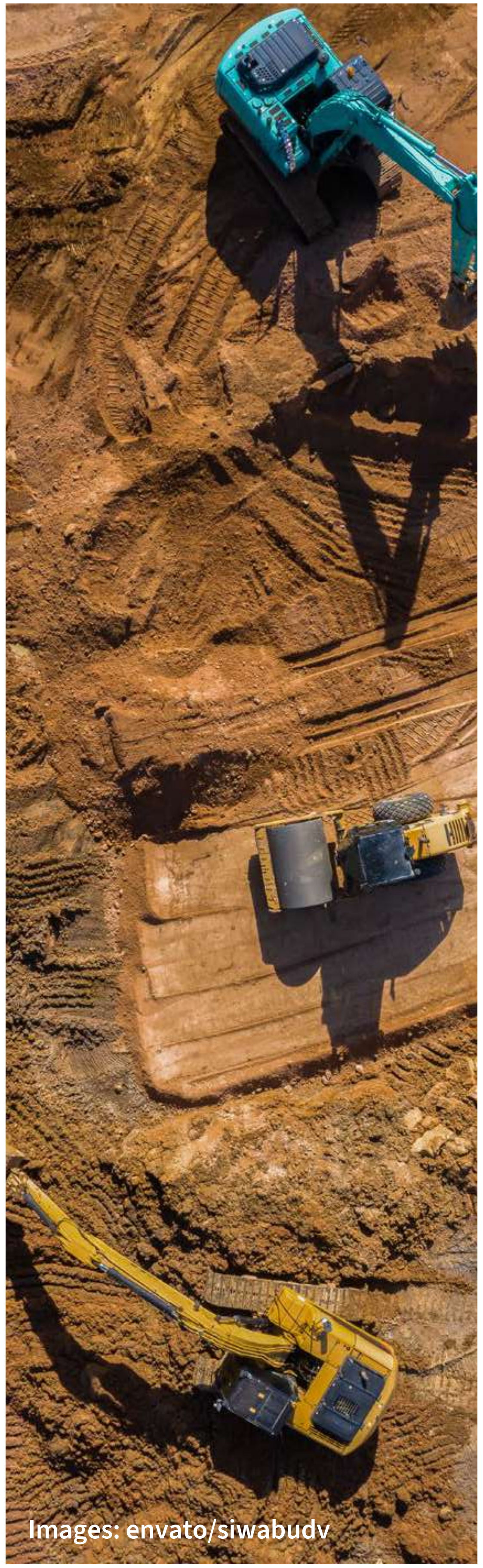
These changes are driven by multiple factors, including rising efficiency requirements, increasing environmental and social regulations, digital transformation, and the growing importance of critical raw materials for future technologies. By analyzing these developments, the report aims to identify existing and emerging technological gaps and to highlight potential application areas for advanced solutions and innovations.

Furthermore, the report presents and evaluates the results of a survey conducted by AHK Chile, designed to capture insider perceptions and assessments from key stakeholders within the sector. The objective of the survey is to identify technology needs, emerging tendencies, and concrete business opportunities from an industry perspective.

The survey findings are complemented by AHK Chile's continuous market observation, direct engagement with companies and institutions, and in-depth sector knowledge.

Based on this combined analytical approach—integrating survey results, institutional expertise, and ongoing industry screening - the report outlines key trends, technological developments, and structural challenges expected to shape the evolution of the Chilean mining sector in the coming years.

German companies play a strategically important role in the Chilean mining industry as reliable providers of high-quality technology, engineering solutions, and innovation. Consequently, the early identification of trends and business opportunities is of mutual importance. While the Chilean mining sector depends on efficient, technologically advanced suppliers to maintain and enhance its international competitiveness, German technology providers must continuously monitor market developments in order to secure first-mover advantages, adapt solutions to local operating conditions, and further innovate in response to evolving sectoral demands. The report therefore serves as a strategic orientation tool for fostering sustainable bilateral cooperation and long-term value creation.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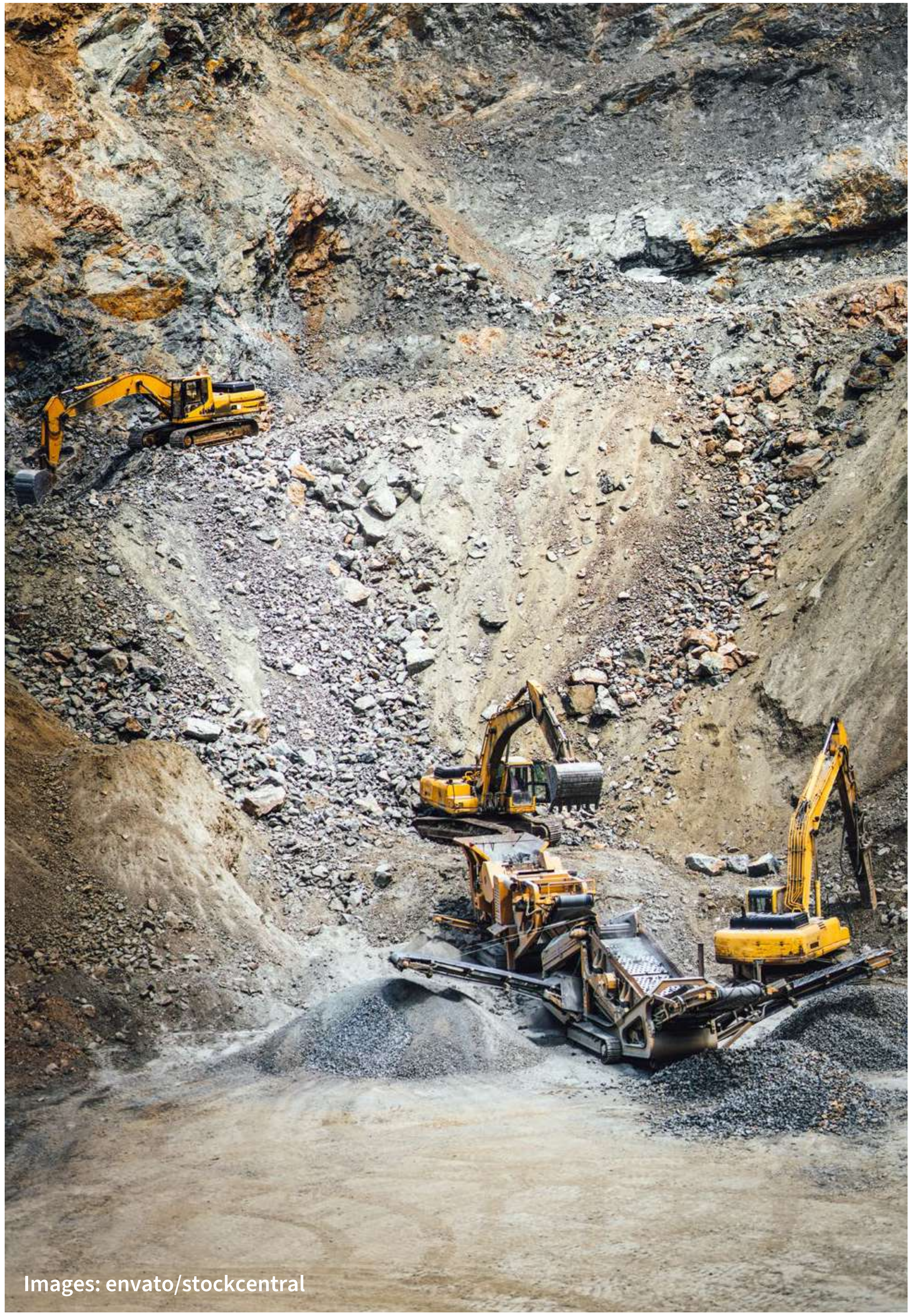
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B
INDUSTRY OVERVIEW MINING IN CHILE

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1 CHILEAN MINING ECOSYSTEM AND DISTRIBUTION OF PRODUCTION

Chile nowadays is a world leader in the copper production, a development that has arisen with the exploitation of big deposits by foreign companies in the beginning of the 20th century. Nevertheless, there has always been an exploitation of deposits on a small scale in the whole Northern part of the country from the region of Antofagasta to the region of Libertador Bernardo O'Higgins. These different levels of production lead to the distinction within the Chilean mining sector between Large-Scale mining (Gran Minería), Medium-Scale mining (Mediana Minería) and Small-Scale mining (Pequeña Minería). In the mid 20th century the state-owned National Mining Company ENAMI (Empresa Nacional de Minería) has been founded to forge the development of small-scale and medium-scale mining. Due to that support, several large mining companies have emerged since then.[1]

Artisanal and small-scale mining are segments of the national mining industry that are categorized by various laws and entities such as SERNAGEOMIN, ENAMI, the Mining Code, and the Income Tax Law. SERNAGEOMIN defines artisanal and small-scale mining based on the hours worked per worker in a year. According to this, small-scale mining is defined as less than 200,000 hours worked per person per year and between 12 and 80 workers employed. Artisanal mining is defined as less than 27,000 hours worked per person per year and fewer than 12 workers employed. In contrast, according to the Mining Act, small-scale mining is defined as operations with fewer than 12 employees, and artisanal mining as operations with fewer than 6 employees. Based on the ENAMI definition, small-scale mining is defined as production of less than 10,000 tons per year.[2]

Nowadays, in terms of production, the companies of the Small-Scale mining are responsible for around 4% (or 86.000 tons per year) of copper production in Chile, whereas Medium-Scale mining accounts for around 14% (or 286.000 tons per year) of copper production and Large-Scale mining is responsible for about 82 % (or 1.727.000 tons per year) of copper production.[3]

[1] *Olmos Maturana et al., **"Enclaustramiento Tecnológico y de Negocio En La Pequeña y Mediana Minería Chilena,"** 2.*
[2] ***Comisión Nacional del Cobre, Monitoreo de Variables e Indicadores Relevantes de la Pequeña y Mediana Minería Chilena,** 1.*
[3] *Olmos Maturana et al., **"Enclaustramiento Tecnológico y de Negocio En La Pequeña y Mediana Minería Chilena,"** 2.*

Images: envato/sedrik2007

In terms of workers, small and medium-sized mining account for a much larger share of the total number of people employed in Chilean copper mining.

Small copper mining employs approximately 30% of the workforce, medium-sized copper mining employs 20%, and large copper mining employs approximately 50%. Small and medium-sized copper mining therefore play a disproportionately large role in the industry. Conversely, this can also be seen in the figures for labor intensity in production. While 104 employees are needed to produce 1,000 tons of copper in small-scale copper mining, the figure is 46 in medium-sized copper mining and 113 in large-scale mining.[4]

Iron and copper are Chile's most important mining products, but various other metals are also produced. With an annual production of 11 million tons, iron accounts for over 65% of the country's mining output, while 5.5 million tons of copper are produced, representing 32.8% of mining output. Other metals are produced in relatively small quantities: gold 35.7 tons per year, silver 1,224 tons, molybdenum 38,970 tons, and lithium 261,000 tons.[5]

Images: envato/Danil_Rudenko

The distribution of mining projects in Chile is relatively clear. The largest number of mining projects are located in the north of the country, with a few projects also located in the extreme south. In 2023, Chile had a total of 202 operational mining projects. Below is a list of projects by region as of 2023[6]:

Arica y Parinacota	7
Tarapacá	15
Antofagasta	46
Atacama	48
Coquimbo	21
Valparaíso	11
Metropolitana	14
Libertador General Bernardo O'Higgins	5
Maule	12
Ñuble	-
Bío Bío	7
Araucanía	3
Los Ríos	1
Los Lagos	1
Aysén del General Carlos Ibáñez del Campo	2
Magallanes y de la Antártica Chilena	9

[4] *Olmos Maturana et al.,* ***"Enclaustramiento Tecnológico y de Negocio En La Pequeña y Mediana Minería Chilena,"*** *2.*
[5] *Consejo Minero,* ***"Cifras actualizadas de la minería," 4.***
[6] *COCHILCO,* ***"Mapa minero de Chile"***

2 PRODUCTION METHODS AND STRATEGIC IMPLICATIONS

Chile ranks as the world's leading copper producer, accounting for 24% of production in 2024. On the other hand, Chile's production has undergone cycles of transformation, driven by changes in the disposition of its main mineral deposits.

According to COCHILCO (2024), mine copper production has varied, showing a tendency to recover after several years of static production. Within this, it is important to distinguish between the following methods:

- Production by flotation: The copper contained in concentrates produced by flotation is sent to smelters for subsequent refining. Concentrates are Chile's main export product, containing mainly copper sulfides.

- Production through leaching: This refers to the production of high-purity copper cathodes in ranges of 99.99% fine copper after being treated by leaching – solvent extraction – electro-winning.
According to metal price projection studies the average price of copper will be $4.3/lb. Despite this, the treatment of oxidized minerals is declining due to their depletion, advancing to deeper areas where sulfides are concentrated, thus moving towards the construction of new concentrator plants or new hydrometallurgical process infrastructures for the leaching of sulfides without having to invest in dismantling existing plants.

2.1 KEY PLAYERS IN LARGE-SCALE AND MEDIUM-SCALE MINING AND THEIR TECHNOLOGICAL STRATEGIES

In Chile, medium and large mining companies are now committed to using sulfide leaching technologies to secure their share of the global copper supply market. Among the leading companies that have set their sights on sulfide leaching are:

CODELCO: The state-owned company has staked its claim as Chile's leading copper producer by spearheading innovation in this methodology. Given the depletion of minerals and low grades in its deposits, it has identified sulfide leaching as an alternative to add value to its copper. The following methodologies have been implemented in its operations:

A) **Chloride leaching:** For secondary enrichment sulfide minerals such as covellite in chalcopyrite for the Radomiro Tomic Division, with future aspirations for minerals such as bornite, enargite, and chalcopyrite.
B) **Bioleaching:** Applicable to secondary sulfides such as covellite and chalcocite, continuing the line of research at the Radomiro Tomic Division.

BHP (Escondida): The world's leading copper producer has put significant investments on the table to maintain and increase its production. Its investment plans include increasing and adapting its sulfide leaching capacity to maintain its commitment to cathode production, not limiting itself solely to the production and marketing of concentrates.

Antofagasta Minerals: It has successfully developed its Cuprochlor-T technology, a brand with a long history of research. The technology is being used on an industrial scale to process 40,000 tons of ore at its Minera Centinela operation, thereby advancing the processing of those minerals within its phases that to date are considered uneconomical within its extraction plans.

Anglo American: The copper giant is conducting studies for the development of sulfide recovery within the waste rock deposits at its Los Bronces mine.

The Mapa Minero, published by the Chilean mining association SONAMI, provides a detailed overview of all mining projects in Chile: *https://www.sonami.cl/v2/mapa-minero/.*


Images: envato/salajean

2.2 SMALL AND MEDIUM-SIZED MINING

Small and medium-sized mining companies make a decisive contribution to the number of people employed in the Chilean mining industry. However, it is precisely here that there are significant technological gaps compared to large mining companies. Small and medium-sized mining companies often find themselves using outdated technology. This is mainly due to the competitive situation and economies of scale that large mining companies can exploit.

Since knowledge, technologies, and alternative equipment are not developed because large mining companies have chosen their standard by maximizing their efficiency based on economies of scale to meet the commercial standards of the copper commodity market, conditions that are not necessarily reproducible on a small or medium scale. As a result, small and medium-sized mining (SMM) remains in a state of low-scale, low-efficiency production, and markets for different technologies or products are not developed due to this confinement.[7]

Images: envato/AveCalvar

There are efforts to promote the use of new technologies for small and medium-sized mining operations. For example, the University of Chile plans to implement two programs that have won awards from the national research and development agency ANID: "CuPEx+," a technology for recovering copper using cleaner processes, and "Integrated Climate and Water System," a service to improve national hydroclimatic monitoring.

Both projects have a duration of 48 months and goal is, to advance in their technological maturity (TRL), with prototypes applicable to the mining, energy, and water management industries. CuPEx+ proposes a mobile and compact technology to optimize copper production from leach-rich solutions (PLS), allowing copper sulfate to be crystallized at lower costs and with a high level of efficiency.

The system will integrate membrane contactors for the liquid-liquid extraction stage (perstraction) and membrane-assisted crystallization (MAACr) in the second phase.This approach will enable the development of a semi-industrial pilot plant to validate the process, with potential application in small and medium-sized mining operations. The objective of the project "Integrated Climate and Water System," is to develop a national hydroclimatic service that generates accurate and consistent estimates of variables such as precipitation, temperature, humidity, snow, and river flows.

3 CHILE'S REGULATORY FRAMEWORK AND SUSTAINABLE DEVELOPMENT

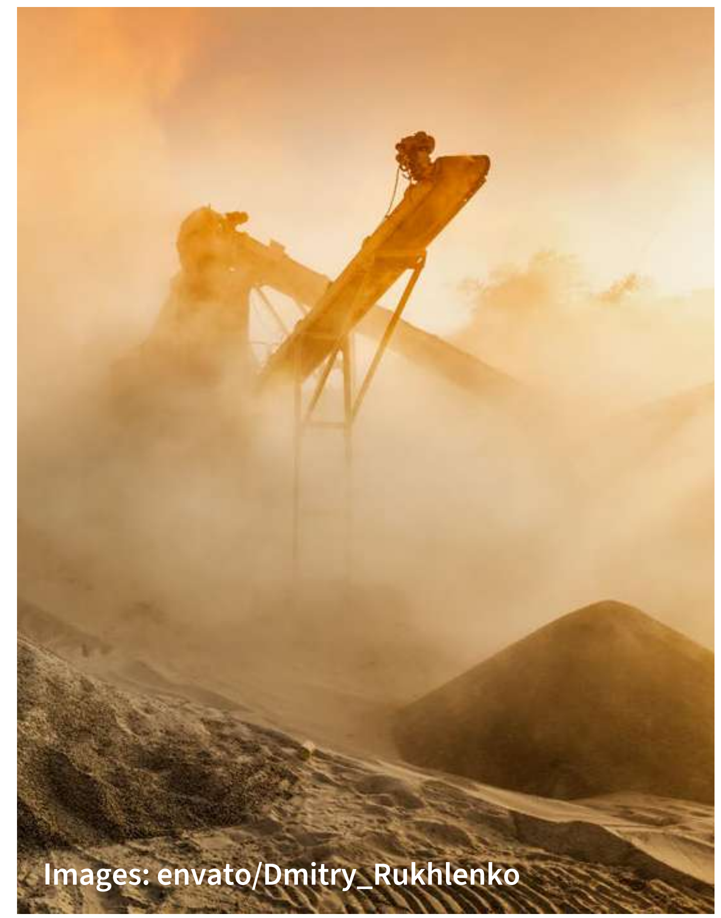
Chilean legislation is very clear regarding production conditions for environmental preservation, requiring producers to adapt their technologies to cleaner and more environmentally friendly ones. Our national legislation includes:

- **Law 19,300 General Environmental Principles:** This regulates all new projects and modifications that must be submitted to the Environmental Impact Assessment System (SEIA), which leads to the search for and investment in technologies that leave a smaller environmental footprint.

- **DS No. 248/2007 (Tailings Regulation):** These are basic standards for the layout, construction, and closure of tailings dams. This encourages advances in leaching technologies, since there are no intermediate treatments such as grinding and flotation that leave traces of tailings, only debris that is easier to manage environmentally.

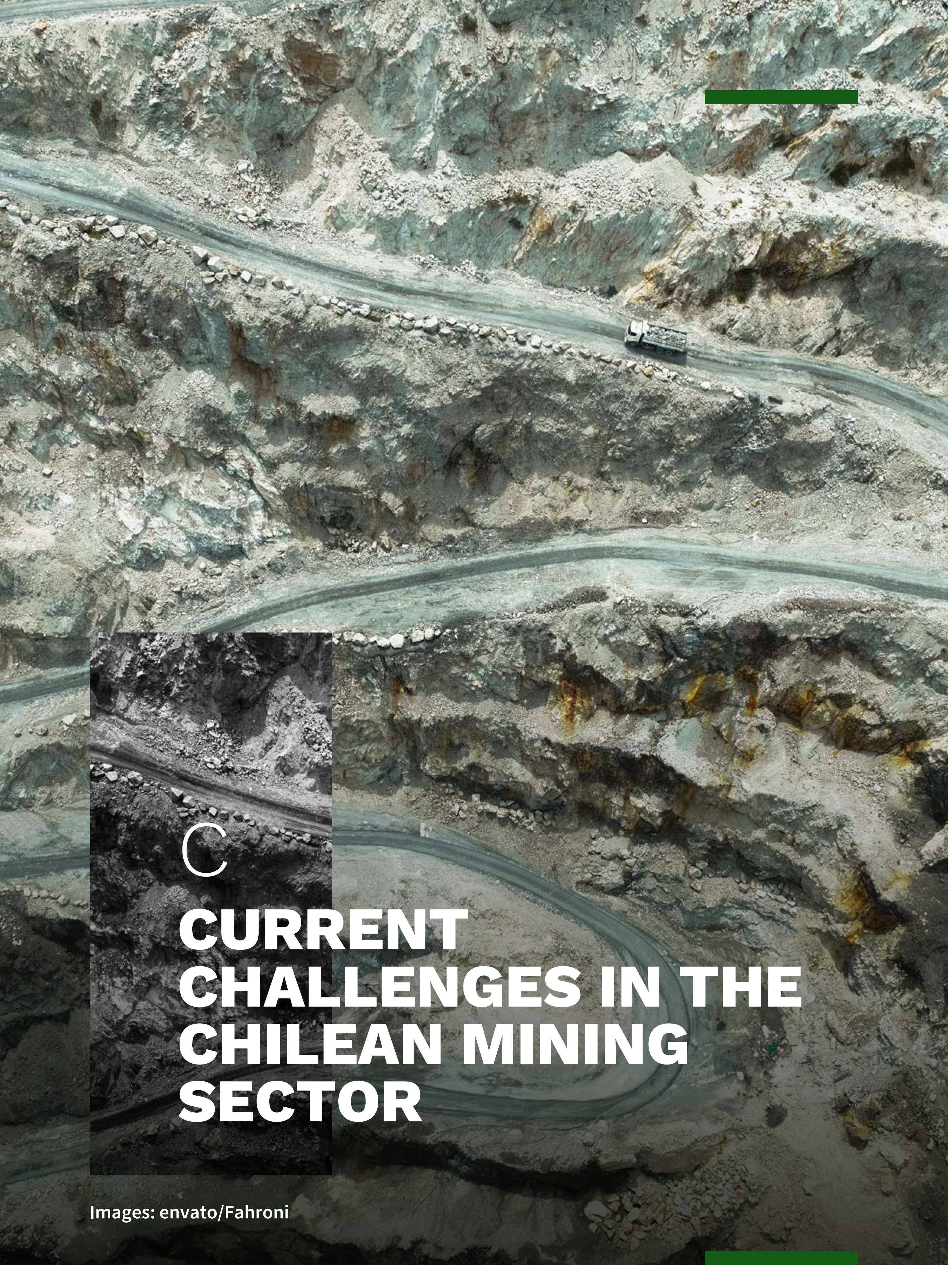
- **DS No. 28/2013 (Emission Standard for Smelters):** This requires detailed frameworks for the production of sulfur dioxide (SO2) and arsenic within copper smelters. This limits the possibility of processing concentrates with high levels of impurities, leading to alternatives such as POX leaching, which can treat concentrates with high impurities.

- **Water code:** Water resources are a variable to consider, with mineral concentration being the main user of this resource.



Images: envato/Dmitry_Rukhlenko

[7] *Olmos Maturana et al., "**Enclaustramiento Tecnológico y de Negocio En La Pequeña y Mediana Minería Chilena,**" 9.*



C

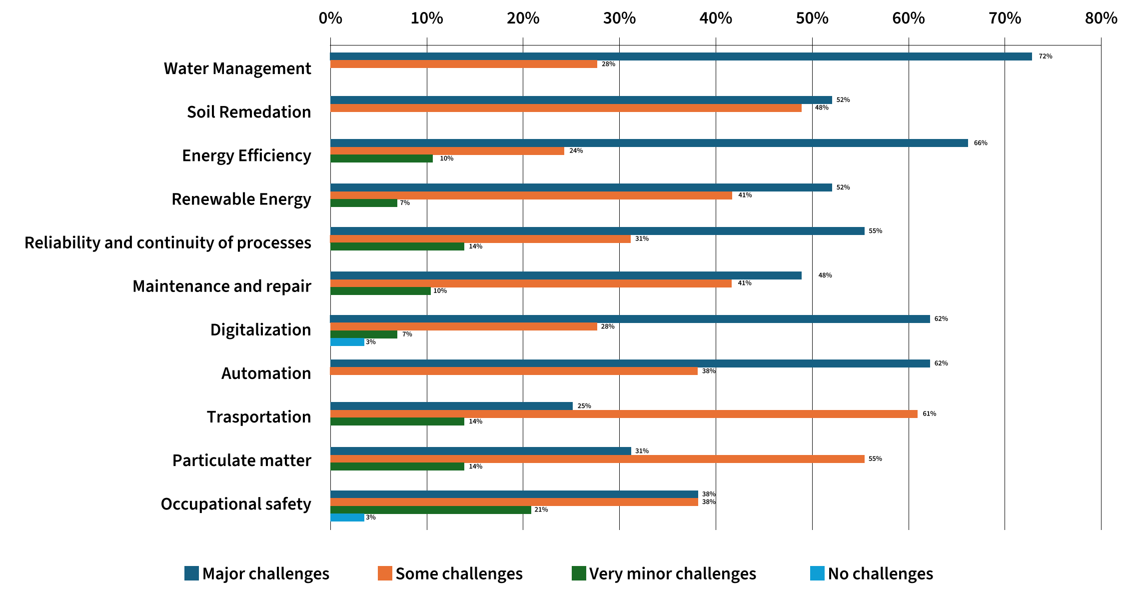
CURRENT CHALLENGES IN THE CHILEAN MINING SECTOR

Images: envato/Fahroni

1 SURVEY RESULTS

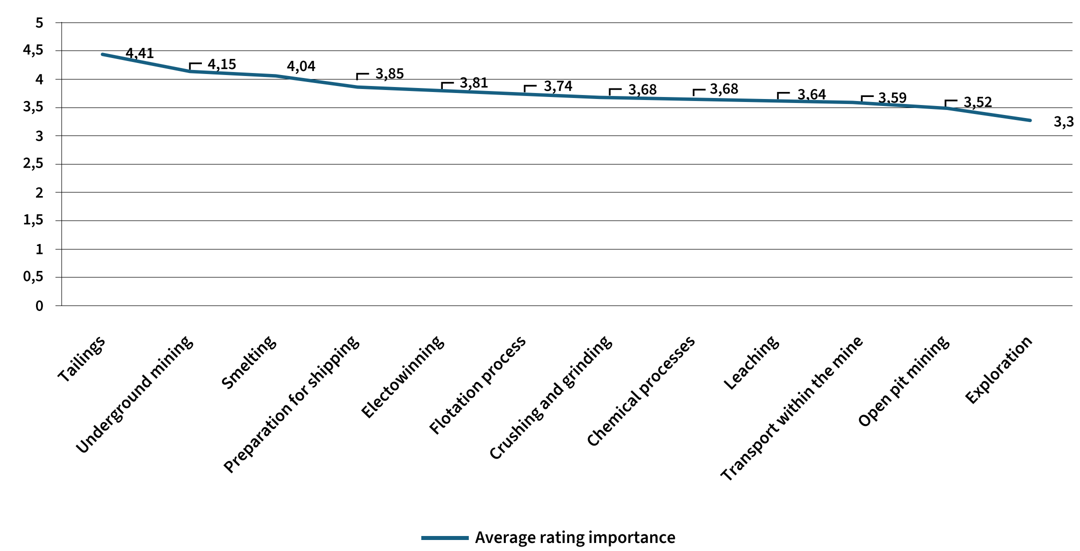
In 2025 AHK Chile conducted an online survey among mining companies, technology suppliers, subcontractors, consulting firms, associations, and public institutions in the mining sector on technological gaps in Chilean mining. A total of 29 people participated in the survey. Of the participants, 18% were from large mining companies, 28.5% from suppliers and subcontractors, 43% from consulting firms, 7% from associations, and 3.5% from public institutions in the mining sector. The results of the survey can be seen in the chart below.

Survey results Technical challenges



In addition, respondents were asked about technological gaps in mining production chain processes, with a relevance rating from 1 (low relevance) to 5 (high relevance). The results can also be seen in the chart below.

Survey results Production chain



2 STRUCTURAL CHALLENGE: FROM THE DEPLETION OF OXIDIZED MINERALS TO SULFIDES

The main challenge today is the energy transition, where the world will require more copper to reduce its carbon footprint to zero. To this end, the modernization of hydrometallurgical processes is key to the treatment of those primary sulfide minerals that have only been processed by flotation. Mineral depletion is causing a large-scale supply shortage, and Chile has a significant number of hydrometallurgical plants that, if not modernized, are at risk of becoming obsolete, as are the smelters within its national territory. Hydrometallurgical processes are attractive to producers because they are less expensive than concentrator plants, especially when treating low-grade sulfide minerals. The goal is to process low-grade and highly refractory sulfides at a lower cost using existing technologies that require modifications to continue operating.

Images: envato/lcrms

3 LEACHING

Bioleaching

This is a treatment that uses the metabolic capabilities of certain types of microorganisms to catalyze the dissolution of sulfide-type minerals. It is currently a highly environmentally friendly process, given that traditional processes have been shown to generate ecological footprints such as carbon emissions and the development of tailings deposits. Bacteria that are ideal for these processes are classified as extremophiles, since they are capable of surviving in conditions of low pH and, in some cases, high temperatures. Bioleaching is a process with positive results, where CAPEX and OPEX are optimal, requiring less water and energy consumption than other processes and with zero sulfur footprints. It is highly recommended for low-grade sulfide minerals that would not be recommended for individual processing unless treated by flotation. Despite this, a disadvantage is its slow kinetics, with leaching cycles that take months or years, requiring stable environmental conditions and limiting its effectiveness with sulfides such as chalcopyrite. It is used for secondary enrichment sulfides such as covellite and chalcocite.

Chloride Leaching

Leaching, when subjected to high concentrations of chloride ions (Cl^-), has emerged as an alternative to more favorable technologies for overcoming the mineralogical characteristics of chalcopyrite and other primary sulfides such as bornite (Cu_5FeS_4) and enargite (Cu_3AsS_4).

The presence of chloride supports catalysis, thereby transforming the electrochemistry of primary copper sulfides. The pioneering and best-performing technologies for this process are:

Cuprochlor-T: Technology developed by Antofagasta Minerals, where heap leaching is designed to treat primary sulfides. This involves the use of chloride salts and controlled heat irradiation of the heap in ranges of 30 to 50°C. It has achieved copper recovery rates of over 70% in 200-day industrial-scale tests.

HydroCopper: Technology developed by Metso, it is a stirred leaching treatment in tanks that operates at atmospheric pressure but at high temperatures of 85 to 95ºC in a concentrated brine of 250 to 300 g/L of NaCl. It requires cupric ion as an oxidizing agent.

Pressure Oxidation Leaching (POX)

This methodology is a hydrometallurgical treatment whose purpose is to inject extreme conditions to overcome the kinetics of mostly refractory minerals. The process is carried out using autoclaves, which are a type of sealed reactor capable of withstanding high temperatures and pressures.
The thermodynamic operation involves increasing the temperature from 200 to 220°C and oxygen pressures of 20 bar. Under these conditions, chalcopyrite and other minerals such as bornite and enargite are dissolved in a matter of hours, achieving copper recoveries of over 98%.
Pressure oxidation technology has proven to be efficient for processing high-grade copper concentrates, where

impurities such as arsenic are present in enargite. One of the advantages is that the POX process at high temperatures, with its ability to oxidize already dissolved arsenic, allows it to be precipitated.

One disadvantage of POX is that it requires high investment costs, as it requires the construction of autoclaves with titanium coatings to handle high pressures and corrosive fluids, and its high operating cost is associated with high energy and oxygen consumption.

CODELCO's subsidiary, Ecometales, has a POX plant in the Northern District, providing technical feasibility that makes it a technology for treating high-grade concentrates with a significant presence of arsenic (as in the Ministro Hales operation).

Other Leaching Technologies

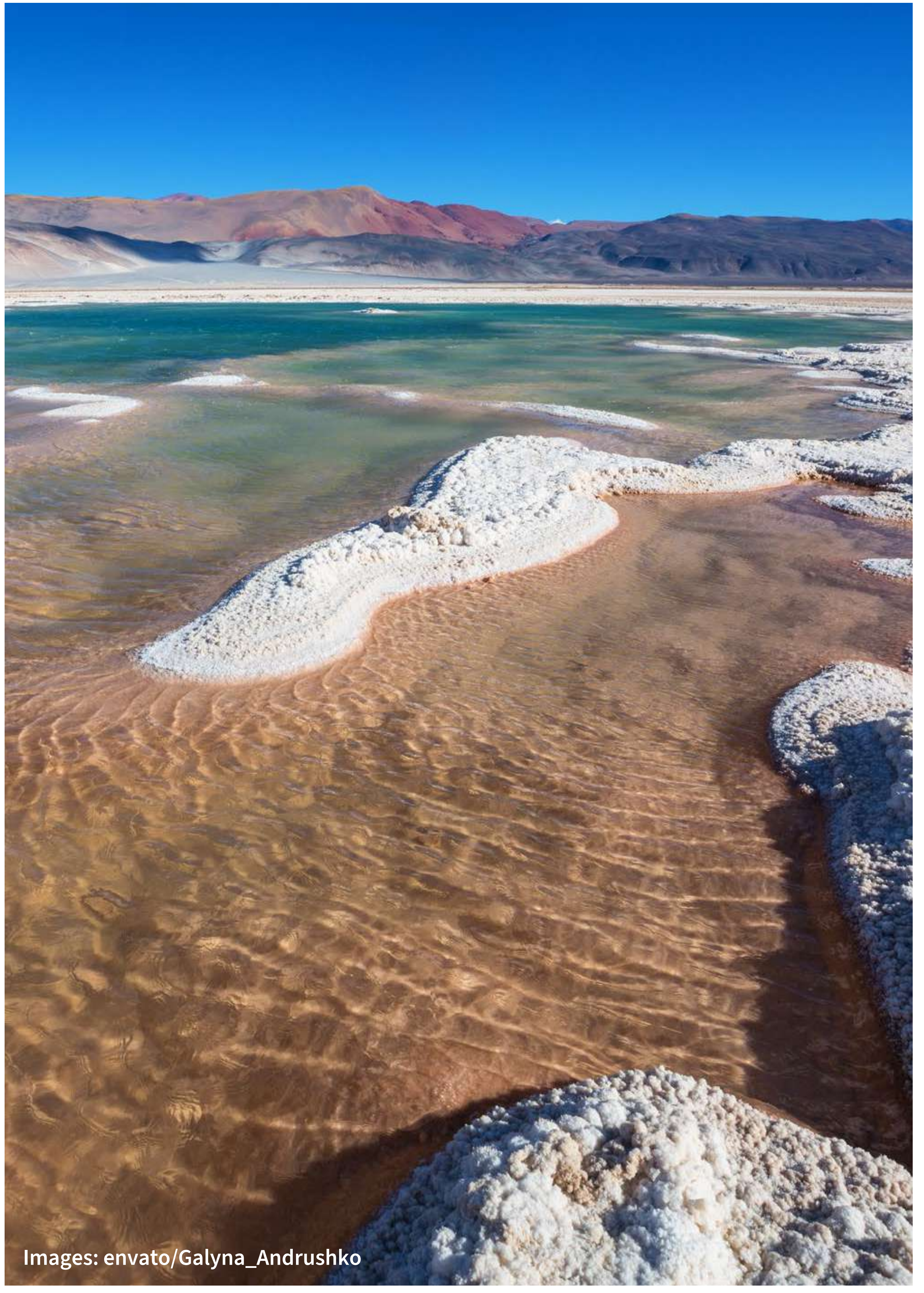
There are other technologies that seek to innovate in the leaching of copper sulfides:

Galvanox: This is an atmospheric leaching treatment at temperatures of 80°C carried out by the University of British Columbia that does not require chlorides, additives, or microorganisms. Its development is based on the use of the galvanic pair between chalcopyrite and pyrite (FeS_2). When crushed and ground pyrite is added to the reactor in a 2:1 ratio to chalcopyrite, the pyrite acts as a cathode for the reduction of the ferric ion. This causes the surface of the chalcopyrite to undergo a slower cathodic reaction, allowing it to act as an anode and be dissolved at higher rates. Copper recoveries of 98% have been achieved as a peak in times of 4 to 6 hours, respectively.

Treatment of refractory and low-grade minerals

Although methodologies such as chlorinated leaching exist, there is currently no low-cost, high-efficiency solution that can be applied to the diversity of low-grade primary sulfides such as chalcopyrite. Current treatments require additional inputs, such as increasing the temperature of the piles or higher concentrations of reagents, which significantly increase operating costs and pose an engineering challenge.

The opportunity for technology providers lies in the implementation of chemical reagents and additives to optimize leaching within the piles, which does not require new innovation, but rather an improvement in already known chemical processes. Some leading German companies in the chemical industry can supply reagents to add value to specific problems. Among them is BASF with its LixTRA product, which consists of a surface active agent (surfactant) manufactured to significantly improve wetting within the ore, in conjunction with its alliance with the US-based nanotechnology company Molear who developed a nanobubble technology, thus seeking to increase oxygen transfer and efficiency within the leachate. This opportunity can expand the change in terms of reaction catalysts, precipitation inhibitors, and selective agents.



Images: envato/Galyna_Andrushko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4 EXPLORATION OF NEW DEPOSITS

There is a challenge in Chile with copper production. The country's production has not increased significantly in the last 20 years. In fact, production in 2023 is lower than in the last 20 years, with copper production in Chile falling by 1.4% compared to the previous year, totaling 5.25 million tons. However, investments in exploration are crucial to maintaining the country's competitiveness in the global market, as they allow for the discovery of new deposits and optimize the recovery of existing resources.[8]

The deposits that remain to be discovered are those that lie deepest, hidden by geological processes, and where the discovery process is extremely technological. This requires more knowledge, science, and the development of technologies that improve the geological characterization of deposits, improving the management and transfer of information.[9]

Companies such as the Australian firm Fleet Space are currently attempting to establish a bigger presence in Chile. The company offers real-time geophysics solutions with real-time 3D images of the subsurface up to 7 km deep and evaluation using AI. Competitors can certainly still enter the market here, including with other technologies for exploring deposits.[10]

[8] *“La Exploración Minera en Chile,” 5.*
[9] *BNamericas.com, “BNamericas - Experto en geología.”*
[10] *Minero, “Fleet Space expande su presencia en Chile para acelerar la exploración de minerales con IA y tecnología espacial.”*
[11] *Suelos en riesgo.*

5 SOIL REMEDIATION

Chile faces a significant environmental challenge due to soil contamination. According to the Ministry of the Environment, there are 9,271 sites nationwide with potential presence of contaminants, of which 40% are attributed to mining activity. The regions most affected by mining are Atacama, Coquimbo, and Valparaíso.[11] The impacts of soil and groundwater contamination are complex, affecting several dimensions simultaneously. Economic activities such as agriculture are compromised, soil productivity declines, and key natural cycles, such as those of water, flora, and fauna, are disrupted, leading to a significant loss of biodiversity.[12]

In order to restore the quality of contaminated soil, it is essential to first determine the hazard and the main contaminants present in the waste through field sampling. This allows for the most appropriate treatment to be applied and compliance with the provisions for hazardous waste.

The process consists of removing contaminants from the environment, which are then transported for subsequent treatment and final disposal in a safe manner.[13]

Decontamination processes require considerable investment, especially when seeking to recover soil for productive, industrial, commercial, or residential uses. There are multiple challenges in this regard, including identifying the solution that best suits each specific situation and is also cost-effective. Unlike markets such as Europe, where remediation is an established practice, Chile is still in a rather early stage. There are business opportunities in the recovery through reprocessing or reuse of tailings from abandoned or inactive deposits. This could help to finance the remediation of these sites. Also, in a context of housing deficit, potentially contaminated land represents an opportunity that we have not yet been able to capitalize on. Thousands of degraded sites remain without a recovery plan, despite their potential to become housing solutions, revitalize neighborhoods, and contain disorderly urban expansion. Incorporating reclaimed land into the productive and social cycle gives it a new purpose that maximizes its value and contributes to the well-being of people and their communities.[14]

In June 2024, Chilean state-owned mining company CODELCO and German state-owned company Wismut, which is responsible for the decommissioning, remediation, and restoration of former mining sites, signed an agreement to promote best practices in mine decommissioning and sustainability.[15]

[12] *Francisca Orellana, “Los Desafíos Que Tiene Chile Para Limpiar Los Suelos Contaminados,” 28.*
[13] *Suelos en riesgo.*
[14] *Francisca Orellana, “Los Desafíos Que Tiene Chile Para Limpiar Los Suelos Contaminados.”*
[15] *https://www.codelco.com/codelco-y-la-empresa-alemana-wismut-firman-acuerdo-para-avanzar-en*


Images: envato/miraclemoments

6 MANAGEMENT OF CRITICAL IMPURITIES (ARSENIC)

The high concentration of arsenic present in areas where primary sulfide enrichment plays an important role, such as in the copper deposits of the Antofagasta region, is a latent problem. Smelting markets, particularly those in China, penalize concentrates containing at least 0.5% arsenic in their composition, even rejecting them for sale. This situation is problematic for entire operations.

The opportunity for Germany to enter the market as a supplier lies in the search for cutting-edge technologies to treat these complex concentrates and reduce the arsenic footprint through stabilization.

In order to treat concentrates with high levels of arsenic, the product must be transformed from one of little interest and value into a high value-added product such as cathodes, with stable residues. The added value is justified by higher investments. German process engineering and plant companies and research institutes

have extensive experience in metallurgical and chemical processes and are skilled in the design, construction, and optimization of hydrometallurgical processes such as POX. The ReAK (Arsenic Reduction in Copper Concentrates) project is a clear example of interest in developing technology to add value to polymetallic concentrates.

7 RENEWABLE ENERGIES

Chile's mining operations rely on both water and energy resources. The scarcity of continental water sources has led to the development of a new water consumption matrix based on seawater, where desalination plants and pumping to sites at altitudes above 3,000 meters require high energy consumption.

In Chilean mining, 70% of the electrical energy used is now generated from renewable sources. By 2026, renewable energy is predicted to cover as much as 80% of demand. However, the demand for electrical energy is also rising sharply. The Chilean state copper commission COCHILCO forecasts that the demand for electrical energy in Chilean mining will rise from 26.9 TWh in 2022 to 32.5 TWh in 2034. This represents a 20.8% increase in energy demand, with copper production forecast to rise by only 5.6% by 2023. The problem is exacerbated by the decline in mineral grades, given that the amount of sterile mineral waste increases to maintain production, which means that more energy must be consumed. Concentration processes will consume 18.7 TWh in 2034, accounting for 57.6% of the electricity consumption of copper mining. In second place is the increasing energy demand for the use of seawater, which will reach 5.4 TWh – mainly due to desalination and pumping power, which will account for 4.3 TWh.

However, the high proportion of renewable energy, especially solar energy, also causes problems. In 2024, 17% or 5,900 GWh of the renewable electricity generated in Chile was not used because the grid did not have sufficient transmission capacity.

This problem is particularly acute in the north of the country, where most mining activities take place, because the conditions there are very favorable for solar energy. The expansion of storage infrastructure has not been able to keep pace with the expansion of renewable energies. In September 2025, the country had a total storage capacity of only 4,592 MWh, mainly in the form of battery storage.

Another critical issue is transmission infrastructure. Current planning does not keep pace with the speed at which generation projects are advancing, causing congestion and limiting the possibility of feeding renewable energy into the system. Added to this is the fact that transmission costs are largely borne by consumers, while generators do not sufficiently internalize this charge. This scheme creates a distortion: Customers end up financing a significant portion of transmission, even though generators use it as much or more. For large industrial consumers, such as mining, this situation increases the final cost of electricity and restricts their ability to plan with certainty.


Images: envato/collab_media

Images: envato/Mint_Images

8 WATER AND ENERGY EFFICIENCY

Since 2021, Chile has had an energy efficiency law that has had a major impact on the country's mining sector. Under the law, all large energy consumers with an annual consumption of more than 50 TCal of energy must implement an energy management system and appoint an energy manager. Furthermore, companies must submit annual energy reports detailing their energy consumption. The law also sets efficiency standards for buildings and vehicles and promotes the use of renewable energies and electromobility.

As a result, the subject of energy efficiency has become increasingly important in Chilean mining and has become a structural element of the business model.

Today, the greatest potential for energy efficiency measures lies primarily in areas where outdated technology is used, such as certain heating processes, where energy efficiency measurement is not yet widespread. There is also great potential in the areas of seawater desalination and pumping, including frequency converters for pumps, as water desalination and pumping account for a large proportion of energy consumption in mines.

In the Chilean Sierra Gordo mine, which produces copper and molybdenum in the north of the country, salt water is now used directly, being brought to the mine via an aqueduct. A total of 1,500 liters per second are pumped into the mine. This also offers great potential for German companies to establish direct salt water use in other mines.[16]

Images: envato/ai

9 ARTIFICIAL INTELLIGENCE

The use of artificial intelligence and machine learning is on the rise in the Chilean mining sector and it is used both in the operation and in the training of personnel. The aim is a greater efficiency, higher material recovery rates, cost reduction and lower environmental impact. [17]

Artificial intelligence is already used for metal classification, optimization of the value chain and in the control of the quality of the materials. It is also supporting companies in environmental monitoring and resource management, such as water and energy. Furthermore, the mining company Antofagasta Minerals is using AI to achieve predictive maintenance and with the aim of keeping people away from exposure to danger. This is also driving the analysis of large volumes of geological and geophysical data, enabling mining companies to improve the accuracy of their exploration activities and reduce the risks associated with investing in new mining areas.[18]

This way machine learning algorithms are changing the rules of the game: by analyzing geological and satellite information, they detect areas with mineral potential more accurately, reducing the need for unnecessary drilling and accelerating strategic decision-making.[19]

In mining, current IT systems may be outdated or not fully compatible with new technologies, so it is necessary to modernize the digital infrastructure and standardize data protocols, aligning the systems and processes of different areas within the mining value chain to integrate AI with existing systems and data. Similarly, it is crucial to address resistance to change in a sector where many employees are accustomed to conventional methods and, therefore, the transition can be challenging. It is therefore essential to invest in training and education programs that not only teach the use of these tools, but also promote an open mindset towards innovation and its benefits.[20]

Another challenge is the implementation of data governance policies and infrastructure within the companies to be able to manage a great amount of data used by AI systems.[21] In their Escondida mine, BHP is using real-time data from concentrator plants and recommendations based on Microsoft's Azure platform, where concentrator operators can adjust operating variables that affect ore processing and quality recovery.[22]

10 AUTOMATIZATION

Images: envato/leungchopan

Large-scale hydrometallurgical processes such as heaps or dumps can cover areas of several square kilometers. Compaction, particle sizes, temperatures, and chemical compositions generate a channel of dead zones, resulting in incomplete copper recovery and misuse of water and sulfuric acid. Although mining is advancing towards Mining 4.0, this is where the application of modern leaching technologies is still in the testing phase.

The opportunities for Germany lie in advancing Industry 4.0 solutions for intelligent leaching processes, where suppliers will need to automate and digitize these transformations with high precision. Siemens can develop integration systems for advanced sensors (such as fiber optics for monitoring temperature and sensors for measuring pH) using platforms with real-time software modeling of leaching piles. These models would simulate fluids and their kinetics, optimizing irrigation cycles, reagent dosing, and copper recovery, thereby maximizing operations.

[16] ***https://consejominero.cl/plataforma-social/uso-de-agua-de-mar-sin-desalar/***
[17] *PricewaterhouseCoopers,* ***"Cómo se está incorporando la ia en la industria minera."***
[18] *PricewaterhouseCoopers,* ***"Cómo se está incorporando la ia en la industria minera."***
[19] *Prieto and TIVIT,* ***"Mes de la Minería."***
[20] *PricewaterhouseCoopers,* ***"Cómo se está incorporando la ia en la industria minera."***
[21] *Prieto and TIVIT,* ***"Mes de la Minería."***
[22] *PricewaterhouseCoopers,* ***"Cómo se está incorporando la ia en la industria minera."***
[23] ***https://www.corporacionaltaley.cl/expertos-coinciden-en-la-importancia-de-clasificar-a-las-escorias-como-subproducto-minero/***

Images: envato/lcrms

10 CIRCULAR ECONOMY AND WASTE RECOVERY

Chile has more than 790 tailings dams, of which more than 170 are abandoned. These tailings deposits are not only an environmental liability and a potential risk due to their stability, but they also contain various metals of economic interest, such as copper, molybdenum, cobalt, and rhenium, among others, which could not be recovered due to the limited advances in technology at the time.

Germany's opportunity in this situation is the use of tailings reprocessing and metallurgy technologies. The term "anthropic mining" for tailings is a gap in which Germany's experience in the circular economy offers significant access. Companies such as Aurubis, a leader in the recycling of complex components and the recovery of metals from scrap, have extensive knowledge of pyrometallurgy and hydrometallurgy for the development of tailings treatment processes. The IME at RWTH Aachen University applies the concept of "Green Metallurgy." The government economic development agency CORFO operates an overview page on mining tailings: https://relavesconvalor.cl. It also contains a 2019 study on Chilean tailings and recommendations for action on tailings mining: https://relavesconvalor.cl/Manual_Uso-Publico_Relaves.pdf.

The topic of foundry slag also offers great potential for further use. Foundry slag is used in the European Union, for example, in road construction and in the manufacture of cement and concrete, as well as an abrasive. In Chile, foundry slag has been classified as waste up to now. However, there are political efforts to change this and enable foundry slag to be used in the construction sector, for example, as a base for road surfacing and for concrete and mortar.

D
STRATEGIES AND ACTION PLAN

Images: envato/karkozphoto

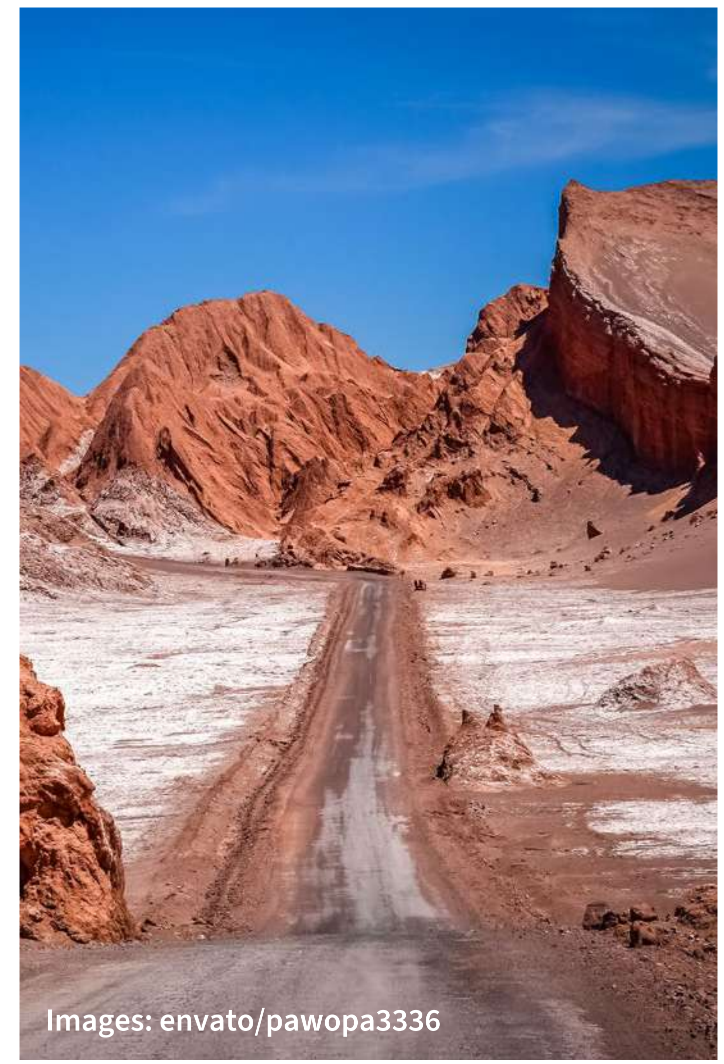
For German companies to be able to capitalize on opportunities within the Chilean mining sector, they need a strategic focus and collaboration with the mining companies.

1 STRATEGIES FOR TECHNOLOGY SUPPLIERS

Added value: The supply of standard mining equipment is high. Investments in technology must be made in cutting-edge technology that solves critical high operating cost issues within the Chilean mining industry. This involves including better methods for mining exploration, specialized chemical reagents that improve metallurgical recoveries for better profitability, improvements in control systems and digitization for water and energy optimization, the implementation of reliant and cost-efficient energy systems, and high-end process engineering design solutions for the control and management of impurities such as arsenic in concentrates.

Local Context: Investments are required in adapting technologies to the extreme conditions of northern Chile, such as geographical altitude, salinity, solar radiation, dust, and the corrosiveness of seawater for chlorinated leaching solutions. Pilot equipment is required in the field, ideally mobile.

Innovative Business Models: Beyond equipment or supply sales as transaction models, German companies should invest in business models that generate value chains. Add service contracts such as technology leasing or risk-sharing agreements that are linked to process gains (such as copper recovery, acid consumption reductions).



Images: envato/pawopa3336

2 INVESTMENT AND COLLABORATION OPPORTUNITIES

Strategic alliances/partnerships with local mining companies: Mining companies with the best investment ratings, such as CODELCO, BHP, and AMSA, are rapidly investing in innovation and development through pilot programs in their operations. Strengthening a joint venture to implement large-scale technology in an operational environment is an effective way to validate it in the market. The pilot projects that have been launched have been well received and have yielded good results for operations such as Radomiro Tomic, Escondida, and Centinela, which are exemplary models for other current operations to adopt. Cooperation with small and medium-sized mining companies can also be very useful, as they often lack the latest technologies and innovative approaches can make a big difference.

Investment in technology startups: There is growth in technology startup ecosystems with an eye on copper mining. Companies such as ChucaoTech, which designs nanobubbles for leaching, are living examples of local innovation. German investments through venture capital funds can be a strong start for startups to scale up at the right time so that the German company has access to the technology and knowledge of the local market.

Define Support Centers in Chile: Research laboratories and technical support should be available in the Antofagasta and Atacama regions, where other German companies should consider establishing a presence near mining operations. This would provide close and immediate technical support to develop adaptation tests for products using minerals from the area and develop solutions for each particular case in collaboration with their customers.

Images: envato/petero31

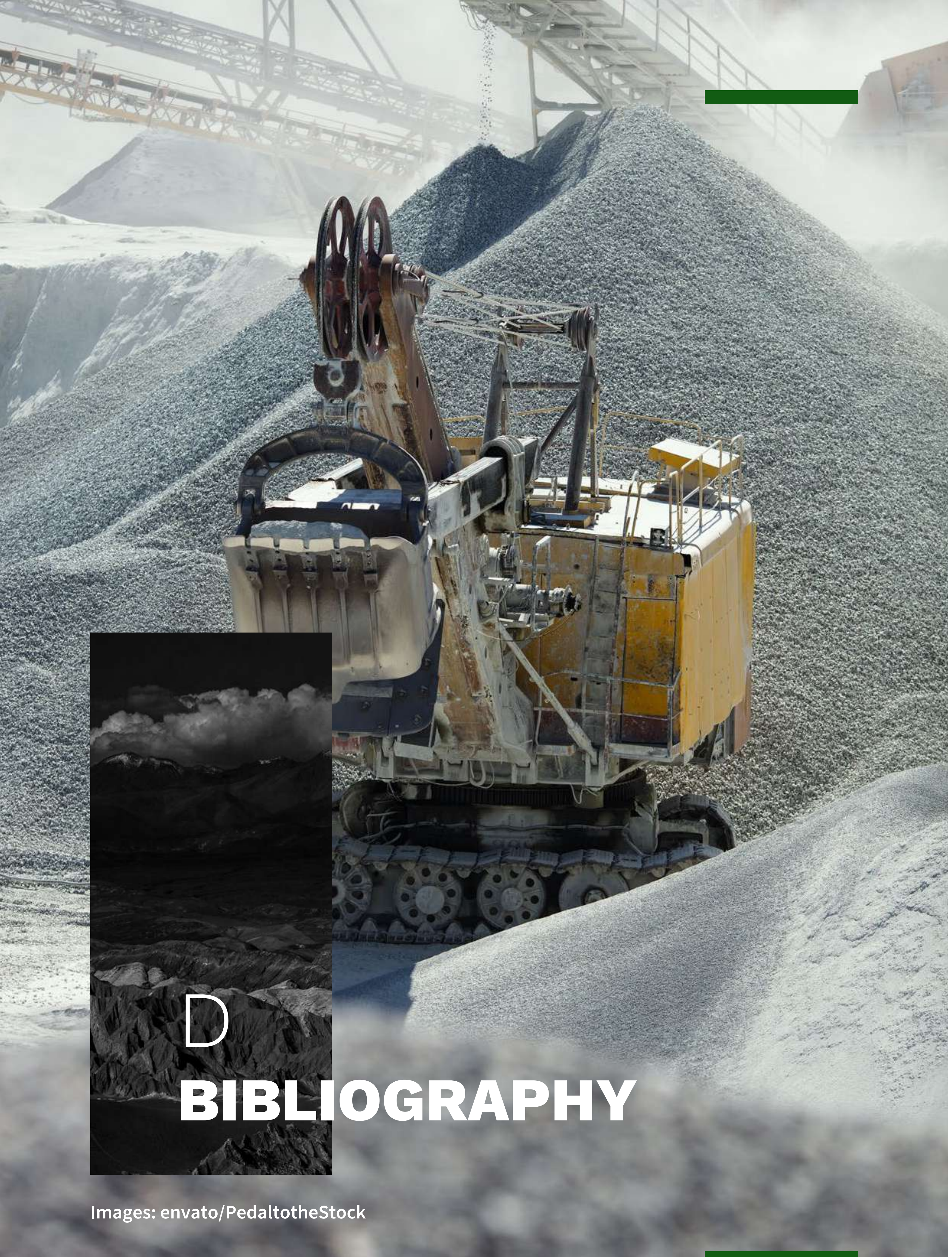
3 SYNERGY WITH GERMAN RESEARCH AND DEVELOPMENT (R&D)

Promote joint research: Research projects should be promoted in collaboration with German science and research institutes and Chilean universities in potential mining areas. Institutes such as Fraunhofer, Helmholtz, and RWTH Aachen University can form strategic alliances with centers such as the Advanced Mining Technology Center at the University of Chile or CODELCO's innovation development centers. Key research areas could include the bioleaching of chalcopyrite at lower temperatures, the stabilization of impurities in concentrates, and the design of more robust sensors to monitor leaching piles. There is also a Fraunhofer Institute in Chile, Fraunhofer Chile Research.

Knowledge in Green Metallurgy: This concept, developed by the IME at RWTH Aachen University, is in line with the objectives of Chilean copper production with “green copper.” Organize seminars and research programs among graduate students as conceptual frameworks for the methodology to new challenges to add value to refined copper.

Binational Financing Programs: The use of programs from both governments to mitigate the economic risks of the innovation and development phases. The project led by ReAK, funded by the CLIENT II program of the German Federal Ministry of Education and Research, is proving to be a successful model for cooperation between both nations in addressing issues related to technologies of mutual interest. There are also other funding programs for research projects in both countries, such as the European EUREKA program, in which Chile, as an associate member, provides funding for joint research projects with European and Chilean partners through the state-owned economic development agency CORFO.

Images: envato/wirestock



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TECHNOLOGICAL CHALLENGES AND BUSINESS OPPORTUNITIES

Deutsch-Chilenische Industrie- und Handelskammer
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