Mineral raw materials in the energy transition and digitisation

The role mining and metallurgy

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MINERAL RAW MATERIALS IN THE ENERGY TRANSITION AND DIGITALISATION

THE ROLE OF MINING AND METALLURGY

Royal Academy of Engineering of Spain - CODEIME

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The role of mining and metallurgy

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The Royal Academy of Engineering in Spain

The Royal Academy of Engineering, created in 1994, aims to promote the quality and competence of Spanish engineering and to encourage the study, research, discussion and dissemination of its techniques and its scientific and social foundations. To meet these objectives, among other activities, it carries out studies and issues reports and opinions. Its territorial scope is the Kingdom of Spain, without prejudice to the possibility of carrying out activities abroad or establishing collaborative relationships with foreign entities of a similar or complementary nature.

CODEIME

Conferencia de Directores/as de Escuelas de Minas y Energía

CODEIME

The Conference of Directors of Mining and Energy Engineering Schools (CODEIME) is constituted as a non-profit association of a private and public law nature whose aims include promoting the constant improvement of the quality of mining and energy engineering studies, promoting the dissemination of the social interest of mining and energy engineering, encouraging research activity in the various fields of mining and energy engineering and highlighting the professional activity of mining and energy engineering to society.

Presentation by the President of the Royal Academy of Engineering

Energy transition and digitalisation are two realities of growing strength. Although their global deployment is and will be uneven across regions, in Europe the penetration of renewables and electrification, with the objective of achieving climate neutrality by the middle of this century, set a clear pattern of intensification of the energy transition in the context of a more digitalised society and economy in all aspects.

Moreover, the risks in the supply chains of raw materials, intermediate products and equipment mean that the principles and instruments for the implementation of energy sovereignty are increasingly present in the EU debate and even at the global level.

In this context, the book in your hands examines the implications of the double transition (energy and digitalisation) on the demand for minerals and metals and comes to the conclusion that more minerals and metals will be needed; and that the demand for them will increase substantially.

With an approach that can be considered novel, the study approaches the supply chain from its origins, i.e. from mining research, to analyse mining with its engineering techniques, as well as the concentration of ores to reach metallurgy. Processes that allow metals to be extracted, which are the basis for the manufacture of the components and equipment needed to meet the challenges.

The authors bear in mind the principles and needs of moving towards a more circular economy and, within this framework, they analyse the supply chain, delving into its economic and industrial aspects. One chapter is dedicated to Spain, in such a way that the reality and possibilities of our country are reflected in it.

No less important is the opening chapter of key messages and recommendations, in which the authors summarise the most relevant points of their work and propose a series of measures and actions.

The Royal Academy of Engineering (RAI) aims to promote the quality and competence of Spanish engineering, as well as to encourage the study, research, discussion and dissemination of techniques and their scientific and social foundations. To achieve these aims, among other activities, the Academy publishes books to encourage multidisciplinary technical debate between academia and society.

This publication comes out shortly after the European Commission published the proposal for a Regulation to establish a framework to ensure a reliable and sustainable supply of critical materials and, in August last year, the Spanish Government approved the roadmap for the sustainable management of mineral raw materials. Therefore, this work can make a significant contribution, so that the developments that take place in these fields have references with an engineering and technical basis; in such a way that it helps the agents that have to propose policies or make decisions.

Moreover, this book is the result of the framework collaboration agreement between our academy and the Conference of Directors of Schools of Mining and Energy Engineering (CODEIME) and we are very pleased that the agreement has resulted in the excellent work that I have the honour to present.

We are convinced that it will contribute to the promotion and dissemination of engineering, particularly that related to mining and metallurgy, in our society; thus serving the aims of our Academy, showing the role that engineering continues to play in today's society.

Quality is a key element for RAI publications, which is why they undergo a review process. In this case, several academics have participated in this process. I would therefore like to thank the RAI reviewers and, of course, the authors - university professors and researchers, well known in their fields - as well as the reviewers from other institutions who have participated in this work.

Antonio Colino Martínez
President of the Spanish Royal Academy of Engineering

Presentation by the President CODEIME

Mining engineering, a branch of technology dedicated to ensuring the supply of mineral raw materials, both energetic and non-energetic, that our society needs for its human and economic development, has more than 245 years of history in Spain since its creation in 1777. During this long period of time, the professionals in this speciality have been, and continue to be in our country, mainly responsible for the prospecting and inventory of mineral deposits, their responsible exploitation, the processing and transformation of the rocks and minerals extracted into raw materials for industry, construction, energy production, etc., and, finally, the closure and environmental restoration of mining operations and industries.

In the current uncertain national and international situation, defined by the growing scientific and technological challenges associated with the desired energy sustainability and also by increasing difficulties in securing the international supply of the raw materials needed to develop the energy transition through clean technologies, mining engineering is essential to ensure the supply chain required for the sustainable economic development of our country.

The aim of this publication is to make available to the technical and scientific community, as well as to the general public, the current state of the art of the main methods and techniques available to this branch of engineering in order to overcome the aforementioned challenges. It is written by a group of professionals, many of them university professors, recognised in the field, who have also been chosen for their extensive experience in writing technical or educational texts on the different areas of their speciality. It describes in a clear, but at the same time rigorous and exhaustively documented way, each of the technologies applicable in the different phases of the chain of activities that go from mining prospecting and research to the delivery of raw materials to the fine industry, and all within a framework of maximum sustainability from an economic and environmental point of view.

Obviously, at the speed at which science and technology are evolving, it is certain that in a few years many of the techniques described here will be obsolete, so that what is described here will necessarily have to be updated, but nevertheless I am also sure that its validity from the documentary point of view will remain very high and its usefulness as a reference work of our times will be maintained.

I must thank the authors for the excellent work they have done together with the RAI review team, which has ensured that the scientific-technical level achieved in this publication is as up-to-date, detailed and complete as possible. I believe that it has succeeded in showing the fundamental role of the different branches of the mining industry (prospecting, exploitation/rehabilitation, mineralogy and metallurgy) in the value chain of mineral raw materials, analysing the future opportunities they can provide in the context of decarbonisation, sustainability and the circular economy, both internationally and in our country. In addition, current initiatives in digitisation and innovation in the aforementioned branches of mining are discussed. Therefore, I am sure it will be useful in many situations, from serving as an introductory text to the subject, to serving as a reference or orientation to other more detailed, but perhaps complex, scientific or technical documents.

Finally, I would like to explicitly thank the RAI and its editorial team for their continued support and encouragement during the long period of creation of the work; the constant search for excellence, in content and form, has served as a motivating incentive for the authors, which has undoubtedly greatly benefited the quality and depth achieved in this publication.

Congratulations and thank you all very much!

Francisco Javier Elorza Tenreiro

President of the Conference of Directors of
Schools of Mining and Energy Engineering (CODEIME)

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The coordinators and authors are very grateful for the work of the reviewers, who have provided numerous comments and who have certainly provided greater quality and rigour to the work. However, as usual, any errors that may remain are solely attributable to the authors. The analyses and comments reflect exclusively their opinion and not necessarily those of the institutions to which they belong or of those in whose collaboration this work has been developed.

Our thanks go especially to Mónica Barrero Bouza, Manuel Bravo López, Juan José del Campo Gorostidi, Vicente Gutiérrez Peinador, Alberto Lavandeira Adán, Juan Luis López Cardenete, Emilio López Jimeno, Juan José López Muñoz, Pedro Antonio Merino García, Fernando Pedrazuela González and José Luis Tejera Oliver, and to the RAI academicians who acted as reviewers, for their dedication, for reading, reviewing and commenting on all or part of the work, as well as for their valuable comments and suggestions.

Taking into account the working method, the coordination and revision of the text, the incorporation of commentaries and the editing work involved a remarkable amount of work. In this work, the coordinators have had the valuable and efficient help of one of the authors, Macarena Larrea Basterra, to whom we would like to express our gratitude.

Foreword

At the end of 2020, a framework collaboration agreement was formalised between the Royal Academy of Engineering (RAI) and the Conference of Directors of Mining and Energy Engineering Schools (CODEIME) whose territorial scope is Spain. In the context of this agreement, a monitoring committee was set up, currently formed by academics Ignacio Romagosa Clariana, José Manuel Sanjurjo Jul and Eloy Álvarez Pelegry, representing the RAI, and by Francisco Javier Elorza Tenreiro, Elena Alonso Prieto and Javier Mulas Pérez, representing CODEIME.

The committee considered and agreed that a concrete project should be carried out. Having considered different topics and possible approaches, and taking into account the relevance of the energy transition and digitalisation as engineering and social realities and their relation to mining and metallurgy, it was decided to carry out a research study on this topic.

With regard to the working method, it was agreed to set up a group of authors made up of teaching and research staff from the schools with an interest in the subject, with contributions from other experts in the topics to be dealt with. It was also decided that there would be two people coordinating the study, one from CODEIME and the other from the RAI, assigning this role to the authors.

The result of the work is a report for publication in which the authors, although they have contributed to a greater or lesser extent to the elaboration of certain chapters, have participated in the study jointly. It is not, therefore, a book of chapters with isolated authorship. This method has required considerable effort and time for coordination and integration, but was preferred because it was considered more suitable, coherent and enriching.

A very relevant element is that this study has been subject to a third party review. On the one hand, by RAI academics, thus complying with the Academy's criteria for publications bearing its seal; and on the other hand, by experts and professionals related to the content covered in the study: energy transition, digitalisation, mining, metallurgy, circular economy, sustainability and economy.

The coordinators and authors are very grateful for the work of the reviewers, who have provided numerous comments and who have certainly provided greater quality and rigour to the work, although, as usual, any errors that may remain are solely attributable to the authors. The analyses and comments reflect exclusively their opinion and not necessarily those of the institutions to which they belong or of those in whose collaboration framework this work has been carried out.

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Bearing in mind the working method, the coordination and revision of the text, the incorporation of comments and the editing work itself involved a considerable amount of work. In this work, the coordinators have benefited from the valuable and efficient help of one of the authors, Macarena Larrea Basterra, to whom we would like to express our gratitude.

The paper addresses aspects relating to the role of mining and metallurgy in the energy transition and digitisation; it therefore begins by examining and describing these processes, highlighting the need for mineral raw materials and, in some cases, metals that are not currently in great demand but which will increase in the coming years as the new industrial model towards a decarbonised and digitised economy develops. Given the relationship between demand and the use of secondary raw materials, the issue of the circular economy is addressed together with sustainability, in this case specifically including mining.

Two chapters present mining and mineralogy on the one hand, and metallurgy on the other, with the intention of describing the processes that allow the reader to acquire a basic knowledge of the methods and techniques used. These chapters are complemented by a chapter on digitisation and innovation in both fields.

Two other topics that we considered fundamental were the value chain (from mining research and exploration to metal processing for components and equipment) and the situation in Spain. In the chapter on Spain, we indicate the mining and metallurgical facilities in operation and existing projects, as well as the economic aspects of mining and metallurgical activities that contribute to the creation of wealth and quality employment in the country.

Although reference is made to relevant regulatory issues, there is no systematic and detailed analysis of the regulations applicable to the activities examined. However, the references included are considered to provide an overview of the general regulatory framework relevant to the topics covered and, in some cases, the applicable environmental regulations are listed in detail.

We would like to point out that, in the process of reviewing this work, at the end of August 2022, the Council of Ministers approved the "Roadmap for the sustainable management of mineral raw materials" in the framework of which the amendment of the Mining Act 22/1973 has been launched.

Similarly, in September 2022, the President of the European Commission announced the initiative for a new legislative proposal for a Critical Raw Material Act. Among its objectives is to ensure a sustainable supply of critical raw materials to support the green and digital transitions.

Among the pillars of this initiative (currently under development), the initiative aims to strengthen the value chain of critical raw materials, from mining to recycling, in a global context, contributing to greater resilience, agility and resistance, in line with European standards and values. In addition, there is a need to create a level, strong and sustainable playing field and to streamline and consolidate standards and operating schemes in order to also be leaders in quality.

Taking into account all of the above, we understand that the scope and structure of this work addresses the issues that, both from the EU and Spanish perspective, are relevant; and we hope that this study will serve as a pedagogical tool, as well as to promote debate and proposals for the sustainable supply of mineral raw materials, creating value in Spain in the supply chains; for a better development of the energy transition and digitisation.

Eloy Álvarez Pelegry and **Francisco Blanco Álvarez**
Coordinators
February 2023

KEY MESSAGES

AND RECOMMENDATIONS

The study "Mineral raw materials in the energy transition and digitalisation. The role of mining and metallurgy" consists of an introduction, seven chapters and annexes that expand on the information in some chapters. After the introductions, foreword and introduction (chapter one), chapter two deals with the role of raw materials for decarbonisation and digitalisation, trends that are pushing up the demand for raw materials. The third chapter describes the technological processes in mining and the fourth chapter those in metallurgy, followed by a presentation of the main digital tools that can be used in the mining and metallurgy sectors. are being deployed in both sectors in chapter five.

Taking into account EU and national strategies, the geopolitical context and the growing risks of supply chain disruption, the sixth chapter addresses the issue of circularity as a tool to support supply (the recovery of secondary raw materials, the role of metallurgy in recycling and industrial symbiosis) framed within the concept of sustainability from the triple pillar (economic, social and environmental). Chapter seven deals with the economic and industrial aspects of mining and metallurgy, first describing the stages of the value chains and, in chapter eight, analysing the situation of both activities in Spain. This is completed with bibliographical references, five annexes, a glossary and a list of acronyms at the end of the study.

The main reflections resulting from the work carried out are presented below. These reflections are organised around two sub-sections, namely **Key Messages** (K.M.) and **Recommendations** (R.).

KEY MESSAGES

M.C.1. The energy transition and digitalisation mean an increasing demand for mineral raw materials.

The energy transition involves a strong development of renewable energies, the electrification of the economy and the deployment of a large fleet of electric vehicles and electric battery storage. The former require, in terms of specific power, larger quantities and a greater variety of minerals and metals than gas, coal or nuclear generation facilities. Battery storage also requires a wide variety of materials and will see an increase in demand.

In Spain, the National Integrated Energy and Climate Plan 2021-2030 (PNIEC) foresees a total installed capacity in the electricity sector of 161 GW by 2030, of which 50 GW will be wind energy, representing an increase of 117%; 39 GW of solar photovoltaic, an increase of 722%; 9.5 GW of pumped storage, an increase of 179%; 7 GW of solar thermal, an increase of 204%; and 6 GW of storage (between pumped storage and other storage technologies).

Globally, studies by the International Energy Agency and other international organisations conclude that mineral raw materials have and will play a key role in facilitating energy transitions and digitisation, and that demand for minerals and metals will increase, in a context where there is a need to boost the circular economy.

As a result, while on the one hand, the strong development of renewables, electricity grids, batteries and electric vehicles leads to greater energy independence by avoiding or reducing imports of gas, coal or oil products, on the other hand, it reinforces the need for the extraction of minerals which, when processed, make it possible to obtain metals for the components and equipment necessary for the energy transition.

By way of example, according to European Commission data from 2020, in 2030, the European Union (EU) would need up to 18 times more lithium and 5 times more cobalt to meet the demand for batteries for electric vehicles and energy storage, and in 2050, almost 60 times more lithium and 15 times more cobalt than today. The demand for rare earths used in permanent magnets, e.g. for electric vehicles, digital technologies or wind generators, could increase tenfold by 2050.

The development of digital technologies, in particular, means increased demand for metals such as gallium, germanium, indium, rare earths (dysprosium, praseodymium, neodymium), selenium, tantalum and tellurium. Electronic displays (including flat and touch screens) have driven consumption of platinum, indium and tin. The storage of the global datasphere projected for 2025 would require up to 80,000 tonnes of neodymium (which would be of the order of about 120 times the EU's annual demand for this material), and the use of emerging technologies such as ferroelectric RAM (or ferroelectric random access memory) up to 40,000 tonnes of platinum (about 600 times the EU's current annual demand).

M.C.2. Europe's vulnerability due to excessive dependence on third countries has not been solved by the development of current initiatives.

The EU launched the Critical Raw Materials Action Plan (the European Critical Raw Materials Act is currently being developed), aimed, among other things, at boosting indigenous mining and thus increasing resilience and strategic autonomy. As a result, measures were taken to improve the knowledge base of current and future deposits of many raw materials and to encourage the extractive industry to develop products to meet new needs.

In addition, the EU has defined principles to harmonise knowledge on raw material extraction (from the initial mining research stage, to the period after mine closure) and processing operations in the EU, as well as redefining the focus on the Sustainable Development Goals (SDGs). However, so far, the success of its initiatives has been modest in terms of developing projects to supply key raw materials for energy transition and digitisation. To make progress on this, a national information system, with the most relevant economic-industrial disaggregation, is needed.

The production of mineral raw materials in the EU does not cover its own needs. In fact, the EU is currently heavily dependent for the supply of critical raw materials on countries such as China (heavy rare earths 98%, light rare earths 99%, magnesium 93%, etc.) and the Democratic Republic of Congo (cobalt 68%).

M.C.3. It is important to increase the use of secondary mineral raw materials, but new mineral raw materials will be needed.

The proposed Long-Term Strategy for a Modern, Competitive and Climate Neutral Spanish Economy in 2050 and the Spanish Circular Economy Strategy, Spain Circular 2030, establish reuse and recycling as the first option for supplying production processes. To this end, the design phase of components, equipment and products is essential in order to optimise the use and management of waste and recycling.

In this framework, the reuse and recycling of primary and secondary raw materials (MPS), sometimes referred to as urban mining, is key. The recovery rate of these will increase, in particular for certain metals for which current recovery rates are very low (e.g. Nd, Pr and Dy). As a consequence, the use of MPS will increase. However, increasing the use of MPS and making mining and metallurgical practices more circular will require continued effort to ensure steady progress.

The energy transition and digitalisation will mean such increases in demand that primary raw materials will also be needed, and therefore from mining to extract more minerals, and from metallurgy to process them.

At each stage from mining research to equipment manufacture, value is added in the process, either by the discovery of resources or reserves, or by the value of the minerals extracted or the metals produced. In addition, knowledge, technology, engineering and related industries are developed in the above processes.

M.C.4. Sustainable and digitised mining and metallurgical activities

Mining and metallurgy face significant challenges and opportunities to advance sustainability. This rests on a balance of three pillars: economic sustainability (economic development), social sustainability (social equity) and ecological sustainability (environmental protection), where the importance of each principle will depend on the uniqueness of the area where it is to be applied and always understanding sustainability as the long-term viability of industrial activity and its social and environmental surroundings.

The need to combine the extraction of raw materials and metals with safety, the protection and conservation of nature and economic and social development has led to increasing regulation and different standards. In this sense, environmental and administrative authorisations and mining and post-mining rehabilitation processes lead to the framing of these activities within the concepts of sustainability and contribution to the SDGs in the medium and long term.

Progress is being made in the development of the smart mine with the use of information technology, measuring instruments, communication and remote control systems in activities along the value chain, from the location of the deposit to the closure of the mine.

Similarly, the use of digital tools is penetrating the metallurgical activity. This makes mining and metallurgy modern activities, adapted to the new context of digitalisation, a fundamental tool to advance and contribute to their sustainability. In fact, the very advance of digitalisation in mining and metallurgy is making these activities more sustainable from a social, economic and environmental point of view.

M.C.5. Integration of the mining and metallurgy value chain

The value chain of mineral resources, mining and metallurgy, for the manufacture of goods and components, starts with mineral research, which is defined as the set of techniques (geological, geochemical and geophysical) used to identify and evaluate those locations in the earth's crust where the concentration of an element is above average values.

The next step is the mining process (extraction, loading and transport). In other words, once the deposit has been technically and economically evaluated and the viability of the investment has been decided, and the relevant administrative and environmental authorisations have been obtained, the rock or mineral is extracted using the most appropriate mining method (open-pit mining and/or underground mining).

The next stage is the transition from mine production to concentrate, which is done through ore preparation and concentration mineralurgy, a set of processing techniques aimed at obtaining products with commercial value and transformable by metallurgy.

The next stage, to obtain the metals of interest, is extractive metallurgy, which includes the processes and techniques for extracting, developing, shaping and treating metals and their alloys from the concentrates obtained in the mineral plant.

At the same time, new opportunities are opening up, the basis for new value chains and, following the redevelopment of the mining area, the land can be used for industrial or energy infrastructure, waste treatment, agricultural and livestock farms, freshwater reservoirs or carbon capture and storage projects.

M.C.6. Structural changes and industrial and technological opportunities

The energy transition and digitalisation do not only change the energy structure and the way of life; they also entail changes in the economic structure, in particular with the creation and implementation of new engineering, industrial and technological activities.

It should not be lost sight of the fact that the stimulus to demand for mineral raw materials comes from end uses. This new economy presents great opportunities in the industrial field (manufacturing and fabrication of equipment and components, metallurgy, mineralogy and mining) and an improvement in strategic autonomy.

In this sense, the development of industrial clusters or ecosystems that integrate mining and metallurgy into value chains is a key element for industrial, mining and metallurgical development, with the necessary adaptation of training for professionals, the stimulation and orientation of innovation, engineering and technology. All this, in order to contribute to a sustainable economy and quality employment in the long term.

Linked to value chains, enhancing circularity and integrating activities such as recycling or reprocessing waste (urban mining), sometimes a proper design can lead to the creation of industries, under the concept of clusters or industrial symbiosis and a more circular perspective leads to the creation of new industries and business models.

M.C.7. Spain must develop its potential and seize opportunities

Spain has the industrial, engineering, technological and knowledge capacities to develop, in its territory, value chains for the energy transition and digitalisation (i.e., manufacture of wind turbines, photovoltaic plants, batteries, etc.).

In 2019, around 3,000 companies were active in the mining and metallurgy sectors in Spain. National mining production accounted for around €3 billion in

2020. In 2020, employment in the mining sector was in the order of 30,000 direct jobs, although most of these were in the extraction of non-metallic rocks and minerals. Since 2005, approximately half of the employment it generated has been lost, having accounted for 0.75% of industrial employment.

Metallurgy (including iron and steel) is of great economic and industrial importance. It produces around 16 million tonnes of metals and alloys, has a turnover of around 28 billion euros and generates around 32,000 direct jobs and 100,000 indirect jobs.

Spain has a long tradition of mining and metallurgy. The contribution of metals produced in Spain to the EU is very relevant to ensure the supply that affects both copper, zinc and lead projects (Iberian Pyrite Belt) and metals such as tin, wolfram, tantalum and niobium. It also has production and experience in precious metals such as gold and silver.

Spain also has potential in other minerals and metals related to energy transmission and digitalisation, with thirteen minerals useful for decarbonisation having been identified in Spain, and there is sufficient evidence to consider the exploration and production of lithium, cobalt-nickel, rare earths, graphite and vanadium resources to be of maximum interest.

Despite the country's potential, in July 2022, there were projects at a standstill in Spain, largely due to the fact that the different regulations at various levels mean that their processing time is difficult for the promoters to assume. Their commissioning, in compliance with the requirements set by current regulations, would reduce dependence on foreign countries and help to strengthen Spain's trade balance.

Furthermore, considering that environmental and labour regulations in Spain are more stringent than in many of the countries from which certain mineral raw materials are imported for the energy transition and digitalisation, the extraction and processing of these raw materials in Spain would bring environmental and labour benefits in the global context.

RECOMMENDATIONS

R.1. Mining and metallurgy value chain development and its integration into productive value chains.

Spain must boost the development and integration of industrial value chains for the equipment and components needed for the energy transition and digitisation, including through investment in engineering and technological innovation.

To do so, it must seize opportunities in the different links of value chains, from mining and metallurgy to the manufacture of components and equipment, and should be involved at all stages of the value chain, particularly where mineral resources are available.

In this sense, the potential of raw material resources should be better known, knowledge of these resources should be ac- tivated and mining research should be promoted in order to obtain an up-to-date prospective assessment of potential resources.

On the other hand, where there are indications of resources, the best possible information on the technical and economic characteristics of indigenous deposits should be made available in order to better understand the resources available in the country, be they lithium, rare earths, copper, zinc, lead, tin, tungsten or others.

If the entire value chain cannot be addressed in-house, international cooperation will be required, especially at the European level (in order to avoid potential supply disruptions), as well as with economically and politically stable or like-minded countries.

It is necessary to incorporate the eco-design of products in the value chain for the energy transition and digitalisation, and to develop the use of circular economy tools such as reuse, remanufacturing and recycling. Efficient recovery of secondary resources will help the demand for primary resources to modulate its growth and promote industrial symbiosis, creating related industries.

R.2. Enhance the development of engineering and industry in the country and clusters linked to the territory.

In the value chain, it is very important to highlight the role of engineering and technology for the development of own resources, trying to encourage the creation of national companies in this type of activity.

Industrial development associated with the mining and metallurgy value chain should be carried out by taking advantage of the existing potential and trying to promote the development of clusters related to productive value chains linked to the territory, which survive mining activity. This requires the involvement of all stakeholders (University, Administrations, Government, companies, investors and society). This is a challenge, but also an opportunity for Spain and its Autonomous Communities in terms of industrial and technological development, quality employment and knowledge.

In this respect, the regulatory possibilities of generating incentives for the territories by promoting the creation, among others, of technology centres with medium-term objectives should be examined.

R.3. Matching training and attracting talent to engineering and technology studies

It is recommended that training and education content and processes be updated to incorporate the knowledge and skills needed in value chains from engineering, mining and metallurgy to the manufacture of equipment needed for energy transition and digitalisation. It would also be necessary to establish tools and campaigns communication strategies to show young people that engineering in general, and the integral management of raw materials for the energy transition and digitalisation in particular, are studies with a professional future in the coming decades.

R.4. Promote favourable policies to seize opportunities and facilitate social acceptability

A commitment is required from policy and/or decision makers to lead the changes so that Spain does not miss out on the opportunities that energy transition and digitalisation open up in terms of reindustrialisation and improving the resilience of the economy.

This commitment could take the form of speeding up the administrative authorisation processes, always in compliance with existing environmental and labour legislation (it is estimated that it can take around seven to ten years for a mining project to come into operation). To this end, one element that would contribute to this would be to reinforce the resources of the mining administration, i.e. to adapt the staff to current and future needs and to reinforce their skills and capacities.

A detailed examination of the barriers or obstacles to the production of mineral raw materials and metals could help to identify concrete proposals to facilitate development and social acceptance. In this respect, the competences related to the different levels of public administration, as well as the different rules that may be involved in an authorisation, should be clarified. This would help to streamline authorisation processes. In this way, regulations should be developed to determine procedures and unify criteria.

It would also be essential to transmit and raise awareness in society of the need for mineral raw materials (in fact, Europe consumes around a third of the raw materials produced in the world), which would probably require education and a cultural change, making mining and metallurgy more visible, as well as their contribution to the development and well-being of society. In this way, the necessary social licence for the development of projects would be more embedded in the territory, achieving the involvement of the inhabitants and economic and social development. Mining projects should also be integrated into the industrial strategy and incentives should be developed for the areas where mining activity takes place.

This can be approached on the basis of the various technical assessment reports which are primarily to be developed in the evaluation phase of a mine site, but which are often necessary for activities such as the implementation of metallurgical plans.

It seems necessary to convey to society that the development of mining and metallurgical processes are consubstantial elements of the energy transition and digitalisation. This is particularly relevant in the mining research and development phases, which are often the ones that generate the most opposition.

This social and political acceptance should preferably be achieved by means of a state pact, taking into account the basis of stable regulations and standards.

The current economic, social, geo-strategic, social and geostrategic situation, etc., should be a driving force for such a State Pact. The current economic, social and geostrategic situation, etc., should provide the impetus for such a state pact.

R.5. Attract creditworthy investments domestically and from favourable geopolitical environments and prioritise security of supply with own resources.

As energy transition and digitalisation processes are a global issue, and taking into consideration the complexity of the current geopolitical context, the regulatory framework and licensing processes need to be such as to attract financing and creditworthy investments, first and foremost from the domestic and favourable geopolitical environments.

Increased visibility of sustainable mining and metallurgy activities in the value chain together with increased awareness of their economic characteristics (e.g. long payback periods) would facilitate interest and outreach for attracting economic resources from different types of investors and financing modalities.

The strategic relevance of security of supply and the development of indigenous raw materials means that geostrategic and security considerations should be at the top of the political agenda and decision-making.

R.6. Conduct detailed studies on specific issues

Global changes, particularly since 2008 and more recently with the health crisis and Russia's invasion of Ukraine, are causing changes in geopolitics, so that there is a need to deepen our knowledge of Spain's vulnerability to problems of raw material supply. As a result, new lines of work are opening up, which should be addressed by different types of agents, in order to support decision-making in policy development and business investment.

Possible lines of future work include i) estimation of the degree of self-sufficiency of mineral raw materials and needs, both for domestic consumption and for export of semi-finished or final products, including quantification of future investments in mining and metallurgy, ii) analysis of mining and metallurgy activities in Spain (i.e. SWOT, structure and ownership), iii) analysis of supply chains and their resilience to possible supply disruptions, iv) assessment of the environmental or carbon footprint and energy consumption of mining and metallurgy processes, v) assessment of the environmental or carbon footprint of mining and metallurgy processes and their resilience to possible supply disruptions, SWOT, structure and ownership), iii) analysis of supply chains and their resilience to possible supply disruptions, iv) assessment of the environmental or carbon footprint and energy consumption of mining and industrial processes for the production of mineral raw materials needed for the energy transition and digitalisation and v) obstacles and barriers to the development and production of mineral raw materials and metals (sociological, NIMBY effect[1] ; legal and bureaucratic).

1 "*Not In* My *Back Yard*". Equivalent to "Yes, but not here".

INDEX

INTRODUCTION AND SCOPE

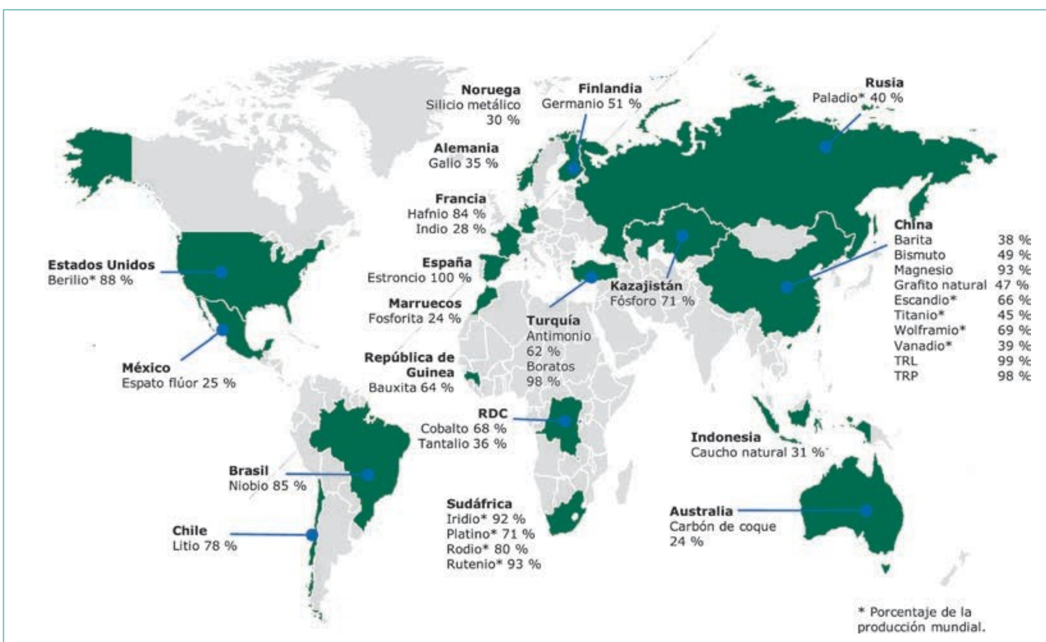
1 European vulnerability

The current energy and global supply chain crises have highlighted why European industry and the European economy as a whole have become vulnerable due to their dependence on imports of certain mineral raw materials. According to Eu- rostat data, each European citizen consumed the equivalent of 14 tons of raw materials in 2019, of which just over 0.7 tons corresponded to metals and 7.2 tons to non-metallic mineral raw materials (Third Vice-Presidency of the Government, Ministry for Ecological Transition and the Demographic Challenge, 2022).

This dependence could be exacerbated by Russia's invasion of Ukraine and the resulting geopolitical changes, as some of these raw materials are critical[1] for digitization and manufacturing of equipment related to energy production and storage (e.g., Pt, Pd, Ni) and, on the other hand, the conflict is introducing tensions in mineral raw material prices.

Likewise, the commodity boom has led to a resurgence of protectionism as mineral-rich countries try to obtain a greater share of the benefits resulting from the rising prices of some mineral commodities and greater controls over the development of local industry (Adánez, 2022). This protectionism has taken different forms such as fees and taxes, property restrictions, compulsory participation in new projects or blocking foreign companies, among others.

All this has made Europe more vulnerable and, as can be seen in Map 1, there is a high dependence on third countries for the supply of critical raw materials.



Map 1. *Main EU dependence on critical raw materials by country. Source: (European Commission, 2020a).*

[1] For more information on the list of EU critical raw materials see Annex 1.

To address this situation, it will be key to understand how the global demand for minerals will grow with different intensities, affected by the technological concentration of each mineral or the increase in the growth of energy technologies compared to current production figures (Álvarez, 2023).

Aware of this vulnerability, the European Commission launched an Action Plan on Critical Raw Materials, aimed at enhancing mining and thus increasing resilience and autonomy. This point is particularly relevant for European mining regions, which should assess whether there are opportunities to extract mineral raw materials in their territories. This is undoubtedly good news for Spain, which has great mining potential (it is the third country in Europe with the most mining resources, some of which have been identified as critical and strategic), and in metal mining.

The development of these new exploitations requires the development of a national strategy that allows the identification and implementation of these projects, a process that the Spanish Government has already begun with the approval by the Council of Ministers on August 30, 2022 of the "Roadmap for the sustainable management of Mineral Raw Materials", which reinforces the country's strategic autonomy and prioritizes efficiency and the circular economy to provide security of supply of key supplies for the energy transition. This Roadmap is aligned with European and national policies, such as the recent REPowerEU Plan or the National Security Strategy (approved in 2021), and includes 46 medium- and long-term actions of a regulatory and sectoral nature, as well as promoting R&D&I and other cross-cutting instruments.

The Roadmap includes five strategic orientations. The first is to achieve maximum efficiency and the implementation of the circular economy in the value chains of the supply of mineral raw materials, integrating and specifying for the extractive industry the objectives and lines of action of the Spain Circular Strategy 2030. Secondly, to promote and consolidate the sustainable and responsible management of mineral raw materials in the Spanish extractive industry. The third guideline consists of guaranteeing security of supply and compliance with environmental, geostrategic and social justice requirements in the import of mineral raw materials. Fourthly, diversification of supply through sustainable and responsible sourcing from third countries. Fifthly, to promote the strategic mineral raw materials industry for the energy and digital transition.

In this context, considerable interest has been aroused by the proposals of the European Commission, which has urged the Member States to identify projects for the extraction, processing of mining resources and revaluation of raw material residues that can be operational by 2025. The aim is to ensure the security of resources in the face of the change in the energy model. The European Commissioner for the Internal Market, Thierry Breton, called for the promotion of what is known as sustainable mining, the mining of the 21st century.

The challenge is to ensure the supply of critical raw materials to meet the objectives of the European Green Pact and the ecological transition, (i) promoting the complete value chain, from the extraction of raw materials necessary for the production process to the final product, (ii) promoting the circular economy as a strategy to reduce the entry of primary raw materials into the production cycle, as well as recycling when technically and economically possible, and (iii) encouraging innovation in industrial technological processes (Moratilla, n.d.).

1.1. The European Commission's approach: resilience, security, sustainability

Promoted by the European Commission in 2015, the raw materials technology initiative EIT Raw Materials was created within the framework of the European Institute of Innovation and Technology (EIT, 2021).

The EU has supported the mining sector through the 7th Framework Program, Horizon 2020, by funding technical, social, political and governance projects on raw materials. The STRADE project[2] 2018 (Schüler et al., 2018), summarizes the European strategic plan in the following two points: (i) reducing import dependency and promoting own production, diversifying raw material supply, improving resource efficiency (including recycling) and finding alternative mineral raw materials and (ii) mitigating environmental, social and health impacts.

In the European framework, the Commission's communication COM (2020) 474 final[3] is very relevant, where it is recalled that the Commission reviews the list of critical raw materials for the EU every three years. It published its first list in 2011, updating it in 2014, 2017 and 2020, with economic importance and supply risk being the two key variables in determining the criticality of raw materials. The EU 2020 list contains thirty raw materials compared to fourteen in 2011, twenty in 2014 and twenty-seven in 2017. Bauxite, titanium and strontium were incorporated in the latest revision.

Less than 5% of the world's key raw materials are sourced or produced in the EU, while its industry accounts for around 20% of the world's consumption of these raw materials. A secure and reliable supply of key raw materials is vital for European industry, especially in sectors such as automotive, steel and healthcare, which employ millions of European citizens. The EU is particularly dependent on imports of fundamental raw materials that are key components of future technologies such as batteries or renewable energy sources.

The supply of many key mineral raw materials is highly concentrated. For example, "*98 % of the rare earths that the EU imports come from China, 98 % of borate comes from Turkey and South Africa supplies 71 % of the platinum needed by the EU and an even higher percentage of iridium, rhodium, ruthenium and platinum group metals*" (GEO World, 2021). Some 68 % of the cobalt comes from Congo. The supply problem is expected to be growing.

Faced with this situation of dependence and vulnerability, which could be due to environmental, economic and political reasons among others, and not to the non-existence of mineral resources in its own territory, the European Commission proposes to improve the EU's resilience, there being a challenge in terms of supply and sustainability since, based on data from the World Bank and the Organization for Economic Cooperation and Development (OECD), among others, the EU's dependence on imports of most metals varies between 75 % and 100 %. El nivel de dependencia es tan elevado que, en términos de suministro de la UE, el autoabastecimiento global de las veinte materias primas minerales más críticas, que se necesitan para la descarbonización de la

2 *Strategic Dialogue on Sustainable Raw Materials for Europe.*

3 (European Commission, 2020).

economy, can be estimated at less than 3%, with more than half with no production or very limited European production (EU Commission, 2017). Along these lines, countries such as China, the United States and Japan are working to guarantee supply to their countries.

To this end, the Commission has established an action plan on key raw materials and considers the development of resilient value chains as a first basic element, highlighting the importance of incorporating mineral raw materials and, in particular, proposing the establishment of a European raw materials alliance, driven by industry.

However, despite the above and the European potential, success is modest, due to, among others, the lack of investment in exploration and mining, the diverse and time-consuming procedures for obtaining permits, as well as the low levels of public acceptance of this type of activities .[4]

However, as indicated by the European Commission (2020), the EU and its Member States have a legislative framework to ensure that mining activity is carried out under appropriate conditions, both socially and environmentally. In fact, it is very difficult to get new projects related to key raw materials to reach the operational phase quickly, partly due to risk and cost, but also due to the lack of incentives, as well as the reasons mentioned above, notably the long project lead times. In addition, innovative technology and digitalization are transforming the extraction and processing of key raw materials (as will be discussed in Chapter 5).

The EU has strict regulations on the granting of mining rights (research, exploration and exploitation of deposits), so that, in environmental and social terms, it may be more appropriate to extract these resources than those located in other territories with less demanding regulations. However, the authorization processes for mining projects should be optimized, given that it can take 10 years or more to explore a deposit and bring a mine into operation in Spain (above the European average of 8-9 years). Spanish mining is a highly regulated sector, with a high density of regulations affecting the extractive activity. In fact, it is the EU country with the greatest legal pressure, with 103 different administrations and more than 112 laws directly or indirectly related to the activity (Cámara Oficial Mineira de Galicia, n.d.).

Neighboring countries such as France, with 69 laws; Portugal, with 25; Germany, with 46; or the United Kingdom, with 69, have a "one-stop shop" and regulatory environments that are much less complex but just as demanding as those of Spain. For economic reasons, exploiting resources in the EU is more costly than doing so in third countries due to both labor and environmental regulations. In these circumstances, obtaining the necessary financing is more complicated, which makes Europe more vulnerable to the rest of the world.

The Commission advocates the identification of projects and investment needs in the field of mining and mineral processing, and of the necessary funding opportunities for the development of key raw materials in the EU, which can be operational by 2025 at the latest, with priority given to mining basins.

4 For more detail see INFACT Project (2018).

The second basic element is the circular use of resources, which is addressed in the circular economy chapter of this study. In this regard, the Commission notes that the EU is at the forefront of the circular economy, having increased the use of secondary raw materials. For example, more than 50 % of some metals, such as iron, zinc and platinum, are recycled, covering more than 25 % of EU consumption. However, in other cases, such as rare earths, the contribution of secondary production is marginal.

The third element of the plan is to exploit the European potential, recalling Europe's long tradition in mining and extractive activities. As regards the EU's internal potential, the importance of developing knowledge and skills in the fields of mining, extraction and processing technologies (including mineral and metallurgy) from 2022 onwards is also highlighted.

The fourth basic element of the EU action plan is the diversification of supplies from third countries. In this line, the EU should enter into strategic partnerships with resource-rich countries, making use of all foreign policy instruments and respecting its international obligations.

To strengthen the EU's strategic autonomy, after a first version presented in 2021, on March 21, 2022, the EU Council session approved the Strategic Compass for EU Security and Defense in the context of Russia's invasion of Ukraine, which sets out an ambitious action plan to strengthen the EU's security and defense policy between now and 2030. The aim is to secure supply chains for critical materials, energy sovereignty and technological independence from potential competitors.

To this end, it provides an assessment of the EU's strategic environment and the threats and challenges it faces. The Compass covers all aspects of security and defense policy and is built around four pillars: (i) acting (rapid military deployment capability and reinforcement of missions and operations), (ii) investing (substantially increasing defense spending to match the collective ambition of reducing essential shortfalls in military and civilian capabilities and strengthening the European defense technological and industrial base), (iii) working in partnership (strengthening cooperation with strategic partners such as NATO, the UN and regional partners such as the OSCE-Organization for Security and Cooperation in Europe, the African Union and ASEAN-Association of Southeast Asian Nations) and (iv) ensuring security (boosting intelligence analysis capabilities and the development of threat response mechanisms and equipment).

In this context, it seems clear that the strengthening of the technological and industrial base should rely on a reliable supply of mineral raw materials and the development and integration of value chains from mining to the manufacture of components and equipment.

In September 2022, the *European Critical Raw Ma- terials Act* was announced, whose proposal was published in March 2023 and whose objectives include (Breton, 2022): (i) securing stable supplies by diversifying them and intensifying efforts to recycle, (ii) boosting the EU's strategic autonomy with domestic production, recovering industrial activity along the value chain and (iii) decreasing dependence on imports. The aim is therefore to secure supply chains, from extraction to refining, from processing to recycling.

In parallel, and as a consequence of the current geopolitical context, especially the Inflation Reduction Act of the United States and the announcement of massive investments in clean technologies by China, the EU published in February 2023 the document "A Green Deal Industrial Plan for the Net-Zero Age", where indicates that the Commission will continue to leverage the EU's network of free trade agreements, as well as new initiatives with like-minded partners (e.g., Australia, Chile, New Zealand, India) to establish a Critical Commodities Club to bring together raw materials consumers and resource-rich countries to ensure global security of supply through a competitive and diversified industrial base (European Commission, 2023a).

The proposed Regulation for the development of a framework to ensure a safe and sustainable supply of critical raw materials, which implements the European Critical Raw Materials Act, aims to improve the functioning of the internal market by establishing a framework to ensure access to a safe and sustainable supply of critical raw materials (European Commission, 2023b).

To this end, it establishes that the EU must produce at least 10 % of the minerals or concentrates it consumes from the raw materials it defines as strategic. It also proposes that processing capacity should cover at least 40 % of its annual consumption and, finally, it contemplates that recycling capacity should amount to at least 15 % of the consumption of strategic raw materials. It also seeks to diversify origins, improve the capacity to monitor and mitigate the risk associated with critical raw materials and guarantee their free movement in the EU market.

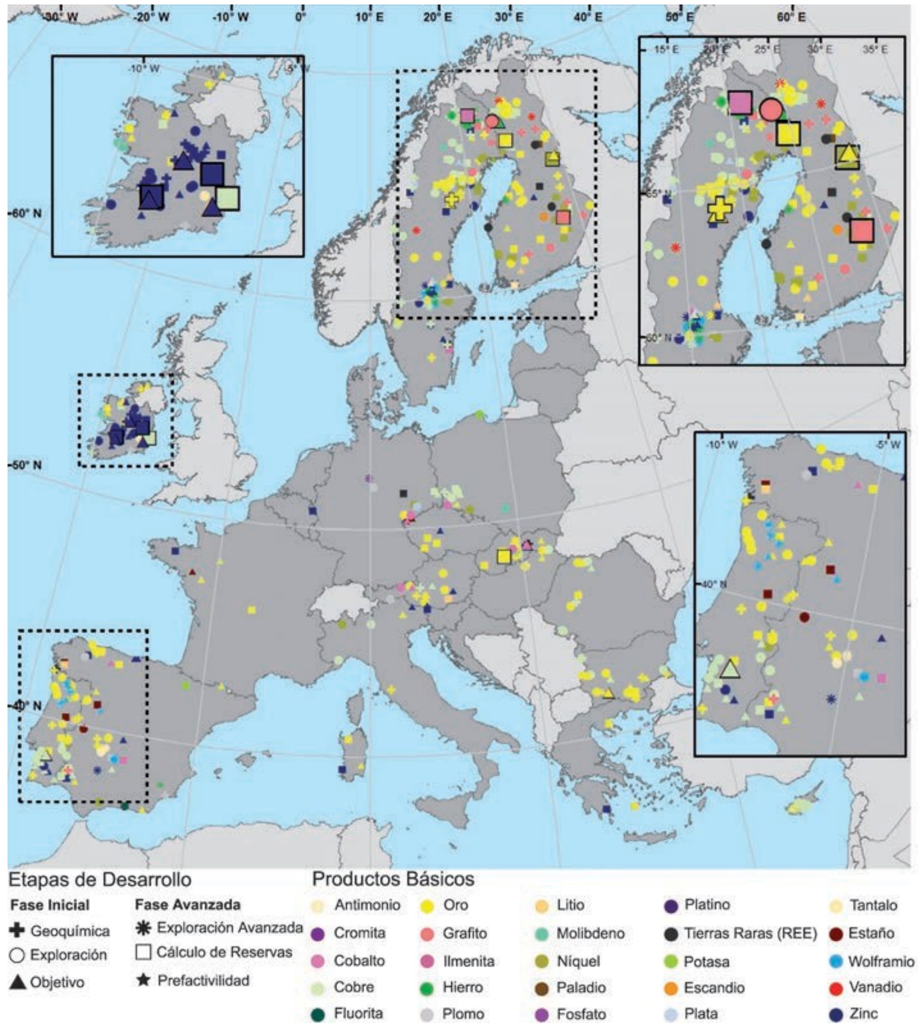
The key elements included are (i) the strengthening of the raw materials value chain at EU level (where the concept of strategic project is identified, together with the procedure for obtaining this distinction and the associated benefits), (ii) monitoring and risk mitigation (including the development of a mechanism for monitoring information on critical raw materials flows and another for carrying out joint purchasing operations), (iii) sustainability and environmental footprint (focused, among others, on the promotion of the circularity of critical raw materials, the recovery of mining waste and the exhaustive monitoring of permanent magnets) and (iv) strategic collaboration.

1.2. Europe's potential in mineral raw materials

For more than 20 years now, the Geological Surveys of the EU countries have been coordinating efforts and there is now GeoERA (European Geological Surveys Research Area), which encompasses 32 European countries and has integrated a computerized database (Mineral4EU) within the framework of the European Geological Data Infrastructure (EGDI) (Geoera, 2023).

Among other projects, they have developed the Mineral Intelligence for Europe (Mintell4EU, 2020), in which maps with the resources of the different mineral raw materials can be visualized. If you look at these maps it is easy to see that there are resources in the EU and that many of them are in Spanish territory. Another public tool, little known, is the National Geochemical Map produced by the Geological and Mining Institute of Spain (IGME), which allows easy integration of geochemical data in Google Earth (Llamas, 2020).

In September 2020, driven by the European Commissioner for the Internal Market (Thierry Breton) and the European Commission Vice-President for Interinstitutional Relations and Foresight (Maroš Šefčovič) the European Raw Materials Alliance (ERMA) was launched. This initiative is



Map 2. *Mineral exploration activities in the EU-27 in 2019. Note: The size of the circle is an indicator of project progress (the larger the size, the more progress). Source: (European Innovation Partnership on Raw Materials, 2021).*

The ERA is closely intertwined with the European Commission's policies on mineral raw materials and targets for the future of the Union. The ERA has identified 28 investment opportunities up to 2023 amounting to some 10 billion euros (M€) (Schäfer, 2022). The initiative places emphasis not only on mining and metallurgy, but also on the entire value chain, hence there is competition between European countries for knowledge, research, mining, industry and employment. In this sense, it is worth mentioning specific initiatives in rare earths for the manufacture of permanent magnets, or lithium for the manufacture of batteries.

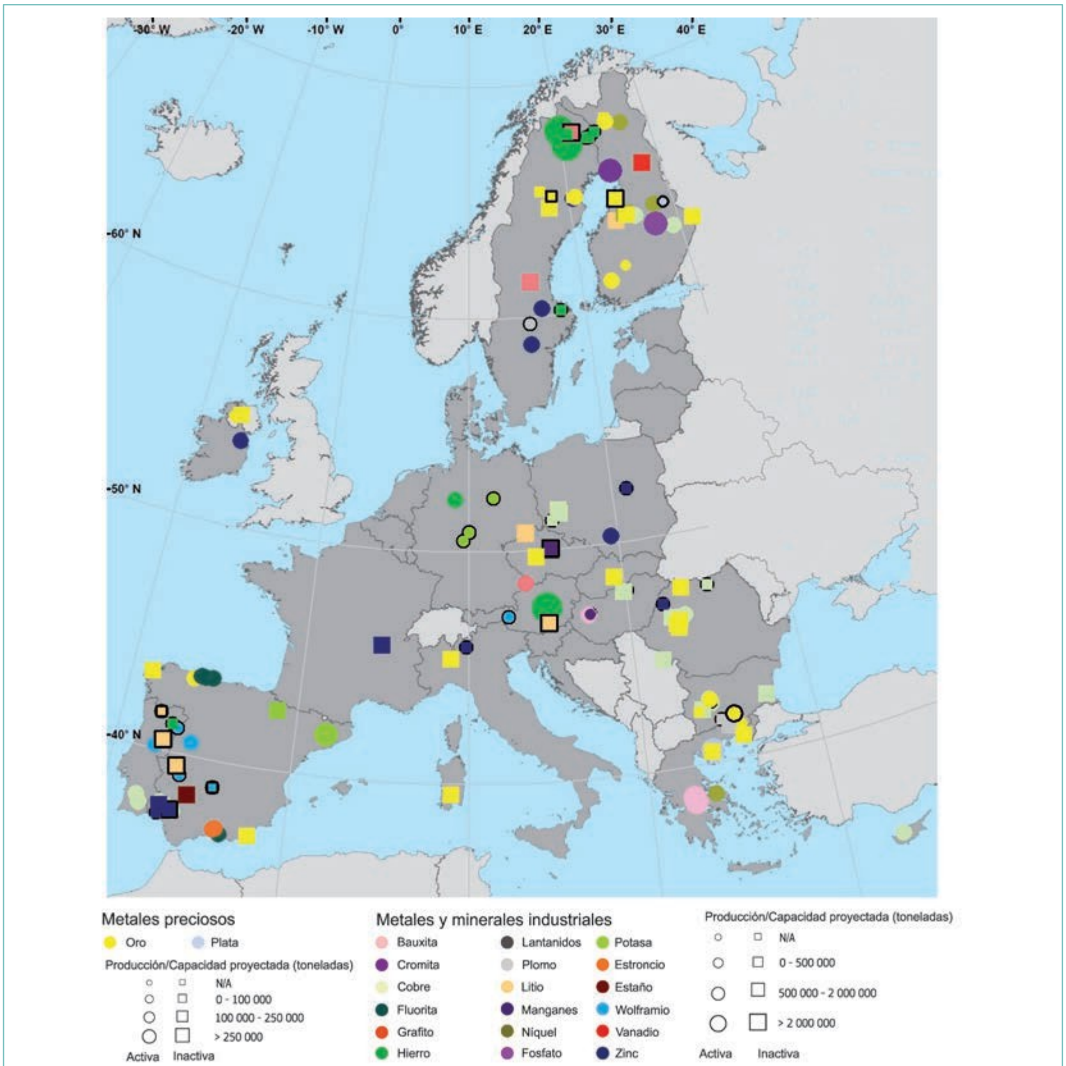
Map 2 of the JRC (Joint Research Centre) summarizes the situation of exploration and exploitation or research projects for minerals and active metals, based on the "Raw Materials Monitoring Indicators" for 2019.

With regard to exploration, the Commission notes that new mineral exploration projects, or at least the maintenance of current levels, are key, with notable differences between Member States.

In this regard it is relevant to highlight the case of Sweden. SveMin (2021) raises the need for metals for the ecological transition and points out that the demand for minerals is expected to increase.

significantly by 2050. It also highlights how Europe has a greater need for metals than other surrounding regions, given its high ambitions in the fight against climate change. The paper also points out that recycling is important, but will not be enough to meet increases in demand and that with Europe being highly dependent on imports of many metals and minerals the Swedish mining industry has an important role to play in the transition to a more sustainable society, adding that the Swedish subsoil is not sufficiently explored.

Turning to the Commission, the Commission notes that, with respect to 2018, there have been more exploration projects. Regarding operating mines, Map 3 reflects the situation in 2019, where there were 13 new mines with respect to the 2017 review. The lithium projects from that year are now active projects.



Map 3. *Mining production of selected industrial metals and minerals in the EU-27 (2019). Note: New projects are indicated by circular dots (active, producers) and squares (active, non-producers) with a black border line. Source: (European Innovation Partnership on Raw Materials, 2021).*

EU mineral production is accounted for by a small handful of Member States (Regueiro and Alonso-Jiménez, 2021). Poland accounts for 56 % of EU copper production, Sweden for 90 % of iron ore production and Greece and Finland for about half each of nickel production. Sweden also accounts for 43 % and Ireland for 32 % of EU lead and zinc production respectively.

The EU's commitments, including the objectives for sustainable development and its own energy policy aimed at renewable energies and reducing the effects of climate change, make it necessary to more than quadruple the production of certain minerals that are considered strategic. As a result, the extractive sector is expected to boom.

Globally, Europe is the world's third largest producer of industrial minerals and produces a quarter of the construction minerals it requires. Around 3.35 billion tons of mineral raw materials are extracted annually. 3 billion are construction materials, 200 million metallic minerals, 150 million industrial minerals (Third Vice-Presidency of the Government, Ministry for Ecological Transition and Demographic Challenge, 2022).

2 Objective and scope

Energy transition and digitalization are manifest trends in the global economy and in particular in the European and Spanish economies. The need for mineral raw materials and the increase in their demand are facts that need to be addressed. Europe is highly dependent on imported mineral raw materials for both processes. This poses a vulnerability and a risk for the energy transition and digitalization to achieve their objectives. In this respect, mining and metallurgy, as the initial links in the value chains, are very necessary, as is the manufacture of components and equipment.

In this context, and taking into account the relevance of mining and metallurgical activities in the creation of quality employment, industrial activity and wealth for the economy, this paper seeks to examine, analyze and answer the question: What is the role of mineral raw materials, and therefore mining and metallurgy, in the energy and digital transition scenario we are heading towards?

To this end, the CODEIME-RAI working group created for this study defined the scope of this work, which first defines and describes what is meant by decarbonization and digitization; and once the scenario is set, it analyzes the role of mineral raw materials in this scenario.

To try to understand this role, the value chain from minerals to components and equipment required in the new context is described, and in particular the mining and metallurgy phases, which, as will be seen, are key elements. This is followed by an analysis of digitalization and technological innovation in both activities.

The role of the circular economy in the supply of mineral raw materials is then addressed, since a future is inconceivable today without incorporating the related concepts and applications. The creation of value from mining research to equipment manufacturing that is carried out from the industry and brings economic benefits is examined in the next chapter of this study. The paper ends with a chapter that attempts to set out the main data on mining and metallurgy in Spain.

The report is accompanied by a set of annexes providing detailed information on mining methods, environmental regulations and different metallurgical processes. The document ends with a glossary and a section of acronyms, abbreviations and abbreviations.

Although a specific chapter has not been dedicated to environmental issues, these are addressed throughout the document, particularly with regard to environmental regulations in Spain relating to mining and the circular economy. A detailed list of these is given in Annex 4.

As a result of the work carried out, possible lines of future work have been identified that have not been the subject of this document, such as the quantification of future investments of national and foreign capital in mining and metallurgy, the analysis of supply chains and their resilience to possible supply cuts, the estimation of the energy consumption required for the extraction of mineral raw materials and their carbon footprint, or the impact of the increase in energy prices on mining and metallurgy.

DECARBONIZATION AND DIGITIZATION OF THE ECONOMY. THE ROLE OF MINERAL RAW MATERIALS

1. Introduction

Decarbonization is, in a broad sense, the process of reducing atmospheric emissions of Greenhouse Gases[5] (hereinafter GHG); in particular, carbon dioxide emissions (CO_2), with the aim of achieving climate neutrality. Climate neutrality (carbon neutrality, zero carbon footprint) is achieved when the levels of CO_2 emitted into the atmosphere are equal to the levels of CO_2 removed by various means, resulting in zero net emissions or leaving the balance at zero. Ideally, no more CO_2 should be emitted than can be absorbed by natural sinks (forests, plants, soils, oceans).

The first step, therefore, is to identify the source of GHG emissions in order to adopt the necessary measures to reduce these emissions at source. In this regard, it is estimated (Ritchie and Roser, 2020) that 73.5% of global GHG emissions come from energy generation and consumption (in industrial activities, transport or the domestic and commercial sector).

Universal access to energy is a fundamental element for human progress, and one of the objectives of the 2030 Agenda for Sustainable Development is to "*Ensure access to affordable, safe, sustainable and modern energy for all*". Achieving a compromise, a balance between ensuring universal access to energy for all people and limiting the effects of energy production and use on the climate is a challenge of such magnitude that it justifies making the energy system one of the priorities of a country's scientific, technological, political, economic and social agendas.

Linked to the aforementioned objective of the 2030 Agenda for Sustainable Development are, among others, three goals to be achieved by 2030: (i) ensure universal access to affordable, reliable and modern energy services, (ii) significantly increase the share of renewable energy in the energy mix, and (iii) double the global rate of improvement in energy efficiency. These goals should constitute the framework for action in decision-making on the design of a country's energy system. In addition, the invasion of Ukraine by Russia is leading to changes in Europe's position vis-à-vis Russia. This is implying an abrupt cut in energy dependence on Russia and the need to restructure the supply chains of (critical) raw materials from that country.

It is in this context that the decarbonization of the economy is conceived, the objective of which is to reduce GHG emissions linked to energy generation and consumption. The changes linked to decarbonization are of such magnitude and scope that they constitute what is known as the energy transition. The keys to this energy transition in technological terms are: (i) increased generation of renewable energies and use of non-emitting or low GHG emission technologies, (ii) development of energy storage technologies, (iii) electrification of consumption where feasible, (iv) improvement of energy efficiency, and (v) incorporation of new energy vectors (e.g. green hydrogen).

In this scenario of decarbonization and in relation to the role of mineral raw materials, the

[5] The direct greenhouse gases estimated in the GHG Inventory are: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride (SF_6) (Third Vice-Presidency of the Government, Ministry for Ecological Transition and Demographic Challenge, n.d.).

World Bank report (The World Bank, 2020) presents an estimate of global average annual mineral demand[6] based on different decarbonization targets for 2050. The following conclusions can be drawn from this report: (i) the more ambitious the decarbonization targets, the higher the demand for mineral raw materials, (ii) the demand for specific mineral raw materials will increase substantially, both in absolute and relative terms depending, ultimately, on the type and intensity of use of the associated technology, and (iii) although materials recycling plays a determining role in this scenario, it will be necessary to resort to primary production of mineral raw materials (extractive industry).

In parallel, the current scenario of production processes can be identified. Industry 4.0[7] is the term that describes the organization of production processes based on devices that communicate with each other autonomously along the value chain and represents a change of such magnitude that it constitutes what is known as the fourth industrial revolution. Industry 4.0 is based on the use of Information and Communication Technologies (ICT), technologies that make it possible to link the physical world (devices, materials, products, machinery and facilities) with the digital world (systems) and increase the productivity and efficiency of production processes.

This phenomenon, which is also called digitalization, basically consists of the massive application of new technologies to all phases of production processes in order to achieve greater efficiency. Other terms that could be considered synonyms for the vast majority of industrial facilities are the following: *Smart Factory*, *Digital Factory* and *Connected Factory*, among others.

From the point of view of mineral raw materials in relation to digitization, it is worth highlighting the conclusions of the report prepared by the European Union (European Commission, 2020b), which points out that ICTs are characterized by: (i) the need for a wide and growing variety of materials with specific properties (electronic, optical, magnetic, mechanical) to manufacture integrated circuits and devices, (ii) a substantial increase in the demand for these materials with respect to current production to manufacture the enormous quantity of integrated circuits and devices that are expected to be needed, and (iii) the speed of development of new ICT technologies, which may exceed the time scales of raw material supply chains.

Therefore, in order to advance in the decarbonization and digitalization of the economy, it is necessary to have access to mineral raw materials, in certain quantity, variety and quality, materials that are indispensable for the generation and storage of energy, the manufacture of innumerable electricity-consuming devices and ICT technologies (wind turbines, photovoltaic panels, electric vehicles, fuel cells, integrated circuits, microchips, cell phones and computers, to cite a few examples).

Moreover, decarbonization and digitization must be framed within the circular economy (CE) model, which aims, as opposed to the linear economy model: (i) to maintain the value of products, materials and resources (water, energy) in the economy for as long as possible, (ii)

6 This work includes estimates of the demand for mineral raw materials from different sources (i.e., World Bank, IEA or European Commission), whose scope and methodology do not necessarily coincide, which is why these demand data vary from one source to another. An attempt has been made in the text to indicate precisely the sources used in each case.
In the case of the World Bank model (The World Bank, 2020) key assumptions include, among others, emission mitigation scenarios based on the International Energy Agency and IRENA outlooks, on technology and sub-technologies needed to achieve those scenarios and the minerals needed to install one megawatt of electricity or one megawatt-hour of storage for each technology included in the model.

7 The term Industry 4.0 was coined by the president of the German Academy of Science and Engineering (ACATECH), Henning Kagermann, and first presented at the Hannover Messe in 2011.

reduce waste generation throughout the production process as much as possible and (iii) convert waste into a resource. It should be noted that the circular economy model extends throughout the life cycle of the product and the raw materials with which it is produced (from the extraction and transformation of the raw material from which each product is manufactured to the consumption and management of waste once its useful life is over), an aspect that is particularly relevant in the case of the extraction of mineral raw materials and that will be discussed later, particularly in chapter six.

Last but not least, the manufacturing processes for components and equipment for decarbonization and digitization must be carried out, right from the extraction of mineral raw materials, in terms of sustainability (environmental compatibility, economic growth and social benefit).

Taking into account that a decarbonized and digitalized economy poses important differences compared to the current situation in terms of mineral raw material needs, especially for metallic minerals, the purpose of this chapter is to analyze the role of mineral raw materials in relation to the objectives of decarbonization and digitalization of the economy. Subsequent chapters will address aspects related to the production of these mineral raw materials, as well as the key elements of the circular economy and digitalization model for the mining and metallurgy value chain.

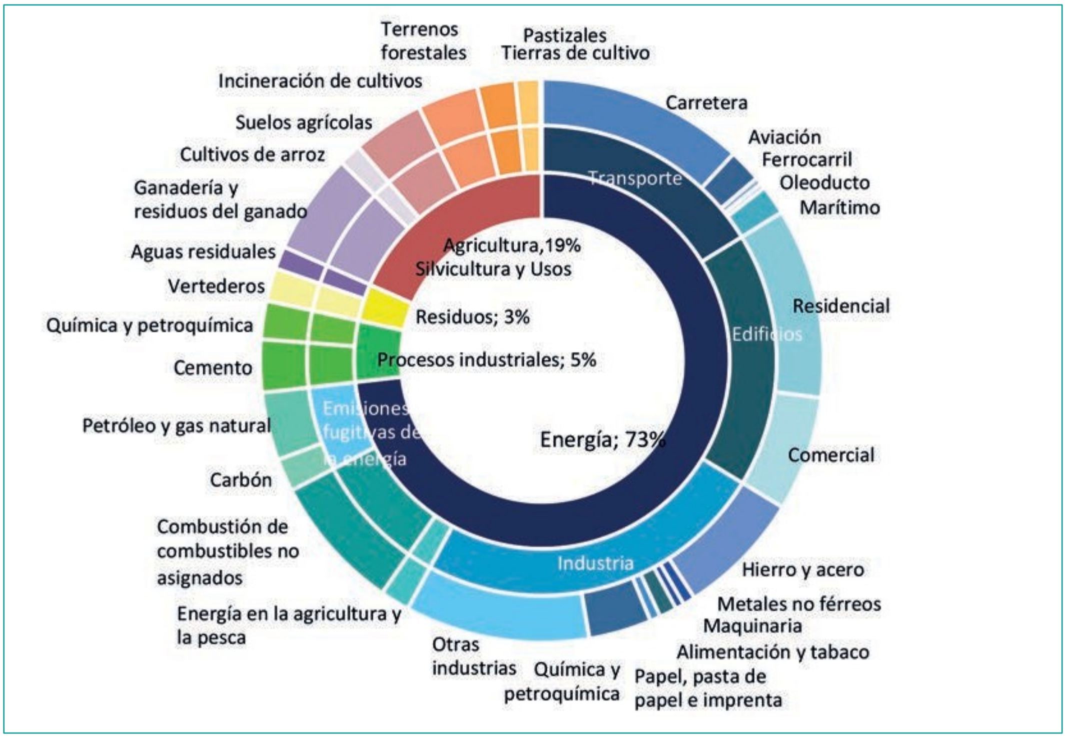
2. Decarbonization and digitalization

2.1. Decarbonization. The energy transition

As previously mentioned, since energy production and consumption are currently responsible for 73.5% of GHG emissions, it is essential to modify the current energy model and adapt it to the new decarbonization objectives.

Graph 1 shows the origin of GHG emissions by sector. Focusing on GHG emissions linked to energy generation and consumption, it is worth noting: (i) in the transportation sector, the main emitter is road transportation, (ii) in relation to building, GHG emissions are distributed between the residential and commercial sectors, and (iii) in industry, iron and steel manufacturing, together with the petrochemical and cement industries, are the main emitters.

The need to decarbonize the economy implies a deep and structural modification of the current energy system in the generation and consumption dimensions, which gives rise to what is known as energy transition. According to Smil (2010) there is no single definition of the term energy transition, although, in general, it is used to describe the change in the composition of the structure of the primary energy supply or the gradual change of a supply model. According to O'Connor (2010) it would be a significant set of changes in the patterns of energy use in a society, with implications for resources, energy carriers, energy conversion systems or equipment, and services.



Origin of emissions GHG emissions by sector. Source: translated and reworked by the authors from (Ritchie, 2020).

Following this conception, Hirsh and Jones (2014) and Nordensvärd and Urban (2015) consider that transitions involve a change in the use of fuels (Miller et al., 2015) and include in the definition of energy transition not only the change in energy sources for energy production, but also in the technologies used for their exploitation.

Some studies take a broader view, encompassing changes in technology, as well as the resulting interrelationship between suppliers, distributors and end users, along with regulators, marketers, etc. (Araújo, 2014); so that it is clear along with the role of technologies to accelerate the process, the need to combine the market with the associated technical or energy developments (Álvarez and Ortiz, 2016).

All these decarbonization-oriented changes require strategic policy efforts (Ro- gge, et al., 2017); and a multiplicity of instruments is needed to foster successful transitions (Hood, 2011). In this sense, the current energy transition process has a number of characteristics of its own and which, to some extent, differentiate it from past energy transitions.

The energy transition is, firstly, being promoted in a particularly active way by international agreements promoted by the United Nations (UN), state governments and public institutions. Secondly, the energy transitions taking place in large, global economies, as is the case here, have been inherently protracted in time (Smil, 2010). They have usually taken decades to complete, and the greater the degree of dependence on an energy source, the longer the duration in the use of pre-existing sources and, therefore, the longer it has taken to replace them. This has been due, among other factors, to the time that elapses between the discovery of a new energy source and its commercially viable industrial application. However, the

The challenge facing the world today is to move towards a low-carbon or net-zero emissions economy within approximately 30 years, when some technological or energy alternatives have not yet been developed on an industrial or commercial scale or are not yet competitive. Third, until now, energy transitions did not aim to completely eliminate those energies with reduced prices or costs or other advantages (Álvarez and Ortiz, 2016).

Following the above considerations, the question now is how the transition to a climate-neutral energy system will be addressed and the cost that this will have in terms of mineral raw material needs (conventional, commonly used, or new), given that new renewable energy technologies require mineral raw materials that account for a significant part of their cost structure (IEA, 2021).

2.1.1. Decarbonization targets

Climate change requires both coordinated solutions at all levels and intense international cooperation to enable countries to move towards a low-carbon economy. In order to address climate change and its negative effects, 197 countries adopted the Paris Agreement at COP21 on December 12, 2015 (United Nations, 2021).

This agreement is the first universal and legally binding agreement on climate change for those States Parties that ratify it, and establishes a global framework for substantially reducing global GHG emissions, with the objective of limiting global warming to below 2°C and continuing efforts to preferably limit it to 1.5°C, based on pre-industrial levels. It also aims to strengthen the capacity of countries to cope with the effects of climate change and to support them in their efforts. The treaty entered into force less than a year later and, as of February 2023, 194 parties (193 countries plus the European Union) had signed it.

The Paris Agreement bridges the gap between current policies and climate neutrality, which requires reductions to be made in accordance with the best available science, as soon as possible, in GHG emissions. In addition, it recognizes the need to achieve a balance in the second half of the century between emissions and removals[8] . As a contribution to the objectives of the agreement, countries have submitted integrated national climate action plans. Although the plans will not be sufficient to achieve the agreed temperature targets, the Agreement charts the way for future action (United Nations, 2021).

The Katowice Policy Code, which was adopted at the United Nations Climate Conference (COP24) in December 2018, captures the set of detailed common rules, guidelines and procedures that operationalize the Paris Agreement. It covers all key areas, including transparency, finance, mitigation and adaptation, and provides flexibility to Parties that require it in light of their capabilities, while enabling them to implement and report on their commitments in a transparent, comprehensive, comparable and consistent manner.

The Chile-Madrid Climate Summit in Madrid (COP25) in 2019, concluded with the adoption of an agreement, called "Chile-Madrid Time to Act", which lays the groundwork for the countries to present their proposals in 2020.

[8] That is, the removal of CO_2, for example, through capture or natural sinks.

The Glasgow COP 26, which was held a year later in the aftermath of the pandemic, closed with a series of agreements including (i) to reduce GHG emissions to contain the temperature increase by 1.5 degrees Celsius (2.5 degrees Fahrenheit). The Glasgow COP 26, which was held a year later as a result of the pandemic, concluded with a series of agreements, including (i) reducing GHG emissions to contain the temperature increase by 1.5°C, (ii) the revision of countries' emission reduction plans in 2022 (three years ahead of schedule), (iii) the progressive and gradual reduction of coal and carbon subsidies, and (iv) the reduction of GHG emissions by 2022 (three years ahead of schedule), and (v) the reduction of carbon dioxide emissions by 2022, (iii) the progressive and gradual reduction of coal and inefficient fossil fuel subsidies, (iv) increased financial assistance to developing countries for adaptation to climate change, and (v) reduction of methane emissions by 30% by 2030.

COP 27, held in Egypt, concluded a global agreement to provide funding for loss and damage to vulnerable countries hard hit by climate disasters. Progress was also made on adaptation to advance the Global Adaptation Goal.

The European Union has been at the forefront of international efforts to combat climate change, with its member states being among the first countries to sign the Kyoto Protocol, playing a key role in reaching the Paris Agreement and continuing to play a global leadership role thereafter.

In 2019, the European Commission published the European Green Pact (European Commission, 2019), a document that provides a concrete and executive action plan to drive resource efficiency by moving to a clean and circular economy, restoring biodiversity and reducing pollution. The European Green Pact thus becomes the roadmap for providing the EU with a truly sustainable economy that transforms climate and environmental challenges into real opportunities.

In December 2020, the EU presented its updated and improved Member State contributions with the objective of reducing GHG emissions by at least 55% by 2030 compared to 1990 levels, as well as information to facilitate clarity, transparency and understanding of the nationally determined contributions. With this, the EU sets itself even more ambitious targets under its broader climate and energy framework for 2030 (Council of the EU, 2020), because the EU's initial nationally determined contribution under the Paris Agreement consisted of a commitment to reduce GHG emissions by at least 40 % by 2030 compared to 1990 levels.

Due to the impact that climate change will have on society, the economy and the environment (Wade, 2016), a large part of governments around the world are setting ambitious decarbonization targets (net zero emissions by 2050 at the latest[9] , except in the case of China, which sets it in 2060 and India in 2070), in order to reach the Paris Agreement target.

By way of summary, Table 1 shows the main decarbonization objectives indicated in the previous paragraphs, including the objectives set in Spain, included in the Integrated Energy and Climate Plan 2021-2030 (PNIEC) (Miteco, 2020), and the Law on Climate Change and Energy Transition.

[9] South Korean President Moon and Japanese Prime Minister Yoshihide Suga stated that their countries were also committed to the goal of net zero emissions by 2050 (Public Agenda, 2020). In April 2021, the president of the United States pledged to rejoin his country to the Paris Agreement after its exit years earlier, as well as to reduce the country's GHG emissions by 50% to 52% below 2005 levels by 2030 (Global Energy, 2021). In total, countries accounting for more than 70 % of global gross domestic product (GDP) have committed to achieving net zero emissions by 2050 (IEA, 2021). They also account for 55 % of total GHG emissions (Public Agenda, 2020).

	GHG emissions reduction (compared to 1990)		Improving energy efficiency	Share of renewable energy in final consumption		Near-zero energy buildings	
Scope	2030	2050	2030	2030	2050	Dec. 2018	Dec. 2020
EU	55 %	80 %[10]	32,5 %	45 %		New public buildings	All new building s
Spain, PNIEC	23 %		39,5 %	42 % 74 % in the electricity mix		Improvem ent of energy efficiency (thermal envelope) of 1,200,000 housing by 2030	
Spain. Climate Change and Energy Transition Law	23 %		35 %	35 %	100 % of the electrical system		

Table 1. *Main energy and climate objectives in Europe and Spain. Source: authors' own elaboration.*

2.2. Digitization of the economy

As previously mentioned, Industry 4.0 is one of the terms used to refer to the process of digitalization of production processes, using information and communication technologies. Figure 1 shows a list of the most relevant ICTs at present and the functions of each technology in production processes.

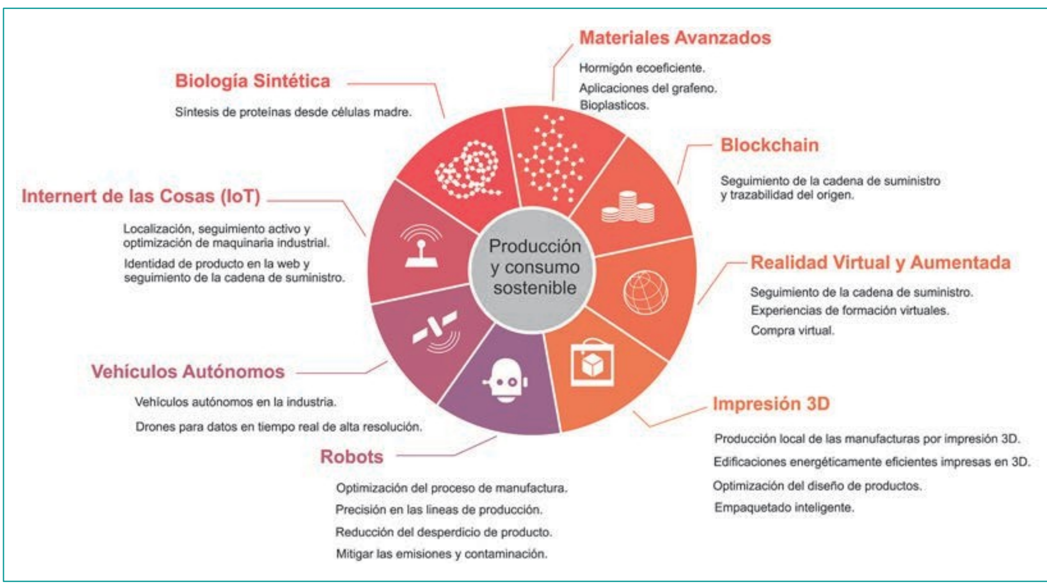
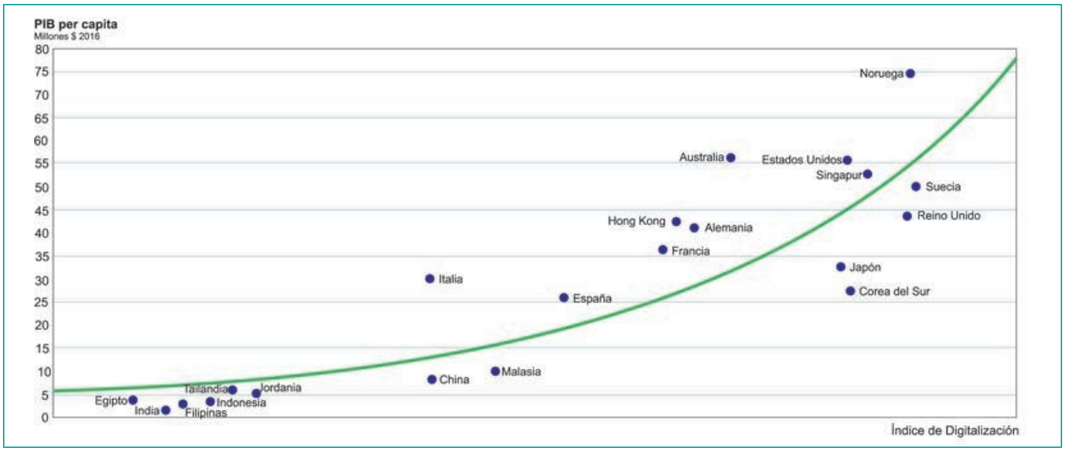


Figure 1. *Functions in the production processes of different ICTs. Source: translated by the authors from (European Commission, 2020b).*

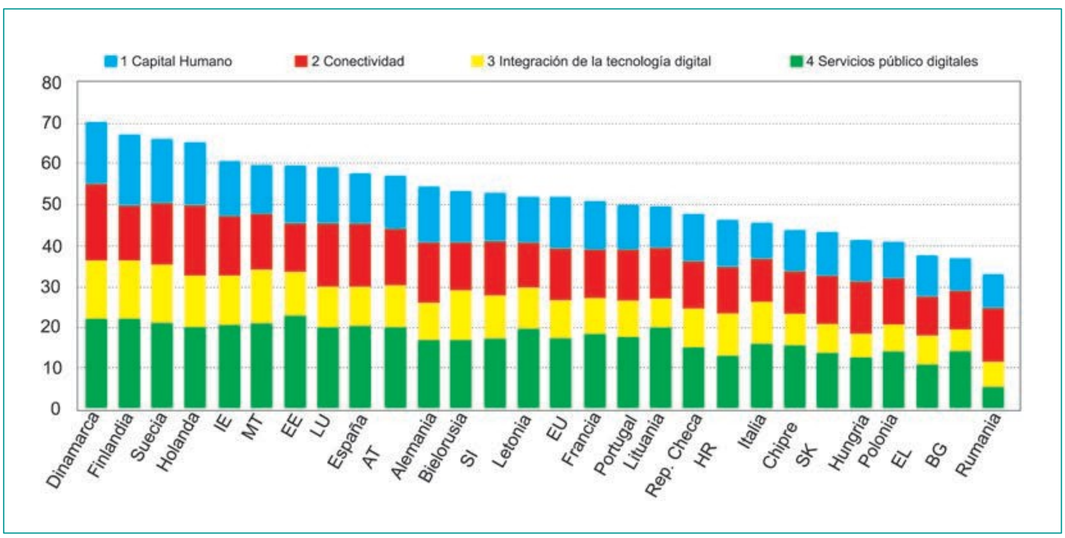
Digitalization is, like the energy transition, a process of change with worldwide repercussions, although with different levels of development in each country. The importance of digitization in a country's economy is decisive for its economic growth, as can be seen in Graph 2, which correlates the digitization index and GDP per capita for different countries. As can be seen in this graph, Spain lags behind countries such as Germany, France, Sweden, the United Kingdom and the United States, among others, in terms of the implementation of digital technology.

[10] The decarbonization target implies achieving climate neutrality by 2050.



Correlation between the degree of digitalization and GDP per capita in different countries. countries. Source: (INCOTEC, 2020).

In relation to digitalization in Spain and its situation in the context of the European Union, Figure 3 shows the Digital *Economy* and *Society Index* 2020 (*DESI*). This indicator is a composite index, which analyzes digital progress in the five dimensions that compose it, and which allows the evolution of the European Union Member States in digital competitiveness to be monitored. These five indicators are: (i) connectivity, (ii) human capital, (iii) internet use, (iv) digital technology integration and (v) digital public services. In 2021, the dimensions were reduced to four, with internet usage disappearing (European Commission, 2022a). Based on the index estimated in 2022, Spain ranked seventh among the EU Member States.



Digital Economy and Society Index of EU countries in 2022. Source: translated and reworked by the authors from (European Commission, 2022a).

The European Union has made a firm commitment to the process of digital transformation of industry. Evidence of this can be found in the European Commission's April 2016 communication entitled "*Digitizing the European Union. Reaping the full benefits of a digital single market*" or the European Parliament's May 2017 report on the digitization of the European Union, among others. These reports identify the benefits of digitization for people (contri- butions technology to improve their daily lives), for businesses (enabling them to be born, grow, innovate and compete fairly) and for the environment (by contributing with digital technologies to achieve climate neutrality). The economic potential of the digitization of industry is estimated to be in the order of 3 to 4 trillion euros (millions of US dollars).

million) by 2025, while at the European level it would reach an annual figure of between 375 and 415 billion euros.

However, it should be noted that digitalization also entails risks. According to the Organisation for Economic Co-operation and Development (OECD), 25% of adult workers in Spain lack digital skills, compared to 15% in the OECD as a whole, hence the importance of training to adapt professional skills to future labor market demand and to turn digitization into an opportunity rather than being perceived exclusively as a risk. On the other hand, this same organization estimates that 12% of jobs in Spain would be at high risk due to automation and another 20% would undergo considerable changes due to it.

In addition, problems in the supply chain of semiconductor electronic circuits (chips) on a global scale have forced the temporary closure of factories in different sectors (e.g., automotive) and a drop in the supply of their products. This has highlighted both the importance of semiconductors to the industry and the heavy dependence on a small group of chip manufacturers.

To ensure digital leadership in 2022 the Commission proposed a set of measures to ensure security of supply, resilience and technological leadership of the territory in semiconductor technologies and applications. As a result, a European Chip Act is being developed that will strengthen Europe's competitiveness and resilience and contribute to the digital and green transition.

2.2.1. Digitization objectives

The objectives set by the EU for 2030 in terms of digitalization (European Union, 2021) are shown in Table 2. These are related to: (i) citizen capabilities, (ii) digital infrastructures, (iii) businesses and (iv) public services.

Thematic	Objectives
Digital capabilities of citizens	- To have 20 million people specialized in ICT with inclusion of gender convergence. - At least 80 % of the population acquires basic digital skills
Secure and sustainable digital infrastructures	- Connectivity: Gigabit for everyone - Doubling the share of EU leading-edge semiconductors in world production. - Data. Edge computing and the cloud: 10,000 highly secure, climate-neutral edge nodes. - Developing the first computer with quantum acceleration
Digital transformation of companies	- Technology uptake: use of cloud, Artificial Intelligence (AI) and big data by 75 % of EU firms - Innovators: increase of growing start-ups and funding to double unicorns[11] in the EU - Late adopters: more than 90 % of SMEs reach at least a basic level of digital intensity
Digitization of public services	- Key utilities: 100% online - e-Health: 100 % of citizens have access to medical records - Digital Identity: 80% of citizens have access to digital identification

Table 2. European Union objectives in digitization. Source: (European Union, 2021).

[11] Technology company reaching a value of $1 billion at some point in its unlisted capital raising process.

In Spain, Digital Spain 2026 is the 2022 update of the strategy launched in July 2020 as the country's digital transformation roadmap. The agenda has ten strategic axes plus two cross-cutting axes, grouped into four thematic blocks, to promote high-impact projects through public-private collaboration and the co-governance of the State and the Autonomous Communities (Table 3).

Thematic	Objectives
Infrastructure and technology	- Digital connectivity: 100% of the population with 100 Mbps coverage by 2025. - Boosting 5G Technology: By 2026, 100 % of the radio spectrum will be ready for 5G. - Cybersecurity: to increase cybersecurity capabilities in Spain, foster the development of the business ecosystem in this sector (industry, R&D&I and talent), and strengthen the country's international leadership in cybersecurity. - Data Economy and Artificial Intelligence: at least 25 % of companies use Artificial Intelligence and Artificial *Big Data* in five years.
Economy	- Digital transformation of the public sector: to promote the digitalization of Public Administrations (General State Administration, Autonomous Communities and Local Entities), particularly in key areas such as Employment, Justice and Social Policies, by updating technological infrastructures. - Digital transformation of the company and digital entrepreneurship: accelerate the digitalization of companies with special attention to SMEs, micro-SMEs and *start-ups* and create favorable conditions for the emergence and maturation of emerging technology-based companies. - Sectoral and sustainable digital transformation: drive digital transformation in strategic sectors such as agri-food, health, mobility, tourism and trade. By 2026, accelerate the dual green and digital transition through the PERTEs and consolidate structural, sustainable and sustainable transformations. - Spain, audiovisual *hub*: to improve Spain's attractiveness as a European platform for business, work and investment in the audiovisual sector, and to promote growth in the different subsectors of the industry.
Persons	- Digital skills: to strengthen the digital skills of the workforce and the citizenry as a whole, reducing the digital divide; to complete the digital transformation of education; to ensure lifelong learning in digital skills; and to increase the percentage of digital specialists. - Digital rights: guaranteeing rights in the new digital environment, and in particular, labor, consumer, citizen and business rights.
Transversal axes	- PERTE (Proyectos Estratégicos para la Recuperación y Transformación Económica): to promote major projects with the capacity to boost economic growth, employment and the competitiveness of the Spanish economy. - RETECH (Territorial Networks of Technological Specialization): in coordination with the Autonomous Communities, projects of high territorial and economic impact are identified.

Table 3. *Objectives of Digital Spain 2026. Source: (First Vice-Presidency of the Government; Ministry of Economic Affairs and Digital Transformation, 2022).*

To this end, there are a series of plans and strategies: (i) Plan for connectivity and digital infrastructures, (ii) Strategy for the promotion of 5G technology, (iii) National Plan for digital skills, (iv) National Cybersecurity Plan, (v) Public Administration Digitalization Plan, (vi) SME Digitalization Promotion Plan, (vii) Spain Audiovisual Hub of Europe Plan and (viii) National Artificial Intelligence Strategy.

3. The role of mineral raw materials in decarbonization and digitization

As mentioned in previous paragraphs, the technological changes brought about by the decarbonization and digitalization of the economy pose significant challenges for the supply of mineral raw materials. New energy sources require a greater diversity of raw materials than traditional energy sources (Valero et al., 2021). It is presented below which mineral raw materials are needed for different technologies and what quantities are estimated to be necessary to achieve the above-mentioned decarbonization and digitalization .[12]

3.1. The role of mineral raw materials in the energy transition to decarbonization

Figure 2 presents a list of the relevant technologies associated with energy generation, transportation, distribution and storage, as well as their consumption. This is not an exhaustive list, and the analysis focuses mainly on mineral raw materials for renewable energies and electrical storage. Thus, technologies that are not yet sufficiently developed (e.g., marine energy such as wave power or special ship hull design to reduce friction and minimize energy consumption) are not considered. Nor do they consider those technologies that are not expected to have a degree of development that would imply a change in the energy paradigm (e.g., new electrical grids).

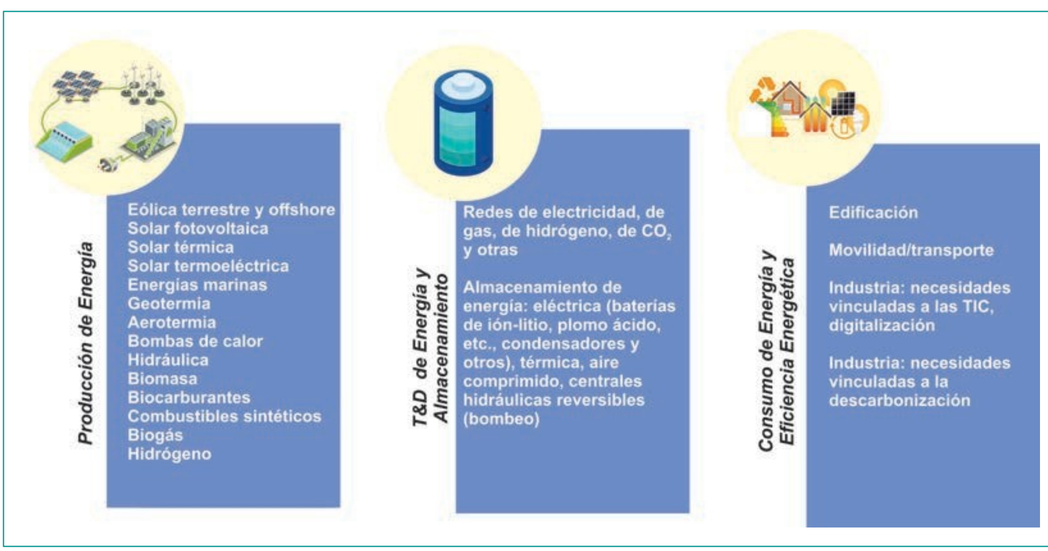
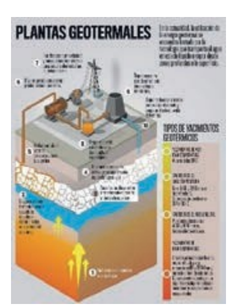


Figure 2. Relationship of the main energy technologies, transport and energy efficiency and distribution (T&D) and energy storage, energy consumption and energy efficiency. Source: authors' own elaboration.

[12] In addition to the studies or reports previously referred to in this chapter and others, a study of interest related to the demand for mineral raw materials in the face of current technological changes is (DERA, 2021). Its scope is broader than that of this paper, given that the 33 technologies it analyzes are presented according to the following clusters: "mobility and aerospace", "digitalization and Industry 4.0", "energy techno- logies and decarbonization", "recycling and water management" and "electricity and data networks". These clusters also examine technologies that are not emerging but are essential, such as power grids.

Table 4 below identifies the main components and the most relevant mineral raw materials required for the manufacture of these components and the equipment associated with each technology.

Technology	Main components	Main materials of mineral origin	
Wind	Bushing, rotor, blades, nacelle, tower, low speed shaft, multi-plier, high speed shaft, generator, controller, cooling unit	Steel (iron-bond alloy), stainless steel (chromium-nickel), zinc, copper and aluminum (86 % turbine weight), rare earths (neodymium, dysprosium and praseodymium), polyester and epoxy (blades)	 Source: Sustainable Mining Platform https://minariasostible.gal/es/inicio/
Offshore wind infrastructure	Fixed foundations (*jackets*, tripods, monopiles, etc.) Floating platform (floating monopile or "spar", semi-submersible platform, tension support platform)	Concrete, steel	
Solar photovoltaic	Photovoltaic cells, power inverters, solar trackers, electrical wiring, structure, etc.	Silicon, aluminum, iron, steel, stainless steel, indium, selenium, gallium, copper, silver, cadmium, tellurium (cadmium telluride, indium copper selenide and gallium)	
Solar thermal	Solar connector, solar storage tank, heat exchanger, solar concentrator,	Silicon, copper, molybdenum, beryllium, germanium, indium, gallium	 Source: (OVACEN, 2013).
Hydraulics	penstock, dam, hydro turbine, electric generator, transformer, power lines, penstocks and hydraulic valves, reservoir, turbine, power lines, penstocks and hydraulic valves, reservoir, turbine	Concrete, steel, copper	 Source: (OVACEN, 2013).
Geothermal	Probes, collectors, geo-thermal piles	Polymers, steel, concrete, sands, copper, high quality steels (nickel, chromium, molybdenum, titanium and manganese), etc.	 Source: (OVACEN, 2013).

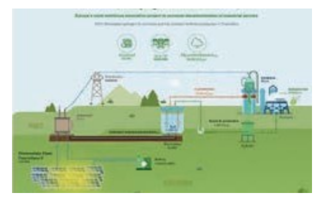
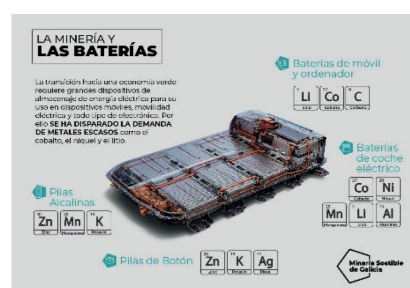
Biomass	Feeding system, combustion chamber (boiler), heat exchanger, cleaning system, control unit, silo, chimney, hydraulics	Steel, galvanized steel, stainless steel, copper, concrete	 Source: (OVACEN, 2013).
Biofuels (bioethanol, bioethanol, biodiesel, biogas, etc.)	Storage tanks, feed pumps, transfer pumps, digesters, turbine, pipelines, etc.	Steel, stainless steel, copper, concrete	 Source: (Campos et al., 2020).
Hydrogen	Electrolyzers, pumps, tanks	Steel, titanium, potassium hydroxide or sodium hydroxide	 Source: (Iberdrola, 2021).

Table 4. Generation technologies of some renewable energy sources, main components and mineral raw materials used in their manufacture and/or construction. Source: own elaboration based on different sources.

Table 5 shows the breakdown for different types of batteries, a key component of the energy transition and where the design will define the requirements for the main mineral raw materials needed .[13]

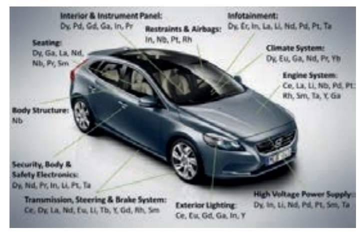
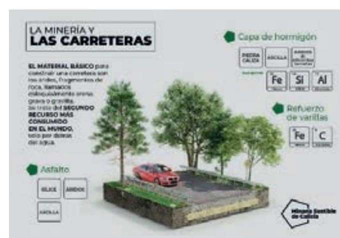
Technology	Main materials of mineral origin	
Cell phone battery and computer	Lithium, cobalt, carbon	
Alkaline batteries	Zinc, manganese, potassium	
Electric car battery	Cobalt, nickel, manganese, lithium, graphite, and aluminum	
Button cells	Zinc, potassium, silver	
Industrial storage batteries	Zinc, vanadium	Source: Sustainable Mining Platform
LFP Batteries (Lithium Ferrum Phosphate)	Lithium, phosphorus, iron, aluminum, graphite, graphite	*https://minariasostible.gal/es/inicio/*

Main energy storage technologies, components and materials and mineral raw materials used in their manufacture and/or construction. Source: own elaboration based on different sources.

Table 6 lists the main components and mineral raw materials of some modes of transport (land, marine and air).

Once the mineral raw materials necessary for the manufacture of the different technologies have been identified, the aspects that characterize the supply of these substances are presented.

[13] For more detail on the current state of storage technologies see (McKinsey & Company, 2021) and (DERA, 2016).

Transportation	Main components	Main materials of mineral origin	
Electric vehicle + Recharging infrastructure	Chassis and body, engine, wiring, battery + Meter, recharging station, power cable	Iron, manganese, aluminum, magnesium, magnesium, vanadium, copper, neptunium, dysprosium, lithium, cobalt, nickel	 Source: Sustainable Mining Platform *https://minariasostible.gal/es/inicio/*
Hybrid vehicle	copper, manganese, magnesium, lithium, molybdenum, neodymium, dysprosium, niobium, cobalt, silver, terbium, tantalum, lanthanum, gold, platinum As an illustrative example for a particular model: 60 kg of Cu, 14 kg of Mn, 9 kg of Mg, 6 kg of Li, 630 g of Mo, 530 g of Nd, 130 g of Dy, 110 g of Nb, 70 g of Co, 50 g of Ag, 20 g of Tb, 12 g of Ta, 8 g of La, 7 g of Au, 5 g of Pt, 1 g of Nb, 1 g of Co, 1 g of Ag, 2 g of Tb, 2 g of Ta, 2 g of La, 2 g of Au, 2 g of Au, 2 g of Pt. (Cullbrand and Magnusson, 2011).		 Source: (Cullbrand and Magnusson, 2011).
Roads	Asphalt, infrastructure, reinforcements	Silica, clay, aggregates, steel, petroleum	 Source: Sustainable Mining Platform *https://minariasostible.gal/es/inicio/*
Aviation	Engines, rods and forgings, wings, black box	Titanium, aluminum, vanadium, iron, chromium, nickel, carbon, magnesium, zinc, aluminum, copper	 Source: Sustainable Mining Platform *https://minariasostible.gal/es/inicio/*
Rail transport	Tracks, catenary, machinery, wagons	Iron, steel, aggregates, ballast, copper, manganese, aluminum, molybdenum, lead	 Source: Sustainable Mining Platform. *https://minariasostible.gal/es/inicio/*

Transportation technologies, main components and materials and mineral raw materials used in their manufacture and/or construction. Source: Authors' own elaboration based on different sources.

In order to have the basis for quantifying the demand for mineral raw materials, Figure 3 shows a summary of the elements required for the manufacture of the main energy generation and storage technologies. As can be seen, there are elements that are necessary in the manufacture of the main energy generation and storage technologies.

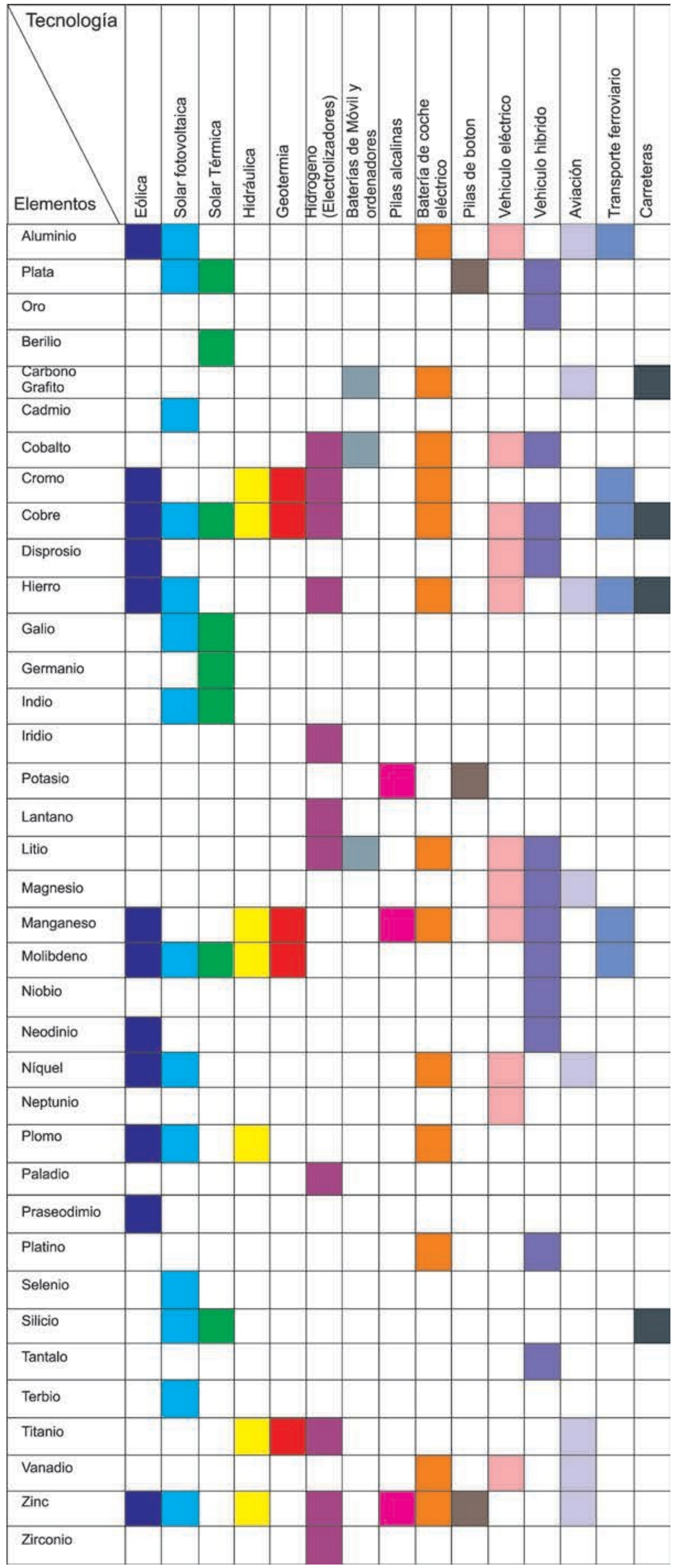


Figure 3. *Elements required in the manufacture of the main generation and storage technologies. of energy. Source: authors' own elaboration based on (The World Bank, 2020).*

The best example of this group is copper, which is used in the manufacture of a wide range of technologies, elements known as *"cross-cutting*". At the other extreme, there are elements (graphite and lithium, for example) that are used in the manufacture of a very small number of technologies and, in particular, energy storage. In the latter case, the demand for these substances will depend directly on the degree of development of the technology in question and the degree of intensity of the minerals or metals involved.

In addition, some of these mineral raw materials are essential, but not exclusive, for certain technologies and are generally of a cross-cutting nature. This is the case of Al for solar photovoltaic technology, power grids and storage technologies, rare earths and Zn for wind power technology, Ni and Cr for geothermal energy, and Cu, Co and Ni also for storage technologies.

However, the question arises as to how much of the above elements will be needed. In this regard, the estimate contained in the World Bank report (World Bank, 2020) is very illustrative. As shown in Graph 4, the more ambitious the decarbonization scenario, the greater the increase in demand for minerals.

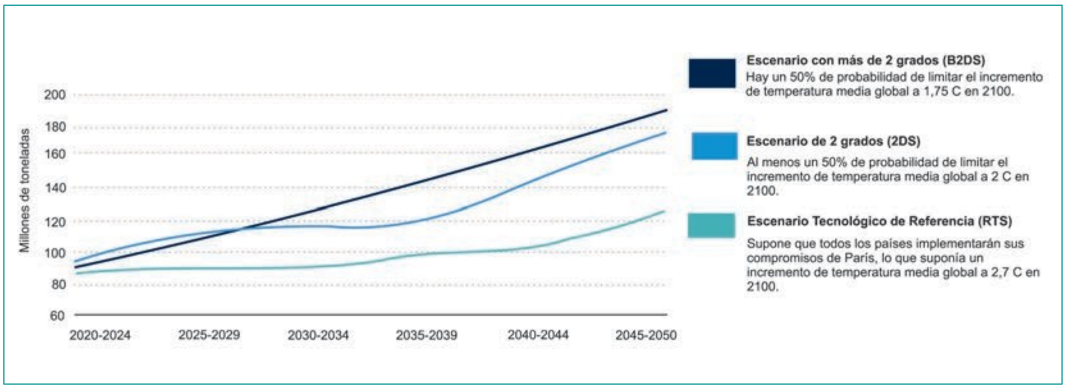


Figure 4.
Estimated average annual mineral demand for 2050 for different decarbonization scenarios proposed by the International Energy Agency (IEA).
The demand estimate is made considering the selection of the elements shown in Figure 3.
Source: translated by the authors from (The World Bank, 2021).

Table 7 presents an estimate of the annual demand for 2050 for 17 elements required for energy technologies and their ratio against the annual production in 2018 for each of them.

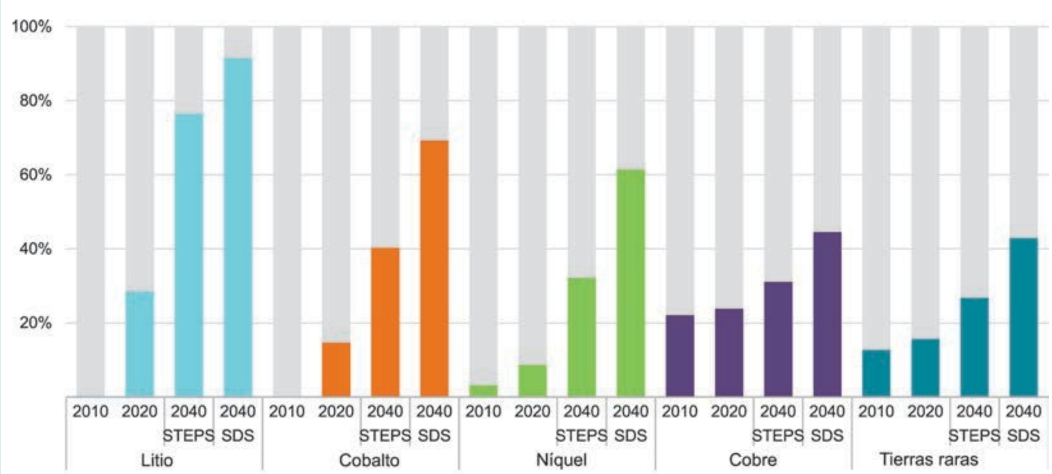
Mineral	Annual production 2018 (thousand t)	Estimated annual demand for energy technologies for 2050 (thousands t)	Estimated projected annual demand for energy technologies in 2050 as a percentage of 2018 production.
Aluminum	60.000	5.583	9 %
Chrome	36.000	366	1 %
Cobalt	140	644	460 %
Copper	21.000	1.378	7 %
Graphite	930	4.590	494 %
Indian	0.75	1.73	231 %
Iron	1.200.000	7.584	1 %
Lead	4.400	781	18 %
Lithium	85	415	488 %
Manganese	18.000	694	4 %

Molybdenum	300	33	11 %
Neodymium	23	8.4	37 %
Nickel	2.300	2.268	99 %
Silver	27	15	56 %
Titanium	6.100	3.44	0 %
Vanadium	73	138	189 %

Table 7. *Estimated annual demand for 2050 for 17 elements in a 2DS scenario. Source: (The World Bank, 2020).*

As can be seen, annual demand in the case of some substances could increase, relative to annual production in 2018, by almost 500 % (case of Co, graphite and Li). In other cases (Al, Cu, Fe) the percentage of annual demand in 2050 compared to annual production in 2018 will be small, but the absolute demand in 2050 will be high.

For its part, the IEA (2020) estimates the percentage of demand for certain mineral raw materials for the manufacture of clean energy generation technologies with respect to the total demand for each raw material. As shown in Graph 5, in all five cases (lithium, cobalt, nickel, copper and rare earths) relative demand in 2040 would increase substantially from 2020 levels. Graph 5 shows the estimate for different scenarios (STEPS, *Stated Policies Scenario* and SDS, *Sustainable Development Scenario*).



Percentage of mineral demand for clean energies with respect to total demand. The clean energies considered are: solar photovoltaic, wind (onshore and offshore), hydro, solar thermal, geothermal, bioenergy, nuclear, electric grids, electric vehicles and batteries. The scenarios correspond to STEPS and SDS. Source: translated and reworked by the authors from (IEA, 2021).

Within the European Union, the report *"Critical materials for strategic technologies and sectors in the EU, a foresight"* (European Commission, 2020b) identifies as critical a set of mineral raw materials necessary for the manufacture of strategic technologies for the EU. In particular, it identifies as strategic technologies those related to the energy sector (electric power, thermal energy and transport): Li-ion batteries, fuel cells, wind power, photovoltaics and electric vehicles (Figure 4).

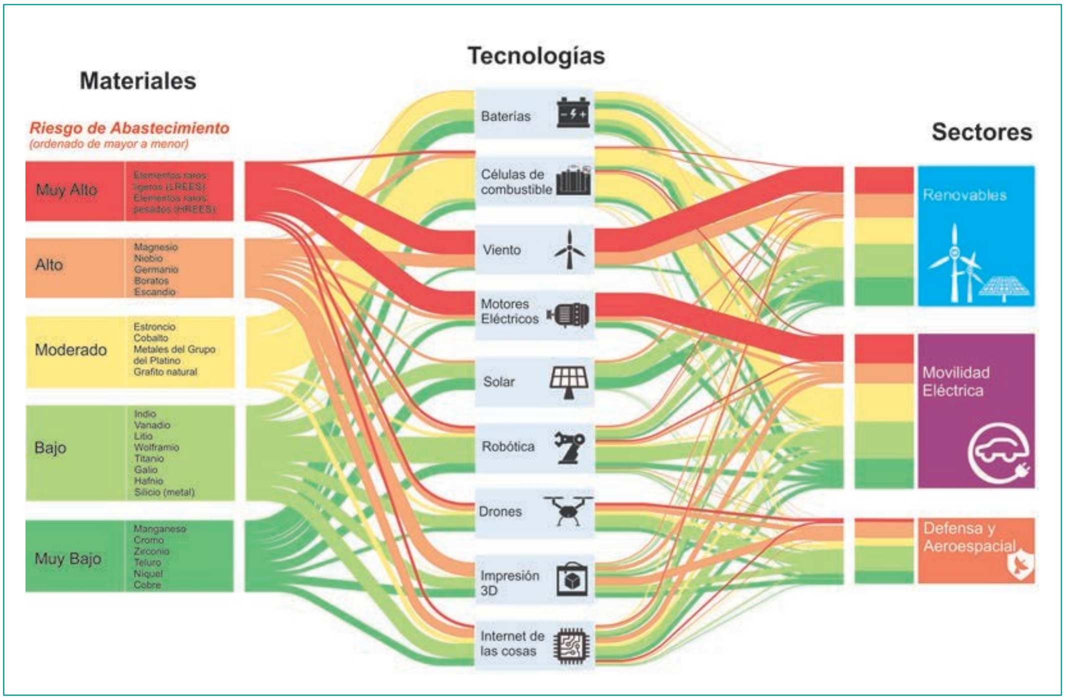


Figure 4.
Mineral raw material flows and supply risks for for the nine technologies identified as critical. Source: (European Commission, 2020b).

3.1.1. The role of recycling in decarbonization

Recycling of materials plays a necessary role in helping to keep materials in the economy for as long as possible, reduce waste in the production process and GHG emissions, being one of the key elements of the circular economy production model .[14]

However, there are still some unresolved aspects of recycling that justify the need to continue extracting mineral raw materials (also called primary mineral raw materials, to distinguish them from recycling or secondary mineral raw materials) in certain quantities to meet the demand associated with decarbonization, as follows: (i) some technological recycling processes are too costly to ensure their economic viability at present, (ii) for certain substances recycling technologies are not developed or the processes are very complex (e.g. recycling of fiberglass from wind turbine blades, (iii) some products need to be made from extremely pure mineral raw materials and recycled material cannot be used (e.g. cobalt used to manufacture batteries), (iv) in some recycling processes there is a loss of material and it is not technically or economically possible to recover 100% of the material (e.g. lithium in lithium-ion batteries) and (v) the availability of scrap is not sufficient to cover the entire demand for aluminum.

Table 8 presents data (worldwide) on the percentage of end-of-life and recycled (secondary) materials recycled as a percentage of the total amount of material used as raw material (primary and secondary material combined). As can be seen, even if 100 % of end-of-life material could be recycled, 100 % manufacturing of a new product from recycled material alone would rarely be achieved. This is why it will continue to be necessary to extract certain quantities of *primary* mineral raw materials.

[14] For more details see chapter 6.

Table 8. Some data on recycling. Source: authors' own elaboration based on (IEA, 2021) and (The World Bank, 2020).

Metal	Percentage of recycled material at end of life (End Of Life)	Percentage of recycled material out of total material
Aluminum	42 %-70 %	34 %-36 %
Cobalt	68 %	32 %
Copper	43 %-53 %	20 %-37 %
Lithium	<1%	<1 %
Nickel	57 %-63 %	29 %-41 %
Gold	80 %-85 %	
Platinum/Palladium	60 %	
Silver	50 %	
Chrome	30 %-40 %	
Zinc	30 %-40 %	

3.2. The role of mineral raw materials in digitization

The role and relevance of mineral raw materials in the manufacture of the equipment and systems that constitute the enabling technologies for digitization (including sensors, IoT, cyber-physical systems, connectivity, augmented reality, simulation and collaborative robotics) is presented below[15] . Table 9 lists the main elements needed to manufacture ICTs.

Table 9. Main elements required to manufacture ICT. Source: authors' own elaboration based on (European Commission, 2020b) and (UNCTAD, 2020).

Element	Use in ICT
Antimony (Sb)	Alloying component for lead batteries, flame retardant.
Beryllium (Be)	Electrical contacts, communication satellites
Boron (B)	Dopant in semiconductors, permanent magnets for hard disk drives
Bromine (Br)	Flame retardant in plastic boxes for telephones
Cesium (Cs)	Photoelectric cell component
Chromium (Cr)	Alloys
Cobalt (Co)	Rechargeable batteries, hard disks, semiconductors, integrated circuits, etc.
Copper (Cu)	Electrical connections (cables, connectors, printed circuit boards)
Gallium (Ga)	Integrated circuits, LEDs, photovoltaic cells, semiconductors
Germanium (Ge)	Fiber optic glass, infrared technologies
Gold (Au)	Electrical contacts (relays, switches), soldering joints, connections

15 For more details on the enabling technologies for digitization, see Annex 2.

Graphite (C)	Rechargeable batteries, graphene production
Helium (He)	Protective gas
Indian (In)	Screens
Rare earths	Magnets for microphones, loudspeakers and hard disks, displays, LEDs, lasers, circuit boards, memory storage technologies
Lead (Pb)	Welding
Lithium (Li)	Rechargeable batteries
Magnesium (Mg)	Alloys for cell phones
Manganese (Mn)	Rechargeable batteries, memory storage technologies
Nickel (Ni)	Microphones, protection of electrical connections
Niobium (Nb)	Alloys
Palladium (Pd), Platinum (Pt), Rhodium (Rh), Osmium (Os) and Iridium (Ir)	Alloys, multilayer ceramic capacitors, screens
Selenium (Se)	Photovoltaic cells
Silicon (Si)	Integrated circuits and electronic components in general
Silver (Ag)	Microelectronic components, soldering alloys, electrical contacts, printed circuit boards
Tantalum (Ta)	Capacitors
Tellurium/Tellurium (Te)	Photovoltaic cells
Tin (Sn)	Welding
Tungsten/Tungsten (W)	Dielectric materials, filaments
Vanadium (V)	Flow batteries

As illustrative examples of the elements required to manufacture ICTs, two commonly used technologies can be presented: computers and smartphones. Table 10 shows this information and their components (capacitors, screens, etc.).

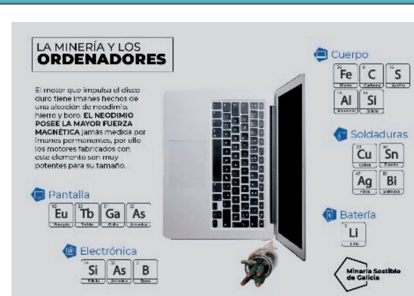
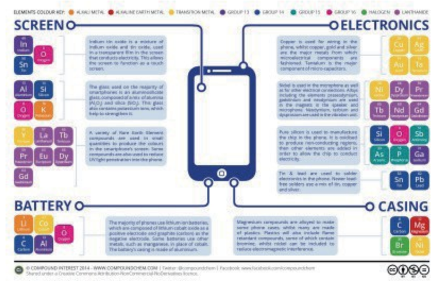
Technology	Main components	Technology
Computer	A computer can be divided, in a simplified way, into structural and functional parts. The materials for making the structural part (Al, Sn, Ni, steel, Mg, Pb) have wide applications in other fields and the use in computers is very small compared to other uses. The functional elements are many and are used in small quantities.	 Source: (Minería Sostenible de Galicia, 2022).

Table 10. *Mineral raw materials required for production of computers and smartphones. Source: authors' own elaboration based on different sources.*

Smartphone	Display, electronics, battery, housing.	 Source: (Compound Interest, 2022).

While the impact of the demand for mineral raw materials for the energy transition has been relatively well studied (reports by the World Bank or The World Bank 2020 and IEA 2021, among others), the demand for mineral raw materials to manufacture *hardware* (computers, fiber optic cables, integrated circuits and their components, such as capacitors, diodes and displays) has been less studied. UNCTAD (2020) analyzes the role of mineral raw materials directly related to *hardware* manufacturing, selecting a total of seven elements: Ga, Ge, In, rare earths (Dy, Pr, Nd), Se, Ta and Te.

These seven items are minor in terms of both volume and value of production in digitization. It serves to illustrate this fact that in 2018 the production value of these seven substan- ces was 0.77 % of the total production value of metals used in digitization, 0.01 % in terms of output. Although these substances are demanded in very small quantities, they have been selected because they are used almost exclusively in the manufacture of ICT technologies. Table 11 shows in which devices they are used.

Element	Cell phones	PCs	Flat TV screens	Laptops and tablets	5G networks	Recharge able batteries	Optic al fiber	Main ICT use
Ga	X	X	X	X			X	LED, microchips, photovoltaics
Ge	X	X		X				Infrared, fiber optic, solar
In	X	X	X	X				Flat panel displays, photovoltaics, semiconductors, welding
Rare earths	X	X	X	X	X			Magnets, LEDs, monitors
See						X		Electronics
Ta	X		X	X				Capacitors, *sputter targets*
Te						X		Control for solar thermoelectric

Table 11. *Use of mineral raw materials (selection of seven elements) in ICT technologies. Source: translated by the authors from (UNCTAD, 2020).*

It is important to note that the small volumes demanded for these elements and the low grades in the deposits make the mining operation not easily profitable, except for rare earths and tantalum. Hence, the origin of the remaining five elements (Ga, Ge, In, Ta and Te) is as a by-product of the processing of other ores.

In relation to the estimation of demand, there is considerable uncertainty because: (i) many of the ICTs are new or under development, so they will probably change in the future and (ii) it is necessary to take into account that it is possible to use alternatives that can provide the same or better properties at an acceptable cost.

By 2035, DERA (2016) estimates: (i) an additional copper demand of 5.3 Mt to cover the needs of 42 emerging technologies, of which ten are ICT (as a reference it should be noted that the total copper demand in 2013 was 21 Mt) and (ii) lithium demand is estimated at four times the 2013 production, cobalt 45 times and for platinum group metals (PGMs) and palladium together a growth of 50% would be estimated.

In the case of some of the above-mentioned elements, Table 12 shows an estimate of the expected demand for 2035.

Element	Total production in 2013 (t)	Demand for 42 technologies in 2013 (% total production)	Demand for 42 technologies in 2035 (t)	Increased demand for the 42 technologies in 2035 (t)
Ga	350	25	130	40
Ge	145	39	118	62
In	790	29	361	128
Rare earths (Dy/Tb)	2.300	85	7.400	5.400
Ta	1.300	38	2.070	1.570

Table 12. *Estimated demand in 2035 for some elements used in ICT.*
Source: translated by the authors from (DERA, 2016) reported in (UNCTAD, 2020).

One of the main consequences of digitization is the enormous amount of data produced and stored in data centers, business infrastructures and devices (PCs, *smartphones*, *IoT* dis- positives), making up the set of all this data what is known as the "*global datasphere*", which is experiencing an enormous advance, estimating a growth from 33 Zettabytes-ZB (10^{21} bytes) in 2018 to 175 in 2025 (Reinsel et al., 2018), which implies an increase in demand for the mineral raw materials needed to manufacture memory devices (Figure 5).

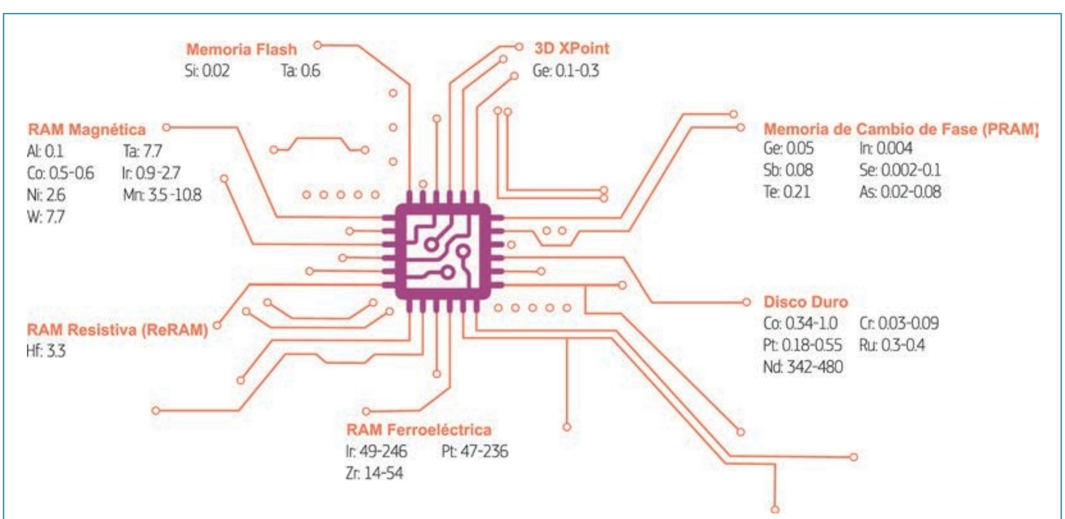


Figure 5. *Estimation of element intensity factors for different memory technologies. Quantities are represented in tons per ZB.*
Source: translated by the authors from (European Commission, 2020b).

3.2.1. The role of recycling in digitization

In relation to the recycling of mineral raw materials used in the manufacture of ICTs it should be noted that in 2020 less than 1 % of ICT elements were recycled at the end of their useful life. It is important to note that the percentage of these substances in ICT devices is very small. As an example, in a PC the average Ga content by weight is only 0.00004 % (Bakas et al., 2016). Taking into account the price of Gallium and its percentage by weight, per computer it would be only 0.02 cents. In contrast, the percentage by weight of gold in a computer is 0.13 %, but with a price of 50,000 to 60,000 United States dollars (US$)/kg it is about 60 € per kg of computer. These figures justify that more than 50% of the gold contained in digital devices is recycled.

It should be noted that there are very few incentives to recycle ICT elements and in some cases the processes are not technologically resolved. Also, there are few economically viable recycling technologies, so it is crucial to develop them. At present (see second column of Table 13), end-of-life recycling rates for these substances are very low, barely 1%.

Element	Percentage of recycled material at end of life (EOL, End Of Life) (%)	Average recycled content in total metal production (%)
Galio	<1	10-25
Germanium	<1	25-50
Indian	<1	25-50
Tantalum	<1	10-25
Beryllium	<1	10-25
Cobalt	>50	25-50
Gold	>50	25-50
Lithium	<1	>1
Palladium	>50	25-50
Ruthenium	10-25	>50
Silver	>50	25-50
Tungsten	10-25	25-50

***Table 13**. Recycling rate for elements used in ICTs and metals from batteries of battery. Source: translated by the authors from (UNCTAD, 2020).*

4. Conclusions

As a result of the Paris Agreement and the agreements of the successive conferences of the parties (COP), the aim is to achieve climate neutrality by the middle of this century. Although there are differences in the deadlines for decarbonization in some countries, in Europe the commitment has been translated into binding regulations to achieve zero net GHG emissions by 2050.

This challenge poses the need for a change in the current structure of energy supply and demand, which will be positively affected, among others, by the progress in the process of digitalization of the economy.

The decarbonization and digitalization processes currently underway are associated with technologies that will require abundant quantities of mineral raw materials, some already widely used and others more novel. A decarbonized and digitized economy poses important differences compared to the current situation, which will reduce dependence on fossil fuels, but will mean the appearance of new and growing demands for mineral materials and raw materials. In this regard, the development of an index of dependence on mineral raw materials could be considered, which could include some related intermediate products (copper concentrates, chips, etc.).

The demand for mineral raw materials needed to manufacture technologies related to energy generation, transportation, distribution and storage will increase substantially, depending on the degree of progress in decarbonization and digitalization. Significant increases in demand of up to almost 500 % by 2050 compared to 2018 production levels are estimated for certain elements or mineral raw materials, especially those linked to the manufacture of energy storage technologies (lithium, graphite and cobalt). However, even those elements whose relative demand increases are lower (e.g. copper) face significant increases in demand in absolute terms.

Meeting the needs associated with digitization will require a variety of mineral raw materials in increasing quantities. Of the elements analyzed in relation to ICT (gallium, germanium, indium, rare earths, selenium, tantalum and tellurium), only rare earths and tantalum are mined as primary products. The rest are obtained as by-products of other production processes, so their recovery is not optimized and a significant amount remains in the tailings, so there are potentially substances of this type in mine waste dumps and accumulations.

Even if in a future scenario the recycling rate increases substantially, the extraction of primary minerals will be necessary to ensure the supply of mineral raw materials linked to decarbonization and digitalization.

Avoiding dependence on fossil fuels with renewable sources of energy may lead to a new dependence on mineral raw materials and metals. The role of mining and metallurgy in the value chain (discussed in the following chapters) must therefore be examined in order to avoid or mitigate the European vulnerability referred to in the introduction.

3

TECHNOLOGY MINING. PROCESSES FOR OBTAINING MINERALS

1. Introduction

Mineral resources are found in the earth's crust, the most superficial solid part of the Earth, which accounts for less than 1% of the land mass, unevenly distributed (Valero et al., 2021). It is composed of a continental crust of about 35 km in average thickness and a thinner oceanic crust, about 7 km thick. The continental crust is heterogeneous, with an average composition of granodioritic type and is formed by rocks of different nature (igneous, metamorphic and sedimentary). The oceanic crust is more homogeneous and basaltic in composition. Most of the earth's crust is made up of eight elements, which are, in order of abundance, oxygen, silicon, aluminum, iron, calcium, sodium, magnesium, and potassium (called major elements) that combine to form most minerals and rocks. Minority elements (also known as *trace elements)*, which include metals, are present in the crust in extremely low average concentrations. Table 14 shows the average content of some elements in the earth's crust.

<table>
<tr><th>Element</th><th>Abundance (%)</th><th>Quantity (t) in the upper 3.5 km of crust</th><th>Element</th><th>Abundance (%)</th><th>Quantity (t) in the upper 3.5 km of crust</th></tr>
<tr><td>Oxygen (O)</td><td>46,4</td><td></td><td>Vanadium (V)</td><td>0,014</td><td>10^{14} -10^{15}</td></tr>
<tr><td>Silicon (Si)</td><td>28,2</td><td rowspan="3">10^{16} -10^{18}</td><td>Chromium (Cr)</td><td>0,010</td><td></td></tr>
<tr><td>Aluminum (Al)</td><td>8,2</td><td>Nickel (Ni)</td><td>0,0075</td><td rowspan="5">10^{13} -10^{14}</td></tr>
<tr><td>Iron (Fe)</td><td>5,6</td><td>Zinc (Zn)</td><td>0,0070</td></tr>
<tr><td>Calcium (Ca)</td><td>4,1</td><td></td><td>Copper (Cu)</td><td>0,0055</td></tr>
<tr><td>Sodium (Na)</td><td>2,4</td><td></td><td>Cobalt (Co)</td><td>0,0025</td></tr>
<tr><td>Magnesium (Mg)</td><td>2,3</td><td>10^{16}-10^{18}</td><td>Lead (Pb)</td><td>0,0013</td></tr>
<tr><td>Potassium (K)</td><td>2,1</td><td></td><td>Uranium (U)</td><td>0,00027</td><td rowspan="5">10^{11} -10^{13}</td></tr>
<tr><td>Titanium (Ti)</td><td>0,57</td><td rowspan="2">10^{15} -10^{16}</td><td>Tin (Sn)</td><td>0,00020</td></tr>
<tr><td>Manganese (Mn)</td><td>0,095</td><td>Wolfram (W)</td><td>0,00015</td></tr>
<tr><td>Barium (Ba)</td><td>0,043</td><td></td><td>Mercury (Hg)</td><td>$8x10^{-6}$</td></tr>
<tr><td>Strontium (Sr)</td><td>0,038</td><td></td><td>Silver (Ag)</td><td>$7x10^{-6}$</td></tr>
<tr><td>Rare earths</td><td>0,023</td><td></td><td>Gold (Au)</td><td>$<5x10^{-6}$</td><td rowspan="2">$<10^{11}$</td></tr>
<tr><td>Zirconium (Zr)</td><td>0,017</td><td>10^{14} -10^{16}</td><td>MGP (Platinum Group Minerals: Pt, Os, Ir, Pd, Pd, Ru, Rh)</td><td>$<5x10^{-6}$</td></tr>
</table>

Table 14. *Average content of some elements in the earth's crust. Note: the third and sixth columns collect the actual amounts of some of the most useful elements, down to a depth of 3.5 km. Source: translated by the authors from (Wills and Finch, 2016).*

Some parts of the earth's crust are characterized by an abundance of some elements above the average value shown in Table 14, forming what is called a mineral deposit. The concentration factor is that which an element must present with respect to its normal concentration in the earth's crust in order to be exploitable or to make its exploitation economically viable.

The existence of a mineral deposit will depend on the geological conditions and processes to which a mineral has been subjected (crystallization, erosion, transport, classification, deposition, compaction, etc.). These conditions will allow the elements, present in the minerals, to concentrate in certain areas of the earth's crust, making their exploitation feasible.

Mining resources can be classified in terms of the mineral to be exploited into: (i) metallic minerals: base minerals (copper, lead, zinc and aluminum), iron, minor metals (chromium, vanadium, molybdenum, uranium, tungsten, lithium), gold and silver, (ii) fossil fuels: steel and thermal coal, bituminous sands and shales, (iii) industrial minerals: used in the manufacture of abrasives, glass, ceramics, plastics, cement, (iv) construction materials: gravels and sands, and (v) diamonds, precious and semiprecious stones.

Minerals contain the elements of interest. Minerals, in turn, are found in rocks. Thus, for example, aluminum is obtained from bauxite, which is a rock containing aluminum and iron minerals whose alumina content ($Al\ O_{23}$) can exceed 50%. Copper occurs mainly in sulfide minerals - chalcocite ($Cu_2\ S$) and chalcopyrite ($CuFeS_2$)-, zinc in blende (ZnS) and lead in galena (PbS). Once extracted from the mine, they are processed in mineralurgical plants, concentrating their grade and reducing impurities, before passing to the metallurgical process.

In nature, metals (Cu, Zn, Pb, Al...) are often accompanied by others. Thus, for example, copper as indicated in the previous paragraph is found in chalcocite ($Cu_2\ S$) and chalcopyrite ($CuFeS_2$), which may also contain silver, gold, arsenic, antimony, selenium, tellurium and other elements. Sometimes these accompanying elements are unwanted impurities that need to be removed (known as penalizing or contaminating elements). However, other times, because they are more valuable than the metal to be obtained (e.g. gold and silver), they are valuable *by-products* that help to make the process profitable.

The mining value chain refers to the operational time sequence of the processes involved in it, as shown in Figure 6, which shows the different phases required to manufacture the end-use material or metal from the minerals and rocks extracted through mining activities, including the reuse, recycling and rehabilitation phases.

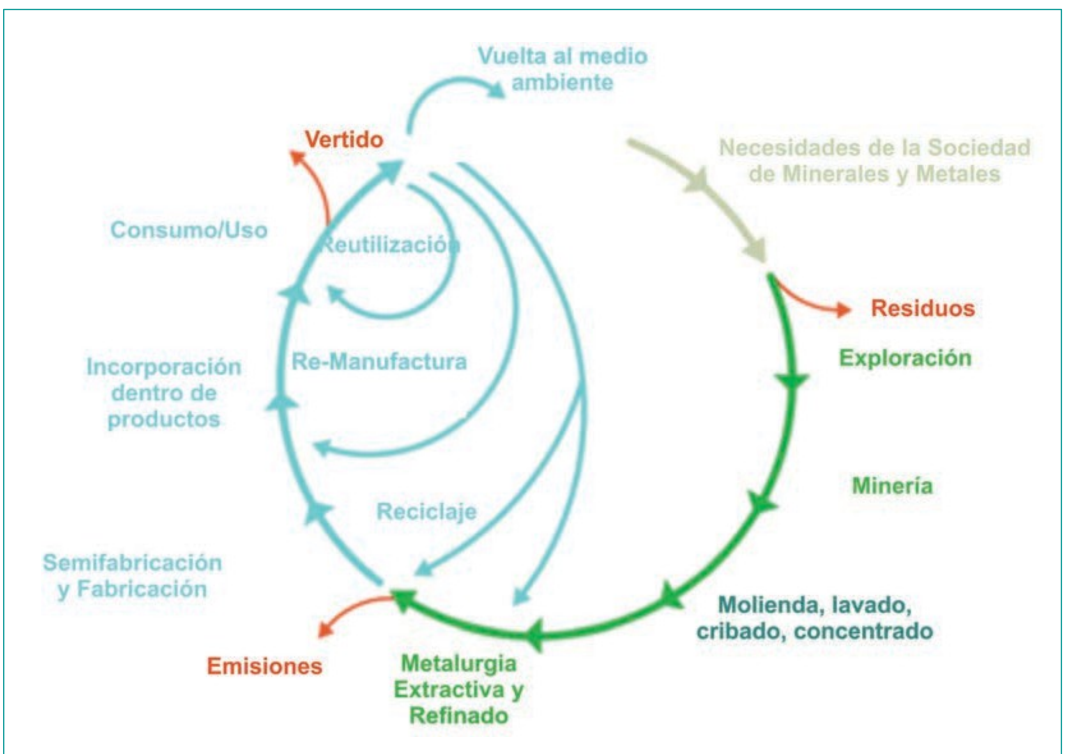


Figure 6. *Main phases of the life cycle of metals and minerals. Source: translated and modified by the authors from (ICMM, 2016).*

The value chain of mineral resources, their mining and metallurgy begins with mining investigation (MI) to discover and evaluate the deposit, followed by the mining process, the mining process, and the metallurgical process.

The last point is the process of closure and rehabilitation of the affected surface. The last point is the process of closure and rehabilitation of the affected area.

The mining industry, unlike other industries, has to take into account the depletion of mineral assets, the knowledge of which is imprecise prior to the commencement of mining. Therefore, it is essential that the industry communicates the risks associated with the investment in an effective and transparent manner in order to obtain the level of confidence necessary to support its activities. This public communication is mainly done through *Public Reports*.

Mineral raw materials and metals are obtained by extracting these substances in mining operations. The development of a mining project is generally a long and complex process, with a high associated cost and high risk that is made up of a series of successive phases that define what is called the *Mining Life Cycle*, which is described in the following section.

2. Mining project

This section presents the phases of the Mining Life Cycle ranging from the investigation -which culminates with the discovery of a deposit-, the evaluation of the deposit, the design and development of the mine plan, to the extraction phase (exploitation) and the rehabilitation/restoration and post-mining phase.

Figure 7 shows the different stages of a mining project and their approximate durations. The cost and duration of each stage can vary greatly from one project to another, so average or benchmark values are usually provided. The technical studies required to carry out mining operations are costly and time consuming. A mining project, including all its phases up to the final feasibility study, can take several years to complete.

Figure 7. *Stages of a mining project. Project life cycle. Source: translated by the authors from (ICMM, 2012).*

The exploitation of a mineral deposit is an activity with high economic risk, involving long-term investments, which are often based on prices subject to strong market fluctuations. A

In turn, costs are incurred that are only recouped in the event of a successful mining operation. The mining industry must ensure that the extraction of mineral resources is carried out at the lowest possible cost and that income and expenditure forecasts provide acceptable returns on investment while respecting the environment.

Throughout the phases of a mining project, decision making is required by all the groups involved (investors, management team, governmental organizations), so it is necessary to work with detailed and clear information about the project and to have a good understanding of the associated risks and uncertainties. The financial market, through the regulatory authorities, establishes a series of rules to control the information that companies publish to the markets about their projects and the way in which this information is made public. For this reason, there are a series of *standards*, also called codes or norms, recognized by the industry and by the financial markets, which contain a series of technical definitions, classifications, requirements and guidelines used in the public reporting of mining companies in relation to all stages of the project .[17]

2.1. Exploration - Mining research[18]

Mining research is the first stage of the mining cycle and involves a series of stages in which a wide variety of prospecting techniques and methods are used to find and characterize a deposit.

The phases of the mining investigation are shown in a simplified form in Figure 8. They are successive phases, so that the next phase is only undertaken if the previous one has satisfactorily met the expected objectives.

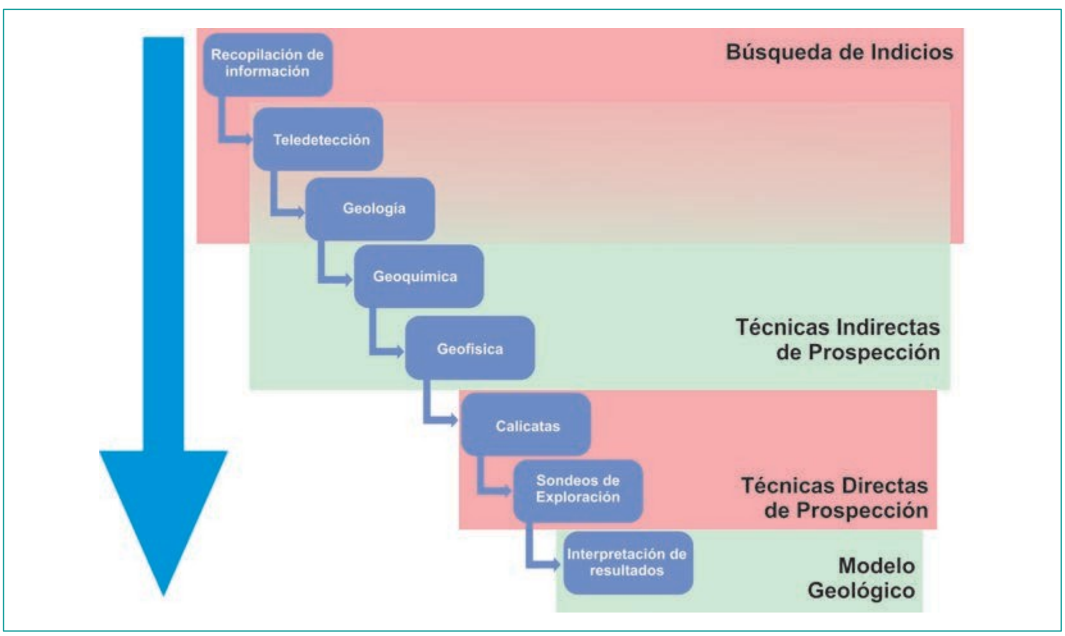


Figure 8. *Phases of mining research. Source: modified by the authors from (Castilla and Herrera, 2012).*

[17] Technical reports are prepared by industry professionals called *Compententent Person* or *Qualified Person* who take responsibility for the correct classification of mineral resources and reserves and their information to the public.

[18] Mining research issues are discussed from a value creation standpoint in Chapter 7.

It begins with a regional investigation of a given area, normally of large extension, and progresses to a detailed investigation. Time and costs increase as the investigation progresses, being inversely proportional to the area investigated or prospected. As the investigation progresses, the risk decreases as knowledge of the geology of the study area increases.

The mining investigation starts with the collection of information on potentially mined areas, through geological surveys and metalogenetic maps/charts, which have usually been carried out by state or regional geological services. In the target areas, remote sensing can be used as an aid in these preliminary phases. It is usually a mainly desk-based work, supported by bibliographic information, maps, aerial photos, satellite images, mining history (mining operations that have existed in the area, mining indications), etc., and may include in situ reconnaissance of the areas of greatest interest, in addition to geological mapping of detailed outcrops and specific sampling for the identification of specific indications.

Once the possibilities of the region have been identified, the next step is the detailed field study. In this phase, the various indirect techniques available will be applied with the final objective of confirming or discarding the initial hypothesis of the existence of mineralization. It then begins with the geochemical prospecting phase, which is based on the systematic performance of chemical analyses. It consists of systematically taking samples of stream sediments, rocks, soils or water, or even of plans, which may concentrate chemical elements related to a given mineralization. The objective of these measures is to locate geochemical anomalies or areas whose structure is indicative of the presence of mineralization.

The cost of these techniques is usually higher than that of geological techniques, since they require a team of several people to take and prepare the samples and the cost of the corresponding analyses in accredited laboratories. Therefore, they are applied when the geology already provides information that allows a reasonable suspicion of the presence of deposits.

Once the geochemical prospecting phase is completed, we move on to geophysical prospecting. In this phase, a whole range of very diverse prospecting techniques are used, both in cost and applicability, depending on the specific mineral being investigated. The objective is to measure sensitive variations in the physical characteristics of the earth's crust, linked to the existence of mineral deposits. The behavior of the ground in response to certain stimuli is studied. Among the various applicable methods are those listed in Table 15: (i) electrical, (ii) electromagnetic, (iii) magnetic, (iv) gravimetric, (v) radiometric and (vi) seismic.

Table 15. *Applicable prospecting methods. Note: For more details see (López Jimeno et al., 2022). Source: own elaboration of the authors.*

Method	Description
Electric	They are based on the study of the electrical conductivity of the ground (or its inverse, resistivity), using relatively simple devices. They are used to identify materials of different conductivities: for example, sulfides and graphite are usually very conductive.
Electromagnetic	They are based on the study of other electrical or electromagnetic properties of the ground. They are used in sulfide prospecting because of their higher chargeability.
Magnetics	They are based on the measurement of the magnetic field of the ground, which can be affected by the rocks existing at a given point, especially if minerals such as magnetite or pyrrhotite are present.
Gravimetric	They are based on the measurement of the earth's gravity field, which may be altered in its normal values by the presence of certain rocks. This technique has been used with great effectiveness in the Iberian Pyritic Belt.

Radiometric	They are based on the detection of radioactivity emitted by the ground, and are mainly used for prospecting uranium deposits, although exceptionally they can be used to identify other elements or rocks.
Seismic	They are based on analyzing the behavior (transmission) of seismic waves through the ground. Two main techniques are distinguished: reflection seismic and refraction seismic. It is only used for the investigation of high value resources.

In this phase, terrain anomalies are identified that justify subsequent studies of greater precision and that require an additional economic investment. Maps are obtained with the distribution of a certain property of a soil or rock. Figure 9 illustrates a geophysical survey using a drone, whose use is gaining ground in the industry during this phase due to its versatility, easy handling and low noise and visual impact, as opposed to traditional geophysical flights. A drone can carry a sensor for geophysical measurements, but in the case of the figure it carries a multispectral camera for remote sensing.

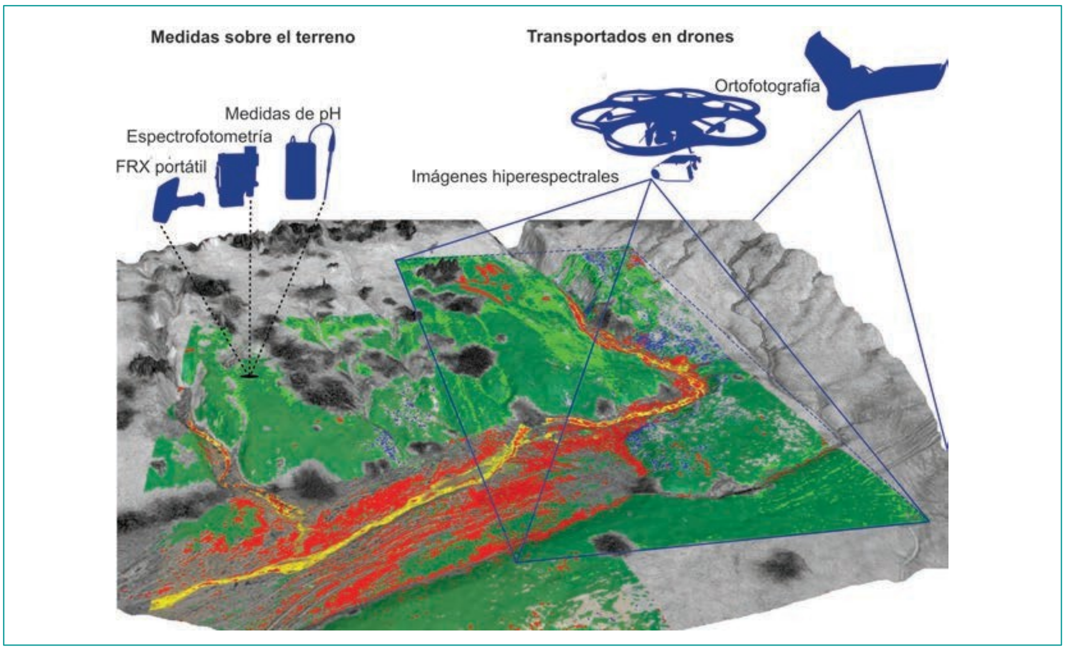


Figure 9. Application of drones in mining research. Source: modified by the authors from (Jackisch et al. 2018).

Figure 10 illustrates the result of the drone application showing resistivity anomalies.

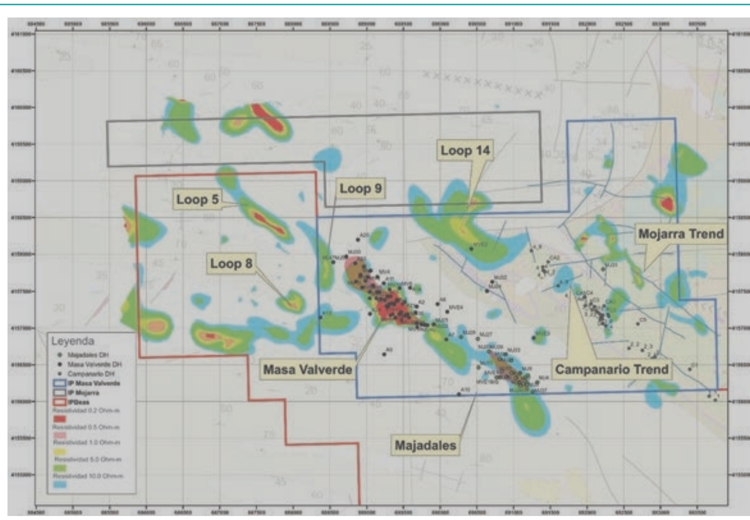


Figure 10. Results of the application of drones in mining research. Map showing resistivity anomalies obtained from an EM SQUID Survey over the Masa Valverde and Majadales. Source: (CSA Global, 2022).

Once the geophysical or geochemical anomalies have been detected, the critical step is to define which values are considered "anomalous" in order to identify whether they are derived from the existence of a mineral deposit. These values will serve as a starting point to define the shape, size and value of the deposit. In these prospecting stages, a large number of data are handled, which must be correctly georeferenced and stored in geographic information systems (GIS, GIS), for their correct representation and integration, with the help of commercial *software* available on the market.

Often, after the development of the previous phases, reasonable doubts remain as to whether or not what is being investigated is of mining interest. Therefore, to verify the information generated in previous phases, a more detailed program is used, which is usually a campaign of calicatas (trenches in the ground of a depth of 1-3 m at most, which allow visualizing the rocks located just below the analyzed or recognized soil), in which mineral samples are obtained and from them the tests are performed to determine metal content or usable substance and the geotechnical characteristics of the rocks.

The drilling of surface drill holes is a very useful tool in advanced stages of mining research, and allows confirming or disproving the interpretations made in the previous phases. Drilling allows obtaining samples from the subsoil at variable depths, providing the most valuable information available about the mineralization until it is reached by mining operations. Drilling can be done from the surface or from subway.

Boreholes can be without or with core recovery. Boreholes without core recovery are made with tricone rotation or with downhole hammer, both with reverse circulation. The cost of this system is relatively low and with drilling yields of 10-15 m/h. Chemical and mineralogical tests are carried out on the samples and geophysical tests are carried out on the boreholes.

Boreholes with core recovery are much more expensive. As they have much lower yields, 15-20 m/reamer, they complement and validate the information provided and allow the geotechnical characterization necessary for the design of slopes in open pit mines and the design of chambers in subway mines.

Drilling is the most important stage of the mining research process, since the information and evidence it provides makes it possible to locate and define the economic value of a mineralization. Figure 11 shows parts of the cycle of a mechanical exploration drill hole and the photographic record of exploration core drill boxes and of the facilities where description (witnessing) and sampling of drill cores are carried out.

Figure 11. *Drilling rig with recovery of (left) and photographic record of core boxes from exploration drilling (center) and description and sampling tasks (right). Source: (Martinez, 2019) and (Ore Reserves Engineering. (2022).*

The drilling stage of exploration wells is a stage that involves a considerable economic investment in terms of means and human resources. The sampling and laboratory analysis of the samples obtained from the boreholes is a fundamental and critical part that requires the establishment of quality control procedures (QA/QC: Quality Assurance & Quality Control) in order to guarantee the representativeness and quality of the samples obtained. The laboratories selected for sample analysis should be certified laboratories with adequate quality systems.

Exploration drilling campaigns cover large areas of the reservoir to try to define its extension, so the drilling grid is usually wide (100x100m, 200x200m). If the results are positive, in advanced stages, additional definition drilling is carried out at smaller distances (50x50m, 25x25m), in order to more accurately delineate the deposit and confirm both the morphology of the body and the geological continuity and grade continuity.

With the data from the drill holes, which correspond to their spatial location and the results of the laboratory analysis of the samples collected in the drilling campaign, through the interpretation of geological plans and sections and by using specific mining *software* (Studio RM-Datamine, Micromine, Leapfrog, Vulcan, etc.), we proceed to the geological modeling of the deposit, which is discussed below, from which the 3D solid model is derived (Figure 12A). From the geological model of the deposit it is possible to estimate the following characteristics: (i) amount (volume and tonnage) of ore present (this is known as cubing and classical cubing techniques - sections, triangulation or polygons - can be used, or block models can be used, employing statistical and geostatistical methods (Figure 12B), (ii) geometry of the mineralization obtained from drill hole data[19] and (iii) ore quality, which in the case of metallic ores is defined on the basis of their grades, the presence or absence of penalizing or bonus elements, as well as the form of occurrence of the metal.

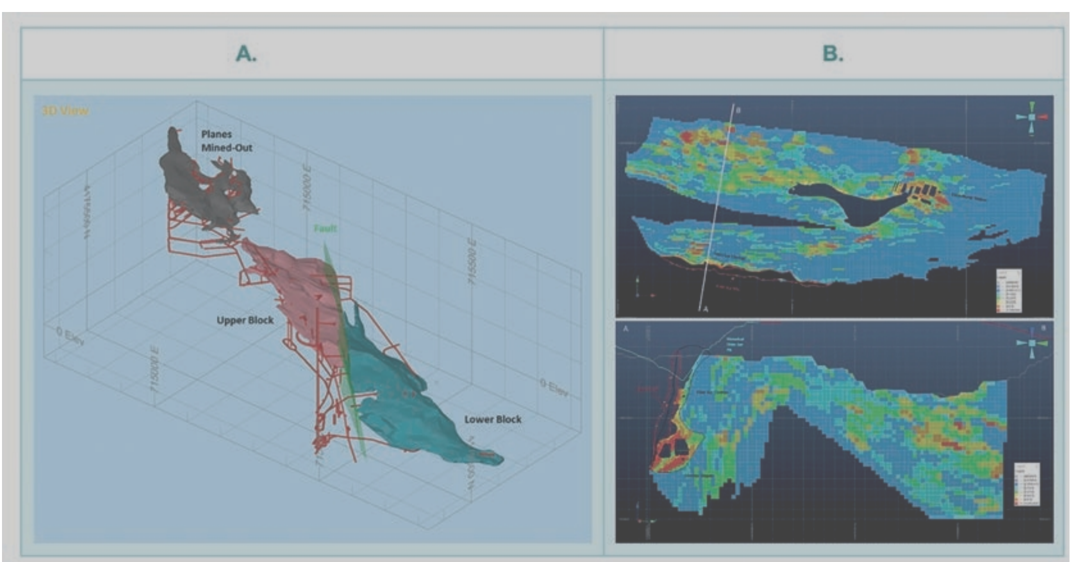


Figure 12. A. *3D view of the modeling of the mineralized bodies of the Planes-San Antonio deposit (Riotinto) carried out with Studio RM-Datamine on the basis of existing drill holes and subway workings.* ***B.*** *Plan view and vertical section of the copper block model of the Cerro Colorado deposit (Riotinto) made with Studio RM-Datamine software. Source: (Ore Reserves Engineering, 2022).*

Exploration results include data and information generated by mining programs that could be useful to investors or potential professional advisors, but are not part of a Mineral Resource statement (PERC asbl, 2021). Exploration results have a high risk, but at the same time generate a high impact on the company's valuation in the markets. For this reason, when exploration results are published, they must contain the following information.

[19] In this regard, the model proposed by Rodríguez-Terente (2007) for the Salave gold mineralization (Tapia de Casa- irrigation), based on drilling data, which identifies depth, extension, geological structure, etc., can be consulted.

nd information sufficient to allow a proper and fair judgment of its significance and importance.

2.2. Reservoir evaluation

The evaluation of the deposit constitutes the stage of technical and economic analysis of the deposit. The technical evaluation is carried out by estimating the tonnage-grade and grade curves using classical or geostatistical methods in order to obtain a mineral inventory of the deposit. Subsequently, the preliminary technical evaluation of the deposit is carried out, in which a series of variables are taken into account, among which are the costs of extraction and treatment of the mineral or the market price of the metals. The objective of this stage is the definition of the mineral resource. Mineral resources are described by the tonnage-grade curve with the *cut-off grade* determined. This cut-off grade defines the minimum grade that the material must contain to be classified as ore.

Once the mineral resource has been defined and classified, and still in the pre-production phases of the project, evaluation studies continue with the identification of all those material factors that may affect the decision to exploit the deposit (known as *Modifying Factors*). From these studies, an estimate of the reserves of the deposit is obtained.

The types of evaluation studies for reserve estimation that will be addressed are *scoping studies*, *pre-feasibility studies*, and *feasibility studies*.

The estimation of mineral resources and reserves requires robust estimation methodologies and specialized considerations in accordance with industry best practices. It is very important to document all parts of the process in a concise and detailed manner, including the procedures used, the parameters selected and the assumptions made. In this sense, the estimation and classification of resources and reserves and their public communication are carried out following international standards recognized by the industry and the markets.

Resources and reserves are classified according to various classification systems that are accepted by the industry, financial authorities and regulatory agencies. The main classifications are those created by government agencies, which are based on the McKelvey classification or diagram. International classifications promote consistency in terminology, definitions, best practices and reporting standards. These include the CRIRSCO (Committee for Mineral Reserves International Reporting Standards) family of codes and the United Nations Classification.

CRIRSCO, formed in 1994, brings together representatives of organizations responsible for the development of codes for the disclosure of information on resources, reserves and exploration results in Australia, Brazil, Canada, Chile, Colombia, Europe, India, Indonesia, Kazakhstan, Mongolia, Russia, South Africa, Turkey and the USA. Map 4 illustrates graphically the location of the codes grouped in CRIRSCO.

The CRIRSCO family of codes includes for example the European Standard PERC (Pan-European Reserves & Resources Reporting Committee), in which several organizations participate such as the Iberian Mining Engineers Board (IMEB), formed by Spain and Portugal, or the European Federation of Geologists (EFG). Other codes in this family are the Australian JORCCode (Joint Ore Reserves Committee) and the definitions and guidelines of the CIM (Canadian Institute of Mining, Metallurgy and Petroleum). In the case of

Specifically in Canada, there is a law or "Mining Rule" called National Instrument (NI) 43-101 established by the Canadian regulatory authorities that incorporates the definitions and guidelines of the CIM.

The objective of these standards or codes is to protect investors by ensuring that the reports issued have terminology and content in accordance with the standards, so that they can be understood and compared. There are minor differences between the CRIRSCO standards as a result of the different regulatory regimes in the countries in which they are used, but they all have identical fundamental definitions and classifications.

Map 4. *CRIRSCO groups most of the mineral producing countries. Source: translated by the authors from (CRIRSCO, n.d.).*

The following is an introduction to the concepts of mineral resource and mineral reserve in accordance with the above-mentioned international codes.

A Mineral Resource is a concentration or occurrence of solid material of economic interest in or on the earth's crust in such form, or quality and quantity, that there are reasonable prospects for eventual economic extraction (PERC asbl, 2021). The location, quantity, grade or quality, continuity and other geological characteristics of a Mineral Resource are known, estimated or interpreted from specific geological tests and knowledge, including sampling .[20]

Mineral Resources are subdivided in order of increasing geological confidence into Inferred, Indicated and Measured categories:

(i) Inferred Mineral Resource is that part of the Mineral Resource for which quantity and grade (or quality) can be estimated on the basis of limited geological evidence and sampling. The geological evidence is sufficient to assume, but not to verify, geological continuity and grade. Most Inferred Mineral Resources can be expected to become Indicated Mineral Resources with additional exploration. An inferred mineral resource is based on limited information and sampling obtained through sampling techniques such as outcrops, drill holes, workings, adits and drill holes.

(ii) Indicated mineral resource: is that part of a mineral resource whose quantity, grade (or quality), density, form and physical characteristics are estimated with sufficient confidence to permit application

[20] Expert judgement is required to indicate the basis on which it will determine that the substance has a reasonable prospect of profitable extraction in the long term. Assumptions should include estimates of cut-off grade and geological continuity at the specific cut-off, metallurgical recovery, calculated royalty payments on exit from the smelter, prices or value of products, method of extraction and processing, operating and processing costs, and general and administrative costs. The qualified person should indicate whether the evaluation is based on direct evidence or on assays.

of *Modifying Factors*[21] in sufficient detail to support mine planning and evaluation of the economic viability of the deposit or ore body. Geological evidence is derived from adequately detailed and reliable exploration, sampling and testing, and is sufficient to assume geological and grade/quality continuity between observation points. An Indicated Mineral Resource has a lower confidence level than that applied to a Measured Mineral Resource. The estimate is based on detailed exploration and collection of information from outcrops, test pits, shafts, mine workings and drill holes, with suitable arrangements or locations to make a reasonable estimate of grades and their spatial continuity.

(iii) Measured Mineral Resource is that part of the Mineral Resource whose quantity, grade (or quality), density, shape and physical characteristics can be estimated with a sufficient level of confidence to allow the application of Modifying Factors to support detailed mine planning and final evaluation of the economic viability of the deposit. Estimation is based on detailed exploration and collection of information from outcrops, test pits, shafts, mine workings and drill holes with appropriate layouts or locations that allow confirmation of grades and their spatial distribution. A measured mineral resource has a higher level of confidence than that applied to an indicated or inferred mineral resource.

Mineral Reserves constitute the economically exploitable part of a Measured Mineral Resource and/or an Indicated Mineral Resource. They include dilution materials[22] and losses that may occur during mining or extraction of the material and are defined by studies at the Pre-Feasibility Study or Feasibility Study level, as appropriate, which include the application of Modifying Factors. Such studies demonstrate that, at the time of reporting, extraction could be reasonably justified (PERC asbl, 2021). Reserves are classified as probable and pro- bated. Probable reserves have a lower level of certainty than proved reserves.

(i) Probable reserve: is the economically mineable portion of the indicated resources, and in some circumstances, of the measured resources. The degree of confidence in the Modifying Factors applied to a probable mineral reserve is less than for a proven mineral reserve.

(ii) Proven reserve: is the economically exploitable part of the measured resources. These reserves imply a high degree of confidence in the application of the Modifying Factors and also imply a high degree of confidence in the estimate.

The framework for the classification of tonnage and grade estimates reflecting the different levels of geological confidence and in the application of the Modifying Factors of the CRIRSCO family codes is shown in the schematic in Figure 13, which reflects the relationship between exploration results, resources and ore reserves (CRIRSCO, 2019).

In certain situations, measured mineral resources could become proven mineral reserves due to the associated uncertainty (indicated by the dotted arrow). Likewise, in other situations, reported mineral reserves could be converted back to mineral resources.

[21] Modifying factors are considerations used to convert mineral resources into reserves. They include, among others, mining, processing, metallurgical, infrastructure, economic, marketing, legal, environmental, social and governmental factors.

[22] Dilution is the process of contamination of the ore with lower grade substances and/or tailings, which occurs during the extraction stage.

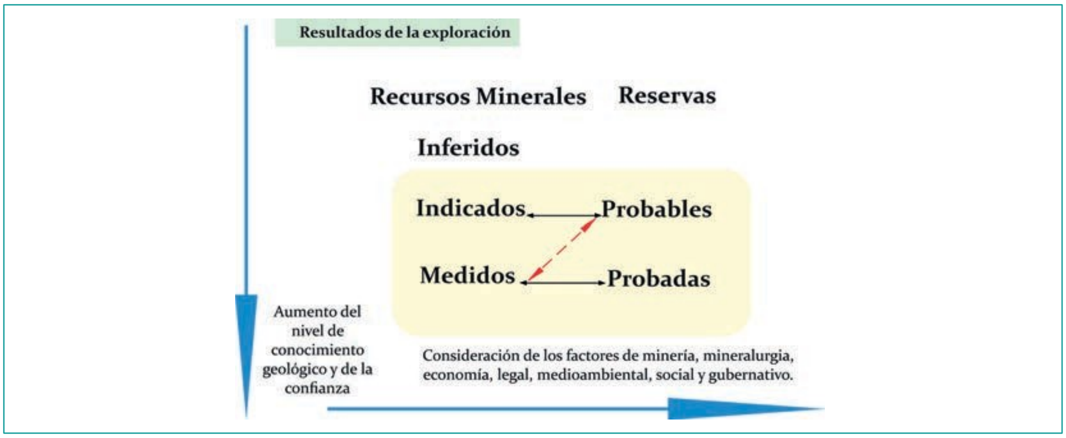


Figure 13. *Diagram or basic scheme of resources and reserves, which shows the relationship between results of exploration, mineral resources and reserves.*
Source: translated by the authors from (CIM, 2014).

However, it is not intended to apply the reclassification of reserves to mineral resources due to changes of a short-term or temporary nature, or when a company's management has made a conscious decision to mine in the short term without profitability.

Resource/reserve estimation is considered a continuous process that continues throughout the development of the deposit. During mine operations the estimates previously made are modified by the results of grade control and reconciliation studies[23] , whereby the tons, grade and metal predicted by the reserves are compared against the tons, grade and metal produced, in order to measure the quality of the estimate. With this technique, predictions of mineralization characterization can be made, improving long term resource estimates and reserve calculations for short and medium term mining plans.

In order to properly assess how much of the resources can be classified as reserves it is necessary to know: (i) the method of ore extraction used in relation to the characteristics of the ore body, since the extraction method determines the mining dilution and ore recovery; (ii) the associated project operating costs resulting from the cut-off grades used; and (iii) the process capacity limits.

The mine planning stage considers the technical and economic viability of the mine, weighing the business risks against the likelihood of profitability in the volatile mining and metals market. During this stage a sizing and modeling of the deposit is carried out to define both the shape and content of the ore and the value of the deposit or amount of ore that can be extracted profitably.

For deposit modeling, specific *software* such as Surpac, Data-Mine, Recmin, Minesight, Vulcan, etc. can be used. These programs are used to model both massive and disseminated deposits, from the information obtained by drilling, as well as to estimate resources and reserves, by obtaining a three-dimensional (3D) model of ore grades and ore bodies.

The realization of the 3D geological model or construction of the solid, as another chapter of the feasibility reports, is fundamental. With the borehole data (lithology and grades of useful metals or minerals) and, above all, the mining-geological experience of the evaluation team, an interpretation is made of the data and the results of the drilling (lithology and grades of useful metals or minerals).

[23] A reconciliation study seeks to measure the performance of the operation, *support the ore inventory, assess the estimation of mineral resources and reserves to provide key performance indicators in the short and long term, as well as minimize losses* (Gutierrez et al., 2014).

The three-dimensional design is based on the profiles, which facilitate understanding and allow for a geometrically possible proposal. This is undoubtedly the most important stage of the whole process. The model will divide the geological solid into fundamental units that will allow the resources and reserves to be classified according to the quality of the available information (generally drilling density) and will also be the basis for defining the optimal extraction design of the reservoir (Figure 14).

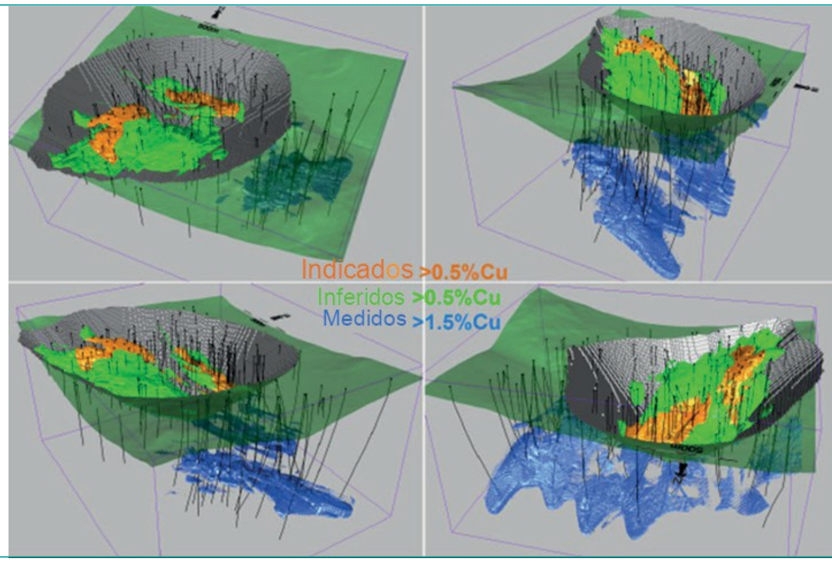


Figure 14. *Classification of the mineral deposit into three categories (inferred, indicated and indicated resources).*
and measured). The figure also shows the profile of the mining shaft.
created by open pit mining (gray) and the mass exploitable by underground mining. Source: translated by the authors from (Nova Copper, 2016).

The preparation of reports for a mining project is practically mandatory, and they accompany the life of the mining operation, but they are also of fundamental importance in the early stages of the project. The reports are typified as follows:

(i) *Scoping Study*: Scoping studies are basic technical and economic studies of the potential viability of mineral resources, including appropriate evaluation of the assumed modifying factors along with any other relevant factors necessary to demonstrate that progress to a pre-feasibility study is reasonably justified (PERC asbl, 2021). This study comprises the analysis of reconnaissance and appraisal soundings and core sampling in order to de- termine a resource and analyze the most suitable extraction method. The scoping study is key in the life cycle of a mining project, as it identifies technical issues that will require further examination or test work. Generally, the end result of the study is a description of the general characteristics and parameters of the project and an estimate of the order of magnitude of the operating costs and capital required for its development. Order of magnitude studies normally do not require prior detailed engineering work.

(ii) Pre-feasibility study: is a comprehensive study of a range of alternatives for the technical and economic feasibility of a mining project that has progressed to a stage where the method of extraction has been established and an efficient method of processing the ore has been determined. It includes a financial analysis based on reasonable assumptions about modifying factors and the evaluation of any other relevant factors sufficient for a competent person, acting reasonably, to determine whether all or part of the mineral resource can be converted to a mineral reserve at the time of reporting. It involves the use of engineering and geotechnical studies directed at resource extraction. In addition, the

The company will study capital forecasts and environmental and permitting costs related to government and land use. It is essential to identify areas that require further investigation. Depending on the level of detail in these studies and the risk of changing factors involved, reserves are stated at this point.

(iii) Feasibility Study: is a comprehensive technical and economic study of the selected development option for a mining project that includes appropriately detailed assessments of applicable modifying factors along with any other relevant operational factors, plus a detailed financial analysis, both of which are necessary to demonstrate at the time of reporting that mining is reasonably justified (PERC asbl, 2021). According to the JORC code *it "analyzes in detail the technical soundness and economic viability of a mining project and serves as the basis for the investment decision*" (JORC, 2012). Ore and recoverable metal reserves can be declared. This phase marks the culmination of a thorough investigation and data collection, where the exploration company makes a decision on whether or not to proceed with the development of the mining project.

Feasibility Studies are the main tool for determining both the cost of the project and the reliability of the estimates made. They should include data on external facilities, infrastructure development needs, administrative authorizations, social and environmental agreements and other requirements. They constitute audits of all geo- logical, engineering, environmental, legal and economic aspects. In general, an independent environmental impact study required by the authorization is also required.

Environmental requirements are currently very strict. The environmental procedure is key for the exploitation permit and even, depending on the site, for the exploration permit (special protection areas). The rehabilitation obligation is associated with the permit, and its cost is part of the total project costs. With this information, we will move on to the planning and technical-economic evaluation stage, which will determine if there are conditions to continue with the development and exploitation of the mine.

(iv) The Financing Report (also called "*bankable*") is a document that outlines the technical risks inherent in the mining project, outlines methods to eliminate and/or mitigate the risks, and quantifies the potential economic benefits that can be achieved. The bank or financial institution itself ultimately defines what needs to be accomplished through a document that will be used to justify the financing of a project.

Typically, a *bankable feasibility study* is a prospective analysis of the economics of a project (with an accuracy of about 15%, to be used by financial institutions to assess creditworthiness in project financing).

When all the reports are positive, and once the corresponding administrative permits have been obtained (which constitute the base element together with the Environmental Impact Study, which must include the rehabilitation and abandonment of workings), the exploitation phase of the deposit begins. These reports can become a tool that can be used to overcome the current barriers to mining development by disseminating their contents through different channels and in a transparent manner.

2.3. Mining

Mining is the stage in which the ore is extracted from the deposit and is generally the longest stage of all, known as *Life Of Mine (LOF)*. Previously, the necessary permits for the mining operation had to be requested from the competent authorities[24] . Once the mining operator receives the favorable report of the mining right requested (exploitation authorization or exploitation concession, depending on the type of substance to be extracted), the preparation phase for the exploitation and later the exploitation of the deposit begins.

The objective of the exploitation phase is to obtain ore production, in a determined quantity and quality, to feed the mineral processing plant. In this phase the operations of start-up, loading and transport of the ore to the mineral processing plant are carried out systematically, which make up what is known as the production cycle (primary, main or basic cycle). The equipment used to carry out the start-up, loading and transport operations and their coupling, make up what is known as the exploitation system (for example: start-up with blasting, loading with a shovel loader and transport with a dump truck).

In open pit mining (OSM) it is necessary to extract the material that surrounds the ore or useful rock (material that has no value and is known in mining jargon as tailings from the tailings heap[25]). The variable that measures the amount of tailings that needs to be extracted per unit of ore is the *stripping ratio* and measures the ratio of tailings to ore (in t/t, m^3 /t or m /m^{33}) of a mining pit. Therefore, it is also necessary to apply the production cycle to the tailings (stripping, loading and haulage operations), in this case deriving the haulage to waste dumps.

Given that the extraction of the tailings (removal, loading and transport to the waste dump) only involves costs (except in cases of revaluation of mining waste), the value of the ratio determines the economic viability of an operation if the amount of tailings to be extracted per ton of ore is excessive. Each operation is unique, but, in general, open-pit mining has a depth limit: (i) for technical reasons (guaranteeing the stability of the mining voids), (ii) economic reasons (assuming the cost associated with an increasingly higher tailings/mineral ratio) and/or (iii) environmental reasons (guaranteeing the proper management of an increasingly higher volume of mining waste). If the deposit continues in appropriate quantity and quality at depth, it can be considered to end open pit mining and start subway mining (MS). Figure 15 shows a schematic of a deposit previously mined by open pit mining (*stoping* in the schematic) and subsequently mined by subway mining.

The spatial and temporal sequence in which excavations are carried out in a mine is known as the mining method. Conventional mining methods are classified into open pit and subway methods .[26]

In open-pit mining methods, the excavation is carried out from the surface, accessing

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[24] This document does not address the description of the procedure for authorization of mining rights by the administration. However, Annex 4 contains a list of regulations applicable to mining projects across all sectors. In relation to mining rights (exploration, research, exploitation authorization and exploitation concession) it is necessary to have, among others, the favorable report of the mining right, the Environmental Impact Study and the Restoration Plan.

[25] Gables are the physical contacts of a reservoir with the surrounding material. The upper contact is called the reservoir *roof* and the lower contact is called the reservoir *wall*.

[26] There is a more general classification: (i) open pit methods, (ii) subway methods and (iii) borehole methods. The latter are not referred to in this document, since they are used for fluid extraction (crude oil and gas), although there are some borehole methods for solid materials, e.g. auger mining, which are not addressed in this document.

The volume of useful mineral or rock to be extracted. When the deposit is located at great depth, it is neither technically nor economically feasible to extract the ore from the surface, so the ore is accessed through what are known as *access workings* (inclined galleries, spirals or vertical shafts), without removing the tailings cover that covers the ore. This is the case of subway mining.

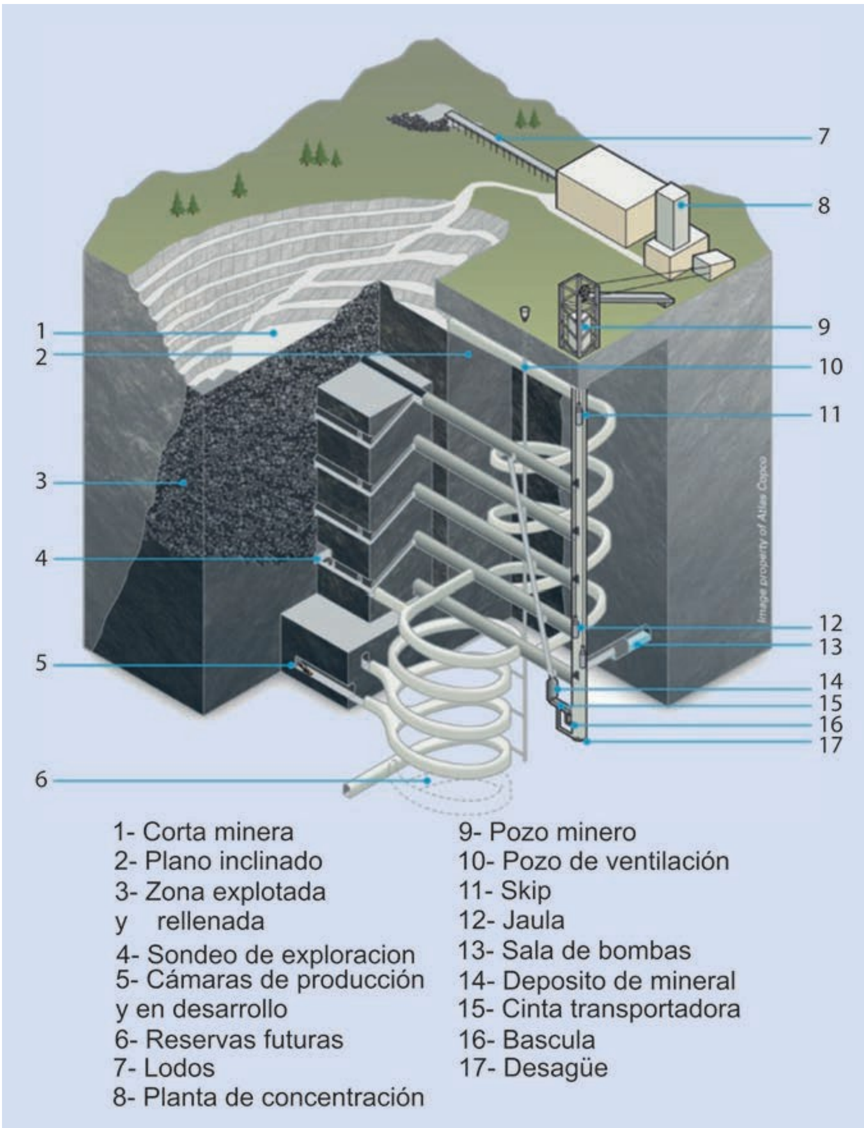


Figure 15. *Main terms used to designate workings in a subway mine. Source: translated by the authors from (Bustillo, 2017).*

Although each deposit is unique and each mining operation is unique, some differences between open pit mining and subway mining can be identified and are presented below:

(i) Open pit mining involves the creation of a shaft that alters and modifies the relief and the landscape and it is almost always necessary to have spaces to permanently locate the waste generated by the extraction of tailings. In the case of subway mining, although tailings are extracted when excavations are made to access the ore, there is no systematic production of tailings as in open pit mining, so tailings management is simpler.

(ii) In open pit mining there is little limitation on the size of the equipment to be used in the operations of starting, loading and transporting. In subway mining there is a limitation of this size, so the mechanization of these operations must take into account the size of the equipment as a requirement, which makes it difficult (although it does not prevent) the mechanization of the operations.

(iii) In open-pit mining, both capital and operating costs are, in general terms, lower than in subway mining. Productivity in general terms is higher in open pit mining than in subway mining.

(iv) Weather and atmospheric conditions have little or no influence on subway mining operations, while they can affect and condition open pit mining operations.

(v) Finally, auxiliary operations are generally more numerous and complex in subway mining. Some auxiliary operations are common to open pit and subway mining. Others are specific to each group. Auxiliary operations common to both groups include: equipment maintenance, power distribution, drainage, water purification and pumping, communication and lighting. Those specific to each group include: slope stability (MCA), excavation support (MS), spoil heap management (MCA), mine track management (MCA), ventilation (MS) and extraction (MS).

The basic description of the most commonly used exploitation methods and exploitation systems is presented in Annex 3. It should be noted that each deposit is unique and therefore each operation is also unique, so the information provided should be understood in general terms.

Figures 16 and 17 show, by means of diagrams and successive images, some operations that are carried out in both open-pit and subway mining, respectively, as well as the equipment most commonly used in start-up, loading and transport operations.

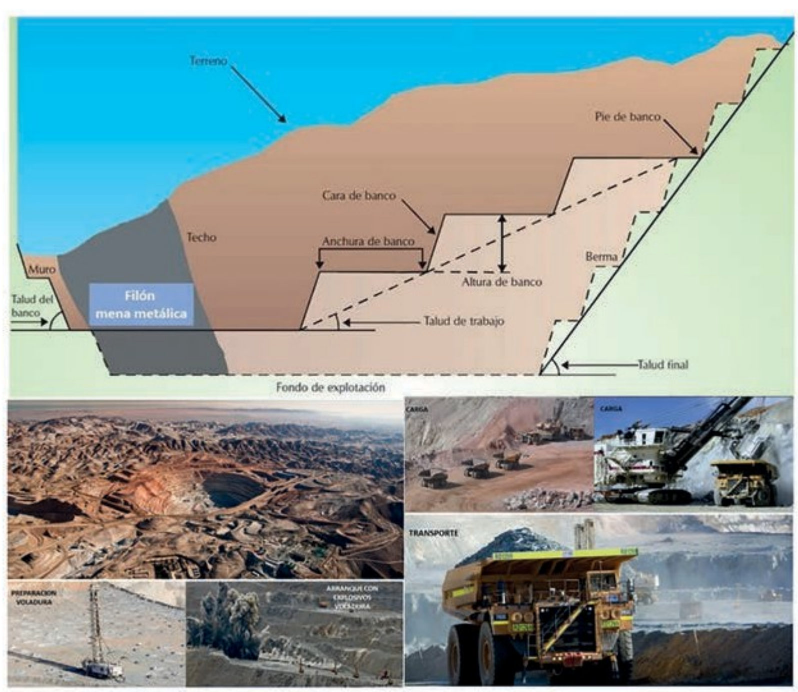


Figure 16. Open pit mining operations and terminology used in the mining shaft. The schematic shows the original geological section, the profile of the shaft at an intermediate stage of the exploitation and the final profile of the mine shaft. Source: (López Jimeno, 2007) and authors' own elaboration.

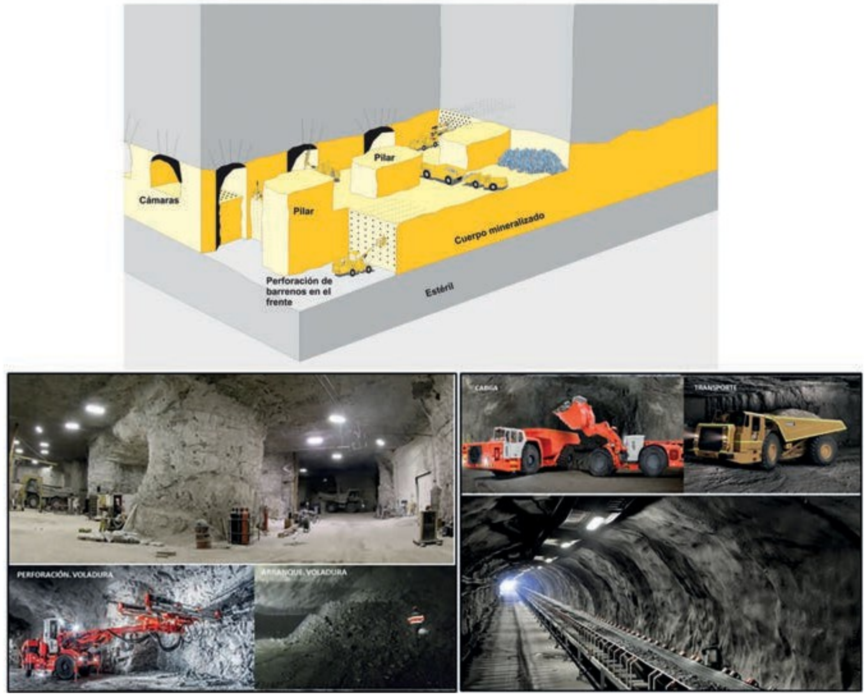


Figure 17.
Schematic diagram of a farm by chamber and pillars (subway mining). Source: modified by the authors from (Atlas Copco, 2007) and authors' own elaboration.

3. Mineralogical technologies

Metallurgical plants, which will be discussed in the next chapter, are fed with concentrates with grades between 30 and 50%. However, the all-in-one extracted during mining usually has grades between 0.4 and 4 %. Concentrates are obtained from the all-one in mineralurgical plants, which are discussed in this section.

The mineralurgical processing of the whole ore modifies its grade and physical characteristics (size and shape), while the chemical or physicochemical characteristics of the different minerals remain unchanged. As a result, three products are obtained: (i) concentrate, which is characterized by reaching the grade required by metallurgy, (ii) tailings, which are residues from the process that must be evacuated and disposed of properly and safely, and (iii) blends, compounds with intermediate grades between that of the all-in-one and that of the concentrate, which must be reprocessed. The production of blends and their control, in the intermediate stages of the mineral processing, allow the processes to be regulated and production costs to be contained.

The liberation of the valuable minerals that are in the whole-one is achieved by size reduction of the whole-one, which involves crushing and grinding to a particle size such that the product is ideally a mixture of materials in which the mineral (ore) and gangue are separated. The size should be as large as possible, as this not only saves energy, but also reduces the amount of fines produced and subsequent separation stages become easier and cheaper to operate. A schematic of the ore liberation process from the all-one size reduction in which ore, tailings and fines are distinguished can be seen in Figure 18.

In practice, the ideal situation is rarely achieved. Figure 18 illustrates the liberation dilemma often faced in mineral processing. The zones identified in the figure as regions A represent the valuable ore. Region AA is rich in valuable ore, but is heavily interspersed with gangue. Size reduction produces a diverse range of fragments, including pure valuable ore (chunk 5) and pure gangue (chunk 6), both of which are fully liberated. Type 1 particles are rich in valuable ore (they are high-grade fragments) and are classified as concentrate. In type 4 fragments the small amount of valuable mineral present is very small and therefore the loss is acceptable. Fragments of types 2 and 3 can be classified as *middlings*, although the degree of milling required to promote mineral liberation from fragment 3 would be greater than in fragment 2. In practice, the all-one is milled to a size determined by laboratory and pilot scale tests to produce an economic liberation grade.

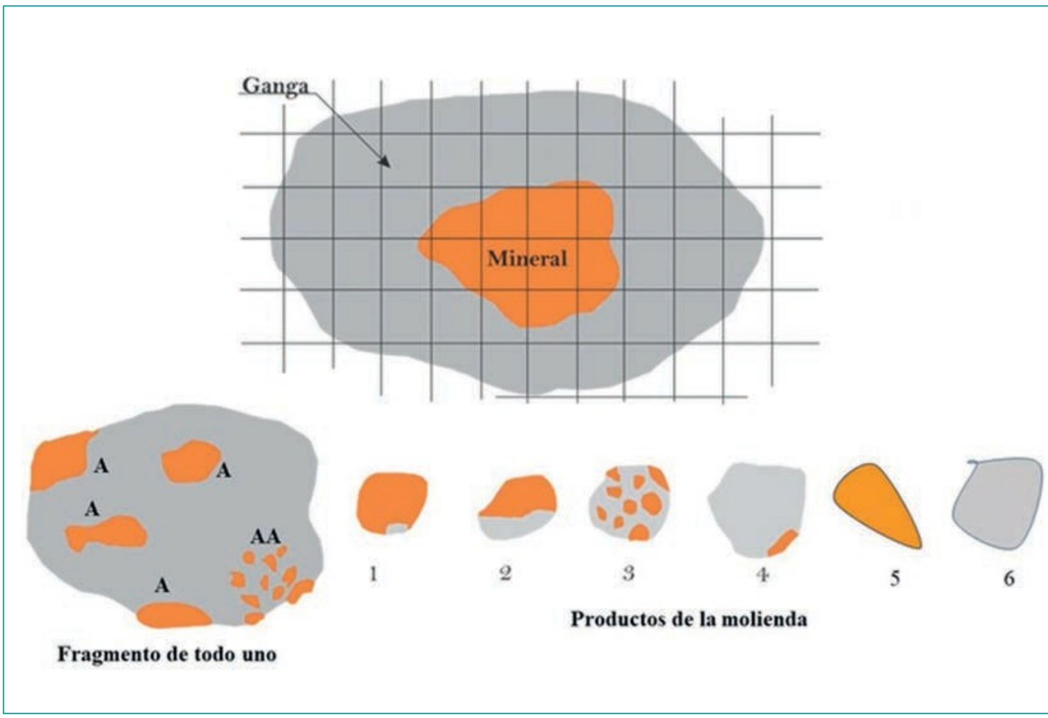


Figure 18. *Illustration of the mineral liberation process from reduction. The size of the whole-one in which the ore and gangue are distinguished. Source: translated by the authors from (Wills and Finch, 2016).*

During the milling of a low grade ore, most of the gangue is liberated at a very coarse tailings size. In certain circumstances, it may be economical to grind to a coarser size to produce, in the subsequent concentration process, a higher media fraction and *tailings*, tailings or *tailings* (product depleted in valuable ore). The mixed fraction is usually regrinded.

Mineral technology consists of two main operations: preparation and concentration[27] , as shown in the diagram in Figure 19. These processes are followed by thickening, filtration and drying.

Preparation is defined as the reduction in size of the whole, which involves multiple crushing and grinding operations: (i) primary crushing (with jaw or gyratory crushers), (ii) primary crushing (with jaw or gyratory crushers), (iii) primary crushing (with gyratory crushers), and (iv) primary crushing (with gyratory crushers).

[27] In general, this section refers to concentration processes using physicochemical properties. However, there are other concentration processes where metals are recovered by dissolution.

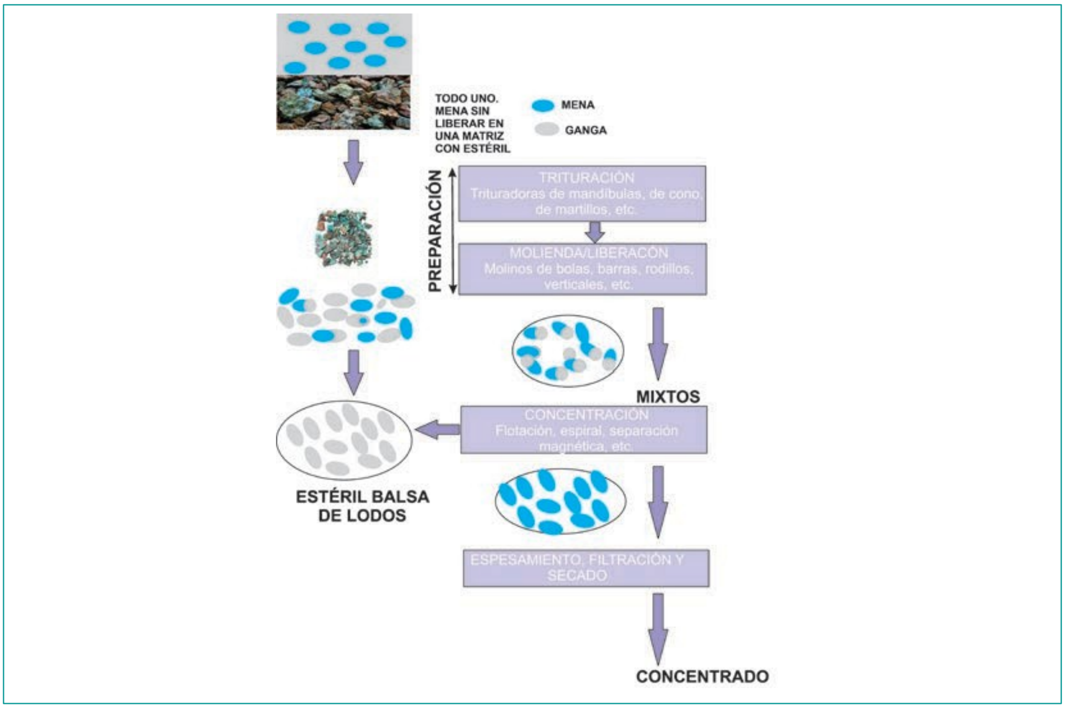


Figure 19. *Ore preparation and concentration operations. Source: authors' own elaboration.*

Figure 20. A. *jaw crusher and* ***B.*** *ball mill. Source: (Wills and Finch, 2016).*

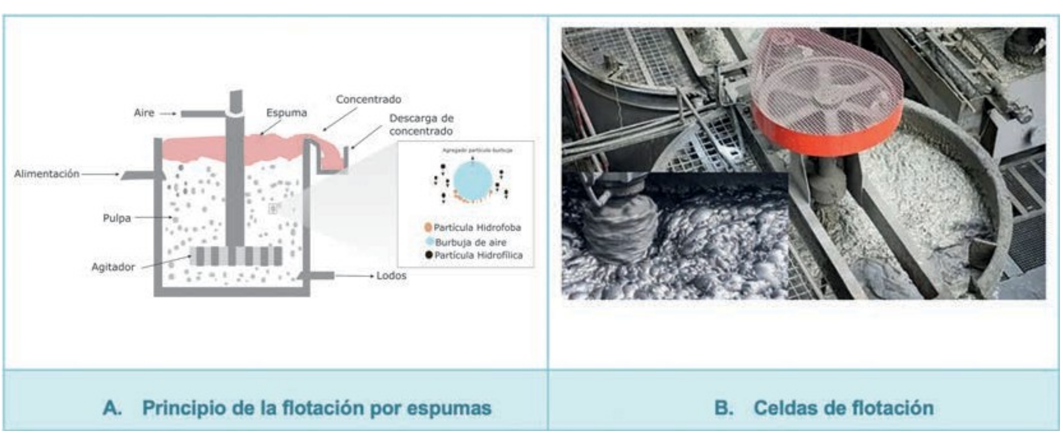


Figure 21. A *Principle of flotation.* ***B.*** *Flotation cells. Source: modified by the authors from (Wills and Finch, 2016).*

secondary crushing (using cone crushers to obtain a particle size in the order of a few centimeters and (iii) grinding (generally using rod or ball mills to obtain a particle size in the order of a few micrometers) (Figure 20).

Concentration encompasses operations to increase the grade of the whole ore to the value required by the process or by the metallurgical market. Several techniques are used for concentration: (i) physical methods: optical separator (which replaces manual stripping), gravimetric separation based on the different density between gangue and ore (shaking table, spirals), separation by dense media (centrifugal screws and cyclones), magnetic separation and electrostatic separation; (ii) physicochemical methods: differential flotation (see Figure 21) and (iii) chemical methods: leaching.

The third stage is thickening, filtration and drying. Thickening[28] removes some of the water from a *slurry* or suspension, thus concentrating the solid particles in the remainder. The liquid recovered from the thickener is recycled for reuse. Flocculants, anionic polyelectrolytes, are added to increase thickening efficiency.

In the filtration operation, pressing is usually used, which allows the separation of solids from a suspension by passing the thickener through a porous medium that retains the solids forming the cake and allows the liquid to pass through, which is recycled.

In order to optimize costs (by reducing transportation costs), all-ore processing is usually carried out at the mine site[29] . Sometimes the operation is not only the separation of the tailings from the main ore, but also the separation of other valuable minerals, e.g. in porphyry copper, molybdenum is obtained.

4. Rehabilitation of mining areas

Because minerals are non-renewable resources[30] , mining operations have a useful or operating life, after which mine closure takes place. Some mines close due to economic or logistical reasons, while others simply run out of ore. In some cases, mines close temporarily until the market improves. In any case, once mining operations have ended, a rehabilitated and environmentally compatible site must be left behind.

All mining operations are required by law to have an exploitation project, an Environmental Impact Assessment (EIA) and a Restoration Plan, before starting the extraction operation, in order to avoid "environmental liabilities". The main objective of this Restoration Plan is to restore or improve the land to the conditions that existed before the site was mined or to adapt it to conditions compatible with the natural habitat of the area.

The term restoration, as used in Royal Decree 2994/1982, on the restoration of natural areas affected by mining activities, means *"to repair, renew or return something to its former state".*

[28] Gravity thickening is achieved by allowing solids to settle under the force of gravity in a settling tank.

[29] In the case of rare earths, by way of example it is necessary to remove 8.5 tons of all-one to produce 1 kilogram of vanadium, 16 for 1 kilogram of cerium, 50 for 1 kilogram of gallium, 200 for 1 kilogram of lutetium and 1,000 tons for 1 kilogram of gold (Piron, 2019).

[30] The concept of renewability of a natural resource means that nature generates resources at a higher rate than the rate at which humanity consumes them. In the case of mineral resources, the difference is enormous: geological time versus years.

Royal Decree 975/2009, on the management of waste from extractive companies, refers to the concept of *"rehabilitation"*, which consists of a repair of the productive processes and ecosystem services. *"Rehabilitation is defined as the treatment of land affected by mining activities, so as to return the land to a satisfactory state, in particular as regards, as the case may be, soil quality, fauna, natural habitats, freshwater systems, landscape, and appropriate beneficial uses."* This regulation, while maintaining the previous terminology (Restoration Plan), confirms the term *rehabilitation* as more accurate and limits the objective of the actions to achieve a "*satisfactory state*", which means implicitly recognizing the impossibility of a total correction of the alterations caused by the mining activity.

Although the rehabilitation operation is associated with the final phase of the mining project, the regulation itself (Royal Decree 975/2009) establishes that "*In any case, the restoration and exploitation plans will be coordinated in such a way that the rehabilitation works are carried out as far ahead as possible as the exploitation is carried out"*. In other words, the rehabilitation of the area affected by extraction must be conceived as part of the project itself, not as an isolated operation to be carried out once the extraction of the resource has been completed. As far as possible, rehabilitation operations should be integrated into the extraction process. Therefore, the environmental control of mining operations and the rehabilitation of the areas caused by them are an unavoidable part of the planning, operation and closure of mining operations, and should start from the beginning of the operation and continue until after mine closure.

The Restoration Plan is, therefore, a technical project, and must necessarily include five parts:

(i) Detailed description of the planned mining environment.

(ii) Measures foreseen for the rehabilitation of the natural area affected by the research and exploitation of mineral resources. It should be noted that, within this part, and in close relation to the rest of the rehabilitation work, the exploiting entity must present a preliminary project for the definitive abandonment of the exploitation work.

(iii) Measures foreseen for the rehabilitation of services and facilities related to the research and exploitation of mineral resources.

(iv) Waste Management Plan.

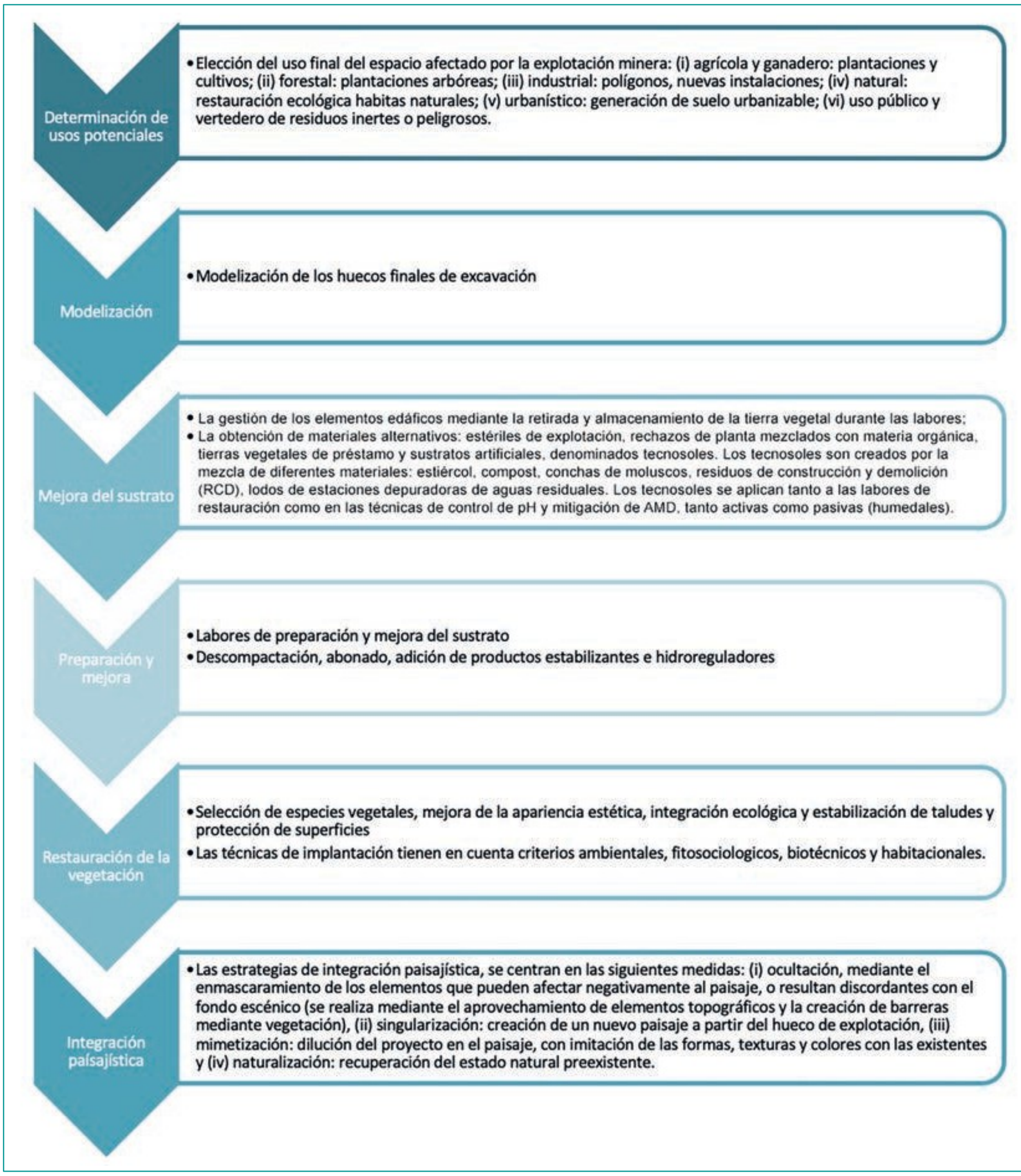
(v) Execution schedule and estimated cost of the rehabilitation works.

The basic stages for the rehabilitation of mining operations are shown in Figure 22. Annex 4 contains information on the structure and content that a reclamation plan should have, according to the applicable regulations.

The closure plan, which is part of the Restoration Plan, must be an integral part of the project life cycle and must be properly designed, taking into account: (i) public health and safety must not be compromised, (ii) environmental resources must not be subject to physical or chemical deterioration, (iii) subsequent use of the site must be beneficial and sustainable in the long term, (iv) all socioeconomic benefits must be maximized, and (v) any adverse socioeconomic impacts must be minimized.

As the mining operation reaches the end of its life, there must be a transition from the operation phase to the closure, decommissioning and, finally, the post-closure stage. This transition consists of, broadly speaking

Figure 22. *Phases of mining rehabilitation. Source: authors' own elaboration.*



This includes engineering work to terminate service and decommission infrastructure, complete rehabilitation, stagger reliefs for effective drainage, seal and cover waste facilities, implement post-closure monitoring networks, and others. It also includes administrative work related to asset transfer, demobilization of the workforce, concession abandonment agreements and other government and social agreements, as well as due diligence in monitoring and reporting on the environmental and social aspects of the site in the post-decommissioning situation.

The environmental priority of a mine is to protect the waters and the surrounding area from the pollutants generated by mining. In recent years, the demands of communities living in a region affected by mining have been very intense, especially in countries where a significant part of the population is engaged in agriculture. Transparency of information, participation in decisions that affect the communities, community development promoted by the mining company, the construction of community services, and the promotion of local employment and training are some of the measures most commonly used in these regions, with the aim of increasing coexistence with the indigenous communities (European Commission, 2021c).

Some mines require monitoring and maintenance after final closure, for example, in order to control water quality or check the safety and stability of the land, preventing possible risk situations for the safety and health of people and the environment. Figure 23 shows a schematic of the acid water treatment plant at the former Touro mine.

Figure 23. *Acid water treatment plant in Touro. Note: The plant treats acidic water originating from historical mining that closed in 1987. Source: (Atalaya Mining, n.d.).*

During the post-mining phase, the area of influence of the mine continues to be monitored. This monitoring process is carried out to ensure that there is no process in the area that could have an adverse effect on the environment. It also serves as a measure to control the sludge and tailings ponds. Groundwater quality is monitored and analyzed to evaluate the influence of flooding from mining operations on the aquifers.

In addition, in this phase there are trends in the creation of environmental assets in the closure of mines through the reuse of waste, shafts and other infrastructures such as the use of mine shafts as energy storage by means of pumping systems and the use of subway space as storage.

Regarding the regulations related to this subject, it is worth mentioning the one previously mentioned: *Royal Decree 975/2009, of June 12, 2009, on the management of waste from extractive industries and the protection and rehabilitation of the area affected by mining activities*, which aims to establish measures, procedures and guidelines to prevent or reduce as far as possible the adverse effects, The purpose of this law is to establish measures, procedures and guidelines to prevent or reduce as far as possible the adverse effects on the environment, particularly on water, air, soil, fauna, flora and landscape, and the risks to human health that may be caused by the research and exploitation of mineral deposits and other geological resources, and, fundamentally, the management of mining waste.

Also noteworthy is *Law 21/2013, of December 9, 2013, on environmental assessment*, a cross-cutting regulation, the application of which is essential to ensure environmental protection. It facilitates the incorporation of sustainability criteria in strategic decision making, through the evaluation of plans and programs. Through the evaluation of projects, it guarantees adequate prevention of the environmental impacts that may be generated, while at the same time establishing effective correction or compensation mechanisms.

It should be noted that the operator is required to provide two financial or equivalent guarantees to ensure compliance with the provisions of the authorized Restoration Plan. The guarantees must be sufficient to cover the cost of the rehabilitation, by an independent and suitably qualified third party, of the land affected by the waste facilities, as described in the following section.

the waste management plan. The latter guarantee shall be established prior to the start of landfill operations at mining waste facilities and shall be adjusted periodically.

The closure of a mining operation should never be the end of a project, but the beginning of others. Mining operations have enormous potential for biodiversity, new ecosystems, geological routes, aquatic activities, agricultural and forestry uses, residential areas, hotels, sports fields, motor racing circuits, etc. In short, the new rehabilitated land can generate other opportunities, mainly related to tourism, leisure and agricultural and forestry activities.

Figure 24 shows some examples of rehabilitation of the mining area. It shows the rehabilitation carried out at the As Pontes lignite mine, the spreading of technosols in the Bama de Cobre San Rafael pit and the rehabilitation of the Boinas pit (Orovalle). In the first case, the hole left by the mine is now an 8.7 km long lake, the largest artificial lake in Spain, with two artificial islets and crowned with a beach of washed quarry sand.

Figure 24. A. *Rehabilitation of the As Pontes open pit mine (A Coruña),* ***B.*** *spread of technosols in the Bama cut. San Rafael Copper and* ***C.*** *Boinás Cut. Source: (Amigo, 2022), (Atalaya Mining, n.d.), (El Valle del Boinás, 2023).*

5. Conclusions

Mining research is the set of techniques (geological, geochemical, geophysical and drilling) used to identify and evaluate economically exploitable mineral deposits.

In mining research processes, there are international standards that establish guidelines and criteria that allow for the preparation of rigorous technical reports on the technical and economic characteristics of mining projects. These independent reports become a tool that should serve to overcome current barriers to mining development by disseminating their content through different channels and always in a transparent manner.

Once the deposit has been technically evaluated and its economic viability has been demonstrated, it i s extracted by the most appropriate mining method, depending on the type of deposit. When the ore body is covered by a limited amount of unusable rock, it can be mined by open pit mining. Otherwise, the ore is extracted from the interior (subway mining).

The next stage in the value chain is the transformation of the product extracted in the mine (all-in-one) to concentrate, which is carried out through mineralurgy (ore preparation and concentration), which is the set of physical, physicochemical and chemical treatment techniques, in order to obtain products with commercial value that can be transformed by metallurgy. The mineral plant is usually located in the immediate vicinity of the mining site. Each rock/mineral has a specific process, depending on the starting conditions (natural, marked by the deposit) and the final ones (substance to be obtained and qualities).

Once mining operations have been completed, the area affected by the activity must be rehabilitated and be compatible with the environment. All mining operations in Spain are required by law to have an authorized Restoration Plan prior to the start of the mining operation, as well as to provide the corresponding financial guarantees to ensure its execution.

4

METALLURGY. TECHNIQUES AND PROCESSES

1. Introduction

The previous chapter showed how mineralurgical processes proceeded with the preparation and concentration of ores in order to obtain the necessary metals. The result was what is called concentrate, which, in turn, had to be further processed to obtain the metals, with specific specifications and requirements. These processes are studied by extractive metallurgy, which is part of the broader discipline of metallurgy .[31]

Within the framework of primary metallurgy, the basic methods considered are hydrometallurgy, pyrometallurgy, electrometallurgy and biometallurgy. Metallurgical processes can also be distinguished according to the starting material: primary or secondary metallurgy. Primary metallurgy is that which obtains metals from ores as they are found in nature, while secondary metallurgy obtains them from scrap or waste. Secondary metallurgy has become increasingly important and it is expected that more materials will be recycled in the future.

This chapter mainly deals with the technical aspects of metallurgy by first defining the extraction and refining processes, and then deals with the basic metallurgical methods (hydrometallurgy, pyrometallurgy, etc.). A second part of the chapter deals with some metallurgical processes (i.e., copper, lithium and rare earths) related to energy transition metals and digitization.

Returning to the fundamental processes, the aim of extraction is to obtain the metals from the minerals that contain them[32] . In refining metallurgy, on the other hand, the crude metal obtained from extraction is refined. Once the metal has been refined to the purity required by the market, high metal grades are achieved, which can reach the purity known as *five* nines (99.999 %).

There are two main techniques or methods, which can be implemented independently or in addition to each other:

(i) Wet processes or hydrometallurgy[33] are those that use water as a medium (aqueous phase reactions) or acid or base solvents to selectively extract metals from ores containing them at low temperatures. Hydrometallurgy involves less investment than pyrometallurgy. As a result, hydrometallurgy is increasingly being used today and now accounts for more than 70% of metallurgical processes.

[31] Metallurgy includes extractive metallurgy, dedicated to the processes of ore beneficiation and obtaining the metal, and physical metallurgy, focused on the study of phase diagrams, solidification, thermo-mechanical transformation of metals and alloys and their heat treatments. The operation of metallurgical facilities is schematized with flow diagrams that indicate the different operations that make up the process for obtaining the metal.
Metallurgy, in a broad sense, comprises the study of metals and alloys, from their production to their applications due to their properties (physical, chemical and mechanical), including heat, mechanical and chemical treatments, forming and testing methods. Thus, extractive metallurgy can be defined as the part of metallurgy that studies the methods necessary to treat an ore concentrate or a material to be recycled in such a way as to obtain, from any of them, a more or less pure metal or one of its compounds.
Metallurgy includes ancient techniques that have existed since man first knew metals and that gave their name to the Copper, Bronze and Iron Ages. However, metals such as aluminum were not obtained until the 19th century and their metallurgy was developed in the 20th century. In other words, metallurgical techniques are constantly developing and innovating.

[32] Although some metals occur natively in nature, they usually occur in combination with other chemical elements included in minerals.

[33] Hydrometallurgy developed from the discovery of electrolysis in the 19th century, since the way to obtain metals from the solutions containing them is by depositing them on the cathodes of electrolytic tanks. However, the wet process does not always use aqueous media that end up in electrolysis, since some metals and their compounds are obtained without applying electrolysis, generally by precipitation.

(ii) Dry or pyrometallurgical processes are those that use heat and, therefore, high temperatures to obtain the metal from the ores that contain it. It is the oldest metallurgy, although it has constantly evolved. Today it is used with efficiency and advantage over hydrometallurgy to obtain metals such as copper or lead. However, its main drawback is its environmental impact compared to hydrometallurgy .[34]

There are also two different routes that are a variation of the previous ones, (i) electro-metallurgical processes, which use electricity and can be part of both the pyrometallurgical and hydrometallurgical routes, and (ii) biometallurgical processes, where the metal is obtained through a process in which bacteria are a supporting element that is complemented by electrometallurgy or precipitation. Electrometallurgy and biometallurgy are usually different processes, often complementary.

2. Metallurgical processes: hydrometallurgy and pyrometallurgy

2.1. Hydrometallurgy

Metal extraction by hydrometallurgy is carried out by means of the following operations or processes that are carried out consecutively.

(i) Leaching: operation in which the chemical attack and solubilization, in aqueous phase, of the valuable metal contained in the ore takes place. It can be acidic, basic or neutral depending on the character of the chemical reagent used, which in turn is a function of the gangue.

(ii) Purification and/or concentration: operation performed on the solution obtained in the previous stage. Its objective is to remove certain impurities from the solution. It is usually carried out by the following methods: (i) precipitation chemicals, (ii) cementation (displacement reaction similar to metallothermia, but in the aqueous phase), (iii) by conventional chemistry reactions, which serve to remove a metal from an aqueous phase, (iv) extraction with solvents (in the case of very dilute solutions) and (v) separation with ion exchange resins (in the case of very dilute solutions).

(iii) Precipitation: the purpose of this operation is to separate the valuable metal from the solution, either in an ele- mental form (almost always) or in an oxidized form (rarely). It is usually carried out by the following methods: (i) aqueous electrolysis (as in the case of copper, zinc and nickel), a process by which the solution is separated into its constituent ions (anions and cations), and the metal is electrodeposited on metal or inert cathodes, thanks to the passage of electric current[35] , (ii) electrodeposition of the metal on the cathodes of the metal itself or inert cathodes, thanks to the passage of electric current , (iii) electro-

[34] However, it is necessary to evaluate the environmental impact of both routes since it is not clear that the latter is more polluting to the extent that hydrometallurgy requires the treatment of purge water.

[35] This process is carried out in an electrolytic cell consisting of two electrodes of an inert metal connected to an electric power source.

(iii) cementation, as in the case of zinc cementation of cyanide gold solutions, and (iv) conventional chemical methods, such as precipitation of metals with hydrogen gas under pressure and at high temperatures (as in the case of nickel and copper).

Figure 25 shows the hydrometallurgy flow diagram where the ore preparation stage and the solvent to be used can be seen. It should be noted that the two stages indicated for ore preparation correspond to the mineralurgical processes of preparation or transformation that have been seen in the previous chapter. The solvent must be prepared by forming aqueous solutions of acids (usually sulfuric) or bases (usually soda), to carry out the dilution (digestion) and achieve the selective dissolution of the metal.

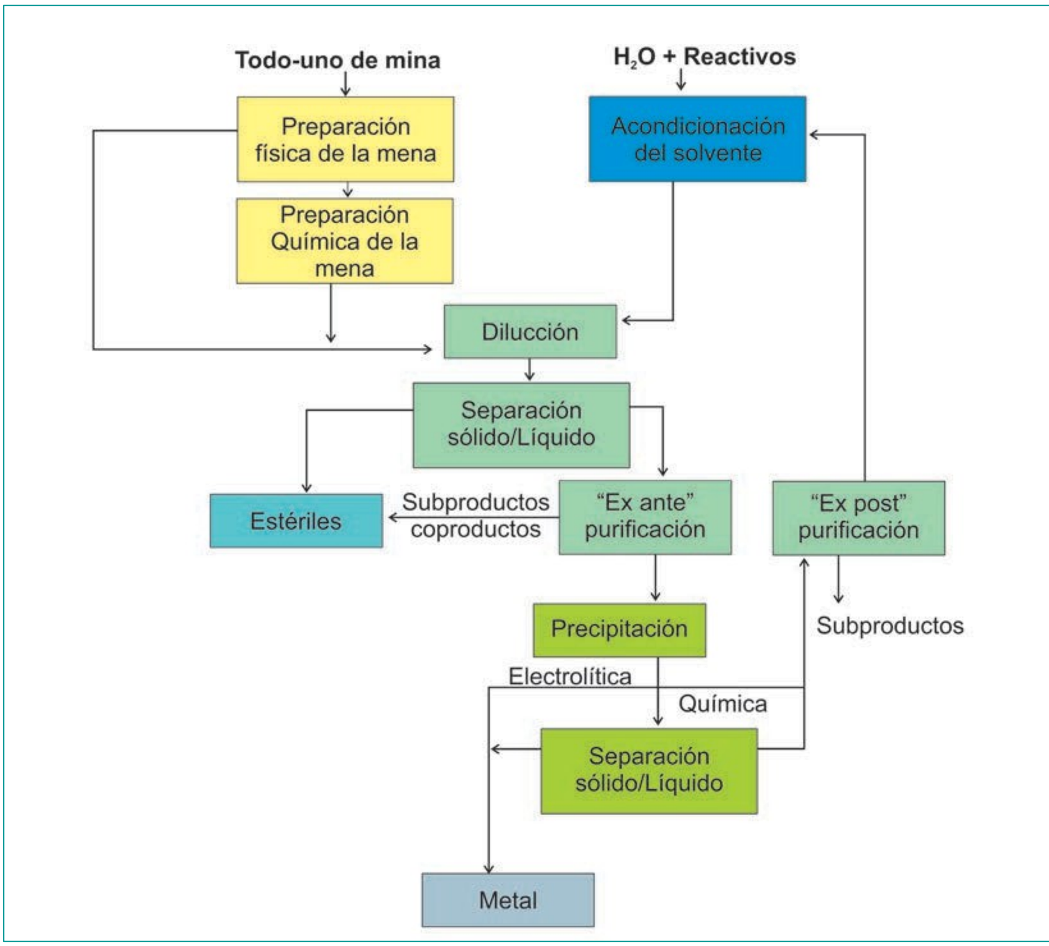


Figure 25. General flow diagram of the hydrometallurgy. Source: modified by the authors from (Tejera, 2022).

Subsequently, solid/liquid separation operations (decanting, filtering) are carried out to separate the rich solution, which carries dissolved metal from the accompanying gangue in the ore (tailings, at this stage of the process, are dumped in the tailings ponds annexed to the metallurgical plant), which is in the form of an insoluble solid phase.

The next operation is the precipitation (physical or electrochemical deposition) of the metal in which a lean liquor remains which is reused at the head of the process with the solvent (in hydro-metallurgical plants the use of the solvent is cyclical, dissolving the metal in the digestion and yielding it in the precipitation).

The metal obtained in precipitation is accompanied by impurities that can be removed before precipitation ("*ex ante*" purification) or after ("*ex post*" purification).

2.2. Pyrometallurgy

The procedures for obtaining a metal by pyrometallurgical means are basically divided into: reduction methods (metal oxides), or oxidation (metal halides, metal sulfides) to facilitate subsequent treatments. The main processes used in the pyrometallurgical metal extraction process are shown in Table 16.

Process	Description
Calcination	Decomposes, by heat, a compound (carbonate, sulfate, hydroxide, etc.) into its forming oxides.
Roasting	Operation by which a sulfide, upon reaction with oxygen in the air, is transformed into an oxide .[36]
Melting (reductive casting or matte casting)	Operation in which, in a suitable furnace working at the required temperature, various molten materials are obtained: metal, slag or matte[37] . It is one of the most widely used operations in extractive metallurgy.
Volatilization	Operation leading to a metal (reducing), a compound (oxidizing), a halide or a metal carbonyl in gaseous form .[38]
Electrolysis of molten salts	To obtain a metal from one of its compounds dissolved in a molten electrolyte and using electric current as a reducing agent .[39]
Metallotherm	Operation in which a metal displaces another of its compounds by being more reactive .[40]

Table 16. *Main processes for metal extraction by pyrometallurgy. Source: own elaboration.*

An additional phase is refining, the purpose of which is to separate the main metal from other elements, considered as impurities, which may or may not be used. The main metal purification or refining operations are: electrolysis in aqueous solution, thermal decomposition and zone melting.

Thermal decomposition is a refining method based on the chemical decomposition of compounds. Two methods are very common: (i) decomposition of metal hydrides and (ii) decomposition of metal carbonyls. An example of the latter is the manufacture of nickel powder by thermal decomposition of nickel carbonyl. Nickel oxide is continuously fed into a reduction furnace with pure hydrogen at 230 °C to produce an impure nickel in granular form. In the second stage, in the volatilization furnace, nickel reacts with carbon monoxide to form nickel carbonyl gas: $Ni + 4CO = Ni(CO)_4$

Nickel carbonyl gas is taken to an adjacent plant for thermal decomposition to form pure nickel powder: $Ni(CO)_4 = Ni + 4CO$

[36] For example, roasting of copper sulfide ores to produce copper oxide or roasting of zinc sulfide ores to produce zinc oxide. This is usually a pre-smelting operation. Sulfate roasting may also be performed instead of oxidizing roasting.

[37] For example, it is used to obtain pig iron or dirty iron in the blast furnace (reductive smelting) or as a preliminary step in obtaining copper (neutral smelting: matte smelting). The slag is formed by reacting the gangue contained in the ore with a flux that is added to the process for this purpose (acid or basic). *Slaking* is a concentration process, in which a portion of the impurities in the charge are brought together to form a light product called slag, which can be separated by gravity from the heavier portion containing practically all the metallic components.

[38] For example, in dry zinc metallurgy, the metal is obtained as a gas by reduction of the oxide.

[39] For example, it is used in the production of aluminum by electrolysis of alumina dissolved in a bath of molten cryolite (Na3AlF6, sodium hexafluoroaluminate).

[40] For example, in the production of titanium, magnesium is used to reduce titanium tetrachloride.

Zone melting is a method for purifying, for example, semiconductor ingots. It is carried out in a quartz crucible that moves with respect to an induction coil, through which radiofrequency current circulates, inducing eddy currents in the semiconductor, eventually melting it by the Joule effect. As the coil moves forward, the melted area also moves forward, dragging with it the im-purities, while the semiconductor recrystallizes as it cools. Several passes are usually made and, at the end, the end containing the accumulated impurities is cut off. This method achieves a concentration of impurities in the treated ingot that can be less than one part per million.

3. Examples of metallurgical processes

The following are four examples of metallurgical processes. Two of them, copper and zinc processes, have been chosen for their relevance and tradition in Spain, adding value to the economy and employment, as well as for their role in the energy transition. The other two, lithium and rare earths, have been chosen for their relevance in decarbonization and digitalization. In the case of lithium for its role in mobility and energy storage[41] and rare earths for their various applications, such as neodymium permanent magnets.

3.1. Copper metallurgy

There are numerous copper (Cu) minerals but not all of them are relevant as ores of the metal. Copper is often found in association with sulfur, so the main copper ores are sulfides: chalcopyrite ($CuFeS_2$), bornite (Cu_5FeS_4), chalcocite (Cu_2S) and covellite (CuS), accompanied by sulfides.

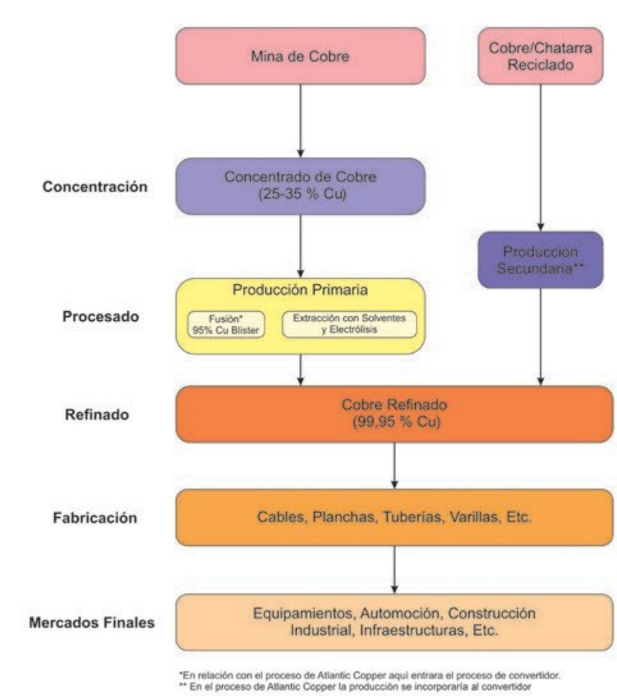


Figure 26.
Metallurgy phases. Source: authors' own elaboration based on (ICSG, 2022) and (IHS Markit,2022).

[41] Despite its relevance, the steel industry, whose main developments are oriented towards decarbonization, has not been included. For further details, CAETS (2022) is recommended. In addition, metallurgical processes for aluminum, cobalt and uranium are included in Annex 5.

and other sulfides of arsenic, antimony and bismuth. Oxides and others include tenorite (CuO), cuprite (Cu_2O), azurite [$Cu(OH)_2 \cdot 2CuCO_3$], malachite [$Cu(OH)_2 \cdot CuCO_3$] and chrysocolla ($CuSiO_3 \cdot 2H_2O$).

The methods of obtaining copper depend logically on the starting ore. Sulphide ores (~[42] 80 %) are treated by pyrometallurgy, where anodes and cathodes are produced, and oxidized ores (~20 %) by hydrometallurgy, where cathodes are produced directly.

Figure 26 shows the value chain from copper concentrates (and previously mining, presented in the previous chapter) to processing, both pyrometallurgical and hydrometallurgical. Refining is common to both routes, in which there is an aqueous electrolysis stage.

3.1.1. Pyrometallurgical process

The concentrate, the result of the ore concentration process, is subjected to drying to remove the water content. Drying sometimes aims to remove some unwanted component by volatilization without melting, for example, to reduce the sulfur content to an optimum value for melting. At present, roasting is not carried out as such in a separate stage.

Figure 27 shows a schematic representation of the smelting and refining metallurgical process at the Atlantic Copper facilities in Huelva, which will allow following the process from the reception of the copper concentrates to the production of cathodes with 99.99% copper.

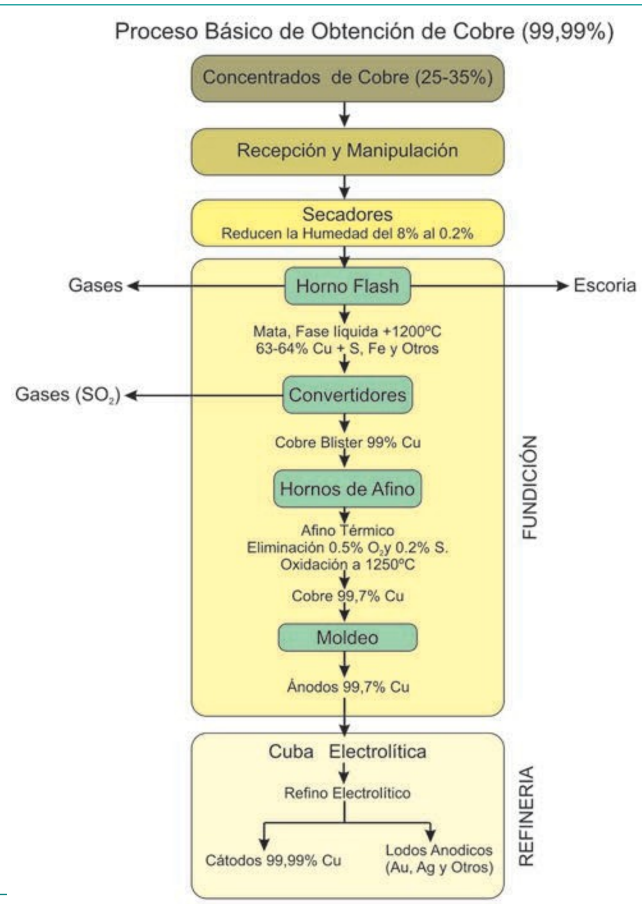


Figure 27. General flow diagram of copper metallurgy. Note: The whole set of processes is not represented, only the basic or main process, and not the auxiliary ones (i.e., production of sulfuric acid, iron silicate, gypsum). Source: authors' own elaboration from the Atlantic Copper website.

[42] ~ = Approximately.

The oxidative smelting of copper concentrates with the addition of fluxes will generate two molten phases: the matte (50-70 % Cu), which is the heavier semi-metallic phase containing most of the sulfides, resulting from the first smelting of the ore and where the copper is concentrated; and the slag, which contains an oxidized and ferrous phase, formed by reaction of iron (II) oxide with the fluxing silica, resulting in fayalite ($2FeO\text{-}SiO_2$ low melting point ferrous silicate). The matte is denser than the slag and forms two immiscible liquid phases, which bleed separately through orifices at different levels of the furnace. Sulfur oxidation of sulfides and iron is exothermic, which makes the process autogenous.

Traditional melting can be carried out in various types of furnaces (tank, reverberatory, electric, etc.), but there is a type of melting called instantaneous or *flash* melting, whose main characteristic is the speed with which the melting process is verified when it is carried out with a burner with preheated air, enriched in oxygen or with industrial oxygen. Instantaneous melting can be autogenous or not. Instantaneous smelting processes include, among others, the OUTOKUMPU process (almost one third of the world's copper is processed in this type of reactor) and the INCO process.

Figure 28 shows a cross-section of the OUTOKUMPU *flash* furnace. The construction of the INCO furnace is similar to that of a reverberatory furnace, but oxygen (95-98 % purity) is injected horizontally from both ends of the furnace.[43]

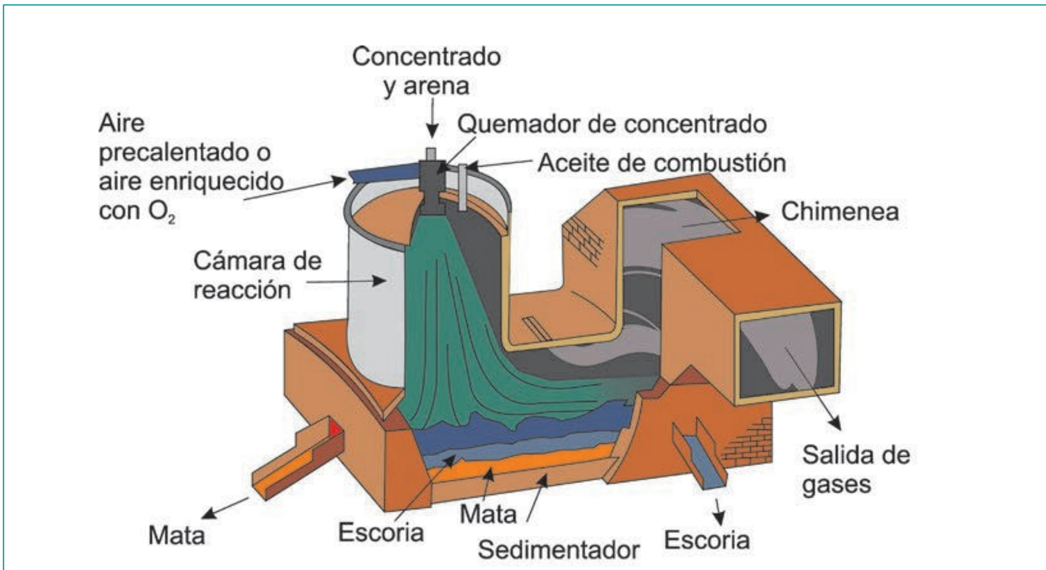


Figure 28. *Schematic of an OUTOKUMPU flash furnace with preheated air. Source: modified by the authors from (Quezada, n.d.).*

In order to increase the copper richness, the liquid matte obtained goes to the conversion process, where it undergoes oxidation with air. The conversion is carried out in two consecutive stages, in the first stage the slag is formed and the iron is removed. The second stage results in metallic copper .[44]

Copper formation in the second stage does not occur until the matte contains less than 1 % Fe, so that almost all Fe is removed from the converter (as slag) before the production of Cu metal begins. The product obtained is blister copper, with 99 % copper, containing between 0.02 and 0.1 % S.

[43] The main reaction of the OUTOKUMPU and INCO processes is:
$4(CuFeS_2) + 5O_2 + SiO_2$ (Flux) = $2(Cu_2S.FeS)$ (matte) + $2FeO.SiO_2$ (slag) + $4SO_2$ Reaction, exothermic, which generates the heat necessary for the process, making it autogenous.

[44] The reactions are as follows: $2FeS + 3O_2 + SiO_2$ (flux) = $2FeO.SiO_2$ (slag)+ $2SO_2$; $Cu_2S + O_2 = 2Cu$ (blister copper) + SO_2

There are different furnaces for conversion, but the most common is the Peirce-Smith, which is a rotary kiln with a cylindrical shape and 40 nozzles in a generatrix through which air is introduced. The liquid matte is introduced through a large central opening and enters the converter at a temperature of 1,100 º C and the heat generated inside, by the oxidation of S and Fe, makes the process autogenous. The conversion process takes between seven and eight hours. These converters are controlled by computers, carrying out the process automatically until the entire mass of Cu is in the form of blister copper (99% Cu). A Peirce-Smith furnace is shown in Figure 29.

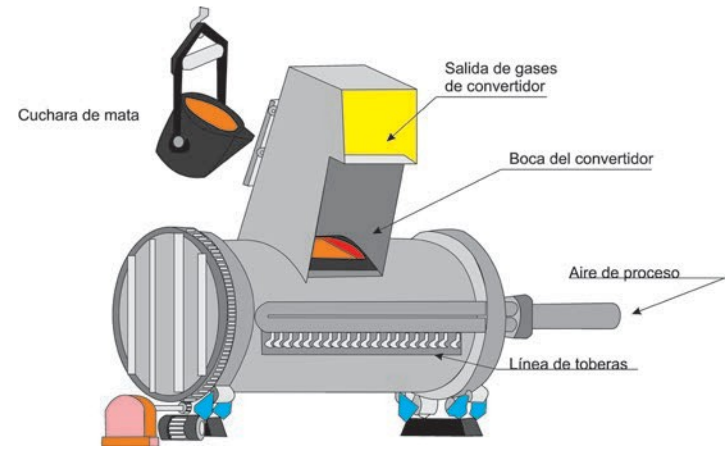


Figure 29. *Schematic of a Peirce-Smith kiln. Source: modified by the authors from (Quezada, n.d.).*

Virtually all copper produced by smelting-conversion is subsequently electrorefined. It must therefore be suitable for casting into thin, strong, smooth anodes for intercalation with the cathodes in the electrolysis vats. This requires the copper to be thermally refined to remove most of its sulfur and oxygen. In the process carried out in the conversion furnace (Figure 29), 0.5% of oxygen and 0.2% of sulfur are eliminated and oxidation is carried out at 1,250 ºC, increasing its copper content to 99.7%. Subsequently, the anodes are cast using a casting wheel with copper molds in the shape of an anode with ears to support it in the electrolysis tank. There are processes that combine matte melting and conversion such as the Mitsubishi process and the Noranda process.

The anodes are taken to the rectangular-shaped electrolytic tanks, where an anode (which is the copper sheet obtained from the smelter) and a cathode (which is a very thin sheet of pure copper) are placed alternately. Electrolytic refining (electrorefining), which is a process of recovery and purification of the copper contained in the anode, is carried out in the tanks. It is based on the application of a continuous electric current circulating between a soluble copper anode (which solubilizes as the current flows) and a copper cathode, both immersed in an acid electrolyte of cupric ions. This process allows obtaining high purity copper (99.99 %), as well as the recovery of small quantities of precious metals contained as impurities in the copper. Both electrodes are in an aqueous solution of cupric sulfate. When an appropriate potential difference is applied, it causes the oxidation of metallic copper to Cu^{2+} at the anode and the reduction of Cu^{2+} to metallic Cu at the cathode. The process occurs because it is easier for the reduction of Cu^{2+} to occur than that of water. The electrolyte contains approximately 50 g copper/l and about 200 g sulfuric acid /l. The working temperature is 60 ºC and organic products are added to improve the cathodic deposit and avoid short circuits .[45]

[45] The reactions of the refining process are:
Anode (oxidation): $Cu \leftrightarrow Cu^{2+} + 2e^{-}$
Cathode (reduction): $Cu^{2+} + 2e^{-} \leftrightarrow Cu$

In the normal procedure, two successive cathodes are obtained from each anode in about 12-14 days and from the more than 300 kg of each anode, two cathodes of about 125-130 kg are obtained. The rest of the anode is recycled as scrap, which accounts for just over 40%. The anode sludge is a by-product of the refining process and contains valuable products such as precious metals. They are periodically collected from the bottom of the vat, filtered and dried, and then treated to recover the valuable products. After initial treatments to solubilize the copper they contain, selenium and tellurium are recovered by melting the precious metals in an alloy called bullion or doré, which is treated by electrolysis to recover the gold and silver.

The cathodes can be sold as is, but the metal is often melted to produce preforms or semi-finished products. The cathodes are melted in various furnaces and alloying agents are added before the product is cast. Casting can be continuous or semi-continuous. The fuels used in the furnaces must not contain sulfur, and the atmosphere must not be oxidizing (to avoid oxidation of the copper). The final product takes the form of billets, plates and extrusion bars up to 12 meters long.

3.1.2. Hydrometallurgical process

The hydrometallurgical process begins by crushing the ore extracted from the mine and then leaching it, using leaching agents such as dilute sulfuric acid, solutions of iron salts, hydrochloric solutions with an oxidizer and ammonia solutions or ammonium salts (ammonium carbonate). The leaching methods can be: in situ, in mine dumps, in heaps, in boxes or caissons and agitated reactor leaching. Bacterial leaching can be used for low grade ores and industrial wastes. Figure 30 shows the copper hydrometallurgical process.

After decanting and washing the leachate, the next step is the extraction stage (copper recovery), which can be carried out by any of the following procedures: extraction with organic solvents (LIX, KEDLEX, ACORGA), ion exchange using resins for selective copper absorption, cementation and precipitation by gaseous reduction, to produce powdered metal.

The electrowinning (EO) process consists of the electrolytic deposition of copper from rich leaching solutions or from solvent extraction, and allows the reduction of copper in solution to its solid state through the application of electrical energy. Two chemical reactions are sought in the electrolytic cell, which is composed of a current-conducting electrolyte, an insolu- ble anode made of lead alloyed with antimony or platinized titanium, where the oxidation reaction occurs, and a cathode, formed by a 316-L stainless steel plate, on which the reduction reaction takes place. On the surface of the anode, the so-called oxygen evolution takes place, in which the water molecule is decomposed by releasing two electrons, gaseous oxygen and protons, according to the reaction .[46]

The copper is reduced on the cathode surface[47] until the cathode has reached the required weight and thickness, around 60 kg, which usually takes 5 to 7 days. Cathodes of 99.9% copper grade are obtained.

The overall process can be summarized according to the diagrams shown in Figure 30 and Figure 31. In this one we can observe the presence of an anode connected to a cathode by means of an electrical connection that includes a source of electrical energy. At the anode, the decomposition of water occurs by oxidation of the oxide, where two electrons are released for each water molecule. At the same time, two moles

[46] Anodic reaction (oxidation): $H_2 0 \leftrightarrow 2H^+ + (1/2)O_2 + 2e^-$

[47] The cathodic reaction is as follows: $Cu^{2+} + 2e^{-} \leftrightarrow Cu$

of protons and half a mole of gaseous oxygen. The copper in solution must diffuse to the cathode surface where it is deposited by capturing electrons.

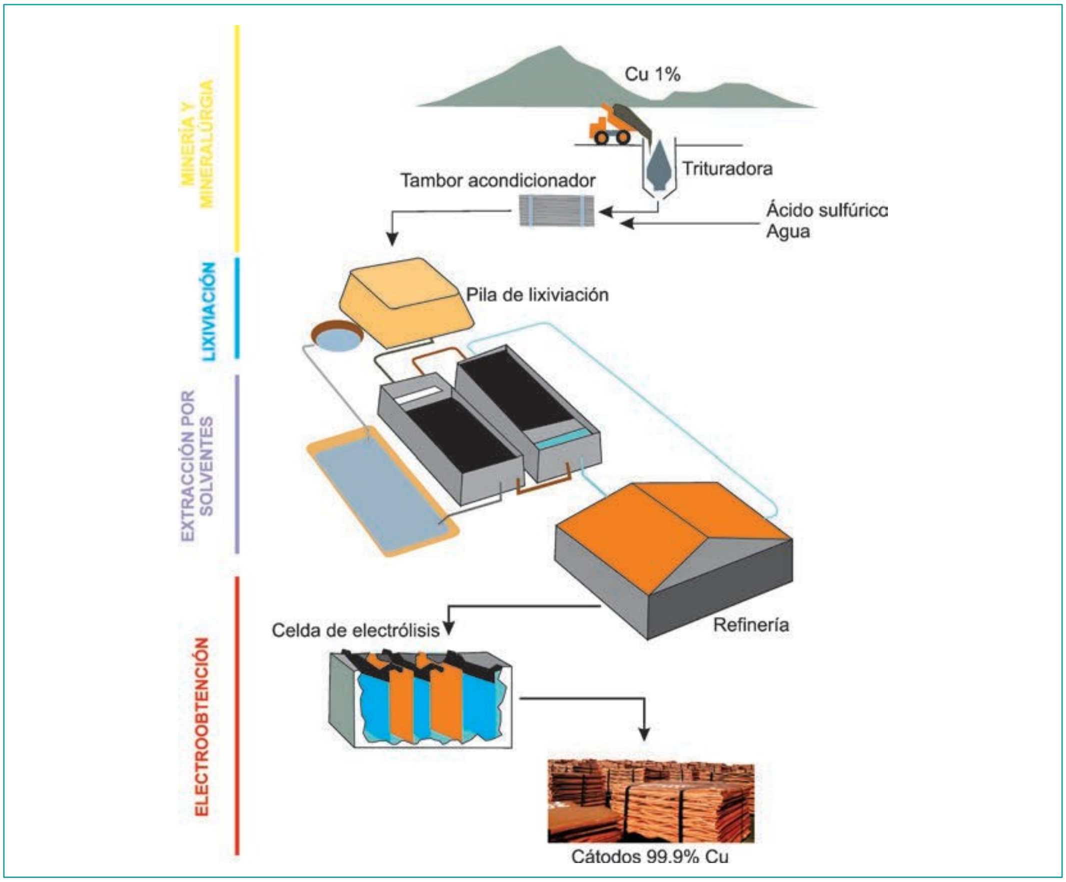


Figure 30. General flow diagram of copper metallurgy by hydrometallurgical route. Source: (Sagredo Gómez, 2021).

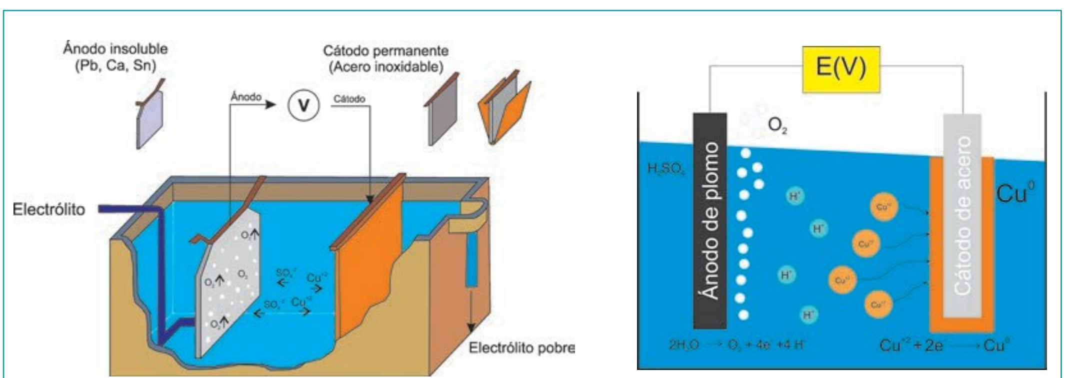


Figure 31. A. Schematic of the copper electro-winning reaction, B. Simplified scheme of the copper electro-winning reaction. Source: reworked and modified by the authors from (Inostroza Flores, 2017).

3.2. Lithium metallurgy[48]

Lithium (Li) is found in about 145 minerals due to its high chemical reactivity. However, only spodumene, petalite, lepidolite, amblygonite and eucryptite have been commercial sources of lithium production.

Spodumene is the most abundant mineral. It is a double silicate of lithium and aluminum, $LiAl(SiO\ )_{32}$ (64.5 % SiO_2 , 27.4 % Al O_{23} , and 8.1 % Li_2 O), which is generally found mixed with quartz,

[48] The main sources for this section are (Piceros, n.d.; Waldron Arentsen, 2020 and Wilkomirsky, 1999).

feldspars and micas and where the lithium content is a maximum of 3.76 %. Spondumene concentrates usually contain 1.9 to 3.3 % Li.

Petalite ($LiAlSi\ O_{410}$) has a silicate structure and its theoretical Li content$_2$ O is 9.8 %. Lepi- dolite is a phyllosilicate that has variable composition and its general formula is $K_2\ (LiAl)_3\ (SiAl)\ O_{410}\ (OH,F)$.$_2$

An important source of lithium, which has increased considerably in the last two decades, is the brines of salt flats, geysers and salt lakes where lithium can be found in the form of chloride, sulfate, double potassium and magnesium salts and lithium borates. The lithium content of the brines varies widely, from 0.02 % as in the Clayton Valley brines in Nevada and Searles Lake in California, to those of the Salar de Atacama in Chile with 0.13 %. By evaporation and fractional crystallization of the contained salts it is possible to reach about 6 % lithium, equivalent to about 21 % LiCl .[49]

Of all these sources, brines currently represent 60% of the world's lithium resources (Chilean Copper Co- mission, 2021) and in the future this percentage could increase further with the progressive exploitation of the Salar de Atacama and other salt flats in the Andes Mountains. Due to continued exploration, identified lithium resources have increased substantially worldwide and totaled around 89 million tons in 2022 (U.S. Geological Survey, Mineral Commodity Summaries, 2022).

Lithium carbonate is the most important base compound among Li salts and its demand accounts for 60 % of Li products. Its importance lies in the fact that it is the starting material for the industrial production of all other lithium compounds, including lithium chloride. Lithium hydroxide is also used as a precursor for the preparation of lithium chloride and lithium fluoride. Figure 32 shows a schematic diagram showing the whole process from ores or brines to lithium and lithium compounds used in batteries and other products.

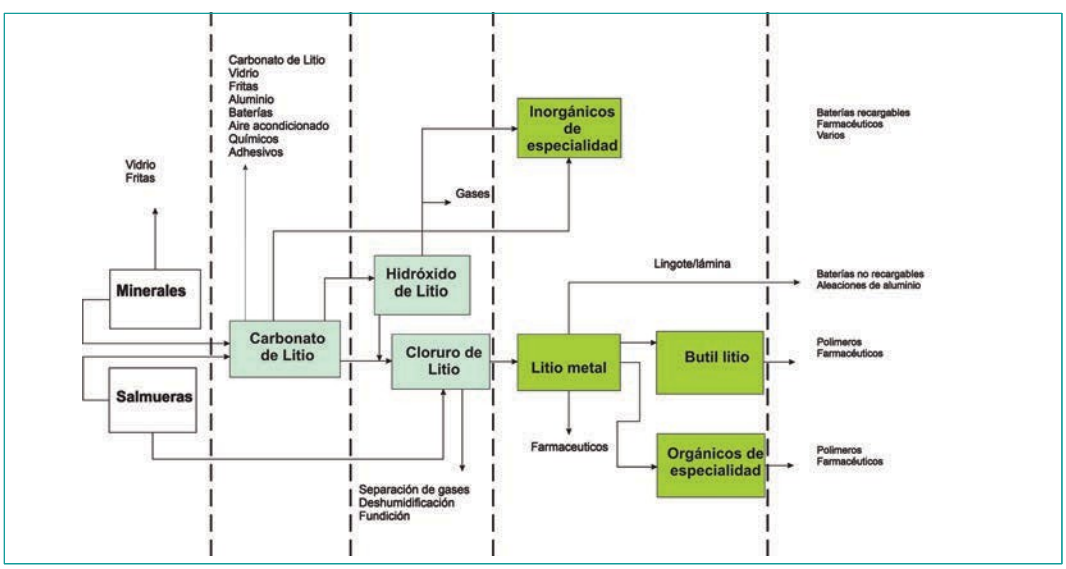


Figure 32. *The tree of lithium compounds. Source: modified by the authors from (Comisión Chilena del Cobre, 2009).*

In the following, the processes from ores and then from brines will be examined first.

[49] For more details on the compositions in different brines, see (Garcés, n.d.).

3.2.1. Processes from ores (spodumene)

The first step in the treatment of the lithium ores mentioned above is physical processing, where crushing and grinding operations are used to separate the lithium minerals from the gangue minerals, followed by gravimetric and froth flotation processes for mineral separation.

3.2.1.1. Obtaining lithium hydroxide from spodumene

In the case of obtaining lithium salts from spodumene, the main strategy is first conversion to carbonate, then to chloride, followed by electrowinning of molten salts. Lithium carbonate is the most common lithium commodity on the market, used as a raw material for the manufacture of different substances and materials. Conversion to carbonate can be done by: (i) alkaline fusion and carbonation, (ii) acid roasting, calcination and carbonation (involving purification and precipitation). These two processes will be discussed below. It can also be carried out by wet leaching with sulfuric acid .[50]

Natural spodumene is in the α-crystalline form, which is practically insoluble in hot sulfuric acid, so it is required to be converted to the tetragonal β-crystalline form by calcination (Piceros, n.d.). Calcination can be simply a decomposition (loss of volatile components) and a structural change, but it can also be performed in the presence of additives (reagents such as limestone, lime or a sulfate donor) and is then described as a roasting process.

In the alkaline process, the spodumene (or lepidolite) concentrate is ground and calcined with limestone. The resulting calcined product is then crushed, ground and treated with water to obtain lithium hydroxide which can be converted to chloride by reaction with hydrochloric acid. Recovery is approximately 85-90 %. The addition of limestone allows the formation of a stable calcium silicate, releasing the lithium oxide, which can be subsequently recovered by leaching, as it is readily soluble in water.[51]

In the acid roasting, calcination and carbonation method, the spodumene is converted from the alpha form to a more reactive beta form by roasting it in a kiln at 1,050-1,100 °C. After calcination or roasting, the next steps are hydrometallurgical, in order to solubilize the lithium in an aqueous medium. The product obtained can be treated in different ways depending on the desired end product.

If lithium hydroxide (LiOH) is to be produced, the calcined product is ground and then leached with water, so that lithium is recovered in aqueous solution as lithium hydroxide .[52]

The leached pulp is sedimented and filtered and the filtrate obtained, containing about 10 % lithium hydroxide in solution, is evaporated and crystallized to form crystals of lithium hydroxide monohydrate $LiOH.H_2O$, which is removed from the crystallizer together with the liquor. It is then centrifuged and dried at 80- 120 °C with indirect steam to have dry crystals of the monohydrate.

The solution obtained in the centrifuge is returned to the crystallizer and a small part is discarded to avoid the accumulation of impurities such as Al, Mg, Ca, K and Cl. The crystallizers quickly become encrusted with lithium hydroxide crystals, which requires weekly washing with hydrochloric acid, HCl, to descale them. This lithium chloride produced with HCl must be treated separately.

50 For more details see (Garcés, n.d.; Piceros, n.d. and Wilkomirsky, 1999).

51 The overall reaction that takes place is as follows: $2LiAl(SiO_3)_2 (s)+4CaCO_3 (s) \rightarrow Li_2O(s) + 4CaSiO_3 (s) + Al_2O_3 (s)+4CO_2 (g)$

52 According to the reaction: $Li_2O(s) +3H_2O \rightarrow 2(LiOH.H_2O)(aq)$

If anhydrous lithium hydroxide is required, the monohydrate is calcined at low temperature in vacuum at 100-120 °C, and the product is then packaged, as it is hydroscopic.

Figure 33 shows the production diagram of anhydrous and monohydrate lithium hydroxide from spodumene.

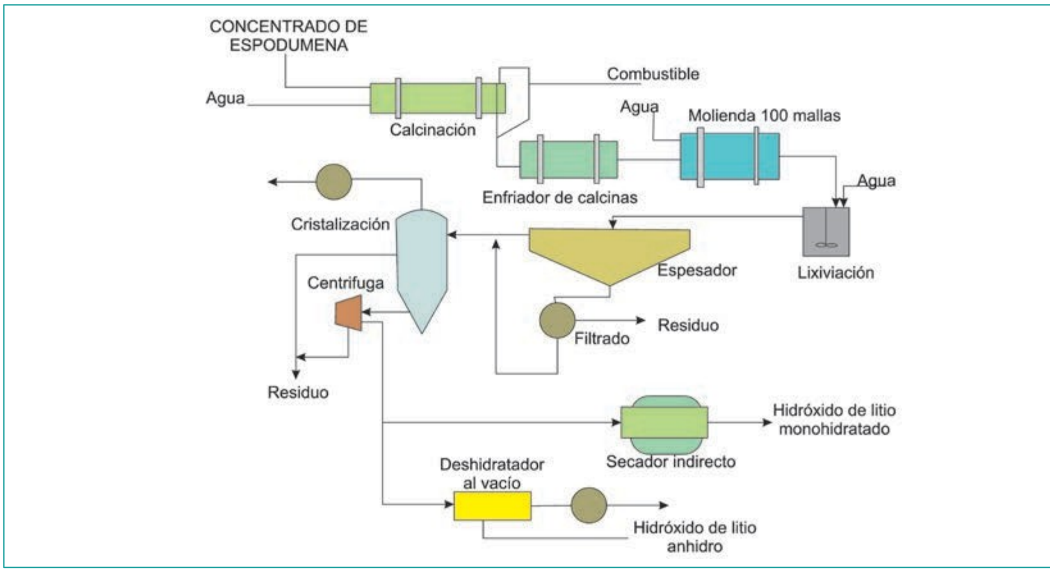


Figure 33. Process diagram to produce anhydrous and monohydrate lithium hydroxide from spodumene concentrates. Source: modified by the authors from (Piceros, n.d.).

3.2.1.2. Obtaining lithium carbonate from spodumene

The calcined spodumene product can also be used to produce lithium carbonate. In this case, the calcine is ground and then treated with concentrated sulfuric acid (96-98 %) at 250 °C in a stirred reactor, thus forming (soluble) lithium sulfate, which is subsequently extracted by water leaching. The pulp is decanted and filtered. The solution obtained is treated with calcium hydroxide to precipitate the sulfates present as calcium sulfate and leave the lithium in solution as hydroxide.

Figure 34 shows a schematic diagram of the processes to obtain lithium carbonate from the calcination of spodumene by sulfation with sulfuric acid, leaching with water and precipitation with sodium carbonate. The product obtained is lithium carbonate with a richness of 98.5 - 99 %.

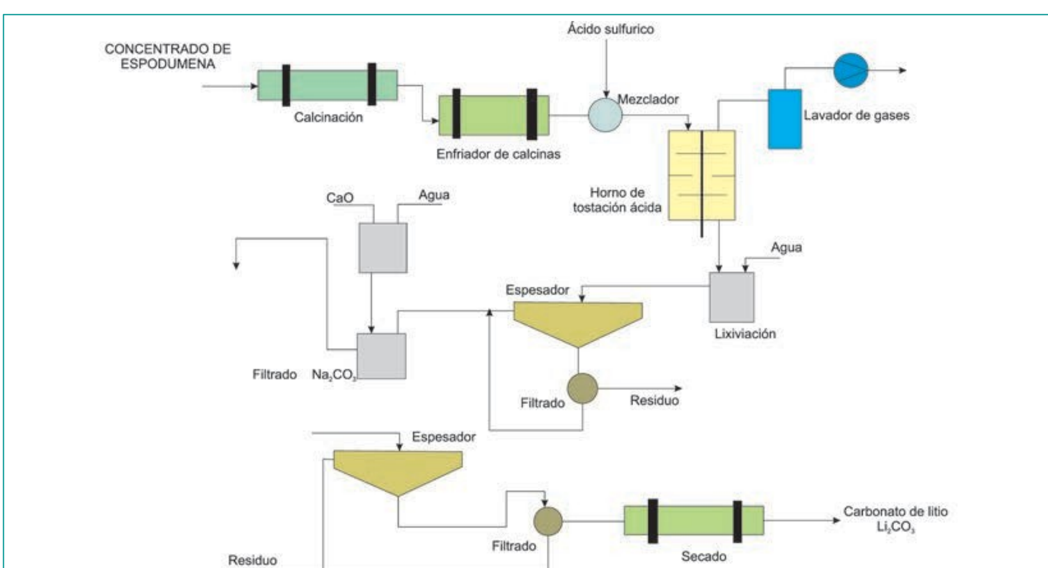


Figure 34. Obtaining lithium carbonate from spodumene concentrate by roasting, leaching and successive precipitations. Source: modified by the authors from (Piceros, n.d.).

The reaction with concentrated sulfuric acid at 250 °C is difficult and complicated and occurs in the form of a semi-plastic paste with the appearance of pasty cement and the generation of highly corrosive gases (SO_2 , SO_3 and gaseous sulfuric acid), which requires stirred reactors such as mixers or deck ovens, with control and neutralization of the exhaust gases .[53]

Lithium carbonate precipitation is carried out at 90-95 °C, as it has inverse solubility with temperature, with about 0.7 g/l at 100 °C and 1.5 g/l at 0 °C, thus avoiding excessive dissolution of the carbonate. Washing of the carbonate is done with client water at 90-95 °C and the washing solutions are recirculated to the process so as not to lose dissolved lithium carbonate.

Lithium carbonate can also be recovered by adding sodium carbonate to the solution after pH adjustment, purification and evaporation.

$$Li_2\,SO_4\,(s) + Na_2\,CO_3\,(aq) \rightarrow LiCO_3\,(s) + Na_2\,SO_4\,(aq)$$

The process of producing lithium carbonate from spodumene encountered some economic problems in the 1990s because the production of lithium carbonate from brines (particularly from the Salar de Atacama) was more profitable and less energy demanding, as the depleted brines (but still containing chlorides and/or sulfates) are returned to the salar.

3.2.2. Lithium carbonate production from brines

Obtaining lithium from natural brines is a growing and important source of lithium in the world as lithium carbonate, chloride and hydroxide. Extraction of lithium from brines and seawater is 30-50% less expensive than extraction from ores.

The composition of commercial brines from which lithium is recovered varies considerably, from brines with low lithium contents (0.02 %) to some with contents close to 0.4 %, and the presence of other elements such as potassium, sodium, calcium, magnesium, iron, boron, bromine, chlorine, nitrates, chlorides, sulfates and carbonates, which requires that each brine be treated according to its composition. As for boron, in general, there are traces in very low concentrations, which are not enough to obtain any boron compound, but it can be considered an impurity to produce lithium compounds, due to the high purity required of the latter.

All brines are previously concentrated by solar evaporation to increase the lithium content and precipitate salts that can be commercial, such as KCI, NaCl, $K_2\,SO_4$, $Na_2\,SO_4$, etc. as well as other double salts such as sylvinite, carnallite, bishoffite, schoenite, kainite, glasserite, glauberite, epsomite or singerite. The most abundant brines are sulfate and chloride brines (see Figure 35, which shows the

[53] The reactions that occur are as follows:

(i) Sulfation with sulfuric acid. Reversible reaction with an inversion temperature of 502 °C.
$2LiAl(SiO\,)_{32}\,(s) + 4H_2\,SO_4\,(l) \rightarrow Li_2\,SO_4\,(s) + Al_2\,(SO\,)_{43}\,(s) + 4SiO_2\,(s) + 4H_2\,O$,

(ii) Precipitation of aluminum as insoluble alumina:
$Al_2\,(SO\,)_{43}\,(s) + 3Ca(OH)_2\,(ag) \rightarrow Al\,O_{23}\,(s) + 3CaSO_4\,(s) + 3H\,O_2$
At this stage, the pulp is thickened and filtered to leave only the lithium sulfate in solution.

(iii) Formation of lithium hydroxide monohydrate (excess $Ca(OH)_2$ is added to form lithium hydroxide): $Li_2\,SO_4\,(aq) + Ca(OH)_2\,(aq) + 2H_2\,O \rightarrow 2(LiOH.H_2\,O)(aq) + CaSO_4\,(s)$
This reaction has a reversal temperature close to 30 °C, so the solution must be cooled to 5-10 °C.

(iv) The lithium in solution is as lithium hydroxide and is finally precipitated from the filtrate to the lithium carbonate form using 20-24 wt.% sodium carbonate:
$LiOH.H_2\,O\,(aq) + NaCO_3\,(aq) \rightarrow LiCO_3\,(aq) + NaOH(aq) + H\,O_2$

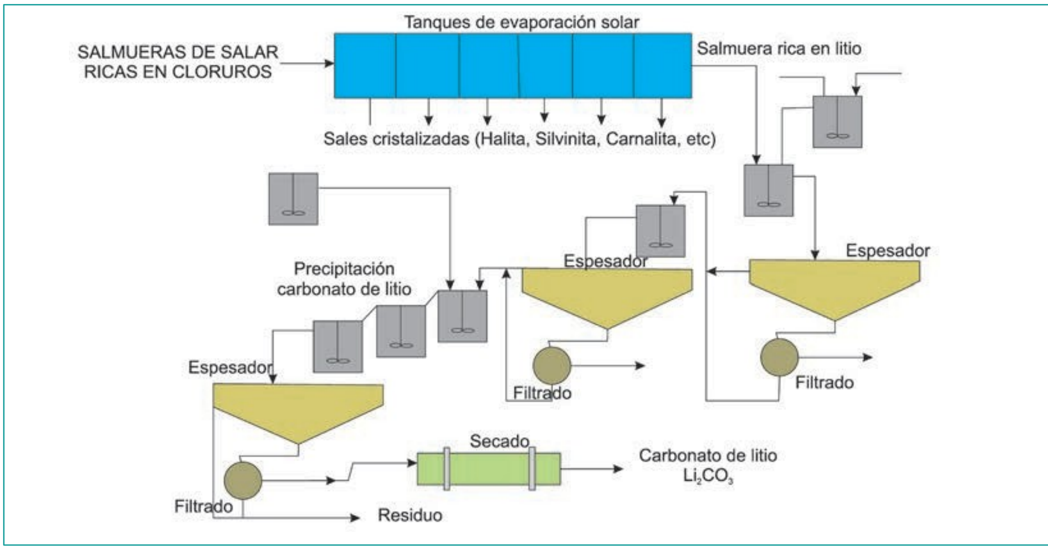


Figure 35. *Obtaining lithium carbonate from natural brines. high in chlorides. Source: modified by the authors from (Piceros, n.d.).*

flow diagram of the process of obtaining lithium carbonate from natural brines high in chlorides).

Brines, although liquid, do not contain free water, since they are saturated and only contain hydration water from the different species that form hydrates. Free water is only a very small fraction of the total brine. However, brines are fluid, transparent and of relatively low viscosity.

Brines, for example, from the Salar de Atacama, are pumped from 30 to 50 m deep in the salar and then allowed to evaporate in pools (ponds) of 1.5 m deep and large dimensions (600 x 800 m or larger) where a sequential crystallization of salts begins. The altitude of the Salar de Atacama (over 1,600 m), the low ambient humidity (<15 %) and the high solar radiation (over 1 kW summer/m^2 , 0.4 kW winter/m^2) favor high brine evaporation, close to 10 cm/day between December and March.

As chloride brines are generally saturated in NaCl, the first salt to precipitate is halite (NaCl) or halite and hydrated calcium sulfate, if sulfates are present. Precipitation continues with sylvinite (KCl-NaCl) and then sylvite (KCl). The latter is a product of industrial use, so that towards the end of the sylvinite precipitation, the brine is transferred to another pool and the precipitated KCl + sylvinite salt is recovered to obtain KCl by differential flotation. The brine is then evaporated to crystallize carnallite ($KCl.MgCl_2 .6H_2 O$) and then bishoffite ($MgCl_2 .6H_2 O$).

At this stage, the lithium has increased to about 4.5 % with a magnesium content of about 4 %. Since the subsequent chemical purification of the brine requires 5.5- 6 % lithium, further evaporation of the brine precipitates lithium carnallite ($LiCl.MgCl_2 . 6H_2 O$), which decreases the yield of the operation. However, it is possible to leach the lithium carnallite with fresh brine to recover some of the lithium content.

The lithium-concentrated brine contains between 5.5 and 6.0 % lithium, equivalent to 33.4-36.5 % LiCl, and is purified in one or two stages to remove the rest of the other elements, essentially the remaining mag- nesium and calcium. Precipitation is done in two stages: first with sodium carbonate and then with calcium hydroxide (lime slurry) as shown in Figure 35. The sulfate present in the form of sodium sulfate also precipitates as calcium sulfate. At this stage, free water is introduced to the system with the 23-24 % Na solution$_2$ CO_3 , so that the system is now aqueous.

The sodium carbonate added in the first stage is done to avoid an excessive amount of magnesium hydroxide precipitate in the second stage, which is difficult to separate from the brine because it is excessively fine (submicron), while it also contributes to precipitate calcium chloride, as calcium carbonate, since normally the amount of sodium sulfate present in the brine is not enough to precipitate all the calcium chloride to calcium sulfate.

The purified brine, previously filtered to separate the suspended solids, is finally treated with hot sodium carbonate (90-95 °C) to precipitate the lithium carbonate .[54]

The precipitated lithium carbonate is sedimented and hot filtered and then extensively washed with hot demineralized water in the filter. The carbonate is dried at 130-160 °C in an indirect rotary dryer and packaged, protected from moisture.

The final product is about 99 % Li_2CO_3 and is the raw material for the production of lithium hydroxide or high purity lithium chloride used in the production of lithium metal by electrolysis of molten salts. In this case, the carbonate is treated with hydrochloric acid to form LiCl again .[55]

3.2.3. Production of lithium hydroxide

To obtain lithium hydroxide from lithium carbonate, lithium carbonate is treated with calcium hydroxide (lime slurry)[56] . The resulting pulp, containing lithium hydroxide in solution and preci- pitated calcium carbonate, is washed in a system of four or five decanters in series in countercurrent to finally obtain a pulp with about 10 % lithium hydroxide in solution (about 24 g $LiOH.H_2O$/l at 20 °C). This, after being filtered in a filter press, is taken to a triple effect evaporator system to crystallize the lithium hydroxide (see Figure 36, which shows the flow diagram of the process for obtaining lithium hydroxide monohydrate from technical lithium carbonate).

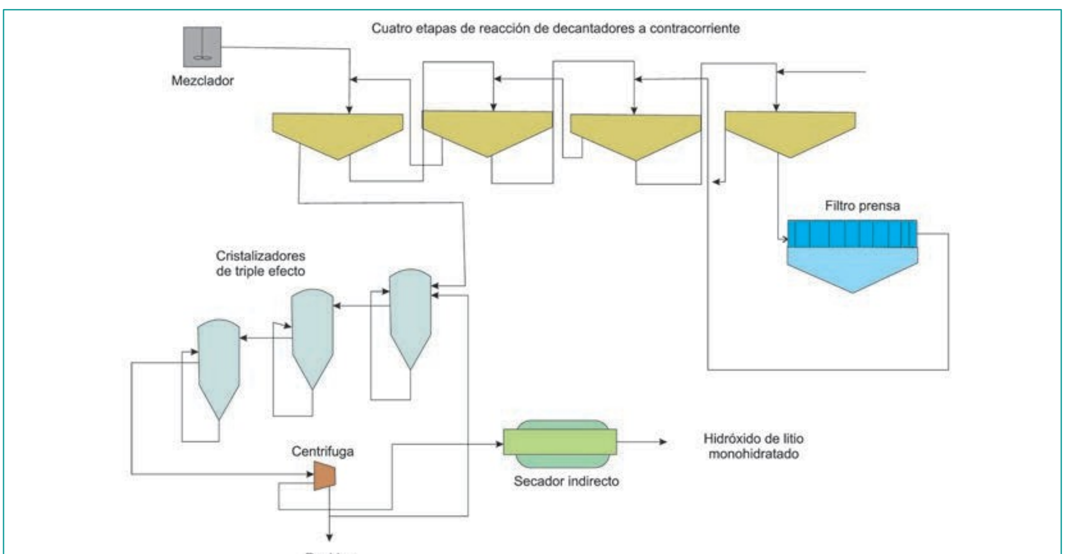


Figure 36. Production of lithium hydroxide monohydrate from technical lithium carbonate. Source: modified by authors of (Piceros, n.d.).

[54] According to the reaction:

$2LiCl_{(aq)} + Na_2CO_{3(aq)} \rightarrow Li_2CO_{3(s)} + 2NaCl_{(aq)}$

[55] For the purpose of converting production and reserves, the following is commonly used: 1 ton of lithium = 5.28 tons of lithium carbonate.

equivalent (LCE)

[56] According to the following reaction:

$Li_2CO_{3(s)} + Ca(OH)_{2(aq)} + 2H_2O \rightarrow 2(LiOH.H_2O)_{(aq)} + CaCO_{3(s)}$

The product obtained is lithium hydroxide monohydrate crystals and liquor, which still contains about 25 g/l of lithium hydroxide. The lithium hydroxide monohydrate crystals are separated in a centrifuge and then dried at 80-100 °C with indirect steam. The solution resulting from the centrifugation of the crystals is returned to the crystallizer, discarding a part of it to avoid the accumulation of impurities such as K, Ca, Na and Mg. If anhydrous lithium hydroxide is desired, it is dried indirectly and in vacuum at 100-120 °C. If lithium chloride is desired, the carbonate is treated with hydrochloric acid to form LiCl .[57]

3.2.4. Obtaining lithium metal

The production of lithium metal requires lithium chloride of 99.9 % purity. Lithium chloride has a solubility of 70.2 g/l at 20 °C and is concentrated by evaporation/crystallization to about 99.9 % LiCl, which is then dried.

Although lithium metal has been produced by reduction metallothermia with aluminum and silicon from lithium chloride or by magnesium from lithium oxide, these methods are not practically applicable and all lithium metal is obtained by electrolysis of molten salts using an electrolyte of lithium chloride (55 wt.%) and potassium chloride (45 wt.%) using graphite anodes. The cells operate at 420-500 ºC and are heated externally with gas or oil burners.

The deposit achieved is at least 99.8% lithium, with a lithium recovery of 98% and a current efficiency of approximately 80%. Contact of the metal with air must be avoided to prevent oxidation and the formation of lithium nitride, which would contaminate it, so it is either bled under inert gas or cooled immediately.

The lithium obtained (liquid) is cast into small ingots for subsequent rolling to the desired shape. All operations must be carried out in a protected atmosphere when the lithium is liquid to avoid contamination.

Figure 37 shows a schematic of a lithium electrolysis cell, which is isolated from the environment, using LiCl-KCl electrolyte. A by-product of the cell is marketable chlorine gas, which is extracted for recovery .[58]

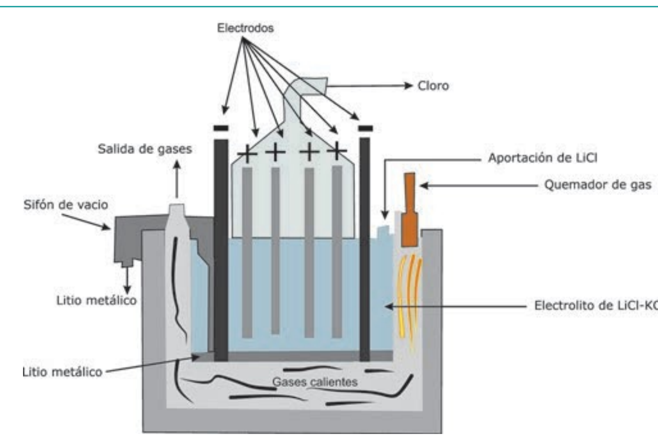


Figure 37. *Lithium metal electrowinning cell. Source: modified by authors of (Piceros, n.d.).*

[57] According to the reaction: $Li_2 CO_{3(s)} + 2HCl_{(aq)} \rightarrow 2LiCl + H_{(aq)\,2} O + CO_{2}(g)$

[58] The reactions that occur in the cell are:
Anode: $LiCl(l) = Li + Cl^{+-}$; $Cl^{-} = Cl(g) + e^{-}$
Cathode: $Li^{+} + e^{-} = Li(l)$

3.3. Rare earth metallurgy

Rare earths are the group of 17 chemical elements: scandium, yttrium and the 15 elements of the lanthanide group (lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium and lutetium). Scandium and yttrium are included among the rare earths because they occur frequently mixed with the lanthanides in the same deposits .[59]

The most important rare earth (REE*)* minerals are monazite, which is a rare earth orthophosphate ($(TR,Th)PO_4$) and bastnasite, which is a fluorocarbonate ($(TR)(CO_3$)F), containing mainly light rare earth elements. Monazite can contain up to 70 % rare earths, mainly Ce and La, as well as significant amounts of Nd, Pr and Sm. The Th content is also quite high, ranging from 4 to 12 %, which is a problem in monazite processing. Bastnasite is the source of 70 % of the world's rare earth elements.

Rare earths do not occur in native form and the stability of their oxides, close to that of calcium oxide or aluminum, makes it difficult to extract them by pyrometallurgy. The hydrometallurgical route is therefore applied, sometimes followed by metallothermic reduction or electrolytic reduction, which will require, given the difficulties of extraction, costly and justifiably sized installations depending on the sale price of the TRs.

In the general process of rare earth production, three phases can be distinguished, which are shown in Figure 38: (i) preparation and concentration of the ore (physical enrichment), (ii) chemical enrichment and (iii) separation and purification .[60]

Figure 38. *General land processing diagram rare. Source: (Avendaño, 2017).*

The first stage involves reducing the size of the ore (crushing and grinding) and then moving on to the concentration stage, which includes gravity, magnetic, electrostatic and flotation techniques.

The most common next stage processing is the hydrometallurgical route, and begins with a leaching of the ore concentrate, with dissolution, which can be either acidic or basic. Table 17 gives an overview of the leaching technologies used both from primary rare earth production and for secondary resources. All processes involve multiple steps and some use acids and alkalis interactively.

[59] For more detail on rare earths, see (Prego, 2019) and (Prego, 2021).

[60] Rare earth processing is concentrated in China (85 %) (European Commission, 2022b).

Table 17. *Summary of leaching technologies in primary production. rare earth oxides. Note: REO = rare earth oxides, LREE = light rare earths, HREE = heavy rare earths. Source: translated by the authors from (Peelman, et al., 2015).*

Mineral	Process	Rare earth performance	Details	Status
Bastnasite	1) HCl leaching to remove non-REE carbonates 2) Calcination of residue to form REO	85-90 %	The oldest form of processing bastnasite concen- trates	Obsolete
	Digestion with HNO_3 or H_2SO_4	98 %	The choice of acid depends on the subsequent treatment: extraction with solvents→precipitation $HNO_3 \rightarrow H_2SO_4$	Obsolete
	1) Roasting at 620 °C releasing CO_2 2) Leaching with 30% HCl	-	Ce^{+III} is oxidized to Ce^{+IV} during roasting. REE fluorides will not leach, the residue is marketable.	Obsolete
	1) Alkaline conversion $REF_3 \rightarrow RE(OH)_3$ 2) Leaching with HCl	-	The process may be preceded by HCl leaching to extract carbonates from REE prior to alkaline conversion.	In use
	1) Sulfuric acid roasting 2) Leaching with NaCl solution 3) Precipitation as double Na	-	The precipitates are converted to chlorides for subsequent purification by solvent extraction.	In use
Monazite	Digestion in hot H_2SO_4	-	The process conditions determine what is leached: REE only or LREE+HREE+Th No pure product is obtained	Obsolete
	1) Digestion in hot NaOH at 60-70 %. 2) Washing the residue with hot water 3) Acid leaching mineral of choice	98 %	Ce cannot leach if Mn is present. Th leaches together with REE. Na_3PO_4 is a marketable by-product.	In use
	1) Heating in a reducing and sulfurous atmosphere with $CaCl_2$ and $CaCO_3$ 2) Leaching with 3 % HCl	89 %	No fine grinding is required. Th does not leach out, it remains in the residue as ThO_2. No Mn problem	In use
Clays with adsorbed rare earth ions	Salt leaching with $(NH_4)_2SO_3$	80-90 %	It targets absorbed REE by cation exchange.	In use
	Seawater leaching	40 %	Inefficient but inexpensive process	I+D
	Acid leaching with strong acid (pH<1)	All	Dissolves all clay, incurs significant additional cost	Not employed

In the chemical enrichment of bastnasite, one of the main difficulties was to extract the fluorides. At present, it has been solved in two different ways: (i) pre/post-treatment by alkaline roasting with sodium hydroxide or (ii) acid roasting with sulfuric acid.

Alkaline treatment is a three-step process. It proceeds with an acid leach with HCl to convert the rare earth carbonates to chlorides. These are then treated with sodium hydroxide at 96°C to convert the rare earth fluorides to hydroxides, and then the hydroxides are dissolved by leaching with HCl[61] . Molycorp reportedly used the alkaline method at the Mountain Pass mine before it closed.

[61] The chemical reactions would be as follows:
$TRF_3 - TR_2(CO)_{33} + 9HCl \rightarrow TRF_3 + 2TRCl_3 + 3ClH + 3H_2O +$
$3CO_2$ $TRF_3 + 3NaOH \rightarrow TR(OH)_3 + 3NaF$
$TR(OH)_3 + 3ClH \rightarrow TRCl_3 + 3H O_2$

In sulfuric acid roasting, the bastnasite concentrate is heated in a 98% solution of $H_2 SO_4$ at a temperature of 400-500 °C for several hours. This decomposes the fluorocarbonate matrix of the bastnasite, releasing CO_2 and hydrofluoric acid. The rare earths are converted to their sulfates and can be selectively precipitated as double Na sulfates by leaching the residue with water containing NaCl. The precipitates are converted to chlorides for further purification with solvent extraction. This process is the one used in chemical enrichment processes in China, particularly at the Bayan Obo mine.

In the case of monazite, the concentrate can be chemically attacked with sulfuric acid or sodium hydroxide to dissolve the rare earth elements. In addition, elements such as thorium, uranium and some sulfates and phosphates present in the concentrate are dissolved.

The alkaline method is currently one of the main monazite leaching technologies[62] . In this case, the monazite concentrate is attacked with a concentrated sodium hydroxide solution (60-70 %) at 140-150 °C for four hours, after which it is passed to a filtration operation. The solid residue is dissolved in a hot acid solution of HNO_3 for solvent extraction using tributyl phosphate or tributyl phosphate (TBP) and $H_2 SO_4$ for solvent extraction using amines. This process requires adequate grinding of the monazite ore prior to treatment (particle size below 45 μm) so that extraction rates of 98 % can be achieved even with relatively low grade ores.

In this process, trisodium phosphate is recovered from the filtrate by evaporation/crystallization. This by-product is marketable, which has been a major attraction for the commercial use of this process. The thorium at the end of the process can end up as nitrate and the uranium as fluoride .[63]

Ion-adsorbed clays are alumina-silicate clays in which rare earth element ions have been adsorbed. Although these clays have an average concentration of only 0.05-0.2 wt%, their ease of processing and relatively high heavy earth fraction make them a viable course. These clays require no pre-processing and contain very few radioactive elements.

In leaching, leaching agents $(NH\ )_{42}\ SO_4$ and NaCl[64] are commonly used as leaching agents. The kinetics of the leaching process is very fast. The industrial process, currently used in China, uses an ionic clay with a concentration of rare earth oxides between 0.08 and 0.8 wt% and a leachate of 7 wt% NaCl and 1-2 wt% $(NH\ )_{42}\ SO_4$ at a pH of 4 (Peelman et al., 2015). A rare earth oxide recovery rate of up to 95 % is achieved.

Separation and purification then seeks to separate the rare earth oxides individually, using a multi-stage system of solvent extraction, precipitation and drying.

For the production of metals, the individual oxides are electrolyzed. The affinity of the rare earth elements for oxygen shows that their reduction to the metallic state is not particularly easy.

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62 The reactions during alkaline leaching are: $TRPO_4$ +
$3NaOH \longrightarrow TR(OH)_3 + Na_3\ PO_4$
$Th_3\ (PO\ )_{44} + 12NaOH \longrightarrow 3Th(OH)_4 + 4Na_3\ PO_4$

63 Merritt has proposed a method in which monazite is heated with $CaCl_2$ and $CaCO_3$ in a reducing and sulfiding atmosphere. This leads to to the conversion of rare earth phosphates into rare earth oxysulfides and oxychlorides, while creating a stable thorium oxide and chloropatite. From this mixture, the rare earths can be selectively leached with 3% HCl.

64 The leaching reaction is as follows:
$[Al_2\ Si\ O_{25}\ (OH)_4\ ].\ TR^{3+} + 3NH_4 + \longrightarrow [Al_2\ Si\ O_{25}\ (OH)_{44}]\ (_3NH^+\ ) + TR^{3+}$

in an aqueous medium or even for a simple chemical reduction. The electrolytic route is applicable for elements with low melting temperature (La, Ce, Pr and Nd). A mixture of rare earth chloride $TRCl_3$ with NaCl or $CaCl_2$, which constitutes the molten salt bath, is electrolyzed in a steel crucible internally lined with graphite serving as cathode and a graphite rod serving as anode. This molten salt electrolysis step is today almost entirely concentrated in China (IRENA, 2022).

Figure 39 shows the flow diagram of the overall process used to obtain neodymium. The roasting and leaching processes applied on the concentrate and the subsequent solvent extraction and precipitation processes to obtain dysprosium and neodymium can be observed.

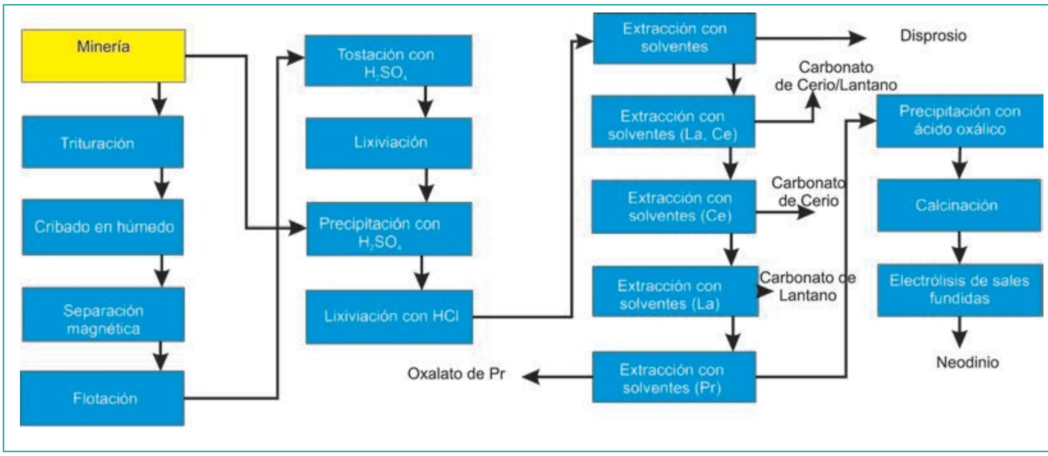


Figure 39. *Flow diagram of the overall process used to obtain, among other products, neodymium, which is a key element for the manufacture of NeFeB magnets. Source: modified by the authors from (IRENA, 2022).*

3.4. Zinc metallurgy[65]

Zinc, like other non-ferrous metals, can be produced by hydrometallurgical or pyrometallurgical processes. Most production units use the electrolytic process (hydrometallurgical route), due to the high quality of the zinc obtained. The electrolytic process, developed commercially in 1917, was a real boost for the zinc industry and currently accounts for the largest tonnage of metal production, producing 85 % of the world's zinc.

Thermal reduction processes (pyrometallurgical route), based on the reactions: $ZnO(s) + CO(g) \rightarrow Zn(g) + CO_2(g)$, $C(s) + CO_2(g) \rightarrow 2CO(g)$ and subsequent condensation, have fundamental differences between them. The different processes are: horizontal retorts, vertical retorts, electro-thermal and reduction in an Imperial Smelting Furnace (ISF). In this case, two further stages are also necessary, one depending on the raw material and the other on the process followed, which are respectively: purification and residue treatment.

Both ways have a common point, which is the need to treat the residues for three main reasons: to increase zinc recovery, to recover the other recoverable metals contained in the concentrates and for environmental reasons.

In the electrolytic way of obtaining zinc, the fundamental stages are: roasting, leaching, purification and electrolysis. There are two other stages, which present multiple variants: smelting and waste treatment.[66]

[65] The main sources used for this section are (Sancho et al., 2000) and (Sinclair, 2005).

[66] The only process that can compete with this procedure is ISF, although in this case the largest furnaces have only reached 80,000 t of zinc and 40,000 t of lead. However, zinc purity is low if fractional distillation is not installed. The largest electrolytic zinc installations produce between 250,000 and 300,000 t per year of 99.995 % quality zinc.

In Spain, the first electrolytic zinc plant started up in 1960 in Cartagena (Murcia), and immediately afterwards, in 1961, the Asturiana de Zinc plant in San Juan de Nieva (Asturias). The latter reached a production of 532,235 t in 2020, remaining in the "Top 3" factories of its sector in the world and the first in the European continent.

At the beginning of zinc metal production, calamine ores ($4ZnO\text{-}2SiO_2\text{-}2H_2O$) were used as ores, but once the calamine deposits were exhausted, sphalerite (ZnS) had to be used, and today it can be said that almost all the world's zinc production is obtained from sulfides concentrated by flotation. Galena and sphalerite are the most common sulfides, but they also occur in significant quantities in cerussite ($PbCO_3$), anglesite ($PbSO_4$) and smithsonite ($ZnCO_3$). A general schematic of a zinc electrolysis plant is shown in Figure 40.

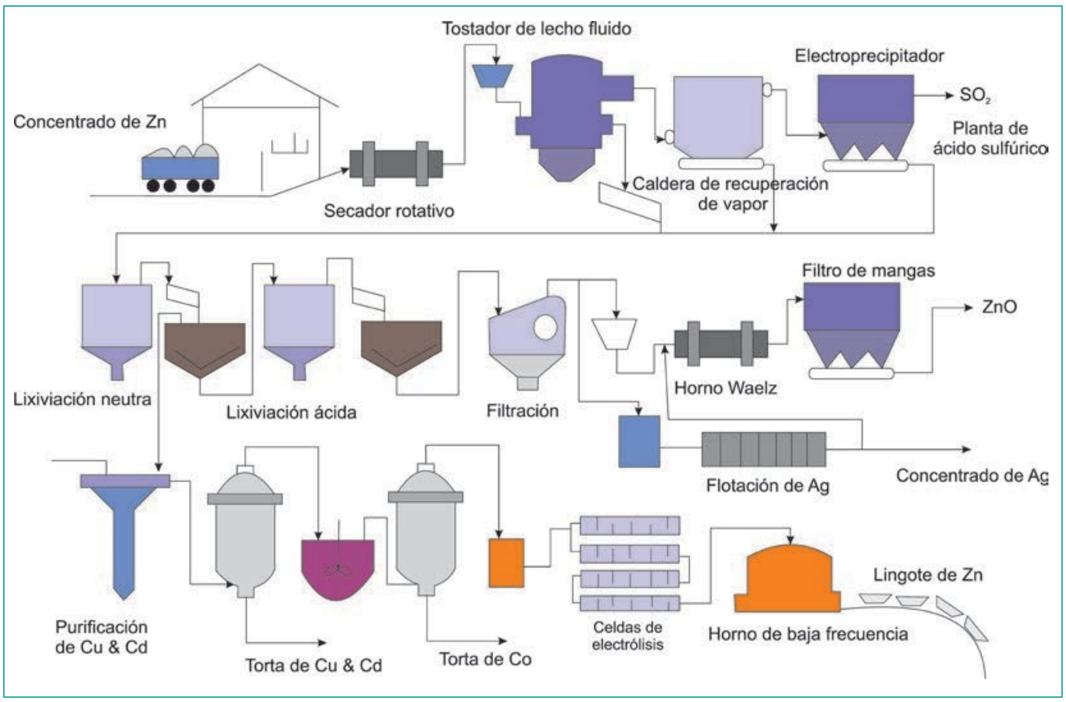


Figure 40. *Flow diagram of a zinc electrolysis plant. Source: modified by the authors from (Huang, 1990).*

The first stage in the zinc manufacturing process is to obtain the concentrate from the ore. Concentration of ores by flotation has solved the problem of mixed ores (increasingly common); however, prior to this operation, grinding is required to liberate the various components of the ore. The normal practice of flotation in mixed ores is to first float the copper ores, depressing the zinc and lead ores. Next, galena is floated, then blende and sometimes finally pyrite.

In the roasting stage, the ore is subjected to oxidizing roasting. This conversion of blende to oxide is required for both pyrometallurgical and hydrometallurgical processes, since sulfide is not easily attacked by acids or bases and is also inert to reduction with carbon[67]. Roasting must be carried out above 700 ºC, in air and with continuous agitation. The sulfur dioxide obtained is sent to the sulfuric acid plant.[68]

[67] The basic reaction of roasting is as follows: $ZnS\ (s) + (3/2)\ O_2\ (g) \rightarrow ZnO\ (s) + SO_2\ (g)$.

[68] If the iron is in substitutional form in the blende, the formation of zinc ferrite, $ZnO\text{-}Fe_2O_3$ (franklinite), is immediate and complete, since when zinc and iron oxides are heated to a certain temperature, this compound is produced. Even if the iron is as pyrite, at the roasting temperature of 900 °C, 90 % of the iron is fixed as zinc ferrite.

The ZnO obtained, known as roasted or calcine, is then sent to the next production stage, which is leaching, whereby the zinc oxide is dissolved in a dilute solution of sulfuric acid (100-150 g/l), forming a solution of zinc sulfate ($ZnSO_4$). This acid concentration only allows the ZnO to dissolve, leaving the ferrites formed in the roasting process, ZnO-Fe O_{23} , unattenuated.

To improve zinc recovery and thus avoid metal losses, hot acid leaching (90-95 ºC) is carried out for 2-4 hours. Under these conditions not only the zinc is dissolved but also the iron associated with the zinc ferrite, obtaining a zinc-rich solution containing between 15-30 g of iron/l (mainly in ferric form), which must be removed from the solution.

Leaching is carried out simultaneously with oxidation and neutralization so that the iron with which impurities such as As, Sb and Ge co-precipitate can be precipitated. Co-loidal silica and aluminum hydroxide are also co-precipitated. This precipitation of Fe^{3+} is currently preferably carried out using jarositic precipitation .[69]

After leaching, the solution is purified in order to eliminate some of the elements present in the solution. This elimination is done by adding zinc powder. The amount of zinc powder required depends on the percentage of impurities in the solution. This purification lasts between one and eight hours. At the end of the process, the zinc particles are recovered by filtration. By means of this addition, Cu, Co and Cd are precipitated and the Sb and Ge content is reduced to acceptable levels. This is possible due to the cementation of these metals by zinc, which is less noble than them. In practice, at 90 °C and a pH of 4, the first to precipitate is Co, followed by Cu, Ni, As and Sb. In a subsequent step, with further addition of zinc, Cd, Tl and Ge precipitate, which occurs at pH equal to 3 and at a temperature of 70-80 ºC .[70]

Once the solution has been purified, it is passed to the installation of the electrolysis tanks, which are rectangular, made of concrete and coated with lead or PVC. The tanks are associated in groups in series and the electrolyte circulates continuously through them.

The anodes are made of lead alloyed with some silver (1 %) to reduce corrosion and, therefore, zinc-lead contamination, and the cathodes are made of aluminum. They are often perforated in order to facilitate the circulation of the electrolyte and help maintain a film of MnO_2 on the surface. Manganese constitutes one of the main impurities in the electrolyte and some of it is partially deposited as MnO_2 on the anodes forming a protective crust that is beneficial as it prevents lead contamination. This deposit falls and forms sludge and sometimes grows too much, increasing the anode voltage, so the tanks and anodes must be cleaned periodically to remove this MnO .$_2$

The cathodes, on the other hand, are made of aluminum and their surface area has more than doubled, thus greatly increasing plant productivity. The production per cell, containing up to 86 cathodes of 1.6 m^2, can reach 3 t/day.

[69] In jarosite precipitation the iron precipitates as jarosite, which is a synthetic crystalline compound whose formula is $_{M2Fe6}(SO_4)_4(OH)_{12}$ where M can be Pb, Na, K, NH4, etc., by adding NH^{4+} or Na^+ to the solution, adjusting the pH to 1.5 and setting a temperature of about 90 ºC. The rest of the iron can be precipitated at pH 3.5 by neutralization. Jarosite has the advantage of separating very well from the solution. This method can allow more iron to be leached out while recovering zinc from the ferrites, thus increasing the zinc recovery from the ore. The precipitation reaction is as follows:
$_{3Fe2}(_{SO4})_3 + 10\ H2O + 2\ NH4OH \rightarrow (_{NH4})\ _{2Fe6}(_{SO4})_4(OH)_{12} + 5\ _{H2SO4}$

[70] It seems that As activates the zinc powder, increasing its selectivity and efficiency. It was therefore sometimes added in the form of an oxide; its dangerousness caused it to be exchanged for Sb and then the conditions vary slightly: at 65-75 ºC, Cu, Ni and Co are precipitated together with some Cd. It is filtered and the solution is treated with more zinc powder to precipitate the rest of the Cd and the other metals. In some plants, the precipitation of metals is done first cold, obtaining Cd and Cu, and then hot, at 90 ºC, precipitating Co and Ge by addition of zinc powder in the presence of Sb.

The electrolysis process requires between 30 and 40 °C and will allow the zinc to be deposited on the cathode from where it will be *stripped* every 24, 48 or 72 hours, depending on the case. The zinc obtained is very pure (99.995 %). It contains less than 50 ppm of impurities, lead being the main one.

Cathodes from electrolysis are not a common commercial form of zinc for sale, so they must be melted. Melting is carried out in low-frequency induction furnaces of up to 1,800 kW. The molten metal feeds casting machines with different ingot formats for sale, once either the corresponding alloy or the pure metal has been prepared.

False air inlets in these induction furnaces can lead to the formation of zinc fats or oxides and foams (2-2.5 %), which remain floating on the molten zinc in the form of solids. Ammonium chloride is added to promote the separation of the two phases.

The oxides, materials and foams produced are treated for recovery in the form of zinc billets which are remelted in a tilting induction furnace. The flow of zinc is passed through a strong stream of air, atomizing the liquid zinc and collecting it in decanting chambers. The zinc powder thus produced is used as a cementing agent in the leaching purification stage.

As mentioned above, zinc can also be obtained by pyrometallurgy, for which the Imperial Smelting Process (ISF) was developed in the United Kingdom in the middle of the last century. The ISF is a blast furnace process for the simultaneous recovery of zinc and lead. It is currently the only one capable of competing with electrolytic zinc recovery. In addition to traditional raw materials such as lead and zinc sulfides, secondary materials such as dust and sludges from steelmaking processes can be used in the ISP. For this reason, the simultaneous production of metallic lead is an advantage of the process, since most recycling materials contain lead as well as zinc. The ISP does not produce lead-containing residues as do other zinc manufacturing processes .[71]

4. Conclusions

Once the concentrate has been obtained in the mineral processing plant, it needs to be processed to obtain the materials and metals required for the energy transition and the digital society. This is done by extractive metallurgy.

There are two main techniques or methods, which can be implemented independently or very often in combination: hydrometallurgy or wet process and pyrometallurgy or dry process.

The wet process or hydrometallurgy includes those processes that use water (aqueous phase reactions) or acid or base solvents to selectively dissolve metals from the ores that contain them and that work at low temperatures. Hydrometallurgy is scalable and the equipment it uses does not require as large an investment as in pyrometallurgy where economy of scale offers

[71] A description of the pyrometallurgical process by the imperial smelting method can be found in (Sancho et al., 2000).

lower costs. Nowadays, hydrometallurgy is increasingly used, representing more than 70 % of metallurgical processes.

On the other hand, dry or pyrometallurgical processes use high temperatures to obtain the metal from the ores that contain it. It is the oldest metallurgy, although it has evolved over time. Today it is used with efficiency and advantage over hydrometallurgy to obtain metals such as copper or lead.

In addition, there are other less common options such as electrometallurgical and bio-metallurgical processes. The former use electricity and can be part of both pyrometallurgical and hydrometallurgical processes, and in the latter, the metal is obtained through a process in which bacteria are a supporting element that is complemented by electrometallurgy. Electrometallurgy and biometallurgy are usually complementary processes.

In addition, this chapter has presented in some detail the metallurgical processes used for four metals relevant to the energy transition and digitization: copper, lithium, rare earths and zinc. This description has highlighted the need for pyrometallurgical and hydrometallurgical processes and their engineering content, supported by scientific and technical knowledge from various disciplines.

5

DIGITALIZATION AND INNOVATION IN MINING AND METALLURGY

1. Introduction

Mining and metallurgy are no strangers to technological innovations. This chapter covers some aspects related to digitization and innovation in mining and metallurgy. It is not intended to be exhaustive, but it has been considered important to dedicate a chapter to it, taking into account the role of mineral raw materials in digitization.

In the case of mining, the first phase is mainly covered, not entering into the processing or transformation of the mineral (mineralurgy) where digitalization; such as sensorization, systems and process monitoring, have been incorporated into the mineral transformation processes.

In recent years, the advancement of ICT and automation has transformed many areas. Automated equipment, heavy machinery, vehicles, devices and many other work tools offer a solution to various problems or simplify manual work. Automation not only reduces the time required to perform a task, thereby reducing the costs associated with it, but also standardizes and optimizes the operations and performance of industries. It also allows operations to run uninterruptedly 24 hours a day. These technological advances are therefore very useful in the mining sector. Like most industries, the mining sector incorporates the requirements and challenges of the 21st century. As a result, the mine is rapidly becoming the smart mine or 4.0.

This chapter deals, on the one hand, with digitization aspects related to what can be called smart mines, of which several cases are briefly described, and, on the other hand, with other technologies related to innovative and/or digitization aspects, both for mining and metallurgy.

2. *Smart mine*[72] and mine of the future

An "Intelligent Mine" is defined as a mine that maximizes the use of information technology, measuring instruments, communication and remote control systems to serve the activities contemplated in the entire value chain, from the location of the deposit to the closure of the exploitation.

The standardization and extension of industrial automation to the field of mining operations involves a series of improvements in different areas, including at least the following: (i) improved efficiency and reliability of production through real-time monitoring of operations in the production chain (from mine to port), (ii) risk reduction and improved protection of personnel through location technologies, the ability to operate remotely and monitor hazardous work areas (with sensors, alarms, regulation of maintenance permits, etc.), (iii) improved safety and security of personnel, and (iv) the ability to monitor and control the operation of the mine and its equipment (with sensors, alarms, maintenance permits, etc.).

[72] *Connected mine*, *Digital mine* or *Mine 4.0*.

(iii) increased productivity through the automatic exchange of information across business processes and applications, and (iv) reduced production costs through real-time visibility of assets, which helps to identify potential problems in advance. Figure 41 summarizes the different areas of digitization for mining companies.

Personnel and work	Sustainability	3. Operations and technology
• *Innovation in the business model* • *Government and staff* • *Collaboration*	• *Security* • *Energy and environment*	• *Remote operations* • *Information integration and visualization* • *Productivity, efficiency and cost reduction* • *Asset management*

Figure 41. *Areas of application of the digital technologies in the mining industry of the future. Source: authors' own elaboration.*

Figure 42 illustrates different digital devices and equipment in an open pit mining complex.

Figure 42. *Presence of digital devices and equipment in an open-pit mining complex. Source: (López Jimeno, C., 2022).*

For their part, mines are using and will increasingly use a whole range of technologies that enable and will enable progress in productivity, safety and economic objectives. Some of these innovative technologies include: power grids, on-demand ventilation, automated dewatering, predictive maintenance, integrated geospatial information modeling, and traffic management. An infographic on mine automation and digitization is shown in Figure 43.

Figure 43. *The mine of the future. Source: (López Jimeno, C., 2022).*

3. Mining digitization initiatives

The following is a list and brief description of various initiatives, some mature and others in the experimental phase, of what is currently considered technically feasible in terms of digitization of the mining sector[73] . Without being exhaustive, the set of initiatives described is illustrative of the actions already in operation. In particular, *software packages* for reservoir modeling, robotic drilling equipment, autonomous dump trucks, fleet management and wireless explosives initiation systems will be briefly described.

3.1. Reservoir modeling and mine design *software* packages

Since the eighties, with the appearance of personal computers, the development and use of computer applications for modeling the deposits under exploitation has been boosted, as already presented in chapter three. The vast majority of the *software* is designed to handle a large volume of data, the result of different drilling campaigns; for example, in metallic deposits there are some developments adapted to the reality of these, which translate a rock mass or deposit with the same lithological characteristics, differentiating a small number of volumes.

Most applications are based on block models, as shown in Figure 44, i.e., small parallelepipeds that are assigned attributes, either because they have been traversed directly by soundings or because the values resulting from interpolation have been assigned.

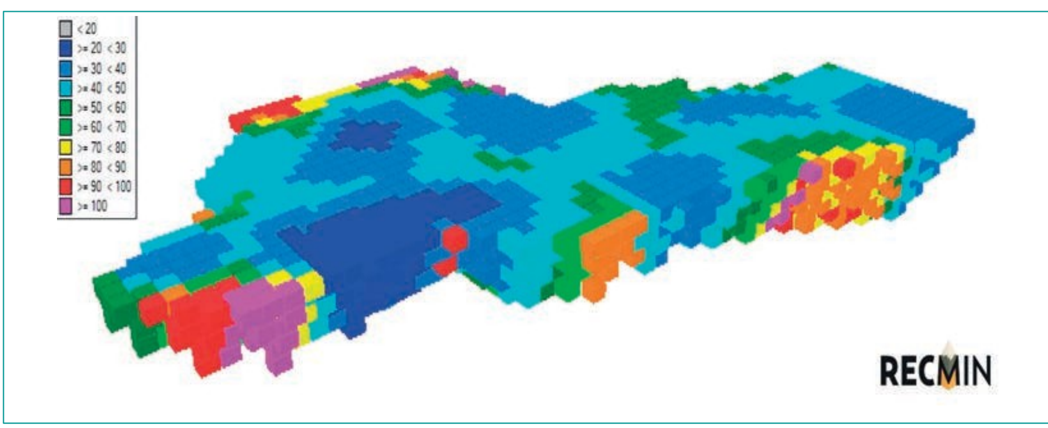


Figure 44. *Cut according to uranium concentrate price (Winter's method). Source: (Jares, 2022).*

Once the corresponding geological model has been created, the so-called economic model is constructed, estimating the value of the deposit based on the grade, estimated costs and the expected metal price. Next, the geometric design of the final shaft is constructed by applying one of the algorithms or techniques of operations research. Designs can be created to maximize ore recovery while meeting conditioning factors such as minimum cut-off grade, financial constraints and ground stability.

[73] The digitization of mining is something that has been developing over the last decades, as derived from Bustillo et al. (2000).

3.2. Drilling equipment

3.2.1. Open sky

Current trends in drilling improvements are basically twofold. First, there is the continuous recording of drilling parameters: drilling speed, thrust, speed and torque. This makes it possible to produce three-dimensional plans, representing the geomechanical characteristics of the ground, constituting a tool for the subsequent design and configuration of the explosive charges to be used, adapting them to these parameters. These logging systems are known as MWD (*Measuring While Drilling*).

Secondly, there is the remote and automated control of several drilling rigs by a single operator with positioning of the drilling rigs by geolocation based on satellite technology (GPS, GLOSSNAS, GALILEO, etc.), eliminating staking errors (Figure 45).

Figure 45. *Sandvik's Automine for drilling. Source: (Sandvik).*

The advantages of these systems are manifold[74] : (i) accurate location in position and elevation, (ii) accurate drilling depth and angle, if any, (iii) application of optimum drilling, thrust and rotational speed parameters at all times, (iv) increased tricone life, (v) reduced supervision before and after drilling, (vi) reduced maintenance costs, (vii) increased production, (viii) improved fragmentation and (ix) reduced repiés.

3.2.2. Subway

The development of computer technology and its application to mining equipment has yielded good results in the so-called drilling jumbos for tunnel and gallery advancement. By means of the on-board computer, it is possible to automate numerous operations carried out by the arms that support the slides with the drilling hammers. In the past, one person was needed for each arm, whereas nowadays one person can supervise the three arms working simultaneously, executing the holes, previously designed following a certain drilling pattern elaborated with *ad hoc software*.

Figure 46 a shows the *AutoMine Concept Underground Drill* "Amelia", a fully autonomous twin-boom development drill rig capable of drilling without human interaction. It has no cab for the operator, creating space for water storage and battery storage,

[74] The manufacturers Caterpillar, Epiroc, Komatsu and Sandvik incorporate these systems.

eliminating the need for supply cables or water hoses during operation. During drilling, Amelia uses an AI-guided automatic bit changer to identify when bits are worn and automatically changes them. The rig uses power as needed, making it even more autonomous.

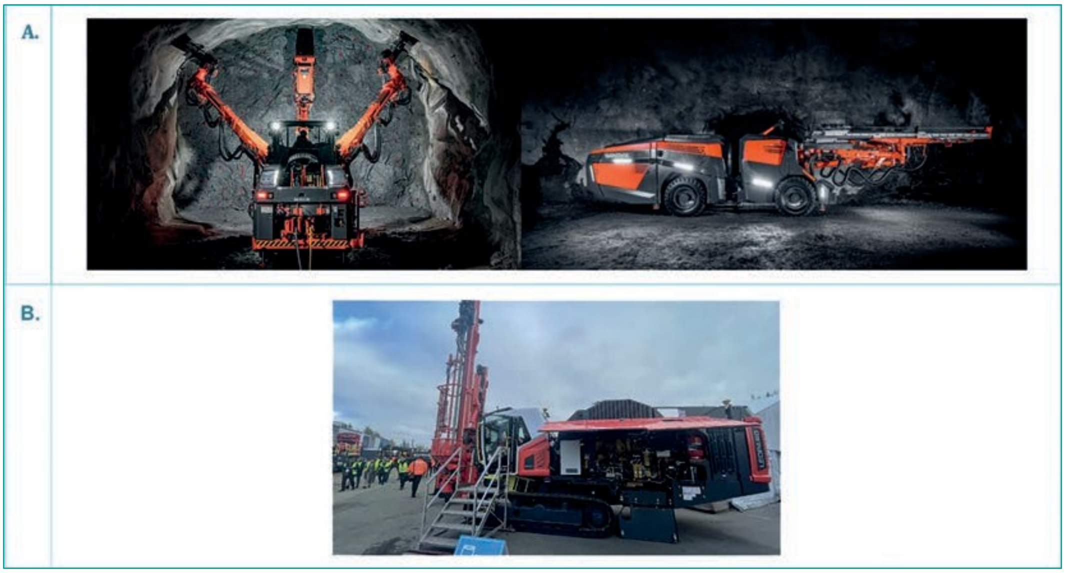


Figure 46. A. *Three-arm robotic jumbo (Sandvik),* ***B.*** *Downhole hammer smart drilling rig. Leopard DI650i. Source: (ProfesionalesHoy, 2021).*

Analogous to the development experienced with drilling equipment, the so-called miners have also incorporated this technology, which allows them high precision and the possibility of controlling the excavated profile, minimizing deviations.

3.3. Autonomous dump trucks

Since the first decade of the 21st century, the world's major dump truck manufacturers, Caterpillar, Komatsu, Liebherr and Hitachi, have carried out a large number of tests on large farms with driverless dump trucks. The benefits obtained were: (i) increased productivity (15-20%), (ii) increased availability (up to 90%), (iii) reduced fuel consumption and GHGs (5-7%), (iv) increased tire and brake life (5-7%), (iv) reduced maintenance costs (17%), (v) greatly increased safety in operations, (vi) reduced staffing levels and (vii) reduced operating costs (30%).

In a study of an Australian mine, it was found that the greatest savings in production cost were due to the increased effectiveness of the operation (85 %), while the reduction in personnel was 10 % and that of tires 4.5 %.

Among the systems available are the AHS (Autonomous Haulage System), Komatsu's FrontRunner and CAT's Command for Hauling. All dump truck manufacturers feature autonomous haulage systems (Hitachi, Liehberr and Belaz).

The AHS was implemented in 2008 at Codelco's Gabriela Mistral mine and was controlled by the Dispatch fleet management system of Modular Mining, a subsidiary of Komatsu. The evolution curve of autonomous units is shown in Figure 47.

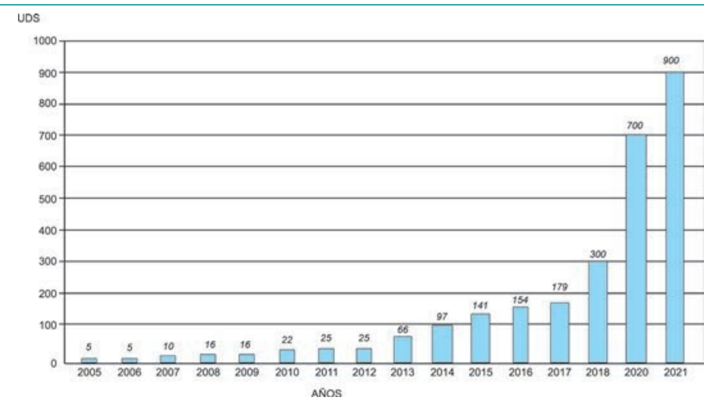


Figure 47. *Evolution of the number of autonomous dump trucks (units). Source: modified by the authors from (López Jimeno, E., 2022).*

A self-contained dump truck consists of four systems: (i) pickup, (ii) control, (iii) geo-reference and (iv) radio.

The former captures real-time information about objects in dynamic or static behavior, as well as rolling surface conditions, providing data for the autonomous control system to make decisions, ensuring the integrity of the vehicle and avoiding collisions or accidents .[75]

The control system brings together all the interactions that occur in the equipment. The drive, steering and braking system receives the reference values calculated by the system algorithm. There are more than 2,000 measuring points on the tipper that guarantee the planned behavior of the operation.

The georeferencing system is based on two GPS receivers, linked to a set of satellites. Loss of signal means that the operation stops.

Through the radio system, the dumper has access to the communications network of the command center and receives information about the other entities in the system, the transport tracks, as well as the *dispatching* production con- signas. Rio Tinto has put into operation three irrigation dumpers (Figure 48), which automatically detect the areas to be irrigated and refill water.

Figure 48. *Autonomous irrigation truck. Source: Caterpillar.*

3.4. Electric dump trucks

Motion Traction ABB and Hitachi Construction Machinery have agreed to develop an all-electric dump truck. This dump truck, which is in varying degrees of development, will be powered through

75 The AHS system uses LIDAR, Radar, high precision geopositioning and inertial sensors.

a catenary, while charging the batteries developed by ABB. The use of the dynamic brake on negative gradient routes will also recharge the batteries.

The energy stored in the batteries will be used to drive the dump truck during loading and unloading maneuvers in the pit and in the crushing plants (Figure 49).

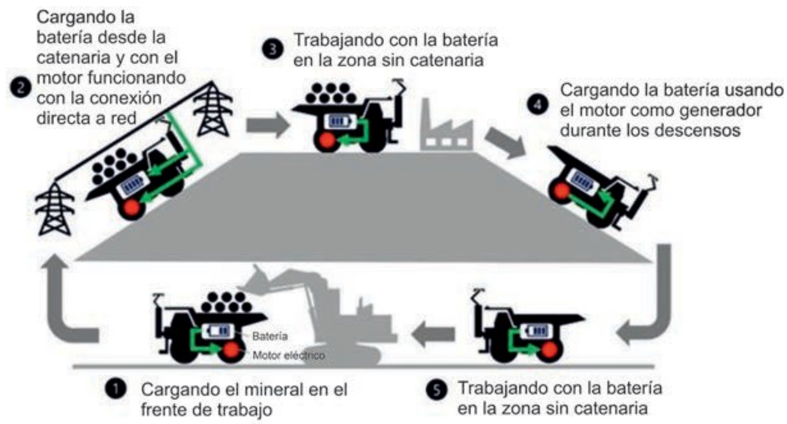


Figure 49. *Hitachi electric dump truck operation. Source: modified and translated by Hitachi authors.*

The advantages of the system include: (i) reduced empty weight of the dumper, (ii) increased productivity and (iii) elimination of diesel fuel (Figure 50).

Figure 50. *Hitachi dump truck powered by trolley. Source: Hitachi.*

3.5. Dump truck fleet management (*Dispatching*)

This technology has been used since the 1980s in large mining operations and is known as the dynamic dump truck dispatching system. Geolocation systems are used to assign each dump truck to a loading equipment and a dumping point. The advantages obtained by its use are the following: (i) increased productivity,
(ii) increased safety with anti-collision systems between vehicles, (iii) improved track maintenance, (iv) better control of ore grades at entry, and (v) on-line decision making information system. Figure 51 shows a mineral processing system (i.e., crusher) of dynamic dump truck assignment inside an open pit mine.

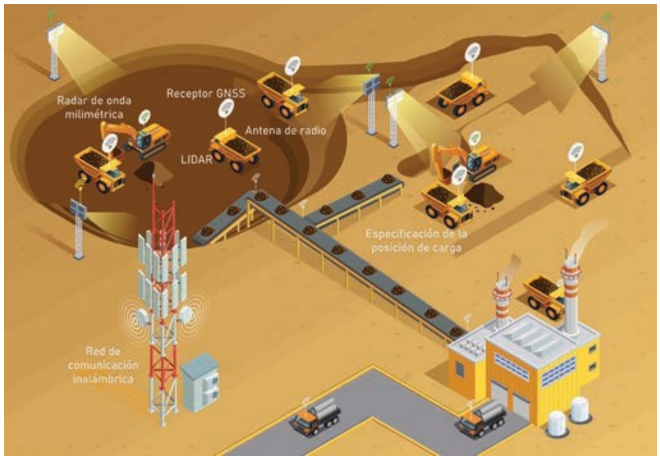


Figure 51. Dynamic assignment of Hitachi dump trucks inside an open pit mine. Source: modified by the authors from (López Jimeno, C., 2022).

3.6. Wireless initiation systems

Unlike traditional wired systems, in wireless initiation systems, the firing signals travel in waves from the blaster to the detonator. For example, ORICA's Webgen™ system communicates with the detonator inside the blast hole using ultra-low frequency waves, called magnetic induction.

The blast sequence is "stored" in the multiplier during the encoding that is performed when loading the blast. All Webgen units™ require the correct single signal to "wake up" and then the correct signal to fire (Figure 52).

The so-called Wireless Primer or wireless multiplier consists of three components: i-KOM™ ; DRX™ and Pentex™ (Figure 53). The electronic detonator i-KOM™ is connected to a receiver comprising a multidirectional antenna and a battery that serves as a power source inside the ground. On the other hand, an encoder controller is required. This encoder contributes to the inherent safety of the system and programs each multiplier with two codes. The first code is a number of

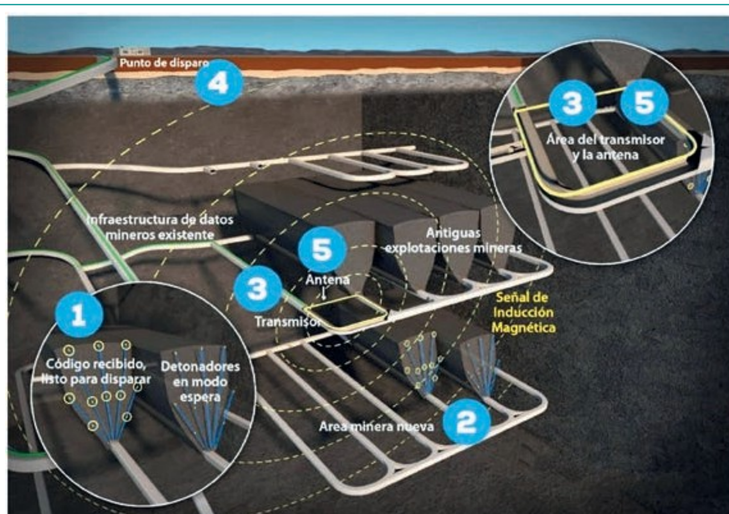


Figure 52. Schematic of a mine using a mining system. wireless initiation of blasting. Source: (López Jimeno, C., 2022).

Figure 53. *Components of the wireless initiation system (WebgenTM, Orica). Source: (Orica, 2022).*

group identifier (GD), which is unique to each mine and is assigned to specific groups of multipliers that will be fired together. The second code is a "return time", specific to the "wireless" primer and blast design.

There is also the transmitter controller that provides the activation commands, and the actual activation, for a group of encoded™ DRXs. Finally, the portfolio can be a portable four-loop for short-range transmission or a 40 m loop for long-range transmission.

3.7. Other technologies

Table 18 lists the digital technological developments that are being used in mining, some of which, at least in part, have been discussed previously.

Table 18. *Mining digitization initiatives. Source: own elaboration of the authors.*

Designation	Description
Digital scanning of core boreholes	Use of scanner devices for the analysis of rock samples obtained by drilling. It allows to speed up the digital storage of a large volume of data in image format, as well as additional information that can be generated through the analysis of samples.
Portable X-ray fluorescence analyzers (XRF)	Analyzers that, in a simple and very fast way, perform a sweep of all the chemical elements that make up the material to be analyzed.
Real-time auger drilling analysis	Monitoring ore grades during blast hole drilling can help to better understand the spatial distribution of mineralization grades and reduce dilution with adjacent tailings or ore loss, resulting in increased ore production and recovery at the plant and ultimately reduced processing costs.
Unmanned aerial vehicles or drones	In open-pit mining, the main applications of drones are: inspection of facilities or work areas that are difficult to access, topographic surveys and cubing of ore stockpiles or tailings dumps; exploration, etc. Subway mining has also begun to use this equipment (spherical drones), with the capacity to fly in subway spaces where GPS signal is not available and to scan and model in 3D such excavations, for the following purposes: (i) subway topography of tunnels, chambers, etc., (ii) inspection and maintenance of infrastructure, (iii) generation of 3D models and high definition virtual reality, and (iv) evaluation of environments for safety and risk prevention.
Traceability	Devices have been developed that allow traceability on farms (RFID Technology). In the event of any incident, it is possible to know the exact location where it has taken place, allowing emergency teams to act immediately. They can also be used to avoid collisions between vehicles inside the mine or the running over of personnel by knowing the relative position of each one. There are mines where smart sensors are combined with traceability devices that ensure that there are no personnel near the blasts that are going to be fired, or where ventilation air management is carried out by sending fresh air flows to where there is a higher concentration of personnel.

Surface drills governed b y remote control	Communication is via a WiFi communication network, so it is independent of the local network infrastructure and can be installed in a vehicle, a trailer or inside a container. It is particularly useful when rigs have to drill at the foot, for example, of slopes where there is a risk of landslides. In addition to the obvious safety advantages, these units also allow for increase productivity as up to three pieces of equipment can be controlled simultaneously.
LHD Blades	The LHD (*Load-Haul-Dump*) shovels perform loading, transporting and dumping. They are operated by remote control and battery-electric drive.
Autonomous drills	At the Rio Tinto Group's Pilbara iron ore mine, seven large rotary drills are operating autonomously under the remote supervision of one operator for every four machines.
Explosives manufacturing and loading trucks	There is an increasing tendency to manufacture explosive charges *on site* by mixing substances that are not intrinsically explosive and sensitizing them just before initiation. For this reason, mobile explosives factories are being designed for both subway and open pit works, which make it possible to work with high safety standards and to adapt the explosive charges in terms of the energies that develop the resistant properties of the rocks that have been previously drilled and, by means of sensors, have made it possible to characterize the rock masses. The latter systems are known as *Measurement While Drilling* (MWD).
Electronic detonators	These accessories have a microchip inside the capsules, which allows programming the detonators so that they have exit times at desired intervals, with a very high precision, of the order of a millisecond, and facilitating that the detonation times of the charges within the blast are not repeated. This results in better fragmentation and reduced vibration intensities.
Remotely operated machinery	Changes or improvements ranging from greater automation of the different operations or movements of the machines, without human intervention, through remote control, so that operators are no longer physically mounted on the machine but at a certain distance if it is found that there are risks due to rock falls, collapses, etc., to the machine being inside the mine and the operator on the surface. At the upper level there will be the autonomous equipment, which act as real robots.
Indoor electric dump trucks	Battery-powered all-electric vehicles have begun to be marketed. At the same time, several hybrid units have been developed, as well as the trolley technology, which originated in Scandinavian countries. In addition, mobile recharging equipment has appeared on the market, eliminating the need for static electric recharging posts or stations.
Connected machinery	Systems that allow communication between equipment of the same brand.
Indoor mobile telephony	In several mines, the mobile communication standard known as *LTE Advanced (Long term evolution*) has been implemented, which allows the quality use of cell phones in subway environments.

4. Metallurgy digitization initiatives

The enabling technologies of Industry 4.0 find application in the metallurgical industry, enabling its digitalization. Metallurgical factories are undergoing a major transformation by incorporating sensors, interconnecting machines and processes, capturing, processing and analyzing data, developing decision-making algorithms and digital twins that emulate physical processes, allowing product improvement and development cycles to be shortened.

Among all the available technologies, the following can be highlighted: microstructural modeling and mechanical properties, internet of things and cyber physical systems, digital twins, data analysis, artificial intelligence, collaborative robotics, virtual reality and augmented reality .[76]

[76] Technologies such as 3D printing (such as *Selective Laser Melting* (SLM) and *Direct Metal Laser Sinte- ring* (DMLS) based on the fusion of powder layers or the *WAAM Wire Arc Additive Manufacturing* process) are not included in this chapter, as they correspond more to a forming technique for the manufacture of components and what is referred to here regarding digitization is more focused on extractive metallurgy processes.
In any case, the aluminum alloy die-casting process can be cited, which allows production automation, incorporating all the enabling technologies of Industry 4.0.

4.1. Microstructural modeling and mechanical properties

The properties of materials depend on their composition and microstructure. The microstructure is the consequence of five factors: cleanliness of the melt, chemical composition of the alloy, solidification process, thermo-mechanical deformation and heat treatment.

It is necessary to understand how each variable intervenes in the mechanical properties of the material subjected to tensile stresses. In this sense, the modeling of the microstructure makes it possible to predict the mechanical behavior in service under different load hypotheses, including fatigue stresses, optimizing the heat treatment process that controls, for example, the size and distribution of precipitates in structural light alloys.

4.2. Internet of things

The Internet of Things (IoT) refers to the set of technologies that enable the harmonious and collaborative integration of all value creation processes in an industry such as metallurgy.

Digitizing is not only about sensorizing the process machines, capturing signals that are uploaded to the Internet, but also about integrating the information into a platform that enables the management of operations and business processes, providing the system with data mining and analytical capabilities that facilitate continuous improvement and the development of decision algorithms.

The IoT is the set of technologies that make it possible to implement the new paradigm of connected industry and the development of cyber-physical systems. In short, it is about implementing systems that facilitate change management in organizations and the optimization of manufacturing processes (Table 19).

Manufacturing operations	**Batch and unit tracking**	**Traceability and genealogy**	***Routing and dispatching***	**Data collection and acquisition**	**Operator training and certification**	**Bill of Materials (BOM)**
	Consumable management	Tool management	Working Instructions/ SOPs	Label and document printing	Task management	Order management
Process engineering	New Product Introduction (NPI)		Receipt management		Experiment management	
Equipment engineering	Equipment tracking		Maintenance management		Calibration	
Quality management	Statistical Process Control (SPC)	Preventive and connecting actions (CAPA)	Non-conformity reports and provisions	Sample-based inspection/ AQL	Document management	Electronic signatures
Planning and logistics	Advanced planning and scheduling		Materials management		Cost calculation	
Visibility and intelligence	Control panels	Reports and analysis	Operational data store and data warehouse	Alarm management	Factory digital twin	Augmented reality
Automation and integration	Equipment integration		Factory automation workflow management		Enterprise integration (ERP, PLM, …)	
IoT data platform						

Table 19. *Systems for change management. IoT. Source: translated and modified by the authors of (Neves, 2022).*

4.3. Digital cufflinks

Digital Twins are digital models that emulate the performance of a process or the behavior of a product. In the metalworking industry, their use is becoming increasingly widespread. Figure 54 presents the enabling technologies and the solutions and services that lead to the creation of a *digital twin* of a blast furnace.

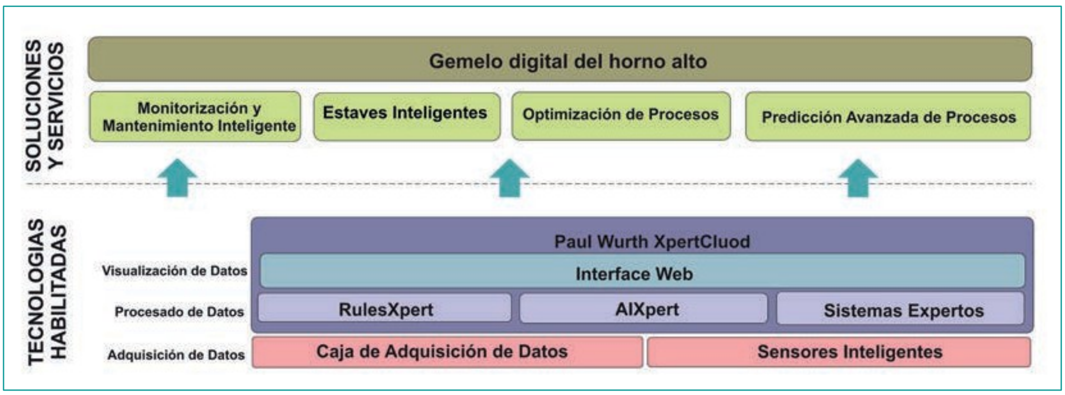


Figure 54. Enabling technologies for digital twins in a blast furnace. Source: translated and modified by the authors of (Weyer et al., 2019).

The essential elements to be included in a digital twin are threefold: context and characteristic data, real-time operational data and implementation of a holistic information model as shown in Figure 55.

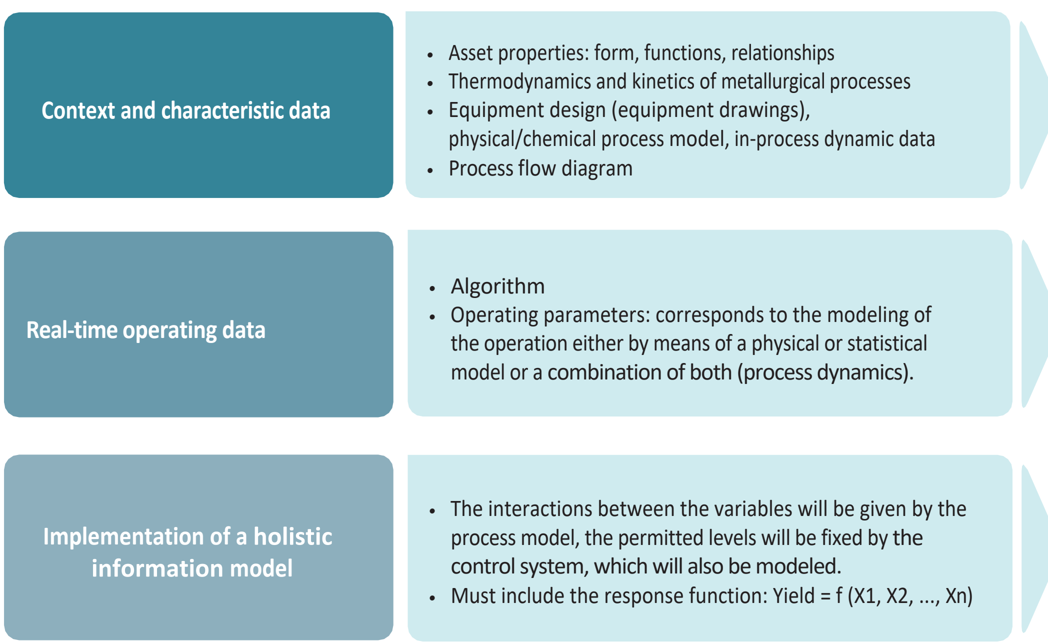


Figure 55. Elements of a digital twin. Source: authors' own elaboration.

4.4. Data mining, big data and data analysis

The collection of huge amounts of data through the sensorization of machines working simultaneously to develop a metallurgical process requires the management of data traffic, its storage, management, cleaning, processing and analysis.

The metallurgical industry has invested heavily in *data mining,* which has made it possible to capture and store information securely, but this is not synonymous with efficient data exploitation. In order to create value from data, it is necessary to extract, clean, combine, visualize and establish relationships. This is what is known as *data analytics* and *business intelligence* .[77]

The data cleaning phase is essential to prevent manual transcription errors from invalidating the results obtained by processing incorrect data. In this sense, the data validation process is essential to avoid the existence of hidden data (those stored in non-integrated databases, in devices not connected to the central server, in Excel sheets, or in non-processable formats). In metallurgy, it is essential that the data be obtained and processed by applying the principles of Six Sigma, a well-known quality technique, whose basic fundamental stages are those of define, measure, analyze, improve and control (DMAIC).

Metallurgical processes cannot be reduced to a mere statistical analysis. Therefore, the analysis must start from the *state-of-the-art* by setting the so-called MCC (Best Known Conditions), opening the field of experimentation following the principles of design of experiments (DOE), setting the number of variables and levels of experimentation, and measuring the response.

Industry 4.0 enabling technologies allow metalworking industries to move from trial and error to the development of algorithms and cyber-physical systems that take into account the interactions of controllable and non-controllable factors.

4.5. Artificial intelligence

Due to the complexity of metallurgical processes, especially in non-ferrous extractive metallurgy, Artificial Intelligence (AI) is having a slower penetration than in globally replicated processes, such as the steel industry, whose differentiating aspects between countries and companies is lower.

Nowadays, artificial intelligence must be seen as a tool to improve processes, facilitating routine decision making, in many cases, dependent on a human decision at the plant.

Artificial intelligence applied to machine vision is a real field of work and improvement. In the laboratory, it enables the automatic processing of metallographic images, and in the plant it facilitates quality and process control systems, as well as improvements in process reliability and productivity.

4.6. Other technologies

In addition to the above, other advances have been made, such as the use of cameras to measure particles or bubbles, velocities, noise and temperature in the control of plants that optimize mineral extraction processes.

[77] A process model must be available to perform the data analysis.

On the other hand, collaborative robotics (Cobot) will be penetrating the metalworking industry, starting with the final part of the manufacturing processes, the most susceptible to robots and people sharing workspace without physical safety barriers between them.

Virtual reality and augmented reality will penetrate design processes more easily, facilitating the implementation of the aforementioned *Design for Six Sigma* methodology, reducing the probability of failure by advancing in the improvement of virtual environment simulation technologies that reliably emulate real conditions, while shortening the time to market for new developments.

5. Conclusions

Digitization methods and techniques are already being applied in mining, mineral processing (mineralurgy) and metal extraction (metallurgy). Their applications are being implemented in areas related to deposit modeling, robotic drilling equipment, autonomous dump trucks, fleet management, core scanning and monitoring of samples and explosives.

In mineral processing, the use of sensors in different parts of the process (i.e. grinding, flotation) allows integrated monitoring and control systems. In metallurgy, modeling of microstructures and mechanical properties, as well as digital twins or data analysis, allow to improve metallurgical processes and their quality.

Digitalization is having, as a result of its implementation in various applications, an improvement in safety, an increase in productivity and access to low or very low grade resources. It also reduces environmental impacts and facilitates innovations and improvements in processes and business models.

Digitalization in mining and metallurgy has opened a path that will allow these activities to become increasingly safer, more sustainable and with less environmental impact.

6

SUSTAINABILITY AND CIRCULAR ECONOMY IN THE SOURCING OF RAW MATERIALS MINERALS

1. Introduction

This chapter examines the role of mining and metallurgy in the context of sustainability and the circular economy. Mining and metallurgy face significant challenges and opportunities to advance sustainability, a concept introduced by the Brundtland report of the United Nations General Assembly-appointed commission ("World Commission on Environment and Development"), which defines sustainable growth as "growth that meets the needs of the present without compromising the ability of future generations to meet their own needs."

In other words, sustainable development is that which allows the present and future generations to have the natural resources necessary for their reasonable development with a certain degree of well-being, while nature has the necessary capacity to maintain its physical, chemical and biological processes, all within the scientific, technological, economic, social and cultural environment existing at any given time. Its implications include minimizing the impact of any activity on the environment, while maximizing its social and economic contribution.

In the case of the circular economy, the paradigm of "extract, make, use and throw away" (linear economy) is replaced by a different one, which can be described as "extract, make, redesign, reduce, reuse, repair, renew and recycle" (circular economy, a concept to which we will return later).

Although from a simplistic viewpoint it can be understood that the circular economy aims only to obtain maximum value from materials by ensuring that they are produced responsibly and remain in use for as long as possible, an in-depth analysis will allow us to understand the breadth of the aspects it covers and the universe of changes and opportunities it brings to the structure of product value chains and how they interact with the world around them, an in-depth analysis will allow us to understand the breadth of the aspects it encompasses and the universe of changes and opportunities it brings to the structure of product value chains and how they interact with the world around them, and thus the implications for all sectors of the economy, and in particular for mining, the production of mineral raw materials, metallurgy and the manufacture of metals for equipment and components.

In line with society, mining and metallurgy are immersed in transformation processes to use circular methods of production and consumption, implementing circularity principles and schemes in management.

This presents challenges and opportunities for the raw materials sector in general, and mining and metallurgy in particular, aligned with the European vision of using resources efficiently, ensuring a sustainable supply of raw materials for the European economy, increasing the benefits for society as a whole, and creating new jobs.

This chapter covers the concepts of sustainability and circular economy, referring in particular to the objectives of sustainable development, the European and Spanish framework and the indicators of sustainable mining and metallurgical management.

It then examines the circular production model in the context of sustainability, the European Union's action plan for the circular economy, addressing the benefits and advantages of circular economy in particular in the mining and metallurgy value chain, as well as the Spanish circular economy strategy.

The final sections discuss the role of metallurgy in the recycling of secondary raw materials, sometimes referred to as urban mining, and industrial symbiosis as a solution for the management of waste from mining activities. Finally, the challenges and opportunities for further integration of the circular economy are presented together with the conclusions of the chapter.

2. On the concept of sustainability

Sustainable development rests on three pillars (Figure 56): economic sustainability (economic growth), social sustainability (social equity) and ecological sustainability (environmental protection), where the importance of each principle will depend on the uniqueness of the region in which it is applied, understanding sustainability as the long-term viability of industrial activity and its social and environmental surroundings.

Figure 56. *Diagram of the three pillars of sustainable development. Source: (Universidad Andina Simón Bolívar, n.d.).*

At the EU level, the Raw Materials Initiative (European Commission et al., 2018), incorporates the fair and sustainable character of the supply of raw materials, both primary and secondary, from global markets and in the EU, as well as the efficient use of resources. As a result, in order to attract investors to a mining project, once the geological potential and economic viability have been assessed, a sustainability analysis must necessarily be completed, which must take into account not only the environmental aspect (key, both during mining operation and rehabilitation), but also the social aspect and in particular that of community relations.

As for the economic perspective, since the 1980s, when it was already pointed out that sustainability would become a spearhead in the mining industry, until today, progress has been made in terms of corporate reporting, so that financial information must be supplemented with information related to the sustainability-ESG (Environmental Social and Governance) duality (Kesler, 2015).

Sustainable development in mining, according to the Australian government, refers to the "*development of a country's mineral and energy resources, onshore and offshore in such a way that maximizes economic and social benefits while minimizing the environmental impacts of mining*" (BBVA, 2023).

A sustainable development policy for the mining sector should cover the entire cycle, from exploration to the rehabilitation of the area affected by the mining activity. It should also include the stages of extraction, production, metallurgical processing and marketing of mineral products and metals, as well as the use and recycling of metals, carrying out these activities as efficiently as possible and maintaining or improving, where appropriate, the quality of the environment for future generations.

In 2015, the UN Sustainable Development Goals (SDGs) were published, which have set out a vision for a future global society based on principles of sustainability. The 17 goals, which make up the agenda and are shown in Figure 57, cover the ecological, economic and social dimensions of sustainability. These goals provide principles and a reference for national and local policy. Businesses are encouraged to commit to improving the sustainability of production processes and policy makers at all levels are asked to align their strategies with the principles of sustainable development.

Figure 57. *Sustainable Development Goals. Source: (United Nations, n.d.).*

Success in meeting the challenge of "good governance of natural resources" requires planning a long-term agenda that finds a framework in the SDGs. Along these lines, there is a roadmap with goals and targets. Its implementation requires joint efforts between government, the private sector and civil society. Carrying out this roadmap implies the recognition of commitments that must be translated into measurable indicators that can be monitored and thus provide real and updated information on the degree of progress.

The SDG framework does not include an explicit target on raw materials, as they can directly or indirectly influence all the goals. The extractive and metals value chain sector can contribute significantly to the achievement of all 17 SDGs, in particular those related to poverty eradication (SDG 1), clean water and sanitation (SDG 6), affordable and sustainable energy (SDG 7), decent work and economic growth (SDG 8), industry and infrastructure (SDG 9), climate action (SDG 13), as well as peace and justice (SDG 16). Table 20 shows different aspects of the mining and metals sector in some of the SDGs.

Table 20. *Influence of the mining and metallurgical sector on some of the SDGS. Source: authors' own elaboration based on (Narrea, 2018). y (World Economic Forum, 2016).*

ODS	Description
1	**Poverty eradication.** Commodity sectors can be a stimulus for the local economy, creating stable and quality employment, increasing the population's income and creating business opportunities.
2	**To end hunger, achieve food security, improve nutrition and promote sustainable agriculture.** The extractive sector and the processing industry supply fertilizers for agriculture, e.g. phosphate and potash. By boosting agricultural productivity, these sectors indirectly contribute to food security.
6	**Ensure availability and sustainable management of water and sanitation for all.** The extraction and processing of raw materials can affect water by creating local water stress, but, on the other hand, it provides essential raw materials for environmental technologies and water treatment.
7	**Ensure access to affordable, reliable, sustainable and modern energy for all.** Raw materials are required for the deployment of low-carbon and renewable technologies and mining operations create and maintain energy infrastructure that can also supply the local population.
8	**Decent work and economic growth.** The production of raw materials and materials generates revenues that governments can invest in socioeconomic development, employment and training opportunities, and technological and new infrastructure development.

9	**Industry, innovation and infrastructure.** Mining activity can contribute to local and regional development through the provision and improvement of physical infrastructure such as road networks, energy and water networks, or health and education systems. Raw materials are widely used in a variety of applications, including machinery. Some critical metals and materials are required for renewable energy components and related technologies, such as batteries for energy storage.
12	**Responsible production and consumption.** Resource efficiency is an objective of both environmental and industrial policy. The raw materials sectors have a key role to play in achieving the goal of resource efficiency, as they produce inputs for other sectors. Natural resources (land, water, energy, etc.) used to extract materials and produce semi-finished products can be optimized through innovative and clean technologies Eco-design (or eco-innovation) allows for improved efficiency.
13	**Climate action.** Industrial activities along the mining and metallurgy value chain produce GHGs, but their use in low-carbon technologies contributes to combating climate change.
17	**Revitalize alliances to achieve objectives.** This is a cross-cutting objective that seeks to encourage and promote effective partnerships in the public, public-private and civil society spheres, taking advantage of the experience and resource-raising strategies of the partnerships. The medium and long-term sustainability of mining projects depends on their public approval by the civil society in the area of influence. For this purpose, social responsibility projects are developed, which, according to national and international regulations, are a duty of the private sector and the government.

Figure 58 highlights the potential contribution of raw materials[78] to the different SDGs along the value chain, from extraction to manufacturing, use and end-of-life. Often, both positive and negative outcomes for the same objective are possible, so the goal is to maximize the former and minimize the latter, so as to have a positive and direct impact.

In December 2019, the European Commission published the European Green Pact (EVP) whose objective is to develop a sustainable economy, for which it proposes a Roadmap of rules and legislative developments.

[78] In this case raw materials include minerals (less energy), paper, wood, rubber and cork.

Figure 58. *Potential contributions of raw materials to SDGs along the supply chain. Source: modified and translated by the authors from (Mancini et al., 2019).*

The report also includes the need to ensure access to sustainable raw materials, especially the critical raw materials needed for clean technologies and digital, space and defense applications. It also includes the need to ensure access to sustainable raw materials, especially the critical raw materials needed for clean technologies and digital, space and defense applications, including the diversification of supply from primary and secondary sources. In addition to updating the list of critical materials in 2020 (mentioned above), a Raw Materials Action Plan was developed.

For its part, the Raw Materials Supply Group (comprising member states, regional authorities, industry associations, civil society, social partners and research organizations) and the European Commission have formulated and agreed on a set of voluntary principles for sustainable raw materials.

The principles are applicable throughout the Union, "*to the extraction and processing phases of non-energy raw materials and to the entire life cycle of mineral value chains, from exploration to post-closure, as well as to the production of secondary raw materials from extractive waste streams, such as waste rock, processing residues/ tailings*" (European Commission, 2021). These principles are listed in Table 21.

Table 21. *EU principles for sustainable raw materials. Source: authors' own elaboration based on (European Commission, 2021).*

Social principles	Economic and governance principles	Environmental principles
Human rights, interaction with communities of interest, employment, health, and safety	Business integrity, transparency and increased economic control	Environmental management and impact mitigation
Sustainable extraction and processing of raw materials support human rights, communities and good governance	The extraction and processing of sustainable raw materials comply with all EU laws and regulations, including the legislation of the EU Treaties.	Sustainable raw material extraction and processing apply good environmental management practices
Sustainable raw material extraction and processing supports decent work by: improving workers' health and safety, continuously improving workers' skills, and respecting workers' rights.	The extraction and processing of sustainable raw materials is an essential basis for sustainable value chains of strategic importance for the economic growth and sustainability of the European economy and society, including the transition towards climate neutrality and a digital economy, respecting the principle of "no significant harm" as set out in the EVP.	The extraction and processing of sustainable raw materials improve and promote energy efficiency, contribute to climate change mitigation and adaptation measures.
	Sustainable extraction and processing of raw materials apply sound financial management	Sustainable raw material extraction and processing include materials management and contribute to the economy. to the extent possible and within the scope of its responsibilities

In addition, 10 actions have been developed to ensure Europe's access to raw materials, which include (European Commission, 2021b): (i) launching the European Raw Materials Alliance, (ii) developing sustainable financing criteria for mining, (iii) research and innovation in waste treatment, advanced materials and substitution, (iv) mapping the potential su- minister of critical secondary raw materials from EU stockpiles and waste, (v) identifying investment needs for mining projects that can be operational by 2025, (vi) develop mining expertise and skills, (vii) deploy land ob- servation programs for exploration, exploitation and environmental management, (viii) develop research and innovation projects on the exploitation and processing of critical raw materials, (ix) develop international strategic partnerships to secure the supply of critical raw materials, and (x) promote responsible mining practices for critical raw materials.

In Spain, the proposed Long-Term Strategy for a Modern, Competitive and Climate Neutral Spanish Economy in 2050 established reuse and recycling as the first option. This strategy should involve the configuration of *a national policy for indigenous raw materials, ensuring that resources are exploited in an economically viable and sustainable way, using the best available techniques, ensuring the reduction of emissions in the sector and reducing dependence on imports as far as possible* (Third Vice-Presidency of the Government, Ministry for Ecological Transition and the Demographic Challenge, 2022).

For its part, the Roadmap, approved by the Council of Ministers on August 30, 2022, for the sustainable management of mineral raw materials, essential for the success of the ecological and digital transition, promotes the exploitation of the opportunities of sustainable indigenous mining in terms of quality employment, wealth and territorial structuring (Third Vice-Presidency of the Government, Ministry for Ecological Transition and the Demographic Challenge, 2022).

This Roadmap includes four strategic orientations: (i) efficiency and circular economy in the mineral raw materials supply value chains; (ii) boosting and consolidating the sustainable management of indigenous mineral raw materials in the Spanish extractive industry; (iii) guaranteeing security of supply and compliance with environmental, geostrategic and social justice requirements in the import of mineral raw materials; and (iv) promoting the mineral raw materials industry linked to the decarbonization process, aligning with European policies on access to resources and sustainability.

2.1. Sustainable mining-mineral-metallurgical management. Standards UNE 22480 and 22470

The Spanish Association for Standardization has developed the UNE 22480 standard "*Sustainable mi-neral-mineral-metallurgical management system. Requirements*" (UNE, 2019a). In this version, the field of application is extended to transformation mineralurgy and extractive metallurgy, which are added to mining and concentration mineralurgy existing in the previous version.

This standard is aligned with the most advanced sustainability initiatives such as the UN Global Compact Principles, the OECD Guidelines for Multinational Enterprises, the UN Guiding Principles on Business and Human Rights, the Equator Principles (one of the largest and most internationally accepted initiatives that

These principles are a voluntary credit risk management framework for identifying, assessing and managing environmental and social risks in project finance operations.) These principles have been promoted by different entities in the financial sector in coordination with the International Finance Corporation (an agency of the World Bank) and the Environmental and Social Sustainability Performance Standards (IFC World Bank). It is also aligned with specific areas of the mining sector such as Better Coal and the Sector Supplement for Mining and Metallurgy of the Global Reporting Initiative.

The UNE 22480 Standard specifies the requirements of a sustainable mining-mineral-metallurgical-metallurgical management system, whose ultimate purpose is to provide organizations working in sectors related to the aforementioned activities with a tool that facilitates the achievement of environmental, social and economic objectives, bringing them closer to the expectations of the environment in which they operate.

The sustainable mining-mineral-metallurgical-metallurgical management system is based on the Plan-Do-Check-Act (PHVA) continuous improvement cycle and is compatible with other management systems of the organizations. Figure 59 represents the continuous improvement cycle of the sustainable mining-mineral-metallurgical-metallurgical management system.

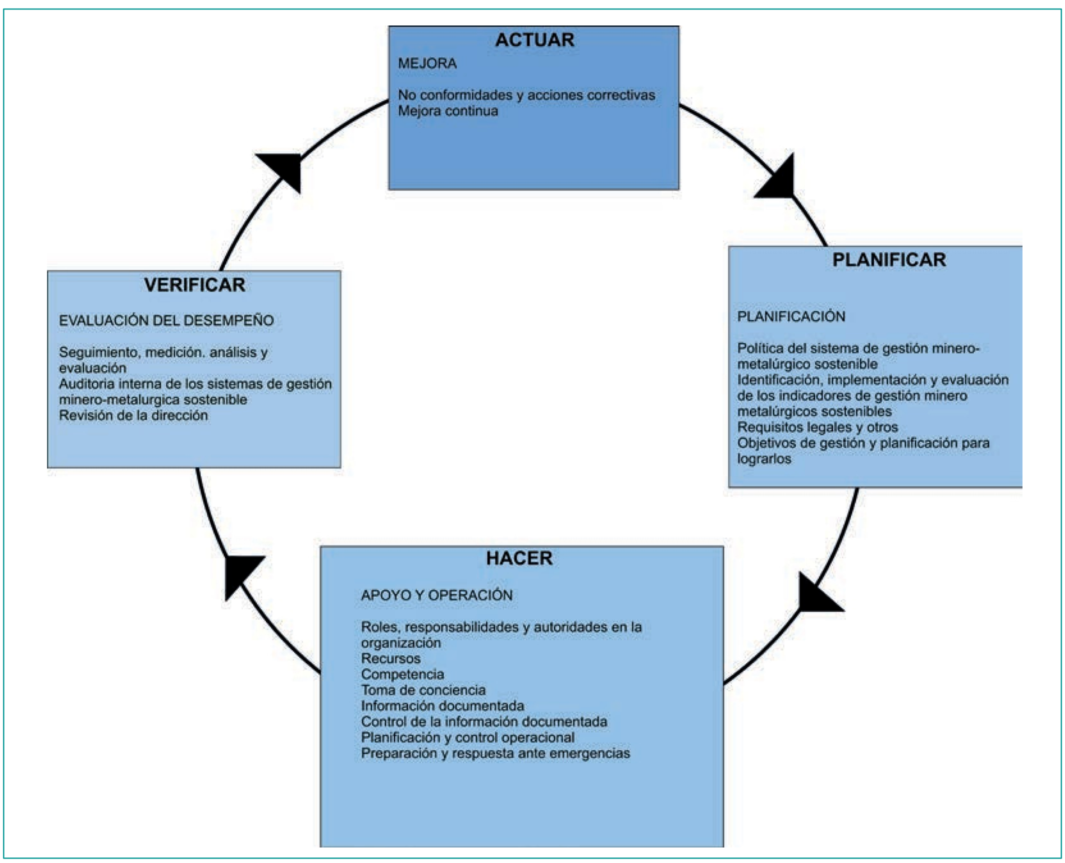


Figure 59. *Model of mining-mineralurgical management system sustainable metallurgy. Source: authors' own elaboration based on (UNE, 2019a).*

This standard is intended to be used in conjunction with UNE 22470 "Sustainable mining-mineral-metallurgical management system. Indicators" (UNE, 2019b), which aims to establish economic, social and environmental indicators (Tables 22, 23 and 24) for the evaluation of the implementation of a sustainable mining-mineral-metallurgical-metallurgical management system. In fact, as a result of the merger of mineral processing and extractive metallurgy, new indicators have been included in the UNE 22470 standard. Thus, it applies to the activities of the mining, concentration or transformation mineralogy and extractive metallurgy industries.

Indicator	Parameter
Economic management indicator	Annual production.
	Annual net sales.
R&D&I Indicator	Ratio of investment in R&D&I to the organization's annual EBITDA (*Earnings Before Interest Taxes, Depreciation and Amortization*).
Geological and Mining Research Indicator	Investment in geological and mining research.
Consumables indicator	Ratio of consumable materials in the extraction and processing of mineral resources or in obtaining products from extractive metallurgy or in geological research and exploration to annual production.

Table 22. *Economic indicators Source: (UNE, 2019b).*

The contribution of the raw materials sectors to employment in the EU goes far beyond the economic activities strictly related to the production of materials, so that incentives are created for local companies to participate as suppliers to the demand of mining and metallurgical companies. An observatory of technical and university careers linked to the professions and trades demanded by mining and metallurgy can also be developed, as there is a worldwide problem of a shortage of qualified professionals in these fields. In countries such as Canada and Australia, 60% of companies consider it important to invest in improving the skills of the workforce in the aforementioned fields (Fraser Institute, 2018).

Indicator	Parameter
Cultural Heritage Protection Indicator	Total expenditure on the protection of cultural heritage.
Indicator of communication with the socio-economic sphere of influence.	Monetary value of contributions from the company to the outside world, in activities of public or social interest, or of interest to the socioeconomic sphere of influence.
	Social response index.
	Number of types of participatory formulas implemented at the initiative of the company that promote the involvement of stakeholders in the socioeconomic sphere of influence.
	Ratio of consumables purchased in the socioeconomic sphere of influence with respect to the total.
	Services contracted in the socioeconomic sphere of influence.
Employment indicator	Total headcount.
	Total outsourced employment.
	Percentage of local labor.
Training indicator	Ratio of total hours of annual training to total employment.
Worker health and safety indicator	Frequency rate of accidents with sick leave for own and subcontracted personnel.
	Incidence rate of accidents resulting in sick leave for own personnel.
	Severity index for own personnel.
	Average duration of sick leave due to accidents among own personnel.
	Frequency rate of occupational incidents in own jobs.
Stakeholder communication indicator (SDI)	Level of stakeholder identification.
	Level of inclusion and effectiveness of stakeholder dialogues.
	Level of stakeholder feedback mechanism.
	Level of reporting.

Table 23. *Social indicators. Source: (UNE, 2019b).*

Indicator	Parameter
Environmental protection indicator	Total environmental spending.
Energy efficiency indicator in the production process	Ratio of total annual direct energy consumption in the production center.
	Percentage of annual energy generation from own renewable sources.
Gas emission indicator	Ratio of tons of CO_2 equivalent (tCO_2 eq.) (GHG) over annual production.
	Ratio of NO_x gas emissions to annual production.
	Ratio of SO emissions$_2$ to annual production.
	Ratio of NH gas emissions$_3$ to annual production.
	Ratio of Non-Methane Volatile Organic Compound (NMVOC) emissions to annual production.
	Percentage of SO recovery, capture or prevention$_2$ and its transformation or elimination with respect to SO_2 produced annually.
Dust particle emission indicator	Ratio of emissions per source of dust particles PM_{10} and $PM_{2,5}$ with respect to production. annual.
	Ratio of diffuse emissions of PM_{10} and $PM_{2,5}$ dust particles to annual production.
Water demand indicator	Ratio of annual net primary water consumption to annual production.
	Percentage of annual water consumption recycled.
	Ratio of total annual water consumption to annual production.
Land demand indicator	Percentage of total area rehabilitated.
	Percentage of land rehabilitated with nature conservation objectives.
Hazardous substance use indicator	Ratio of very toxic and toxic substances for humans and living organisms used in the facilities.
	Ratio of substances that are harmful to humans and/or may cause long-term negative effects on the environment, used in the facilities.
Discharge indicator	Ratio of liquid discharges, by pollutant and as a whole, with respect to annual production.
Waste indicator	Ratio of inert mining waste landfilled in dumps, ponds or dams, with respect to annual production.
	Ratio of non-hazardous non-inert mining waste landfilled in dumps, ponds or dams to annual production.
	Ratio of hazardous mining waste landfilled in dumps, ponds or dams to annual production.
	Percentage of mining waste reused and/or recycled and/or recovered and/or used for reclamation.
	Percentage of external inert waste reused, and/or recycled, and/or recovered, and/or used for reclamation, refurbishment or backfilling, with respect to the total materials used in the reclamation.
	Ratio of other waste generated in the production process.
	Ratio of domestic or similar waste generated in the production center with respect to hours worked.
	Category A waste storage facilities .[79]
	Ratio of treatment tailings declared as waste to annual production.
	Ratio of slag declared as waste to annual production.
Environmental incident indicator	Environmental incidents and accidents.

Table 24.
Environmental indicators. Source: (UNE, 2019b).

In the environmental field, the literature also includes indicators related to the circular economy (De la Torre et al. 2022). These include the proportion in which recycled material replaces natural resource extraction and the proportion in which it is reincorporated into the economy. Also related are the ISO Technical Committee 323 and Circular Economy 59004, 59010 and 59020, which are in the "Committee Draft" phase and contain the indicators and methodology for assessing circularity.

[79] A waste facility will be classified in category A (Royal Decree 975/2009, of June 12, on the management of waste from extractive industries and the protection and rehabilitation of the area affected by mining activities), if: (i) according to a risk assessment carried out taking into account factors such as the current or future size, location and environmental impact of the waste facility, a major accident could occur as a result of a failure or malfunction, e.g., (ii) if it contains waste classified as dangerous according to Directive 91/689/EEC above a certain threshold, or (iii) if it contains substances or preparations classified as dangerous according to Directives 67/548/EEC or 1999/45/EC above a certain threshold.

In this context, technological excellence is also a fundamental element. Authors such as De la Torre et al. (2022) include it as another pillar of sustainability. Indeed, resource efficiency, in terms of process efficiency, is the main asset of mining companies. The mining industry is forced to work with a long-term vision due to the time to develop projects and, especially, the payback periods of its investments. For this reason, the industry needs new technologies to be supported long enough to ensure a return on investment.

The technological efficiency indicators described by Jacobs and Weber-Youngman (2017) take into account both physical and digital technologies by measuring the ability to: (i) increase production, (ii) increase productivity, (iii) increase efficiency and (iv) improve safety and reduce the risk of human error.

Currently, the prospect of a sustainable mining activity is a key element for the continuity of the extractive operation. However, gathering indicators is sometimes not an easy task. The data used are not always sufficiently homogeneous and, in general, are not easy to obtain.

2.2. Circular economy and sustainability

The idea of feedback and cycles in systems is ancient and was present in several philosophical schools, creating different branches of thought[80] . It resurfaced in industrialized countries after World War II, when computerized studies of nonlinear systems revealed the complex, connected and unpredictable nature of the world, which is more like a metabolism than a machine. However, it was in the late 1970s that it gained momentum, thanks to academics, opinion leaders and companies that brought its practical application to modern economic systems and industrial processes.

Gradually, it gained interest and attention and in 2015 the Eu- ropean Commission's communication "Closing the loop: an EU action plan for the circular economy" was published and in 2020, as a result of the aforementioned EVP, a Circular Economy Action Plan was adopted, which includes measures in the life cycle of products, to adapt the economy to a green future and strengthen competitiveness.

Circular economy (CE) is a concept of sustainable economy where companies and consumers are concerned about the full product cycle; including what happens *downstream,* once the product is consumed, when you have to look at how waste is managed and what commitments companies make to not pollute and to ensure they take back their products (European Union External Action Service - EEAS, 2018).

The circular economy is being considered by the main mining and metallurgical companies as an important part of the improvement and competitiveness strategies, since it means a new and more efficient use of resources.

[80] The current circular economy model synthesizes several schools of thought: the *Performance Economics* of Walter Stahel; the Cradle *to* Cradle™ design philosophy of American architect William McDonough and German chemist Michael Braungart, a design philosophy that compares industrial and commercial processes to a process of biological metabolism, where waste is equivalent to nutrients that can be recovered and reused; the idea of biomimetics presented by Janine Benyus (author of *Biomimicry: Innovation Inspired by Nature*), a discipline that invites us to study the phenomena of nature in order to find solutions to human problems; the *industrial ecology* of Reid Lifset and Thomas Graedel; the *natural capitalism* of Amory and Hunter Lovins and Paul Hawkens; the *blue economy* approach as described by Gunter Pauli, or *Regenerative Design*. All of these are philosophies that emphasize what the circular economy is and how it can be applied today. Thus, CE is a solution framework with a systemic vision that addresses global challenges such as climate change, biodiversity loss, waste and pollution.

The new way of operating is based on the opportunities of process reengineering, the circularity of operations and the opportunities offered by the product-service concept. No less important is the regulatory and legislative framework which, at the European level, promotes the progressive implementation of these principles of sustainable production, reducing consumption and waste generation.

The concepts of sustainable development and circular economy have similarities: both are global in nature and emphasize the importance of better integrating environmental and social aspects with economic progress. Both concepts draw attention to the obligations between different generations due to environmental hazards and both point to the importance of increasing the involvement of authorities and civil society.

As a complete reinvention of value chains is required, waste generation would be discarded. Products are returned to the production system, growth is decoupled from consumption (except for energy) and materials are kept within the production process. In this sense, circularity is also a driver for the creation of opportunities in all industries, where through innovative business models and new technologies, the very concept of waste is redefined (Spindler et al., 2020).

CE is linked to environmental sustainability and the achievement of the objectives of the Paris Agreement. In the fight against climate change, CE is a development option of particular interest. Research suggests that GHG emissions can be reduced by approximately 50% with significant improvements in energy and operational efficiency and the large-scale implementation of renewable energy solutions. The remaining 50 % must come from a complete transformation in the way goods are produced and consumed (Spindler et al., 2020).

CE development policies and climate change policies are not only compatible, but mutually beneficial. The GHG emission mitigation potential of recycling, the development of circular business models and resource efficiency is enormous and could effectively complement existing climate change strategies, although energy consumption and emissions in recycling processes need to be included in the analysis.

The CE is underpinned by the transition to renewable energy and materials, as a circular economy decouples economic activity from the consumption of finite resources (Ellen MacArthur Foundation, 2022). The circular economy seeks to be regenerative by "giving more than is needed" while delivering solid economic value (Morris, 2020).

2.3. Linear model vs. circular economy

The current economic system is mostly based on a growth model that relies on the production of goods and services under the "extract-manufacture-consume-dispose" guidelines (Figure 60). This linear model has clear impacts on the environment and would eventually deplete the sources of supply of raw materials, since it operates under a system in which everything manufactured has an end, which is generally single-use or has a short useful life.

The linear model involves impacts on resources and ecosystems, waste, GHGs and pollution. These impacts take on an additional dimension when referring to nonrenewable or scarce resources, and when it comes to key inputs in the production of certain goods and equipment. In addition, the impacts of the linear model are aggravated by programmed obsolescence and consumption habits increasingly associated with "fast fashion", with renewal rates of goods that do not exhaust the product's useful life cycle, as is the case, for example, with clothing or electronic devices.

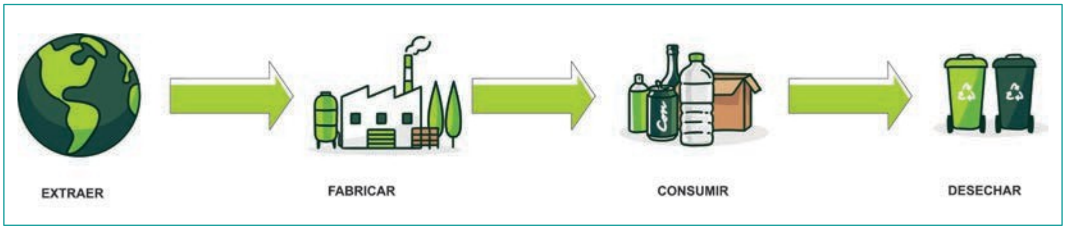


Figure 60. Concept of linear economy. Source: authors' own elaboration.

In the linear economy model, there is a strong dependence on the availability of raw materials, which entails a risk associated with supply, with potentially high and volatile prices, as well as a significant reduction in natural capital, It is therefore necessary to take steps towards the incorporation of concepts and processes of the circular economy (Figure 61), based on three fundamental principles:

(i) Incorporate, from the product design phase, technologies (e.g. Artificial Intelligence), as well as criteria to optimize the consumption of raw materials in their production and increase the recycling of their components.

(ii) Extend the useful economic life of materials and resources as much as possible, so that they remain as long as possible in the life cycle, reducing as much as possible or eliminating waste generation and pollution.

(iii) Maximize available resources by making products and materials "circular": raw materials are extracted, products are manufactured and materials and substances are recovered from the waste generated and reincorporated into the production process. In this way, at least part of the resources are kept in a closed circuit, avoiding the extraction of new virgin raw materials and extending the life of natural resources .[81]

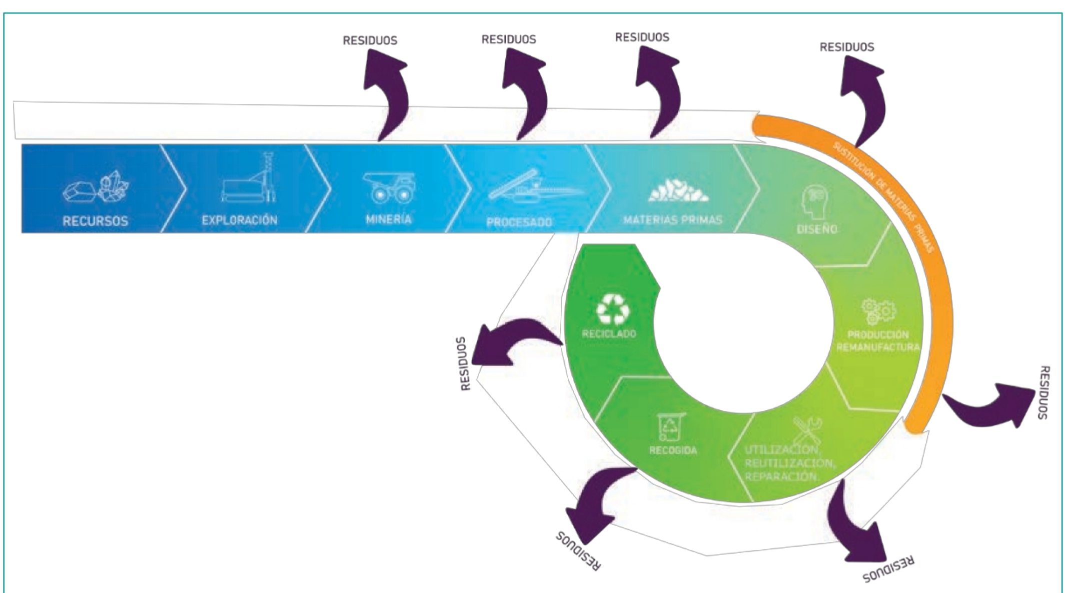


Figure 61. Concept of circular economy in the mining industry. Source: translated and reworked by the authors from (EIT, Raw Materials, 2022).

[81] In any case, energy (increasingly renewable) will continue to be consumed for reprocessing.

The application of the above circular economy principles implies a different vision of eco- nomy: it is about designing differently from the outset, rather than concentrating efforts on mitigating and reducing the impacts of something that has already occurred[82] . In this sense the CE approach, rather than better waste management, emphasizes that waste is reduced and can be eventually eliminated through better design. Morris (2020) points out the distinction between designing out of desires and designing without waste.

According to Cheatle et al. (2020) the circular economy offers a realistic solution (an alternative) to the *busi- ness-as-usual*, advocating an economic system that embraces and encourages recycling, reduction, reuse, repair and "remanufacturing" of resources, ultimately creating a circular or closed-loop system that reduces the need for new mineral raw materials. In this light, the need for eco-design is recognized as an instrument to achieve a more circular economy with a higher level of recycling (Valero and Valero, 2021).

3. On the circular economy at the European level

According to data from the European Commission, in 2011, each person in the EU consumed on average 16 tons of materials annually, of which six tons were wasted and half went to landfill. On average, Europeans consume resources at twice the rate at which the planet can renew them (Eu- ropean Commission, 2017).

Over the past four decades, global materials use nearly tripled from 26,700 mi- lion tons in 1970, to 92.1 billion tons in 2017, and is projected to be between 170 billion and 184 billion tons in 2050 (The Platform for Accelerating the Circular Economy - PACE, 2019). The Gross World Product (world GDP) developed similarly as well, growing from $2.6 trillion in 1900, to $14.5 trillion in 1970, and $94 trillion in 2021. According to International Monetary Fund (IMF) projections, the world economy is expected to reach $104 trillion by 2022. Driven by economic expansion, it is estimated to be between $140 trillion and $165 trillion by 2050.

A report by the UN-supported Circle Economy estimates that 100.6 billion tons of minerals, fossil fuels, metals and biomass enter the global economy annually, and notes that reuse and efficiency are only applied in 9% of that production. It can be said that only 9% of the current global economy is circular (The Platform for Accelerating the Circular Economy - PACE, 2019).

It is estimated that a reduction of just 1 % in resource consumption in the global economy could result in annual savings of approximately 840 million tons of metals, fossil fuels, minerals and biomass, as well as 39.2 trillion liters of water (Rubel et al., 2017).

[82] One of the CE models is that of the Ellen MacArthur Foundation which describes the integration of the natural (biological) life cycle where resources are limited and materials have a use, which is reincorporated in the productive processes in a circular (technological) way.

Europe could take advantage of the change of model to generate a net benefit of 1.8 trillion euros by 2030, i.e. 0.9 trillion more than in the current linear model (The Platform for Accelerating the Circular Economy - PACE, 2019). In addition, it is estimated that around 580,000 new jobs could be generated, 30% of which would be associated with compliance with EU regulations on waste and eco-innovation (Cotec Foundation for Innovation, 2019).

In turn, increasing material use efficiency in the EU economy from 17% to 24% would help to
% could boost GDP by up to 3.3% and create 1.4 to 2.8 million jobs. By using resources more efficiently, companies could benefit from savings in the range of €245-604 billion per year, representing 3-8 % of their annual turnover. This would imply a reduction of 2-4 % of total EU GHG emissions (European Commission, 2014).

The European Commission plans to develop strong investments from the European Regional Development Fund, through smart specialization, the LIFE program and Horizon Europe to complement private innovation funding and support the entire innovation cycle with the aim of bringing solutions to the market, circular business models and new production and recycling technologies, including exploring the potential of metallurgical and chemical recycling; and taking into account the role of digital tools to achieve circular goals.

In the EU, barely 12 % of secondary materials and resources re-enter the economy; and in the context of sustainability, in the section on this issue, it has already been indicated that the EVP considers access to sustainable raw materials and envisages an ambitious Roadmap towards a climate-neutral circular economy. The European Commission believes that extending the application of circular economy principles to key economic actors will make a decisive contribution to achieving climate neutrality by 2050 (so that every last gram of GHG emissions can be absorbed by nature or removed) and decoupling economic growth from resource use, while ensuring the EU's long-term competitiveness. To meet this ambition, the EU needs to decisively accelerate the transition to regenerative growth (European Commission, 2021a).

The EU action plan includes measures to make sustainable products the norm (lasting longer, easy to reuse, repair and recycle, and incorporating recycled material instead of primary raw materials wherever possible). It is also a question of empowering consumers and focusing on the most resource-intensive sectors with a high potential for circularity. In this regard, it is announced that the Commission will adopt specific measures on electronics and ICT, batteries and vehicles, packaging, plastics, textiles, construction and housing, and food.

In the current context of digitization and decarbonization of economies, the principles of the circular economy fit very well in a scenario where resources can be used in a more efficient way.

Digital technologies can track the movement of products, components and materials and make the resulting data securely accessible. The European data space for smart circular applications being developed and implemented will provide the architecture and governance system to drive applications and services such as product passports, resource mapping and consumer information (European Commission, 2021a).

For the European Commission, the transition to the circular economy will be systemic, profound and transformative, both within the EU and beyond. It will be disruptive, so it has to be fair and will require alignment and cooperation of all stakeholders and at all levels, international, EU, national, regional and local (European Commission, 2021a).

4. Spain's circular economy strategy

In June 2020, the Government of Spain approved the Spanish circular economy strategy called "Spain Circular 2030", whose objectives for the decade are, among others: (i) to reduce by 30% the national consumption of materials, in relation to GDP, taking 2010 as the reference year, (ii) to reduce by 15% the generation of waste compared to 2010 and (iii) to reduce GHG emissions to below 10 million tons of CO_2 equivalent. Its implementation will be materialized through three-year action plans. The first, already published, is for the period 2021-2023.

This circular economy action plan includes five main lines of action: (i) production, (ii) consumption, (iii) waste management, (iv) water reuse and purification, and (v) performance of secondary raw materials; and three lines of action (i) research, innovation and competitiveness, (ii) participation and awareness, and (iii) employment and training.

In the production axis, reference is made to promoting the design/redesign of processes and products to optimize the use of non-renewable natural resources in production, encouraging the incorporation of secondary raw materials and recycled materials and minimizing the incorporation of harmful substances in order to obtain more easily recyclable and repairable products, redirecting the economy towards more sustainable and efficient modes. The aim is to "*achieve the integration of CE measures in the conception and design phase and in the production or distribution phase, firstly to improve the durability of materials and products by restricting single-use products, avoiding programmed obsolescence or the destruction of unsold products, and secondly to increase the possibilities for updating and reuse and also to facilitate, at the end of their useful life, their remanufacturing and recycling, taking into account the presence of hazardous chemical products and improving the efficiency of materials*".

In the consumption axis, the objective is to reduce the ecological footprint by changing consumption patterns towards a more responsible one that avoids waste and non-renewable raw materials.

In the area of waste management, the aim is to apply the principle of the waste hierarchy, favoring reduction and preparation for reuse and recycling. The Ministry for Ecological Transition and the Demographic Challenge (MITRED) is working on the revision of waste regulations to, among other actions, review the procedures for the application of the concept of by-product and the end of the waste condition. Also included in this area is the "*strengthening of the legal regime for the management of waste electrical and electronic equipment*" and end-of-life vehicles, as well as batteries and their waste.

In the area of water reuse and purification, the objective is to promote the efficient use of water resources to reconcile the protection of the quality and quantity of water bodies with its sustainable and innovative use.

In the secondary raw materials (SPM) line of action, the objective is to ensure the protection of the environment and human health by reducing the use of non-renewable natural resources and reincorporating the materials contained in waste as secondary raw materials into the production cycle.

Relevant to the case discussed in this document are the measures to improve the prevention and management of waste streams, as they include a pilot project for the reuse of photovoltaic modules and automotive lithium batteries in domestic self-consumption applications; as well as a guide for the development of environmental criteria to be taken into account in the dismantling and repowering of wind power generation facilities .[83]

A very relevant axis is that of MPS, which aims at the "reintroduction of secondary raw materials into the production cycle". "*This reduces dependence on virgin raw materials while ensuring the supply of environmentally and economically viable alternatives. In this sense the term MPS encompasses the legal concepts of by-product and end of waste status as defined respectively in Articles 4 and 5 of Law 22/2011 of 28 July on waste and contaminated soils*."

This axis recognizes that *"the substitution of virgin raw material by MPS is not always feasible in market terms, since issues such as the quantity and quality of available MPS, as well as the price of MPS with respect to raw material from natural resources, come into play*". In this sense, the action plan advocates carrying out a study aimed at determining the number of companies benefiting from each of the approved orders, the actual implementation by the affected sector, the volume of waste that is incorporated back into the production cycle as MPS and thus, the environmental benefits by avoiding landfill and its contribution to the implementation of European and national objectives.

Another important aspect included in this axis is that related to key raw materials (CPMs). The action plan refers to the European Commission document "Resilience of key raw materials: Charting the way towards a higher degree of security and sustainability" and states that "*Spain must make progress in the identification and use of PPMs and other essential raw materials, the proper management of which must contribute to the competitiveness of the Spanish economy, its reduced dependence on foreign trade and efficiency in the use of resources, within the framework of the principles of the CE*".

In particular, the action plan contemplates the creation of a national inventory of extractive industry waste containing key raw materials and the approval of a Roadmap for the sustainable management of mineral raw materials to ensure the supply of indigenous mineral resources in the most sustainable and efficient manner, maximizing benefits along the value chain, adding that reuse and recycling will be considered as the first option to feed productive processes.

5. Circular economy in the value chain: mining and metallurgy

Increased demand for minerals and metals for green technologies[84] means more mines and more mineral processing. At the same time, the mining industry is also seeking to reduce or eliminate emissions and reduce waste production in its operations (CIM),

[83] In this regard, see (Fundación Naturgy, 2022).

[84] Green technologies or clean technologies are those that include techniques, processes, materials and methods applicable in the economy in general in order to improve the quality of life, while preserving and recovering the environment.

2022). Efficient recovery of secondary resources will help the demand for primary resources to modulate its growth. Therefore, metals mining companies need to determine where to focus in order to take advantage of the circular economy and clean technology trends (Bartels and Morrison, 2019).

The implications for the mining and metallurgical industry are far-reaching, as they imply a major transformation in the design of mining projects and in the supply of mineral raw materials in the future. It is clear that recycling activity will intensify in the coming years, with "recyclers" entering the markets in a decisive way, as end consumers will demand to know the origin of the product content and recycled products will become increasingly desirable by virtue of their nature (Cheatle and Freele, 2020).

Achieving the development of circular economy principles and their implementation requires all economic sectors, including the mining sector, to redesign their value and supply chains to keep their resources in use for as long as possible. In short, products that have reached the end of their useful life can be reused and returned to the initial stages of the circular economy model to boost the economy and retain the inherent value of the waste (Averda, 2022).

Figure 62 illustrates the main stages of the life cycle of minerals and metals, and allows differentiating the different degrees of management, governance or responsibility at the different stages. Although mining generates a considerable amount of tailings and residues in the processes of mining operations, ore concentration and subsequent smelting and refining processes, tailings and residues can be used for other purposes.

On the other hand, mining operations can move towards the circular economy with a systemic vision, in which, among other aspects, technical systems are adapted to maximize value, waste is reduced or eliminated, new design strategies are considered, and value is created in waste through industrial symbiosis .[85]

Given that much of the mining operations are not vertically integrated downstream in the value chain, it is not easy to act on circular economy operations in the design and manufacture of

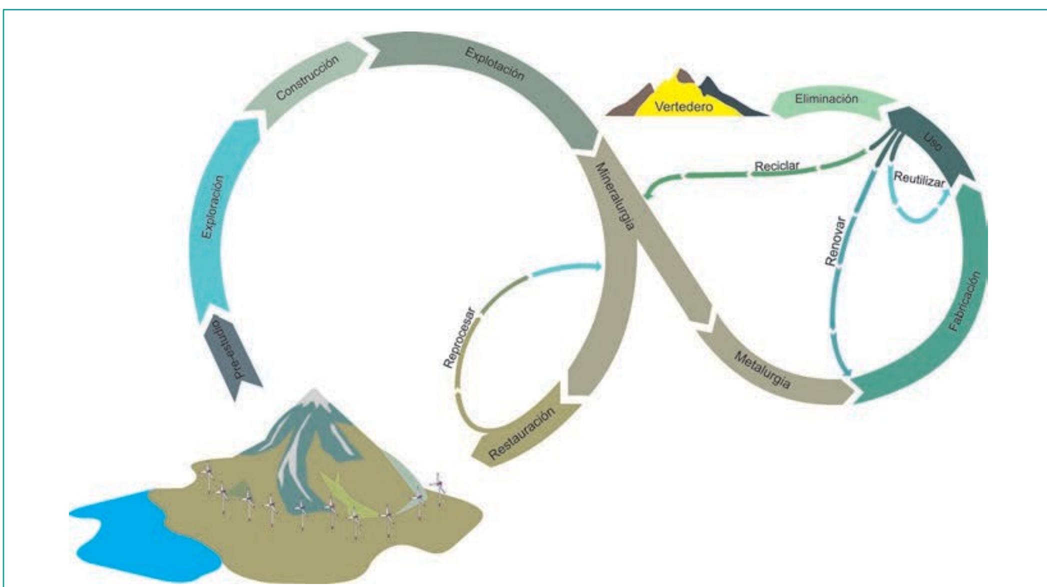


Figure 62. *Main phases of the life cycle of metals and minerals. Source: translated and modified by the authors from (Cheatle and Freele, 2020).*

[85] For more details see (Young, et al., 2021).

products, which are key to the concept of a circular economy. However, it is in metallurgical plants for obtaining metals by pyrometallurgical and refining processes that a significant contribution to the circular economy can be made by processing waste and secondary metals, as will be seen below.

According to Pinchuk et al. (2019), the application of the circular economy concept in the mining industry will im- plicate the creation of innovative forms of production, increase the possibility of reuse of goods and materials, with lower resource costs and promote the efficient use and protection of natural resources. The impact of the circular economy on the mining industry is direct and potentially disruptive to the industry as more products are recycled.

Understanding where the opportunities lie for the mining industry is a complex and challenging process, as it is not simply a matter of increasing recycling rates. Mining companies have traditionally been focused on the production of raw materials and little thought has been given to maximizing the flow of recycled metals. However, the reality is that as circularity increases, the relative demand for commodities will modulate, especially as waste and material losses are reduced.

5.1. Recovery of secondary raw materials

CE is particularly relevant for mining ("*extension & extraction*") and metallurgy ("*process- sing*") as can be seen in Figure 63. The volume of waste is particularly high in the mining and metallurgy stages, being lower in other stages of the value chain, although it is also relevant in the *manufacturing* stage.

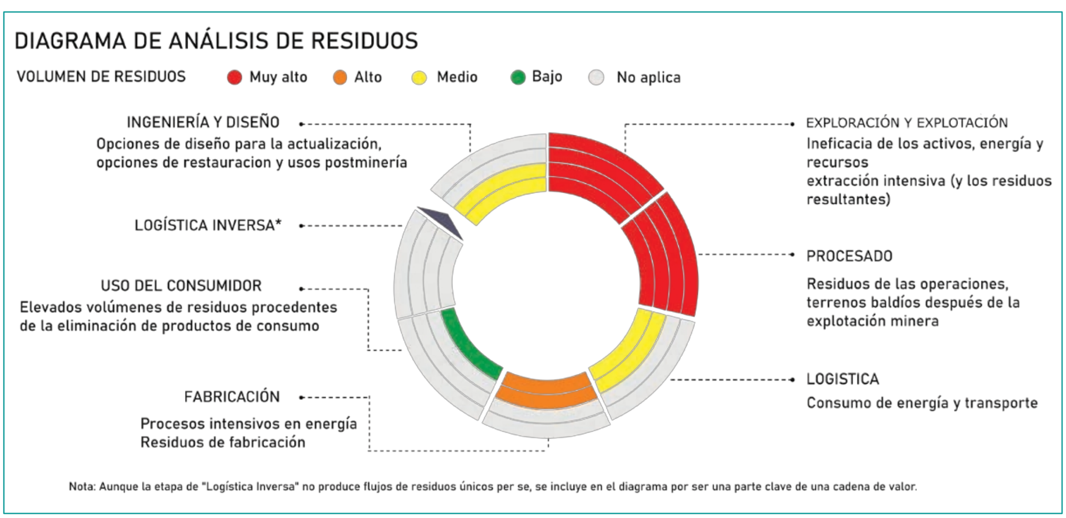


Figure 63. *Diagram of residue analysis. Source: modified by the authors from (Lacy et al., 2020).*

Some examples may help to understand the role of secondary resource recovery and how these, however, cannot fully meet the demand for primary raw materials, although their recovery is essential.

Recycling 41 cell phones can produce as much gold as can be obtained from one ton of primary ore at a grade of 1 g/t. However, it is unlikely that all the cell phones in the world will be recycled.

The demand for gold in the markets would be impossible to meet even if it were to be recycled at the same time. Another illustrative example is aluminum, where a single ton of recycled aluminum saves nine tons of CO_2 (Cheatle and Freele, 2020). About 90 % of the titanium in circulation today is recycled. However, this only meets about 50 % of current demand (Leonida, 2022).

Steel is the most recycled material in the world (Figure 64). All scrap comes from demolished structures, end-of-life vehicles and machinery, as well as from material losses in the manufacturing process, which are collected and recycled. The current overall recycling rate is estimated at around 85 %. Approximately 630 Mt of scrap metal is recycled each year, which avoids the emission of about 950 Mt of CO_2 . Since 1900, around 25,000 Mt of scrap metal have been recycled, saving 35,000 Mt of iron ore consumption, as well as 18,000 Mt of coking coal. Steel plants have a recycling component, and the steelmaking processes, which are predominant today, use scrap, up to 100 % if the production is by electric arc furnace and up to 30 % in blast furnace and subsequent processes. For the production of 1,000 kg of steel, illustrative values for blast furnace production could be: 1,370 kg of iron ore, 125 kg of scrap, 270 kg of limestone and 780 kg of coal, while electric arc production would be: 710 kg of scrap, 586 kg of iron ore, 88 kg of limestone and 150 kg of coal (World Steel Association, 2020b).

Figure 64. *Life cycle of steel. Source: translated by the authors from (World Steel Association, 2020b).*

Future expansion of steel production from scrap will depend on the availability of high quality scrap. While the supply of iron ore can be matched to demand, the overall availability of scrap is a function of the demand for steel and the generation of scrap at the end of the useful life of steel-containing products.

In the chapter on the role of raw materials in the energy transition and digitalization, it already became clear that the energy transition and digitalization will lead to significant or very strong increases in the demand for minerals and metals. In this context, the circular economy is a promising solution to the resource challenges in the metals and mining industry, where a possible 250 % increase in the demand for metals by 2030 (Spindler, Long, and Morrison, 2020) and even an increase in demand for some metals such as copper by 600 % (and up to 900 %) in the next twenty years (Fundación Chile, 2022) is foreseen, which will generate an increase in extraction, processing and waste generation activities. Under the development of the European Green Pact, batteries, mainly for electric vehicles, are expected to increase the demand for lithium in the EU by almost 6,000 % by 2050, which is a clear example of the absolute necessity to find substitute materials or to use recycled lithium.

For example, 90 % of the tailings stored in landfills or dumps come from metal mines and still contain a large amount of valuable materials that can be recovered with today's technologies, such as rare earth elements, gold, nickel, cobalt and tungsten. Mine waste rock, treatment plant tailings, slags and even rock dust can be disposed of and reused in a wide variety of applications, from construction materials to solar energy, agricultural soil additives, and countless other applications (Cheatle and Freele, 2020). Naturally, the realization of the potential must be supported, among other things, by the economics of the recovery processes that make it worthwhile.

5.2. The role of metallurgy in the recycling of secondary raw materials

One of the key drivers of the circular economy is metallurgy and recycling. If consumer products were simple and made from a single material (most likely aesthetically unattractive and lacking all the complex functionality required by modern products), recycled ones could obviously be 100 % pure. The circular economy would then, and in principle, be a seemingly easy task.

However, the reality today is that modern consumer products are characterized by a high degree of complexity in their composition, being made up of functional metals, complexly bonded nanometals and micrometals, as well as alloys linked to functional inorganic materials and plastics.

Moreover, an additional issue arises, since there are two types of recycling: (i) that at the end of the product's life (post-consumer), which for most critical elements is very low, and (ii) recycling of the product from which they are extracted during processing and manufacturing (waste may be produced at these stages), which is much higher, due to the fact that, in general, pre-consumer waste material is easier to exploit, as it is usually much less dispersed and contaminated and, therefore, much easier to collect and process (Moss et al., 2013).

In the case of the end of life of the product, it is low because in some of them, certain elements appear in concentrations lower than those found in the earth's crust and their recovery is practically unfeasible; in other cases they are elements that, like Nd, Pr and Dy, have only started to be used relatively recently. Moreover, where they are used in larger quantities, such as in engines for wind power generation, they are still a long way from completing their useful life and there are technological problems in achieving the same quality in the final product when it is obtained from recycled elements.

Figure 65 illustrates the different designs, compositions and types of recycle fragments for different LED lamp designs.

Setting the limit for the resource efficiency of the complex and highly interconnected systems of a circular economy requires a thorough understanding of the different elements that make up products along with their materials, and how they move in a circular economy system. In addition, products are often short-lived, complex and intensively produced and consumed, making it difficult to recover their constituent metals from large volumes recycled with complex mixtures.

Figure 65. Relationship between design, particle composition and recyclate quality, as well as fragment/particle and recyclate compositions for the different (re)designs of LED lamps. Source: translated and modified by the authors from (Reuter and Schaik, 2015).

The circular economy can be defined, in this case, in terms of the metallurgical Internet of Things (m-IoT), i.e. a production system of materials that are interconnected, which is an integral and necessary requirement for "closing the loop" and maximizing resource efficiency. Minerals, both from manufacturing from primary mineral raw materials and from recycling, are the common element and the link between the two processes. Some of the aspects that affect the recycling rate of mineral-based products include

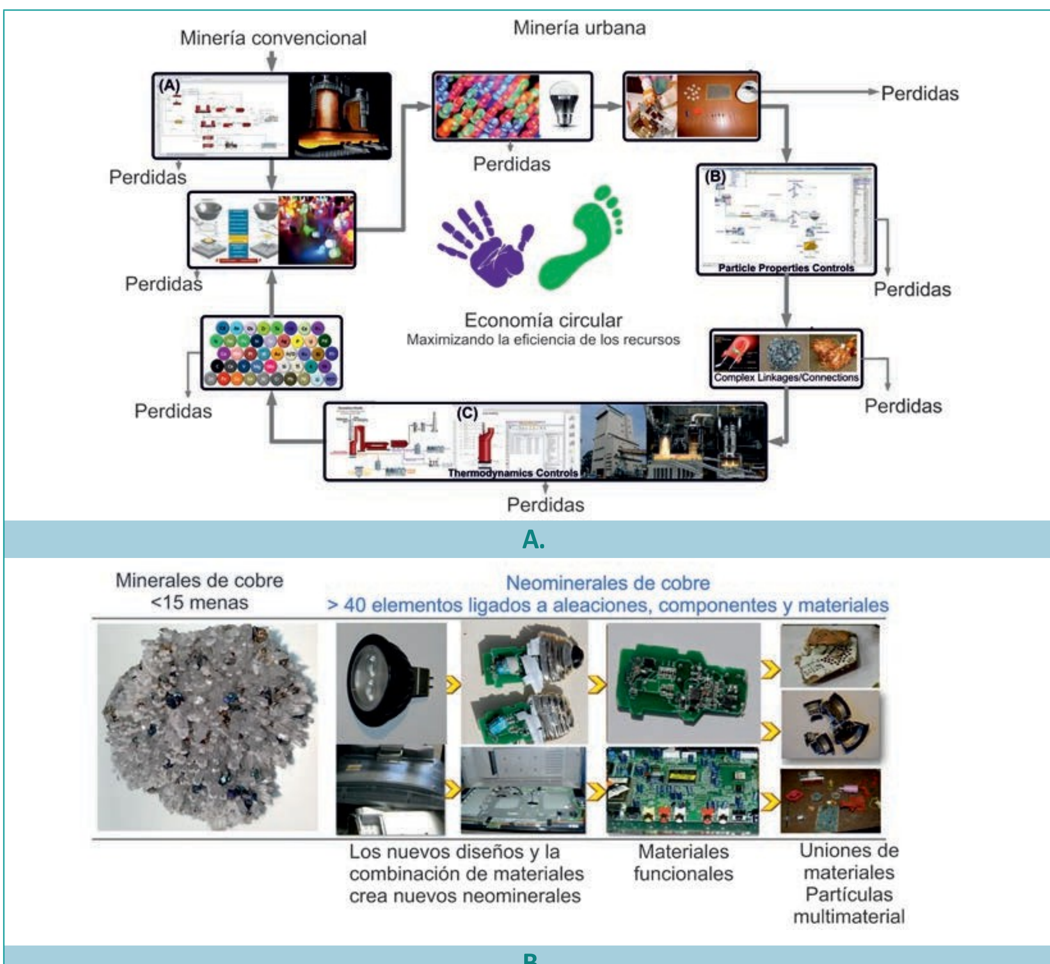


Figure 66. A. Summary of issues affecting end-of-life product recycling rates as included in recycling models, B. Complexity of geologic minerals versus engineered urban minerals. Source: modified by the authors from (Reuter and Schaik, 2015).

The end-of-life consumption are: time and property distributions, product design, degree of liberation, physical separation, metallurgical thermodynamics and smelting processing technology.

Figure 66A, attempts to illustrate the relationship between environmental footprint minimization and product design with geological and "urban" mines, a key issue for a circular economy. It can be seen that the treatment of materials from an "urban mine" is based on the same operations and processes as the treatment of natural minerals, i.e. dismantling, crushing and grinding, physical separation and extractive metallurgy (pyrometallurgical and hydrometallurgical routes). For its part, Figure 66 B shows the complexity of materials in a product and the possible issues affecting liberation behavior, the inevitable recycling (in)efficiency and thus system losses.

The variability of products and materials demands a dynamic and agile metallurgical processing infrastructure to absorb and process into high quality products so many combinations of complexly linked materials. As a result, policy should recognize the key importance of metallurgy for a circular economy.

5.3. Industrial symbiosis as an approach to the management of waste from mining activities

Waste from metallurgical industries can be used by other related industries, but this requires the development of a strategy for the exchange of mineral raw materials for processing between companies, the application of low-waste generation technologies and the availability of qualified personnel. Regulations must also accompany this process.

Figure 67 shows the co-products generated during steel production, among which the most important is slag, both granulated and crystallized, which is used by external companies, such as cement and civil works companies. It can be seen how part of the waste or co-products are used internally by the company.

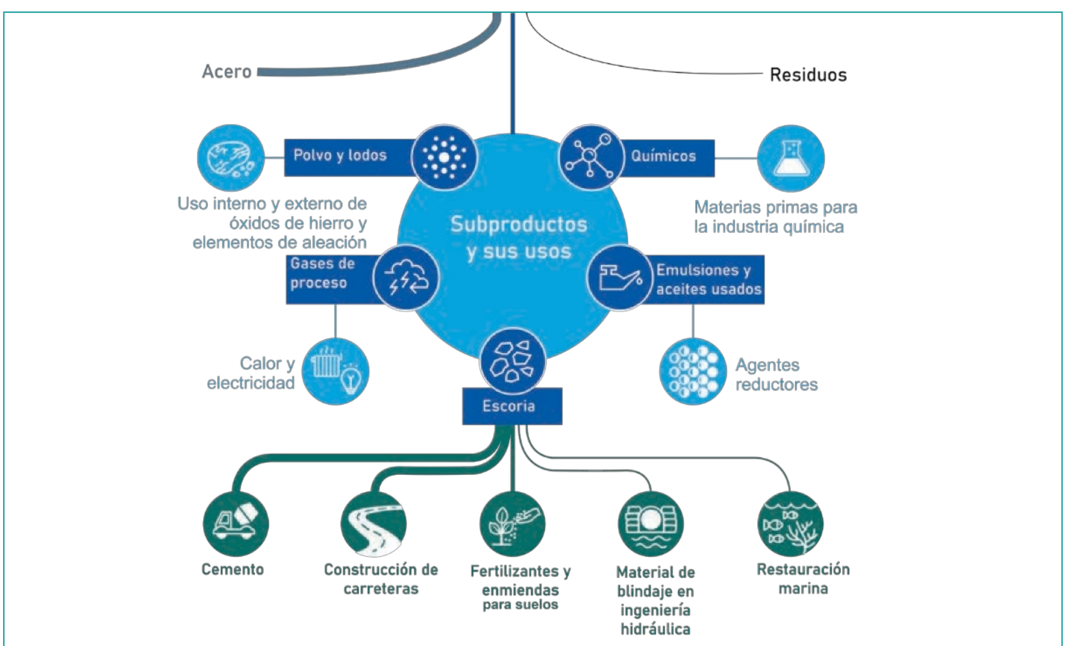


Figure 67. *Co-products in the steel industry and their uses. Source: translated by the authors from (World Steel Association, 2020a).*

A reduction in the final generation of waste and its reuse, either by the company that produces it or by an external company, will lead to a reduction in waste, which means advantages in terms of the need for waste storage tanks (landfills), which occupy land, as well as optimizing the use of all natural raw materials and minimizing damage to the environment.

However, achieving total production without waste in the mining industry is not an easy task, given the volume of waste, as we have seen in the section on the recovery of secondary raw materials. This will require communication and collaboration between companies, heterogeneous among themselves, but united in an eco-industrial park, the result of which will result in resource conservation, reduction of energy consumption, reduction of emissions of all kinds and improvements in environmental quality (Pinchuk et al., 2019).

The chapter on economic and industrial aspects of the mineral commodity value chain will address the industrial aspects of industrial clusters and ecosystems, as a set of companies from related industries and with competencies covering a wide range of related or interdependent industries.

In this framework we can place what in the circular economy and waste and recycling management is sometimes called industrial symbiosis, as stated in the document I Circular Economy Action Plan 2021-2023 of the Spanish Circular Economy Strategy (Government of Spain, Fourth Vice-Presidency of the Government, Ministry for Ecological Transition and the Demographic Challenge, 2021).

Examples of this type of symbiosis are found when waste products or residues can be returned to enrichment plants and mining-mineral companies for enhanced recovery, or when residues in the form of slag or ash are used for construction materials. Other wastes can be disposed of in the chemical and pharmaceutical industries. In this way, the development of a circular economy helps to reduce the dependence of the Spanish and European economies on the outside world.

In the current context of digitalization and decarbonization of economies, the principles of CE fit very well with a vision that resources can be used more efficiently, which in turn allows a reduction of emissions and generates more wealth in the value chain of mineral raw materials. However, it must be taken into account that recycling solutions do not have a negative environmental, economic or social balance. For this purpose, valuation tools such as Life Cycle Analysis (LCA) and Environmental Cost Benefit Analysis are available.

Within the framework of the CE and in the process of developing a new economic and technological structure, the transition from industrial parks to eco-industrial parks is necessary. The construction of an eco-industrial park will allow the use, at least partially, of waste from production and processing, giving rise to industrial symbiosis, waste minimization, recycling and exchange of materials and resources among the different industries.

This can be implemented through Industry 4.0 due to the need to very effectively coordinate the flow of materials and information. For Pinchuk et al. (2019), the reason why the circular economy is not implemented today is the lack of information, and the digital economy is the "missing link" for its implementation. In his opinion, the main weight should fall on technologies such as: cyber-physical systems, automated market and logistics platforms, IoT and *blockchain*. In this way, the application of CE principles in the mining industry will generate economic, environmental and social benefits for the state, the region, mining companies and a number of related companies, which will operate in the structure of the eco-industrial park, which is consistent with the concept of sustainable development.

On the other hand, the application of the elements of the circular economy in different fields of action offers the opportunity to increase the competitiveness of the regions, increase the efficiency of the courses, energy efficiency and preserve the environment. However, there are challenges to overcome. As a result, ingenuity and innovation have never been more critical for the sustainable transition to circularity at scale (Accenture, 2020).

The above considerations point to the fact that the current situation requires an adaptation of the industrial fabric, as well as the adaptation of human resources (through education and training). The next chapter will return to this issue, which is reflected here in the scope of the industrial approach to waste and recycling in the context of the circular economy.

In the context of CE, Leonida, C. (2022) three steps can be identified for its implementation. Some of them, as will be seen, are related to ecosystems and industrial symbiosis. The first would be the development of circular operations in mining and metallurgical activities, such as, for example:
(i) partnering or forming partnerships with suppliers to extend the useful life of capital goods through real-time monitoring, analysis and predictive maintenance of assets such as trucks, conveyors, etc., while promoting remanufacturing and recycling at the end of their useful life; (ii) selling production waste to other industries, as may be the case in construction; and (iii) sharing ownership of heavy equipment with low utilization rates, e.g., between sites and/or with other local industries.

The second step would be to innovate new circular products and services. This should involve engaging and interacting with downstream users of the materials produced in the mining operation to jointly create innovative circular products and services, which may include: (i) leasing of materials, enabled by advanced tracking and tracing systems; (ii) support in the certification of customer products, to enable reuse and easy remanufacturing; and (iii) improved scrap recovery, reprocessing and reuse processes. Production and material costs can be reduced while creating new potential sources of revenue.

Third, it would involve collaborating with customers to build a circular ecosystem of partners and, finally, proactively collaborating across mine supply chains to build industry momentum to: (i) create favorable regulatory regimes to enhance circularity; (ii) establish cross-industry partnerships to develop the Mining and Metals Roadmap to extend product life and retain ownership; and (iii) develop cross-sector standards to validate the integrity of products/materials for end-of-life return and reuse.

6. Challenges and opportunities for further integration in the circular economy

Mining projects should look for ways to reuse their tailings in other processes and reintroduce their tailings to become part of the resource pool. Mines can thus potentially reduce their management and operating costs. Many of the CE actions in the mining sector to date have focused on water recycling, value extraction from by-products and waste reuse and rehabilitations.

By Averda (2022), companies need to adapt in this changing world. Taking the first steps towards a CE will help mining companies to better position themselves for the future, enabling them to develop long-term resilience and generate revenue from waste. The environmental and social benefits of a CE will also enable mines to access potential new business models.

One aspect that fosters the emergence and development of circular innovations and new business models is financing. Increasingly, leading mining companies are incorporating circular concepts into their long-term strategic planning and models, indicating a transformation from being "mineral commodity miners" to "metals and minerals solution providers" (Cheatle and Freele, 2020).

For Accenture (2020) the circular economy provides organizations with three major opportunities to create additional value, namely: (i) scaling renewable inputs to reduce energy costs, consumption and carbon footprint; (ii) incorporating circularity into site operations to reduce or eliminate mineral and non-mineral waste streams; and (iii) implementing innovative circular business models and downstream recycling solutions to include the entire value chain.

Torrubia et al. (2023) consider that the opportunities in the circular economy are as great as the challenges. For example, in the case of electrical equipment, the challenges are related to the heterogeneity of waste, the lack of traceability of waste, the scarcity of incentives and legislation for the recovery of critical raw materials and the extension of the life of equipment.

Currently, the most common application of CE in mining involves the reprocessing of materials from tailings ponds and dumps to extract the remaining valuable minerals, but there are many other opportunities to take advantage of available resources, such as the reconditioning and reuse of used equipment in main or auxiliary production operations (CIM, 2022).

Better management of natural resources is just one way in which mines can benefit from circular principles. Circular practices have been introducing mechanisms to reduce water and energy consumption, as well as CO emissions$_2$. To get the most value from these initiatives, a holistic approach to business circularity and the mine's life cycle is desirable.

One of the main drivers is the collaboration and partnership of different corporations and industry sectors. For CIM (2022), rather than individually developed environmental innovations, it may be more beneficial to encourage knowledge sharing along the supply chain to integrate it in the most efficient way into operations and generate value.

Every mine is different so there is no one-size-fits-all approach to what a mine will look like operating under CE schemes. Mines that follow accepted responsible mining standards, such as the Canadian Mining Association's Towards Sustainable Mining, may be implementing many elements of a CE approach in their operations, but there is a great opportunity for mining companies to generate value by moving from incremental improvements to comprehensive transformational change (CIM, 2022).

7. Conclusions

Sustainable development is based on the balance of three basic components of sustainability: (i) economic, (ii) social and (iii) ecological. The circular economy is a concept of sustainable economy in which all stakeholders (i.e. companies and consumers) take into account the entire product cycle.

The concepts of sustainability and circular economy are related and increasingly present in policies, regulations and in the mining and metallurgy value chain. This is reflected in guidelines and regulations, both at EU and national level, as well as in business strategies.

The circular economy begins in the design phase of components, equipment and end-use products, which will favor the use and management of waste and its recycling.

Good governance of natural resources requires a long-term agenda that finds in the SDGs a framework, with roadmaps and targets. Their implementation requires joint efforts by all actors. Although the general framework of the SDGs does not include an explicit target on raw materials, they can influence, directly or indirectly, several of the goals.

Mining and metallurgy are necessary elements for sustainability and CE, and while they have considerable challenges to address, they will also be able to take advantage of opportunities. Sustainability is already part of the evaluation of mining and metallurgical projects, among others, on the investor side. Metallurgy, with its engineering and techniques, is key to responding to the recycling of components, equipment and products. Steps have been taken to advance in terms of circular economy in mining and metallurgy, and this progress should be continued.

An integrative vision of the value chain at the industrial level will allow the development of the concept of industrial symbiosis, which can be framed in regional clusters and industrial ecosystems. This symbiosis occurs when products or intermediate products can be used in the process itself or in enrichment plants and mining-mineral companies to improve recovery, or when residues (i.e., slag or ash) are used for construction and infrastructure materials for road transport.

Among the challenges in moving forward in terms of sustainability and CE, as with other initiatives, the key will be steady progress. Each and every change, no matter how small, should be addressed and its results will have a cumulative effect that will be seen over time.

ECONOMIC AND INDUSTRIAL ASPECTS OF THE VALUE CHAIN OF MINERAL RAW MATERIALS

1. Introduction

As previously indicated, the extraction of ores and their mineralurgical and metallurgical processing provide the metals needed to manufacture components and equipment for the energy transition and digitization. The different stages of the chain or process, under the right conditions, provide quantifiable economic value. They also contribute other elements (in terms of employment, wealth for the region, investment, technology, and entrepreneurship). This leads to the potential creation of true clusters or internal groupings in a given territory, or in a region, which may have transnational approaches. They can also generate industrial and technological chains that ensure the economic sustainability of the regions where they develop.

It can be argued that there is a growing interest in strengthening the supply chains of different materials (e.g., the EU-US alliance to strengthen the battery supply chain (Smartgridsinfo, 2022)). The focus is not only on rare earths, but also on other elements such as tungsten (which makes phones vibrate), nickel (used to form alloys with steel), cobalt (used in batteries), coltan (columbite and tantalite, main components of microcapacitors that control the flow of current inside circuit boards), lithium and other minerals such as magnesium, vanadium or graphite. As an example, Figure 68 illustrates the role of mineral raw materials and metals in the manufacture of photovoltaic panels.

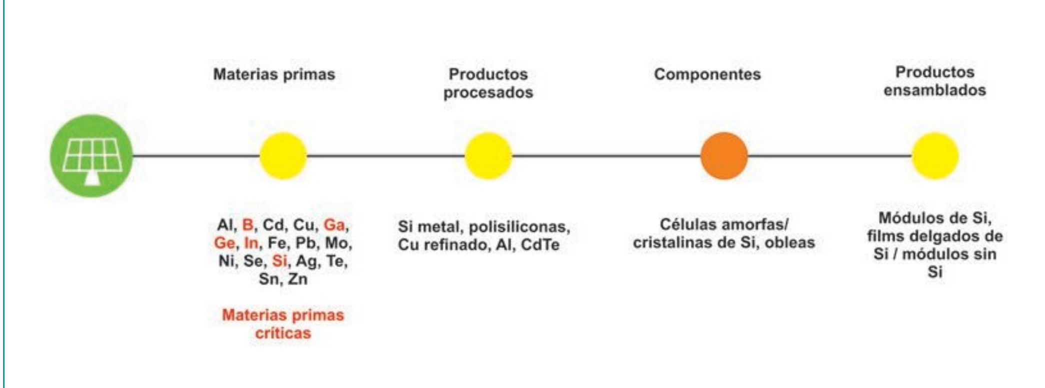


Figure 68. *Solar photovoltaic energy: a view of the value chain.* *Source: modified and translated by the authors of (European Commission, 2020b).*

Resource demand is driven by global economic growth and the type of resources demanded. According to (Regueiro and Alonso-Jiménez, 2021), there is a direct correlation between GDP growth and mining. In this line, the European Commission considers that by 2030, the EU would need up to 18 times more lithium and 5 times more cobalt than its current consumption to cover the demand for batteries for electric vehicles and energy storage. By 2050, the demand for these would be 60 times and 15 times higher than today (European Parliament, 2021).

From the point of view of a secure supply strategy, industrial clusters, clusters, ecosystems or clusters reduce the risk of supply disruptions, make better use of existing resources and collaborate in their maintenance through new discoveries. In this way, mining, mineralogy and metallurgy play an important role, firstly by complementing the local value chain, and secondly by being able to create a more complete industrial ecosystem that outlives mining activity itself and continues to generate quality employment, wealth and investment.

in the future. To achieve this, the standards of economic, technological and environmental efficiency must be adequate, so it is necessary to demonstrate the existence of balanced relationships between technological, environmental and economic aspects.

This chapter addresses the stages of value creation in mining and metallurgy, as well as the development of industrial ecosystems.

1.1. The value of the mining activity and metallurgy in general

Mining, mineralogy and metallurgy, closely related activities, play a vital role in the economic development of many countries. On a commercial scale, these activities generate employment opportunities and skills transfer to a large number of workers, and their multiplier effect increases this benefit by a factor of 2 to 5 (Walser, 2000).

Most economic research on mining is primarily concerned with the macroeconomic impact of the industry, analyzing the benefits, or lack thereof, to national economies. There is no doubt that mining can be an important source of foreign exchange and tax revenues for governments, provided that an appropriate legal and fiscal framework is in place. When well managed, these resources can be used as an engine of economic growth and, therefore, mining operations can have a significant impact on national economies.

However, mining is often perceived as a controversial activity, as it is associated with a number of economic, environmental and social problems. As a result, the contribution of mining to sustainability must be considered in terms of economic, technical, ecological and social viability. According to The World Bank (2020), to achieve this, governments, mining companies and local communities must work together.

The Mining Department of the World Bank has conducted a study on the economic and social impact of mining in several South American, African and Asian countries. It shows that there are significant social and economic benefits for communities, especially those related to the growth of local small and micro-enterprise activities.

For years, the ICMM (The International Council on Mining and Metals) has been publishing a study on the effects of the development of natural resources, especially minerals, on the economies of all the world's nations. For this purpose, it has constructed an indicator, the Mining Contribution Index (MCI). The 2020 report (ICMM, 2020) confirms that many of the world's countries continue to depend on their natural resources and, therefore, on mining as the main driver of economic activity. Spain is ranked 85th with an ICM of 47.9.

Other indicators, such as the Natural Resource Governance Institute's (NRGI) Resource Governance Index and the World Bank's Worldwide Governance Indicators (WGI), assess natural resource governance in many of these countries (i.e., whether it is weak, deficient or failing). Despite this, much remains to be done to ensure that the contribution of mining to national economies is maximized. From ICMM's own research it is known that, in low- and middle-income mining-dependent countries, responsible mining practices can be transformative, lead to substantial reductions in poverty levels, and can be used as a tool to reduce poverty.

and to overall improvements in social welfare. However, governance of mineral resources is key to ensuring that wealth is translated into economic and social benefits.

In Spain, the Roadmap for the sustainable management of mineral raw materials has 46 lines of action that will boost the country's strategic autonomy thanks to the supply of indigenous mineral raw materials in a more sustainable and efficient way, to maximize the benefits along the value chain and, also responding to the real threat of a new geopolitics and the risks inherent to it, promoting, supporting and developing, among others, sustainable extractive activities in Spain to obtain mineral raw materials.

This chapter examines the mining value chain and clusters or ecosystems, as these are considered very relevant, given that their design and implementation in the mining and metallurgy field would add value to mining and metallurgy activities and contribute to making them more sustainable.

The section on the value chain provides a detailed analysis of the process, from mining research and exploration to closure and related operations, including production or exploitation operations. Value creation is analyzed as the process progresses and sectoral economic data is provided, in some cases of a global nature. Likewise, although more concise, an analysis is made of the metallurgy value chain.

The macroeconomic aspects and those related to mining and metallurgy in Spain, as well as the review of the list of projects in our country, given their relevance, are dealt with in the following chapter.

2. Stages of the mining and metallurgy value chain - economic value

As we have already seen in chapter three, mining research consists of a series of interrelated and sequential stages, which can also be seen in Figure 69. This figure reflects the elements of the value chain and therefore includes, in addition to the technical stages, other aspects related to investments and management control. The mining activity has traditionally been characterized as an activity where results are rarely easily achieved. In the case of

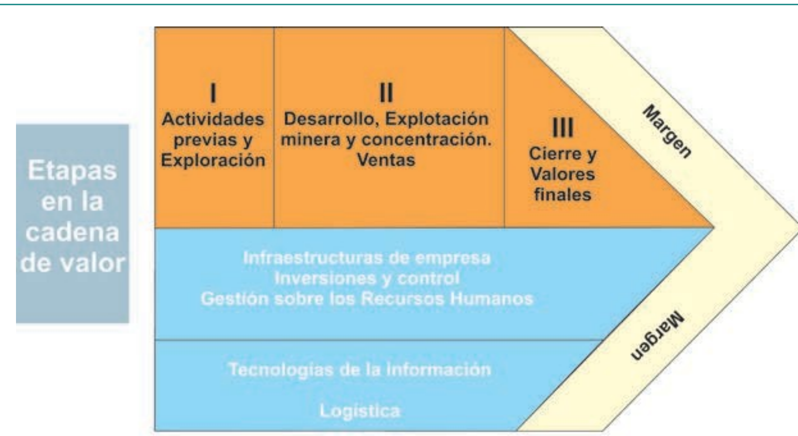


Figure 69. *Stages of the value chain summarized in mining. Source: Authors' own elaboration.*

of Spanish mining SMEs (with annual turnover of less than US$100 million), out of 1,000 projects studied, only 100 passed the detailed evaluation, and of these, only 10 were successful (Regueiro and Espí, 2019).

The activities that generate value in a mineral resource production chain are very broad. Thus, in a company, the first value creation arises from the constitution of a team dedicated to the promotion of new projects as an engine for the survival or growth of that organization. At the other extreme are the administrative obligations after the closure of a mining operation, which also generates added value for society.

All mining projects follow a very complete value chain agreed by international standards that seek to ensure the confidence of their valuations in the quality of the methods used. Moreover, the sequence of reports, which are more or less continuously released by the companies, corresponds to an economic valuation of the projects in the specialized markets. Thus, in the last phase prior to the operation, the company reaches the category of "bankable" project, which means the level or quality reached that can satisfy the financial entity interested in its development.

Figure 70 shows the illustrative value curve of a mineral development project. It highlights the high risk of the first phase and its origin: the limited knowledge of the beginning of the process, exploration, mining research, as well as the time employed and the limited temporal growth of the value generated. In Europe, and especially in Spain, the periods represented are longer.

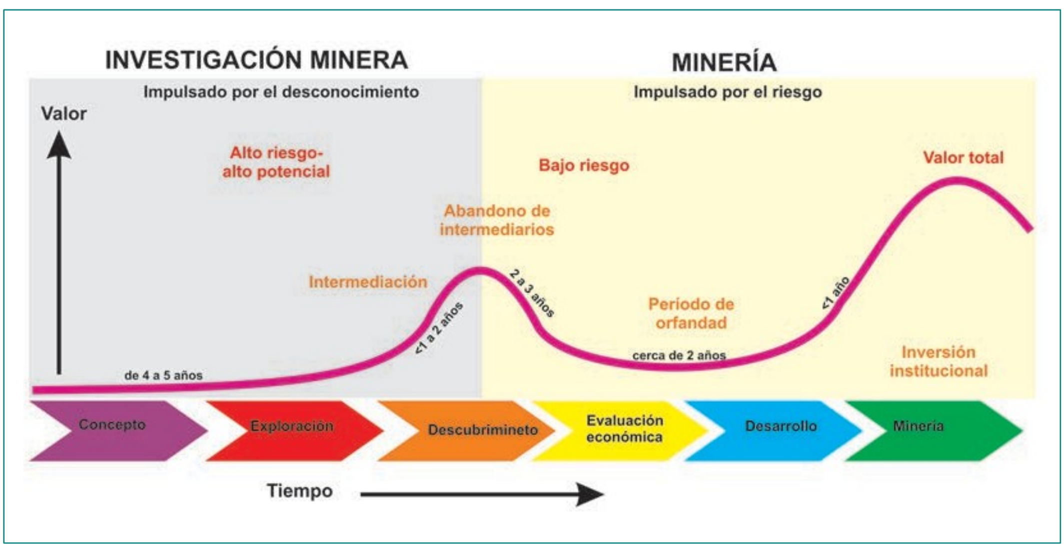


Figure 70. *Traditional value curve, showing, in addition to the value of the process, the normal time invested and the origin of the risk. Source: authors' own elaboration.*

In exploration or mining research, value can also be produced, since, for example, the business value of a sale of rights can reach very high prices, since permits with a high potential value are placed on the market. Furthermore, in the last phase, once the negative value of the closure has been settled, successful industrial clusters, poles or clusters may have been consolidated that can last over time and transcend the value of mining itself.

Table 25 shows the stages of activity in the value chain of a mining process, detailing the content in the different phases of the process and the applicable or reference methodologies.

Table 25. Content of the phases of the mining value chain. Note: I= Exploration or mining research, II=Exploitation, III=Closing and final values. Source: authors' own elaboration.

Economic value chain in mining			
PHASE	STAGE	Content	Valuation methodology
I	Team	Junior/Senior	Type
I	Idea or proposal	Size and components	Examples
I	Administrative permits	Economic summary	Calculation
I	Development of the research/evaluation	Stages	Accounting expense
I	Appraisal of the finding	Value of the right	Proprietary methodology
I	Acquisition	Corporate strategy	Market value
II	Standard reports according to international quality systems	From PEA to Technical Report	Profitability and efficiency indicators
II	Validation of initial reports and new Technical Reports	Incorporation of modifications and/or variations	Profitability, efficiency and risk indicators
II	Administrative and environmental permits and social opinion	Summary in financial and environmental economics	Economic principles and environmental values
II	Business valuation	Business development	Indicators
III	Circular/residual value	Future value	Models
III	Social and administrative obligation	Economic environmental values	Environmental economics

2.1. Upstream activities and exploration: mining research

Mining research is the first phase of the mining life cycle and comprises the technical and management processes and activities aimed at the discovery, definition and evaluation of the mineral deposit.

After the definition of large areas and identification of targets, higher cost exploration activities begin, in order to discover mineral deposits with satisfactory economic potential and where a drilling campaign of sufficient accuracy can lead to the definition of mineral resources with sufficient reliability to be recognized under an international valuation code.

As the first environmental and social footprint of an area's mineral resource development, managing exploration in a responsible and transparent manner is critical to gaining social permission to operate.

2.1.1. First stage: exploration or mining research

The ownership of rights to mineral substances is part of the State's domain. Therefore, no person may carry out exploration and prospecting or exploitation activities without a permit or license issued by the government authority having jurisdiction over the mineral domain.

Moreover, the mining industry is capital intensive, from exploration to mine closure. Investment in exploration is affected by the demand for metals and their supply, prices, the ability to raise capital and shareholder remuneration, as well as by administrative obstacles and environmental constraints. The sum of all these factors determines the reasons that make mining an activity with its peculiarities compared to other economic activities. Nevertheless, in some respects similarities can be found in the energy field, for example, in the exploration and production of oil or gas, or in decisions about certain power generation technologies.

2.1.1.1. Investments

Figure 71 shows, at the bottom, the flow of expenditures (or investments) required to produce the metal units at the top of the graph. It should be noted that exploration never ends and that the quality of the production units (grades or riches) declines over the life of the project.

The same figure shows the magnitude of the investments required to start up and maintain the activity of a mining project. The inflection point in the use of resources begins when the feasibility study phase is passed. The expectation of production from these expenditures is very limited due to the high risk involved in this phase.

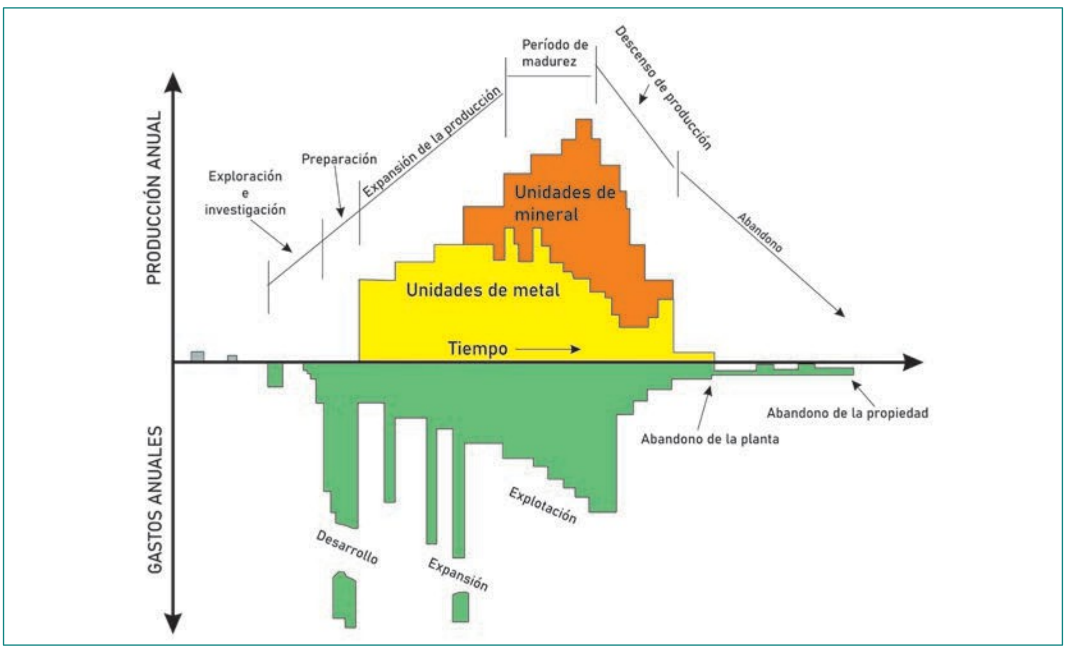


Figure 71. *Relationship of cost to total investment of a mining project. Source: (IGME, 1997).*

The global exploration budget for 2021 (from S&P Glo- bal Market Intelligence's Corporate Exploration Strategies series), shows that the mineral exploration sector has overcome the recession caused by the COVID-19 pandemic (Figure 72). According to that figure, global exploration investments reached US$11.2 billion in 2021.

According to the Prospectors & Developers Association of Canada (PDAC) global exploration activity in 2021 increased by 35%. This increase can largely be attributed to the upward trend in the prices of most mineral commodities[86] and a stronger financial environment in 2020. In addition, there are other less important factors: (i) the discovery of a World Class or World Class deposit, and (ii) the discovery of a World Class or World Class deposit.

[86] For more details on the evolution of the prices of some critical raw materials for the energy transition, see (Larrea and Cisneros, 2023).

Figure 72. Global investments in mineral exploration during the period 1996-2021. Source: translated by the authors from (S&P Global Market Intelligence, 2021).

(ii) new geological models or the emergence of a new technology: Carlin (new metalogenetic model for gold in Nevada), heap leaching (heap cyanidation for gold) and (iii) promotion policies by administrations interested in the mining development of their territory.

By metals, for decades gold has been the metal with the highest investment in exploration, followed by the base metals (Cu, Zn, Pb and Ni) according to MinEx Consulting (2017). This is due to its unit price, but also to aspects related to the difficulty of its prospection and its cost. In addition, today, faced with the verti- ginous demand for metals related to new technologies, there is a trend towards specific exploration of these substances. In 2020, the tendency to explore mainly for gold remained unchanged (52 % of the total). Copper was second (21 %) and zinc-lead, 5 % (S&P Global Market Intelligence, 2021).

Figure 73 shows exploration investments by type of company. It can be seen that the market environment for *junior* mining companies[87] is very dynamic and depends, to a large extent, on the capital market and investors. This opens up opportunities, but also entails great risks. Its importance in certain periods may be accompanied by decreases in others.

Capital volumes in the mining industry for *senior* companies range on average from US$350 million to US$500 million (Table 26).

Figure 73. Exploration investments by type of company. Source: Prepared by the authors with data from (PDAC, 2021).

[87] A junior mining company is focused on prospecting and exploration for metal resources. As they do not yet operate their own mineral extraction facilities, they do not generate revenues and profits from their current business, relying on investors to cover their expenses.

Type of company	Field of action	Revenues	Market capitalization
Junior	Exploration	New capital	< $500 million
Intermediate	Exploration and Mining	Partially cash	< $1,000 million
Senior	Mining	Cash generation	> or equal to $1,000m

Table 26. *Classification of mining companies. Source: translated by the authors from (One Stone Consulting, 2021).*

2.1.1.2. Mining project financing risks

Exploration is a high-risk business that often involves large investments with seemingly little return. Exploration is an investment in replenishing and growing a company's asset base; it is not the only growth opportunity available and competes with other options. It must yield a realizable value that is competitive with the other alternatives.

Figure 74 shows the number of projects that move through the more advanced stages up to development. It can be seen how, out of a set of 500-1,000 projects, only one reaches the production phase. Due to their high uncertainty, effective risk management as well as quantification of economic risk is critical.

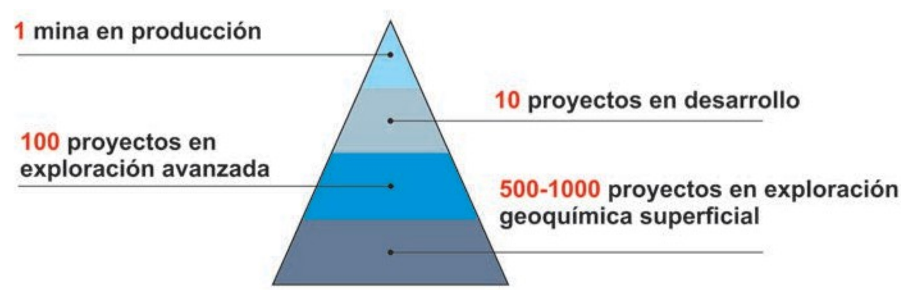


Figure 74. *According to Eggert (2010), less than 1 % of exploration projects progress to the development stage. Source: authors' own elaboration.*

Due to the financial size and high risk involved, it is common for the start-up of a mining project to require a financial structure to ensure its development. Today, a common modality is "Project Finance", where the project is developed through a loan from a financial entity (*lender*), which assumes the risk of the promoted project, and managed by the *sponsor*(s) who own interests in the company that owns the mining project. In this scheme, the risk is shared with the financial group or banks that assume the role of resource provider. This means that the financial entity must ensure feasibility and good execution in a technical framework that is not its own. To this end, it hires groups of experts or, where appropriate, auditing companies to monitor the project.

2.1.1.3. Activity costs

An exploration strategy is driven by the need for business growth, the price of metals, the availability of venture capital and new discoveries, opening up new areas for exploration. Resource growth can be achieved through direct investment in exploration, or by counting or acquiring resources from third parties (e.g. *junior* companies).

At one time, *junior* mining companies accounted for almost 50% of the world's exploration expenditures. Their success is due to seven competitive advantages, such as: (i) cost efficiency, (ii) the selection of the best available personnel (exploration technicians), (iii) the formation of a multi-skilled team, and (iv) the development of a multi-skilled team.

(iv) the development of meaningful incentive schemes, (v) exploration in areas with good expectations of success, (vi) the design of long-term programs and (vii) the selection of objectives.

For their part, large ("*senior*") companies spend between US$100 million and US$200 million a year on maintaining their project portfolios. Research is becoming more and more expensive, while hopes of finding large mineral deposits are becoming more and more remote.

Discovery costs

As shown in Figure 75, since 1950 the unit costs to describe a pound of copper have remained more or less constant. It is only since the end of the last century that they have increased steadily. This is evidence that surface resources are becoming scarcer and that there is a need to move towards subway mining. Another option would be the promotion of extraction methodologies with higher production volume and low cost, such as *block caving*. This has occurred in a couple of mines in Chile, where most of the increase in production has been due to the use of heap leaching of oxides and expansions in the treatment capacity of existing plants.

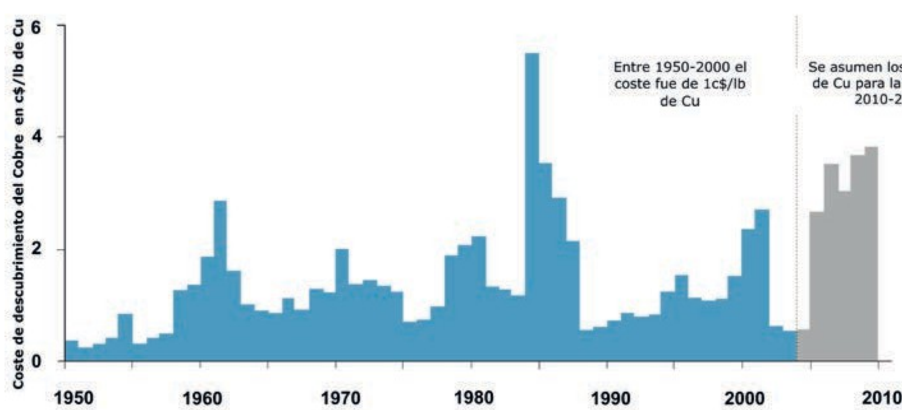


Figure 75. *Unit costs of discovering a pound of copper in the western world and in the period 1950-2010. Source: adapted by the authors from (MinEx Consulting, 2009).*

According to D. L. Stevens, vice president of Noranda Mining and Exploration, a successful exploration campaign requires both a high probability of finding the target ore body and reasonable costs.

2.1.1.4. Value creation: the value of mineral property rights

Many deposits are not exploited for multiple reasons: insufficient research effort, low tonnage or wealth at the time of the investment decision, socio-economic or environmental reasons, or legal limitations. This, however, does not mean that the property is worthless.

In this sense, the term "*The Most Convenient Market Value*" is defined as the highest price of an administrative permit between the value for the buyer and the seller, both fully informed, and related to the time and conditions prevailing on a given date. The appraiser's objective is to employ a methodology that eliminates as much subjectivity as possible and establishes an appropriate market price.

The methods for valuing an exploration asset, or a mineral resource not yet in operation, present the same difficulties as those used to determine the value of a mineral property in operation. In addition, this type of valuation has a very elaborate body of doctrine.

The factor that most determines the methodology is the degree of knowledge that, at that time, is available on the quality of the existing resources or reserves, the technological conditions of their exploitation, the characteristics of their available administrative, social or environmental surroundings, etc. At present, different systems are used, as shown in Table 27, of which the first three are the fundamental methodologies for the valuation of mining properties.

Methodology	Method	Description
On costs	*Appraised Value*	Research costs already incurred plus those necessary to achieve the last objective
	Comparable transactions	Costs less any significant debt
On revenues	DCF (*discounted cash flow*) analysis, with or without risk analysis	NPV (Net Present Value) of cash flows
	Real options, with or without Risk Analysis	Assuming irreversible investments under conditions of uncertainty
Market	Comparable transactions: sales, option agreements, and others	Principle that similar properties must have similar values
	Market capitalization by reserves	Market value of companies divided by total reserves or resources
	Market capitalization by production	Market value of the company divided by pro- duction
Others	Geoscientific Factor	Assignment of categories according to the characteristics of the property and reference to a standard value per hectare. It is highly questioned
	Decision Trees	Analysis with a probability factor
	Statistical/Probabilistic	NPV affected by a statistical factor
	Gross value "in situ	Value/ton of resource

Table 27. *Mineral property valuation methodologies. Source: authors' own elaboration based on various sources.*

The number of discoveries per se does not adequately take into account the potential economic value. For this purpose, success rates can be calculated by relating exploration expenditures to the estimated gross value of the economic minerals contained in the discovered ore. More complex are attempts to calculate discounted pre-tax net returns on exploration expenditure .[88]

2.1.1.5. Mineral exploration growth strategies

There are different mineral exploration strategies. First, the *Greenfield* exploration strategy (basic exploration in virgin areas) focuses on the discovery of new mineral deposits in areas where other deposits have already been discovered, or in areas with no previous discoveries but which show favorable geological conditions. *Brownfield* exploration focuses on the environment of existing mining operations and aims at the discovery of extensions and repeats of deposits. Mergers and acquisitions and strategic alliances should also be mentioned, especially between large, small (*juniors*) and medium-sized companies.

[88] For more detail see (Regueiro and Espí, 2019).

The "discovery" growth strategy is considered to be "low risk and high uncertainty", as the amount of capital invested in it can be controlled, but the probability of success is usually low. Similarly, the risk in *Brownfields* exploration is low and the uncertainty somewhat lower. Therefore, growth through exploration can be considered a conservative, low-risk strategy. For example, AngloGold's exploration strategy has traditionally consisted of discovering gold reserves through exploration of *Brownfields* fields with a cost of less than US$9/oz of gold reserves discovered, and *Greenfields* with an exploration cost of less than US$30/oz.

Acquisitive growth strategies are characterized by preferably seeking a low level of uncertainty. In general, the exploration strategies of most producing companies seek a balance between exploration and acquisition strategies, carrying out their own exploration programs and, at the same time, following up on acquisition opportunities.

Another important strategic aspect is the fact that exploration investment tends to go to countries and regions with a stable and favorable legal framework and to areas with high discovery potential. However, some of the "world class" deposits had unknown metallogenesis when they were discovered. This occurred in the absence of experience or lack of similar deposits, such as Neves Corvo, Candelaria and Century.

2.1.1.6. Environmental and social impact of exploration. Value creation in research/exploration.

The exploration process, in principle, does not significantly and permanently affect the use of the land where it takes place and, therefore, does not generate significant social or environmental impacts or, in any case, they are of a transitory nature. However, mining exploration represents the initial interaction between the mining company and the local communities and is therefore a delicate moment in the building of a relationship of trust between stakeholders. In general, opposition to future mining projects is often found in the early stages of mining exploration. Therefore, good process management, including environmental management, in the exploration phases is essential to achieve a permanent social license.

Virtually all countries require the mandatory submission of an Environmental Impact Assessment as a prior step to obtaining mining exploration permits. Highly sensitive countries, such as Australia and Canada, have voluntary codes of conduct, with activity guidelines in accordance with principles of equity with the owners and inhabitants of the site, while at the same time providing guidance on the environmental quality of the actions carried out in this first phase of the life cycle of a mining project.

2.1.2. Second stage: operation

Sometimes it is not easy to distinguish exploration from the beginning of exploitation. In principle, exploitation begins after the identification of projects that pass a profitability threshold and are incorporated into reserves, which generally coincides with the economic feasibility study and the increase in relative value. Figure 76 shows alternatives for increasing the value of resources already in exploitation (in red) through cross-cutting actions, involving organizational, research, logistical, commercial and other support elements.

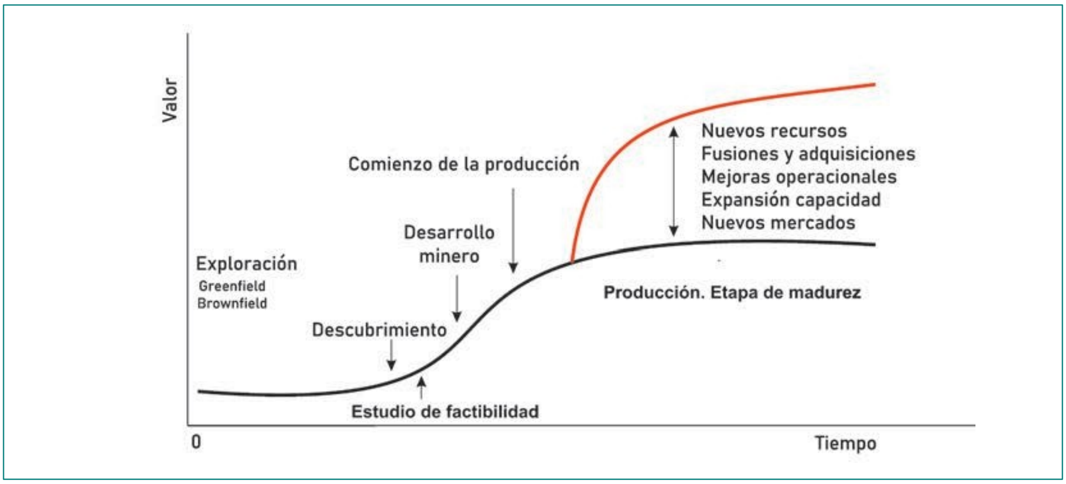


Figure 76. *Value growth opportunities at the beginning of production or already in the mature stage. Source: authors' own elaboration.*

The mining industry provides essential materials for all sectors of the economy and also generates employment and revenues for governments. Moreover, it cannot be understood without the metallurgical industry, which, as will be seen, generates value "downstream". Also, during the mine's exploitation phase, industrial clusters or poles may develop around the mine that could outlive the mine itself. Figure 77 shows various stages of the value chain from the mine to the market, comprising interdependent steps and corresponding activities.

Figure 77. *The mine-to-market value chain comprises interdependent steps and corresponding activities. Source: modified and translated by the authors from (McKinsey & Company, 2020).*

Extraction costs are highly variable and depend on each mine. They can range from a few cents of a euro per tonne mined to several tens of euros. Large-scale mining operations (large moving tonnages) reduce operating costs, but require high initial investments. This is justified when large deposits are mined, which amortize the large initial investment.

2.1.2.1. Investments

Mining is, in general terms, an operation that requires significant investment. Now more than ever because the extraction and processing of minerals is becoming increasingly complex for many reasons: the depletion of deposits that are more easily accessible and easier to extract[89] , the need to process lower grade ores, environmental and social obligations, disputes over land use, and the rising cost of basic inputs (water and energy, above all). Table 28 shows aggregate project data for different metals.

[89] For this reason, mining companies, whenever possible, seek projects to expand existing mines rather than build new ones.

Metal	No. of projects	Maximum investment (US$ MILLION)	NO. Projects with Inv.>1000 M US$	Average Inv. all projects (M US$)	Average project investment > US$ 1,000 M
Iron ore	16	16.000	10	3.200	4.800
Copper	53	8.000	33	1.590	2.300
Nickel	13	2.500	5	860	1.540
Zinc	14	2.500	1	490	2.500
Gold	73	6.700	15	490	2.380
Silver	7	740	-	350	-
MGP	5	2.000	2	1.000	1.700
Diamonds	6	2.100	3	1.100	1.800
Uranium	10	1.400	2	430	1.300
Lithium and TR	10	1.300	1	450	1.300

Table 28. *Global data on investment in mining of the main metallic materials. Source: authors' own elaboration based on (E&MJ, 2021).*

In the mining industry, worldwide, there are more than 13,000 active large and medium-sized projects, representing a total investment value of 1.18 trillion (European) dollars, according to Industrial Info's Business Intelligence (Govreau, 2021). Iron ore projects stand out, where almost all the investment is directed towards the construction of large supply and, above all, transport and storage infrastructures. In addition, large copper projects are numerous and, in many cases, coincide with capacity expansions or more complex transformations, such as the change from open-pit mining to highly productive subway *block caving* systems.

Figure 78 shows the production values of the 20 most important countries, excluding fossil fuel production, which highlights countries such as China, USA and Australia.

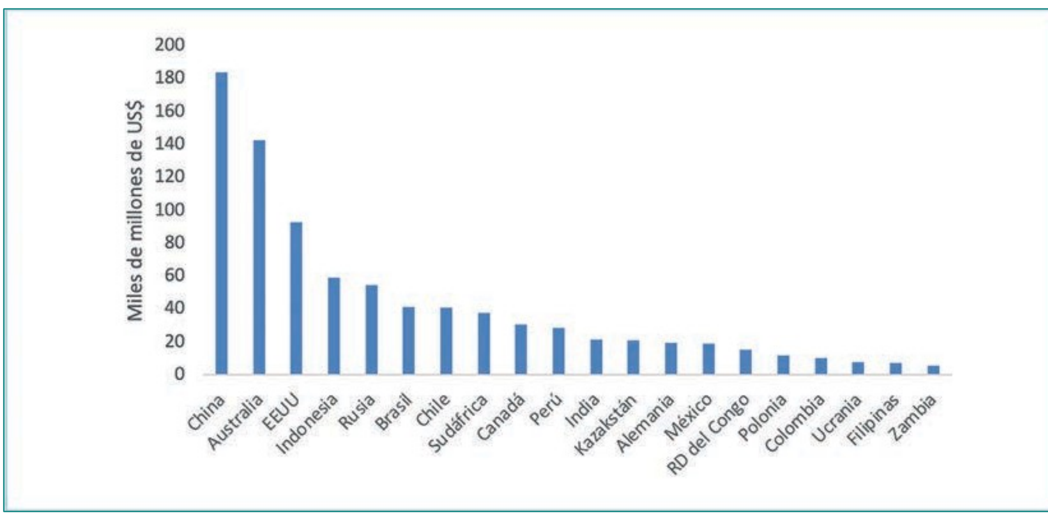


Figure 78. *20 largest producing countries of minerals (non-fuel) in 2017 (billions of US$). Source: (US Geological Survey, Mineral Commodity Summaries, 2022).*

In 2019, the mining sector increased its investments at a rate of 12 %, continuing a trend of increasing capital expenditures, which began in 2017. However, the COVID-19 pandemic led to the postponement of investments, halting or slowing down their projects. Since then, companies learned to operate safely in a pandemic environment by introducing new automation systems, digitization, remote access or related services (Govreau, 2021).

Against a backdrop of uncertainty, in 2020, gold surpassed US$2,000/oz for the first time (as a safe-haven investment). Copper and iron ore prices reached seven-year highs at the end of 2020. Producers around the world welcomed these prices, which are boosting investment and are likely to be buoyed by the shared view of many analysts that the downturn will not be a major source of income for the world's poor.

pandemic of 2020 would be replaced in 2021 by the decarbonization rush (Govreau, 2021). However, in 2022, there were, in many cases, drops in prices from the peak levels they had reached.

In 2021, of the top 20 countries for the development of mining projects, China was the leader, followed by Australia, India and Canada. In addition to Canada, the Americas are represented by Brazil, the United States, Chile and Argentina. Africa continues to be a continent with increasing mineral exploration and development activity (especially South Africa, Guinea, Mozambique, Congo, Ghana and Namibia) driven by many countries, including China and India, seeking to secure long-term resource supplies. Peru in South America and Mali and Burkina Faso in Africa are also relevant, particularly in gold mining.

These countries do not include any European country, which points, on the one hand, to the lack of production weight and consequently to European vulnerability measured as dependence on third countries (which reaches between 75 and 100 % depending on the type of mineral raw materials) and, on the other hand, to the potential for value creation in the territories where minerals and metals are produced for the energy transition and digitalization.

2.1.2.2. Activity costs

The costs associated with mining activity are enormously varied, as are the natural and other circumstances (such as administrative, social, labor or technological) in which it is carried out. Nevertheless, the knowledge created around the supply-demand relationship facilitates the forecasts for designing projects. Table 29 shows the cost structure.

Cash Cost Direct	Mining operation Processing operation Mine administration expenses Essential operation services: water, power, tailings management Smelting and refining Transportation and insurance of external shipments Commercial expenses
Indirect *Cash Cost*	Production fees and royalties Administrative and environmental permitting costs Social responsibility costs
Maintenance costs	In mining: renewal of machinery and fleet, non-operational clearings, subway developments Processing plant: replacement of major equipment in treatment plant New infrastructure Rehabilitation and closures
Total Cash Cost	

Table 29. *Example of cost structure carried out by SRK Consulting in 2016. Source: authors' own elaboration based on (SRK Consulting, 2016b).*

Cost drivers are varied. Perhaps the most representative is size. Under this parameter, there are fixed costs, which do not vary with production (e.g. labor costs to a certain extent, overhead costs, taxes or support costs at the place of operations) and variable costs (depending on the level of production). As a consequence, as production increases, fixed costs see their share of total unit cost decrease, as shown in Figure 79. Costs are also relevant in determining the gross operating margin.

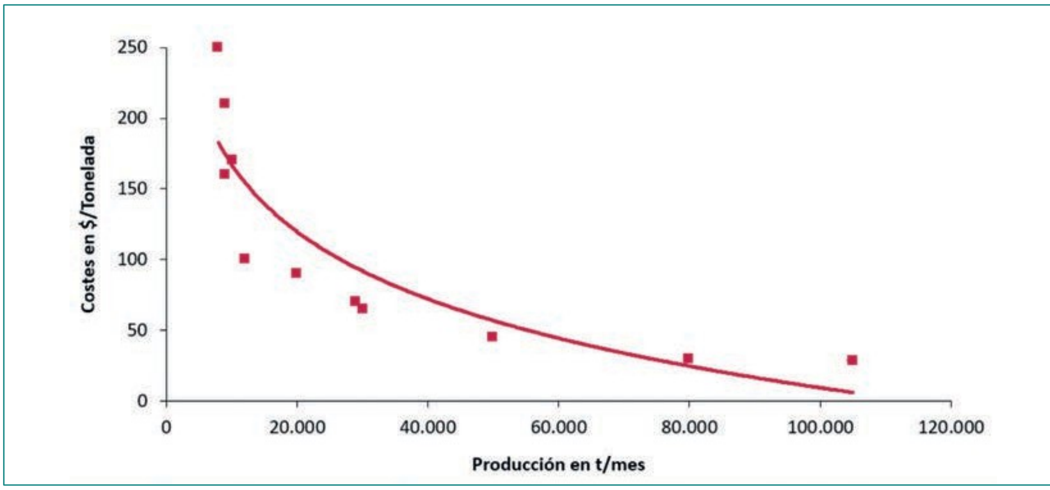


Figure 79. *Example of the effect of production variation on unit cost. Source: authors' own elaboration based on (SRK Consulting, 2016a).*

2.1.2.3. Value creation: formation of mineral prices

The prices of mineral commodities and metals, in general, are determined by supply/demand and not by a single variable. In this case, supply, demand or both are usually in continuous change as shown in Figure 80, which shows an index of some of them.

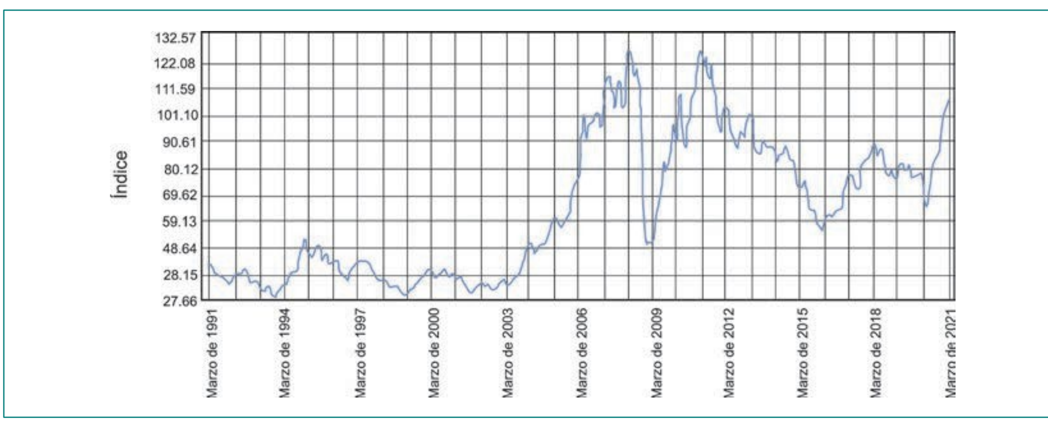


Figure 80. *Evolution of the Commodity Metals Price Index, which includes copper, aluminum, iron ore, tin, nickel, zinc, lead and zinc, and uranium (2005 = 100, 1990-2020). Source: authors' own elaboration based on the Index Mundi indicator.*

Production tends to be more stable and predictable than demand. Demand, on the other hand, participates in markets in a fluctuating manner and almost always linked to economic activity. In the short term, strong variations in demand are more difficult to understand (De La Torre and Espí, 2022).

The variability in the prices of mineral raw materials is a recurring source of concern for governments, investors, manufacturers and mining companies (De La Torre and Espí, 2022). In addition, the price of metals is topical and its variations are news (Espí et al., 2021). As this is an activity where the input is provided by nature, the quality of the same mineral becomes a variable that will influence the economics of the project. This is in addition to the different operating costs.

Another variable, which contributes to the complexity, is the need to comply with sustainable exploitation criteria, which includes reviewing the social and environmental character of each mining project. The importance of these criteria is such that they can prevent the change from resource status to exploitable reserves, or more directly, extinguish or prevent the granting of the necessary operating license.

Metals are bought and sold in different ways and under different arrangements that reflect their ease of storage and transportation, as well as their degree of standardization or differentiation. Typically are traded on commodity exchanges (whose prices directly or indirectly govern all the day's transactions), OTC (*Over The Counter*) markets, or through prices negotiated with producers. Supply and demand can come not only from industrial producing companies and buyers, but also from intermediaries and investors of all kinds.

The London Metal Exchange (LME) is the world's leading metals market, covering approximately 90% of global transactions in the metals it manages, including aluminum and its alloys, copper, tin, nickel, zinc, lead, cobalt, molybdenum, as well as billet and scrap steel. It is also worth mentioning the New York Mercantile Exchange (Nymex) and its Comex division (Al, Cu, Au, Ag, Pt, Pd, U) and the Shanghai Metal Exchange. Prices on the exchanges are set daily (during trading hours), balancing supply and demand in the *spot market* and allowing futures transactions. As usual in this type of market, operations are anonymous and the market itself provides guarantees for participants.

OTC markets are direct trading markets between agents (supply and demand) and where *default* risks are assumed by the participants (e.g. London Bullion Market Association, LBMA and London Platinum and Palladium Market, LPPM). Producer pricing occurs in cases where there are few producers, with similar selling prices. In this case, the producer announces or determines the price (e.g., diamonds, PGMs, potash).

Finally, negotiated prices are obtained in bilateral seller/buyer contracts without institutional structure. They are common for mineral commodities with differential characteristics (iron ore, coal), sold in small quantities (Cd, Nb) or with other characteristics that do not allow them to be sold in markets. Reference prices appear in Metal Bulletin, Platts Metal Week and Indus- trial Minerals.

When resources are depleted or production costs rise, there is a greater interest in controlling the prices of mineral raw materials. Conversely, the opening of new mines (which come on stream at irregular intervals), or a decline in demand, tends to reduce the prices of mineral commodities. A widespread use of financial products, such as options, affects the supply/demand mechanism and therefore has an impact on prices.

Forward pricing is a risky but unavoidable operation in a company. Investment projects in new mineral deposits, future forecasts of ongoing businesses and other situations require the determination of a price. Finding the right price means setting a figure that meets the conditions for defending against price volatility, with sufficient knowledge of the opportunity in the markets. In addition to the quality factors of the field itself, experience and the adequacy of the available technology will shape the criteria for choosing this figure. Therefore, it is up to the company to decide the appropriate strategy for its risk acceptance profile and the formulation of quality objectives, always under an expert geological view (Espí and De la Torre, 2013).

The most common methods for price determination are based on forward-looking market studies, which move in the fields of business strategies and investment availability, financing strategies and risk appetite. The methodologies most commonly used by companies in the sector are (i) the average of average prices over the last three years (sometimes up to the last five years), (ii) assimilation of the experience of other projects and (iii) the decision of a group of designers who make use of their experience in each project.

2.1.2.4. Production value

The value of world mineral production is not easy to obtain and data from different sources do not always coincide. Table 30 presents the dollar value of production attributed to the world's top ten producing countries. The top six are in coal and iron ore, which, in addition to copper and gold, are of great value to their producers.

Table 30. *Value of mining production by country. Note: ICMM data include metallic and coal mining. Source: authors' own elaboration based on (ICMM, 2020).*

Country	Value of production in 2018 in billions of US $ (ICMM 2020)
China	183,8
Australia	142,9
USA USA	92,9
Indonesia	59,2
Russia	54,6
Brazil	41,6
Chile	40,9
South Africa	37,8
Canada	30,8
Peru	28,9
Total, worldwide	**713.4** (top 10 only)

Table 31 shows the total world production value of the main metals. They can be classified into three groups: (i) metals from "*bulk*" ores (produced in large quantities), which account for most of the total value (72.1%) (including iron and aluminum, as well as copper and gold);
(ii) base metals (zinc, lead, nickel) and titanium, which represent 21.7%, and (iii) technological metals (mainly critical or strategic) and uranium, whose economic value amounts to 6.2% of the total.

Table 31. *Value of metal production in 2019 in US$. Note: value of metal contained in ores. Source: authors' own elaboration based on (Statista, 2022c).*

Metal	Value in billions of U.S. $	Metal	Value in billions of U.S. $
Gold	170	**Copper**	155
Aluminum	165	**Iron ore**	137
Zinc	49	**Nickel**	27
Manganese	40	**Silver**	17
Lead	30	**Titanium**	13
Palladium	10	**Tin**	7
Rare Earths	9	**Molybdenum**	4
Platinum	8	**Uranium**	4
Cobalt	8	**Lithium**	3

2.1.2.5. Margins and overall results

A key economic indicator is the *cut-off* grade[90] . By definition, the cut-off grade is the metal concentration that equals or exceeds the costs incurred in mining and beneficiation. It considers the total operating costs, including those of the mining process, ore concentration, administrative costs, metallurgical recoveries, metal prices and smelting and refining costs.

[90] For more details see chapter 3 and the glossary of terms.

Once the *cut-off* has been defined, any portion of the deposit that exceeds this grade must be considered as economically exploitable. The mineral input to the processing plant will have an average grade higher than this *cut-off*, and the difference will be the margin that will provide the project with sufficient resources to carry it through and make the business work.

Another way to visualize the theoretical margin (in addition to visualizing the competitive position of the project) is to refer it to the price of metal at a given moment on the unit costs of accumulated world production, referring to specific projects or companies.

2.1.2.6. Productivity and capitalization

The productivity of a mining operation can be evaluated in various ways, usually by determining the amount of ore or metal produced per person. However, the wage bill is increasingly decreasing due to technological changes. Therefore, it is almost universal to refer productivity to the metal produced, comparing the results with the most important projects at a global level.

A good indicator of the economic importance of a company is its capitalization. For this reason, the top ten companies in the sector are presented in Table 32, highlighting the large iron ore producers, although in general, to a lesser or greater extent, they are diversified.

Company	Capitalization US$ million	Country	Mineral substance/ Metal
BHP	179. 000	Australia	Iron ore, copper, coal
Rio Tinto	132.000	Australia	Iron ore, aluminum, copper
Vale	112.000	Brazil	Iron ore, nickel
Glencore	55.000	Switzerland	Copper, cobalt, zinc, nickel
Norilsk Nickel	54.000	Russia	Palladium, nickel
Freeport-McMoRan	52.000	USA. USA.	Copper
Anglo American	52.000	UK	Diamonds, copper, platinum, iron ore, coal, coal
Fortescue Metals	51.000	Australia	Iron ore
Newmont Goldcorp	50.000	USA. USA.	Gold
Southern Copper	47.000	USA. USA.	Copper

Table 32. *Market capitalization of the top ten global mining companies.*
Source: authors' own elaboration based on (Elements, 2021).

Mining companies in the aftermath of the COVID-19 pandemic have an encouraging outlook as the economy recovers. The market is expected to reach a value of nearly $1.86 trillion by 2022, due to the growing demand for minerals for renewable energy power generation technologies (Venditti, 2021).

2.1.3. The third stage: closing and final values

The last phase of the mining process refers to the period from the beginning of the stoppage of production until the end of the commitment acquired with the Administration in the environmental surveillance and monitoring of the site of operations[91] . The footprint of mining should be positive, both environmentally and socially. This would be the case of an industrial cluster.

91 For more details on the rehabilitation of mining areas, see Chapter 3.

2.1.3.1. Closure and environmental commitments

In the past, in a mining project, closure planning was the responsibility of a company's operational management and focused on environmental aspects, among which community involvement was often reduced to information consultation processes. To the extent that the community participates with ideas and suggestions in the post-mining project phase, the initiatives are likely to be better received and more durable.

With a broad vision, today it is considered that, for a mining project to contribute positively to the development of the area where it is developed, impacts and closure must be considered from the beginning (Table 33). In addition to the Closure Plan, there are subsequent (post-mining) obligations that have an impact on the cost of the final phase. The main one is the maintenance of the facilities integrated into the natural environment.

Installation	**Frequency of maintenance and post-closure follow-up**						
	Maintenance (Mto)			Follow-up (Segto)			
	Mto. Physical	Mto. Hydrologic	Mto. Biological	Physical Secto.	Segto. Geochemical and water quality	Hydrological Secto.	Biological Safety
Job	Annual	Annual		Annual	Quarterly	Annual	
Mine areas reclaimed for closure	Five-year		Annual	Annual			Annual
Tailings dam	Five-Year	Annual		Annual	Quarterly	Annual	
Debris collection	Five-Year	Annual		Annual	Quarterly	Annual	
Hydraulic structures for water management at closure	Five-Year	Annual		Annual	Quarterly	Annual	

Table 33. *Concepts of the final phase of the rehabilitation following the Anglo American, Walsh scheme. Source: authors' own elaboration based on (Anglo American, Walsh, n.d.).*

2.1.3.2. Costs and value of the final phase

The costs of these last stages of the mining process vary widely. In addition to the volume of operation, there are significant differences depending on the mineral substance, method and depth of mining, difficulty of processing, natural environment and many more.

An economic component of the closure phase is the guarantee required by the government from the mining company to secure the commitment acquired by the company at the time of granting the economic activity permits. Normally, the amount of the financial guarantee is a function of the estimated costs for the execution of the closure plan.

The value of the facilities, once the operations are completed, is, in general, a positive economic flow in the phase of closing or decommissioning of the facilities. It is mainly made up of the value of the sale of equipment and the sale of scrap, especially copper from machinery. But because of its uncertainty, it is rarely taken into account in an investment project. There are also other assets that are rarely realized, such as water supply, restored agricultural land, general buildings and others. The municipalities or nearby communities are sometimes the beneficiaries and, when they are not, they remain tied to the vicissitudes of the evolution of the property.

Adequate management by the mining property and the Administrations where it is developed can generate industrial clusters or groupings. Also, without becoming a cluster, the industrial chains generated by local industrial and service companies sometimes manage to become independent from the mining activity, surviving it and creating periods of stable economic activity[92] . This has been the origin of industrial cities and major economic clusters (steel industry in the Basque Country and ceramic industry in Castellón, for example).

2.2. Metallurgy value chain

Metallurgy is the stage after mining and the preparation and concentration of the ore. It begins with the treatment of the mining concentrates of the metallic ores to first obtain the raw metal and then continues with the refining operations to obtain the metal that is finally placed on the market.

Metal-bearing ores have two main characteristics. The first is that the metal grade in the ore is highly variable, depending on the metal and the deposit from which it is extracted. For example, in bauxites (to obtain aluminum) the grade is 55%, in the form of alumina, which does not require concentration of the ore. However, in chalcopyrites (to obtain copper) the grade may be 0.5%, which requires concentration.

The second characteristic is that, except in native metals, metals are rarely alone; they are usually accompanied by other metals. This can be favorable (as in the case of the presence of gold in copper ore) or, usually, a complication, because its presence impurifies the metal being sought.

Large mining companies (Alcoa, Angloamerican, FreportMacMoran, BHP and others with annual sales of more than US$20 billion) have integrated the metallurgical process until the commercial metal is obtained. This vertical integration means that the mining company, which extracts the ore at the mine with normally low metal grades (0.5-10%), has to concentrate it with mineralurgical operations (Chapter 3) to obtain a metal grade that allows it to enter the metallurgical process (30-40%).

As mentioned above, the price of metal is set by the Metal Exchanges. The law of supply and demand mainly determines the price of metals on the exchanges. The value of the concentrate depends on its grade in the metal and rises as the grade increases up to that of refined metal, which can have a "five nines grade" (99.999%).

Ore plants are usually in the pit and it would be reasonable for metallurgical plants to be close by. However, because concentrates move because of their high price and because some metallurgical processes (e.g., Bayer-Hall-Héroult process for obtaining aluminum from bauxite) require large amounts of electricity for their electrolysis operations, metallurgical plants may be located in locations not close to the mine. This involves transporting concentrates from the producing countries to the consuming countries.

92 It is more likely to happen when the mining company is a technology leader.

By way of example, in the second half of the last century, when the first great oil crisis of 1973 had not yet occurred and electricity was considered abundant and cheap, metallurgical complexes for the production of aluminum (the second most produced metal in the world after iron) were built in countries where there were no bauxite mines and which were far away from them. In China, too, government-owned metallurgical complexes were built (where strategic rather than economic interests were paramount), which purchased metal concentrates wherever they were available in the world to produce the metal needed for their industry.

Metallurgical processes, despite being at an advanced stage of the value chain (not taking into account recycling), facilitate the possibility or not of opening a mine, since if there is no metallurgical process to treat the ore, the mine cannot be opened. In addition, metallurgical processes are constantly evolving and the development that has taken place thanks to innovation has made it possible to treat tailings dumps that had metals that were not extracted at the time because the technology was not available or was not economically attractive.

The fact that metals are recyclable means that secondary metallurgy, which was discussed in the fourth and sixth chapters, now accounts for more than 50 % of the production of the four non-ferrous metals. Secondary metallurgy is carried out in recycling processes that begin with the collection and concentration of scrap metal from metal equipment that has reached the end of its useful life, in some countries, with "integrated collection systems", in specialized centers where, in addition to concentrating, a selection is made of the different metals to be recycled. In the sorting operations, other materials that accompany the metals are discarded. Once the selected scrap metals have been sorted, they are shredded to the size required for subsequent operations.

Concentration operations are carried out to separate the different metals and through magnetic separation operations and others, the metals are obtained, ready to enter pyro-metallurgical plants, recycled and converted back into useful metals. This is a contribution of secondary metallurgy to the value chain.

3. Industrial poles, clusters or ecosystems

As noted, mining activity can lead to the creation of industrial poles, clusters or ecosystems[93] during the different phases of mining activity, which can outlive the mining activity itself, creating positive value for the area, and even extending beyond the operational life of the mine. There are several definitions of the term cluster[94] which are given below.

According to the European Cluster Collaboration Platform (ECCP) a cluster is a regional ecosystem of related industries and competencies covering a wide range of interdependencies. They are defined as groups of companies, related economic agents and institutions located close to each other and which have achieved sufficient scale to develop specialized expertise, services, resources, suppliers and *skills*.

[93] For the purposes of this paper, the terms industrial pole, cluster, industrial ecosystem and agglomeration are used interchangeably.

[94] Clusters should be distinguished from cluster organizations, which are legal entities that support collaborative effort, *networking*, learning and innovation (European Cluster Collaboration Platform (ECCP), n.d.).

For their part, Delgado et al. (2014) define clusters as geographic concentrations of related industries and associated institutions. The agglomeration of related economic activities is a central aspect of economic geography.

For Porter (1998), clusters are geographic concentrations of interconnected firms, suppliers of specialized goods and services, firms in related industries and associated institutions (e.g., universities, standardization agencies or trade associations), which in a given field compete, but also cooperate.

Other authors have highlighted factors that drive agglomerations or clusters, namely: *input-output* linkages, pooling of human resources and *knowledge spillovers* that are associated or related to cost or productivity advantages for firms.

Geographic or district clusters have been seen as the territorial configuration most likely to enhance learning processes, especially those influencing the diffusion of knowledge and innovation. Companies with a certain geographical proximity can benefit from agglomeration and develop common-use infrastructures promoted by regional institutions.

One of the main reasons for the success of clusters is that companies that carry out similar activities and are located in the same geographical environment are in a situation in which each of their actions can be observed, analyzed, researched and compared by the rest.

Regional institutions (universities, research institutes, technology and technical assistance centers and others) facilitate the development of competitive capabilities among local companies by acting as engines of information exchange and promoting collaborative processes.

It is important, because of their relationship with the value chain, to refer to clusters in Europe, which are often associated with industrial ecosystems, understood as the set of agents or actors operating in the value chain, from small *start-ups* to large companies, from academia and research, to service providers and suppliers.

The literature on competitive advantages of clusters suggests that in places where there is a critical mass of companies around a given economic activity, a process of improvement of competitive advantages occurs through interaction between companies or between companies and specialized institutions and consumers. This process can take different forms, such as greater product differentiation to enter more dynamic markets; incorporation into higher-value links in the chain; innovations to improve efficiency and productivity; or even changes towards spin-off economic activities that have greater development prospects.

3.1. European clusters and other international references

A recent paper examining the landscape of European clusters notes that they are a key aspect of the European economy and that they are concentrated in activities related to trade and manufacturing. These clusters provide a wide range of services, particularly in in transversal functions, facilitating collaboration among its members, supporting research, development and innovation, or promoting access to financing, internationalization, communication, the internal market, *location branding* and the management of intellectual property rights (Franco et al., 2021).

The same report highlights the low relevance of clusters related to mining and metallurgy. The report uses a classification based on the two-digit National Classification of Economic Activities (CNAE) codes[95] . However, three clusters are listed: (i) "Metaindustry cluster of advanced manufacturing of metal industry" in Asturias, (ii) "Steel Innovation Center/Polo del Acero" and (iii) "Iberian Sustainable Mining Cluster". Also noteworthy is the role of ICAMYL (International Center for Advanced Materials and Raw Materials of Castilla y León), which participates in the strategy of efficient management of industrial resources, energy efficiency, eco-innovation and substitution of critical materials. Its objective is to promote the development of advanced materials for the region's industry and the creation of wealth based on the raw materials of Castilla y León, in line with its Smart Specialization Strategy (RIS3).

In terms of employment and number of clusters, the report does not include metal ore mining (B07) or mining support services activities (B09), given their limited relevance in the EU. However, value chains related to the manufacture of base metals (C24)[96] and fabricated metal products, except machinery and equipment (C25), are included, as can be seen in Figure 6.

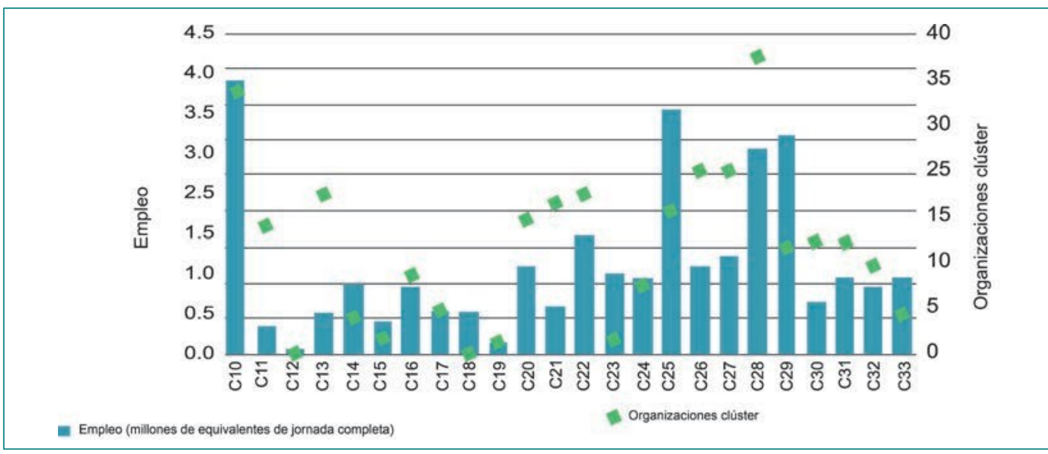


Figure 6. *Employment and cluster organizations in EU-27 industry (2018). Source: translated by the authors from (Franco et al., 2021).*

In the international arena, a reference of interest is the "Canadian Mining Cluster". Among the success factors are the size and diversity of mineral resources, the existence of a stable legal framework (legal security), the proximity to the main markets, the close links with some technological innovation centers and the development of a sector of machinery and equipment producers specialized in communication with mining companies.

The description of the agglomeration around mining in Canada includes an extraordinary diversity of specialized actors, including mining companies and their suppliers, consultants and other professional services, financial institutions, universities, associations and even the specialized press. Dis-

[95] Those related to the value chain of this study, would be: B07 *Mining of metal ores*; B09 *Mining support service activities*; C24 *Manu- facture of basic metals*; and C25 *Manufacture of fabricated metal products, except machinery and equipment*. Another code related to this work would be C27 *Manufacture of electrical equipment*.

[96] This code includes, for example, the manufacture of products from the primary processing of steel, aluminum, lead, zinc, brass, copper and other non-ferrous metals.

The interaction between all stakeholders has produced proprietary knowledge and capabilities that distinguish Canadian mining companies from their global competitors. The interaction among all stakeholders has produced proprietary knowledge and capabilities that distinguish Canadian mining companies from their global competitors. The agglomeration's potential for developing new competitive advantages lies mainly outside the core production chain, in the area of environmental knowledge application.

The concept and development of the mining cluster in Canada should be framed by its minerals plan and meta- les (Minerals Canada, 2019). Such a plan "*includes the vision, principles and strategic directions that the Go- vernment, industry and stakeholders can seek to advance to achieve industry competitiveness and long-term success*." The vision is for Canada to have a responsible, competitive and sustainable minerals industry that benefits all Canadians. To achieve the vision, the plan includes six strategic directions, one of which is "science, technology and innovation", which aims to develop innovation ecosystems in mining at all stages of the minerals value chain where incentives are promoted to support a "supercluster" that addresses the major technological challenges.

4. Conclusions

From the early stages (including mining research), value is created by identifying mineral deposits of interest to the market and generating reports that have a value in themselves, which is increased when, as a result, companies and stakeholders acquire rights that, in turn, also have value. Value is also created in the pre-exploitation phase by developing relations with the environment and the Administration and in the preparation of environmental impact studies.

As research and exploration progresses, knowledge of resources generally improves. The economic value at this stage depends, on the one hand, on the level of risk and uncertainty and, on the other hand, on the type of investigation or resource being worked on, whether in virgin, unexploited areas with little geological knowledge, or in those where there have been previous detailed investigations or mining operations.

An essential component of value creation is to achieve return on investment, operating margins, gross margins or operating profit, similar to other industrial and economic activities.

Once the investment decisions have been made, the mining development of the operation represents a significant advance in value creation, since the production process begins and, therefore, tangible products of interest to the market are produced. In this phase the linkages are evident upstream: mineralurgical facilities and metallurgical plants, transportation to the markets; and downstream, such as with suppliers and providers of inputs and industrial facilities.

It is also here where the interrelation of companies, institutions and the territory play a key role in the creation of value that goes beyond the linear conception of the value chain, underpinned and framed by the concept of clusters.

The conception of clusters and the development of industrial ecosystems are key elements for industrial and mining development, for the adequacy of training, the obtaining of financing, the stimulation and orientation of innovation, engineering and technology; and for the contribution to a sustainable economy and quality employment in the medium and long term. The scarce number of clusters in Europe and Spain related to mining and metallurgy shows, on the one hand, their scarce implementation; but on the other hand, it represents a great opportunity given their potential. In this sense, the Canadian case can be an example to study and follow.

The final stages of closure and post-mining, within the framework of compliance with environmental and administrative authorizations and supported by a cluster concept, can add value and convert what could be environmental liabilities into assets and the creation of new industries or economic activities.

Metallurgy begins with the treatment of the mining concentrates of metallic ores to first obtain the raw metal and then continues with refining operations to obtain the metal that is finally placed on the market.

Metallurgical processes add value to the mining activity. They are constantly evolving and developing, and thanks to innovation it has been possible to treat tailings dumps by extracting metals that were not extracted at the time because the technology was not available. Moreover, the metals, which are recyclable, are suitable for secondary metallurgy, adding value to a chain that does not originate from primary mineral raw materials.

ABOUT MINING AND METALLURGY IN SPAIN

1. Introduction

As has been shown in the section on European vulnerability in the Introduction, the EU is highly dependent on the supply of mineral raw materials from third countries. Despite the fact that there is cobalt production in Finland, or hafnium in France, and that in Spain the geological diversity gives rise to a varied and important mining production, 95% of the rare earths coming to Europe come from China.

Metals produced in Spain are indispensable in the policy of securing the supply of mineral raw materials. This refers both to metals such as copper, zinc and lead from the IPB (Iberian Pyrite Belt) / FPI (Faja Pirítica Ibérica) and to those known as technological (such as tin, wolfram, tantalum and lithium). In addition, Spain has an important potential in minerals related to the energy transition, having identified 13 minerals useful for decarbonization in the national territory (Gil, 2022), including lithium, cobalt, nickel, manganese, copper, wolfram and vanadium.

Despite this, there are currently around 30 mining projects paralyzed in Spain (Arce, 2021). The direct consequences are according to Arce (2021) that (i) almost 10 billion euros are spent annually on importing minerals and non-ferrous metals, according to figures from the Ministry of Industry, Trade and Tourism, and (ii) the industry is subject to supply restrictions and at the expense of the commercial strategy of countries such as China.

Although the Spanish economy is a high exporter (Table 34) of group 25 products (i.e. salt, gypsum), it is an importer of group 26 products[97] . Moreover, no major changes are observed in the last decade (2010-2020).

	2010		2015		2020	
	Exports	Imports	Exports	Imports	Exports	Imports
Thousands of euros						
25 Salt, gypsum, stones S/ to work S/ to work	934.994,30	523.883,35	1.199.526,81	532.313,25	1.104.907,94	626.042,45
26 Ores, slag and ash	867.753,76	3.504.037,61	1.498.627,87	3.492.975,90	1.360.409,51	3.416.728,63
28 Inorganic chemicals	767.330,91	1.795.353,89	1.183.639,86	2.037.399,57	1.246.837,75	1.882.695,25
Tons						
25 Salt, gypsum, stones S/ to work S/ to work	13.985.601,51	7.250.542,06	20.977.101,99	5.610.319,82	22.855.502,24	8.162.241,36
26 Ores, slag and ash	779.158,72	12.393.567,33	2.469.436,11	13.680.211,85	2.232.863,52	11.080.150,77
28 Inorganic chemicals	3.656.460,50	2.672.140,47	5.548.484,34	3.251.148,59	5.545.486,95	3.666.905,18

Table 34. *Evolution of exports and imports of products of groups 25, 26 and 28. Source: Prepared by the Company from the authors based on Datacomex.*

In 2020, the main products exported in monetary terms were copper ores, hydraulic cements, artificial corundum, slags, ashes and residues, zinc ores and concentrates, carbonates and peroxocarbonates, and aluminum sulfates. In tons, these were natural gypsum, anhydrite and gypsum, hydraulic cements, casts (calcareous fluxes used in the production of gypsum and gypsum products), hydraulic cements, castings (calcareous fluxes used in the manufacture of

97 Groups of the CNAE classification.

when the ore to be smelted contains a lot of clay), sulfates, alumina, pebbles, gravel and stones, artificial corundum and sulfuric acid.

In terms of imports, copper, zinc, iron ore, precious metals, radioactive chemical elements, aluminum ores and carbonates are the most important in economic terms. In terms of tons, the largest imports were aluminum ores, iron ores, feldspar, leucite and nepheline, kaolin and other associated clays, copper ores, hydraulic cements and zinc ores.

Taking into account the above and the needs raised in the second chapter on the role of mineral raw materials in the energy transition and the digitalization of the economy, in order to meet the objectives of the European Green Pact and the 2050 decarbonization target, in addition to possible trade agreements with third supplier countries and the importance of recycling or recovery, the EU's own supply capacity is essential, also taking into account that there is a potential supply and supply risk.

With regard to resources in Spain, Map 5 shows the main raw material deposits in the country.

Map 5. *Main raw material deposits in Spain.*
Source: IGN (2019).

Given the existing potential, it would be advisable to promote and facilitate the development of projects in Spain, particularly those related to the mineral raw materials needed for the energy transition and digitalization, such as lithium and rare earths. Along the same lines, a section on natural capital could be included in the national accounts; a chapter that, by way of example, has recently been incorporated as an element of a territorial competitiveness scheme .[98]

The "Roadmap for the sustainable management of mineral raw materials" (Ministry of Transi-

[98] For more details see (Orkestra, 2021).

The report on the Ecological and Demographic Challenge, 2022), among other issues, points out that "*it is necessary to improve knowledge of the available indigenous mineral resources (primary and secondary) and to identify priority raw materials for the Spanish economy as a whole".* It also indicates that the development of indigenous mineral resources, in addition to guaranteeing greater security of supply, creates and maintains value chains.

The following section presents information on mining production and projects in Spain. This is followed by data on Spanish metallurgy, and then the value chain with economic information on mining and metallurgical activities in Spain.

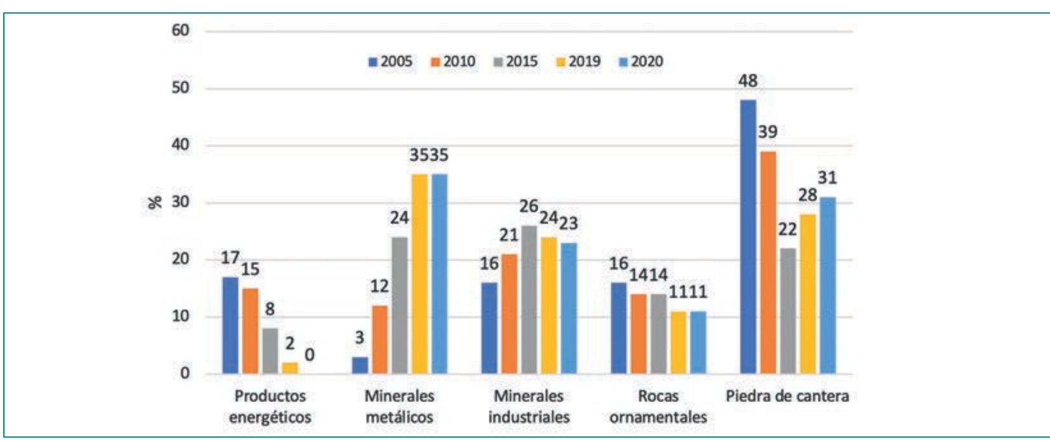
2. About mining production

Overall, Spanish mining production accounted for 0.3% of national GDP and metallic mining around 0.1%[99] (Secretaría de Estado de Energía, and Dirección General de Política Energética y Minas, 2019). The contribution of energy mining to GDP has fallen in recent years.

Domestic mining production in 2020 reached €3,061 million, 8% lower than the 2019 value. Since 2018, when the maximum value was achieved, production has been falling. The year 2020 was anomalous, as a consequence of the situation generated by COVID-19, due to the reduction in demand, and the stoppage of exploitations.

In 2020 (Figure 7), 31 % of the value of mining production was quarried stone (936.6 million euros), 35 % metallic minerals (1,064.1 million euros), 23 % industrial minerals (695.5 million), 11 % ornamental rocks (351.1 million euros) and energy products made up the rest (about 13.7 million euros).

Graph 7. Percentage concentration of value of production by subsectors. Source: authors' own elaboration based on (Secretaría de Estado de Energía, Dirección General de Política Energética y Minas, 2020; Secretaría de Estado de Energía, Dirección General de Política Energética y Minas, 2022).



Spain stands out as the third European country for its potential in critical raw materials and the second in rare earths in absolute terms. The economic value of critical raw materials as a whole exceeded €42 million in 2020, slightly lower than the figure achieved in 2019, which was

[99] By way of example, in the same year the electricity, gas, steam and air conditioning supply sector accounted for 2.94 % of GVA, the paper industry for 0.35 % and oil refining for 0.29 %.

45.5, but higher than the total value of mining production in some autonomous communities (Secretary of State for Energy, and General Directorate of Energy Policy and Mines, 2020).

In 2020, the mineral most produced in Spain was gypsum, with approximately 13.4 million metric tons, an increase of 19 % over 2019 . Gypsum is followed by salt, whose production in 2019 amounted to approximately five million metric tons (Secretaría de Estado de Energía, and Dirección General de Política Energética y Minas, 2020).

Spain is the leading producer of fluorspar (fluorspar), celestine (strontium), wolfram and tantalum, among others. In the case of celestine, Spain is the only European producer and one of the few worldwide, having developed new wolfram mines in the 21st century. It is also the only European producer of sepiolite. Tantalum appeared, in 2019, associated with tin mining (Secretary of State for Energy, General Directorate for Energy Policy and Mines, 2020). The production of ornamental rock is also very prominent, being the first producer of roofing slate. It is the third largest producer of copper ore, second of magnesite and potassium salts, and sixth of bentonite in Europe.

Table 35 shows data on the projects in the pipeline, by Autonomous Community, related to metallic mining, grouped by metals, including information on investment and associated employment. It can be seen that the projects in the pipeline represent an investment of close to 7,000 M€ and the creation of some 30,000 direct and indirect jobs.

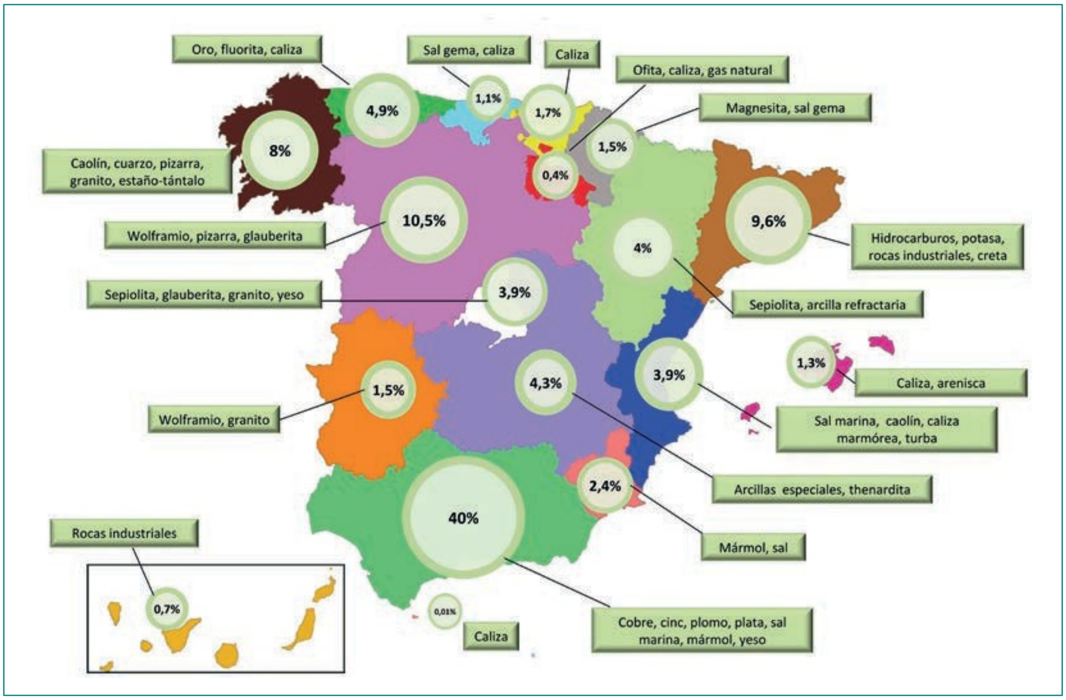
	Andalucia	Asturias	Castilla-Leon	Catalonia	Extremehard	Galicia	Madrid	Murcia	Total
Industrial Minerals		1		1			5		6
Metallic Mining (Au, Cu, Zn, Sn...)	7	4	4		11	3		1	30
Approximate investment (M€)	1.500	900	800	400	2.000	500	400	100	6.700
Jobs (direct+indirect)	7.500	3.100	3.000	1.500	10.000	1.800	1.300	500	28.700

Table 35. *Projects in process with the administration of the Autonomous Communities (Autonomous Communities). Source: (Secretaría de Estado de Energía, and Dirección General de Política Energética y Minas, 2019).*

The distribution of the value of production by territory varies between Autonomous Communities, as shown in Map 6. Andalusia and Asturias (followed by Extremadura) produce a large part of the country's metallic minerals. In 2020, Andalusia accounted for around 40% of total production. As far as industrial minerals are concerned (e.g. limestone, clays, sand or gravel), Catalonia, Castile and Leon, Madrid and Castile-La Mancha accounted for 70 % of the total[100] . In Galicia and Castilla y León, 63 % of the ornamental rocks were extracted. These are also important in the Valencian Community, Extremadura, Andalusia and Murcia. Quarried stone is extracted in all the Autonomous Communities and in Ceuta, although Andalusia, Catalonia and Castile and Leon stand out. In Almería, gypsum production is very important, accounting for around 60% of the total (Secretaría de Estado de Energía, Dirección General de Política Energética y Minas, 2020).

[100] Mining of energy products is not analyzed in this analysis. However, it can be said that coal mining decreased and gas mining remained

stable in recent years. These energy sources were extracted in Catalonia, Andalusia and La Rioja (Viura).



Map 6. *Distribution of the value of mining production by Autonomous Communities and main minerals extracted. Source: (State Secretariat of Energy, Directorate General of Energy Policy and Mines, 2020).*

Metallic mining continues to be, as in recent years, the engine of Spanish mining. Overall, copper, zinc and lead projects have good economic characteristics, with metal prices setting the current trend. However, there are appreciable differences that are largely related to the great variety of geochemical, mineralogical, textural and geometrical characteristics of the deposits.

In the Iberian Pyritic Belt there are three subway complex sulfide mines in operation, which produce copper, zinc and lead concentrates, with significant silver content, and two open pit mines that produce copper or copper concentrate. The Atalaya Mining project stands out for its low total operating costs with respect to the copper contained in its ores, due to its low mining costs (large volume of mineral movement, low *stripping ratio*), approaching those characteristic of a classic porphyry copper mine. The rest of the FPI projects remain at very similar values (subway mining, complexity and cost of the metallurgical system of Cobre Las Cruces, CLC).

The gold mine (Asturias) and the tin-tantalum mine (Galicia) have also continued their activity. Tungsten production has decreased with the depletion of the Los Santos mine, although two other mines have restarted commercial production, one in Castilla y León and the other in Extremadura.

There are hardly any tin deposits of economic importance in Europe. Only the Oropesa deposit can be mentioned. Its normalized annual exploitation would mean an input of
2,000 - 4,000 tons of tin per year. In addition, as a by-product, tin is also produced in tungsten deposits (Barruecopardo). This project does not belong to the most abundant typology in Europe including the Iberian Peninsula. It stands out for its relatively high grades and an important part of the deposit is susceptible to open-pit mining, without excessive stripping ratio. The project is in its final acceptance phase and its advance, once the design regime is reached, could account for 1.4% of world tin production. After a price rebound in 2013 the collapse of tin prices has inhibited both its research and the

reopening of old deposits. Thus, it should be expected that another rise in the price of this metal could act as an incentive for exploration, albeit of the brownfield type .[101]

In recent years, the attractiveness of prices in Spain has driven the development of three new tungsten projects. Adding some successes in Portugal, when the exploitation of the projects starts, 8% of the world's wolfram will be produced, with Spain accounting for 5.5%. Most of the new projects are abandoned after a short period of exploitation. In Spain there are also other projects with good expectations, but for the moment they are paralyzed for administrative and social acceptance reasons. This is the case of San Finx, Santa Comba, Morille and El Moto-Abenójar.

In the case of lithium, in the Iberian Peninsula, the Valdeflórez and Las Navas projects in Spain and the Barroso project in Portugal are being considered[102] . The projects do not seem to have full social acceptance.

There is only one gold production project in Spain, Orovalle, although there are also several others under study or in the exploration phase. Its production, less than 100,000 oz Au/year, also includes some copper as a by-product. High gold prices will undoubtedly favor the start-up of projects or the reactivation of those that are wintering.

2.1. Mining projects in Spain. Current situation.

The projects recognized in the Spanish territory can be classified according to whether they are metallic or non-metallic mining and in the following categories: (i) projects in production or that have stopped or ended their productive life in 2019 (A), (ii) projects that, having a technical report accredited by an international standard, have reached accredited valuation of their resource-reserves and are in a state of development (B) and (iii) projects that are in situation B or, are about to reach it, although they have not started the development phase, or are awaiting permits to do so (C).

The following is a brief description of mining projects related to the metals and non-metals value chain (see Table 36[103] , Table 37 and Table 38) .[104]

[101] It should be noted that the extraordinary increase in the price of tin was the reason for its mining to develop in an unusual way in the 70s of the last century. Since then, only a short price peak, around 2014, has created hope for a new development.

[102] In addition to these two projects, there are other smaller lithium projects in Spain and Portugal.

[103] The direct and indirect employment data in Table 37 are from a non-exhaustive search of company reports or websites or press reports on project announcements. In the case of Atalaya Mining (2022) the company commissioned a study based on input-output methodology which concludes that direct full-time employment was 318 people, based on a total of 485 contracts. Indirect employment associated with the Riotinto mine in companies supplying goods and/or services is 1,361 jobs and induced employment, generated by the consumption of goods and services by employees of companies operating directly or indirectly in the mine's activity, is 676.
The ratios of direct to indirect and induced employment are highly dependent on the region. Moritz, T. et al. (2017) analyzed the employment impact of mining in northern Sweden. For this they developed a methodology based on an econometric analysis showing that one job in mining results in the creation of another job in other sectors. The study also emphasized job creation in the investment phase, advocating the creation of clusters, taking into account the tendency for mining to be more capital and technology intensive.
An approach also of interest is the one carried out by IISD which indicates that, according to estimates, the sector contributes 1-2 % of direct employment in a country and when indirect and induced employment is considered the contribution becomes 3-15 % (IISD, 2019).

[104] These are not exhaustive tables. Information is collected from projects that are considered relevant.

Table 36. Metallic mining projects in Spain. Note 1 (*): For the state, A = projects in production or that have stopped or ended their productive life in the year.
year 2019; B = projects that, having at their disposal
a technical report accredited by an international standard, have had their resources-reserves valuations accredited and are in a state of development, C = projects that are in a state of development, C = projects that are in situation B or, they are about to reach it, even if they have not yet started the phase
development, or are awaiting permits to do so; I = Investigation and P = Paralyzed. Note 2: (**) Annual production in metal contained in the saleable concentrates and ROM ore (sent to the plant), (***) Cumulative investment (initial and maintenance). Note 3: The table is not exhaustive due in large part to
because the information available is sometimes not complete enough. Source: authors' own elaboration based on (Peña et al., 2021), (Secretaría de Estado de Energía, Dirección General de Política Energética y Minas, 2022), websites of the owner companies and press reports.

METAL	Mining Project	Status (*)	Property	Annual production 2021 (t)** Annual production 2021 (t)** Annual production 2021 (t)** Annual production	Investment***/ Employment (direct and indirect)
COPPER[105]	Las Cruces Copper[106] (CLC)	A	First Quantum Minerals Ltd.	12,000 t Cu	1.100 M€ (280 + 520)
	Aguas Teñidas Mines (MATSA)[107]	A	Sandfire Resources Ltd	66,000 t Cu 4.5 Mt/year	1.590 M€ (730)
	Riotinto	A	Atalaya Mining Plc	56,140 t Cu 15.8 Mt/year	358 M[108] (485+632)[109]
	Touro	B	S. Rafael Copper. Atalaya Mining Plc	30,000 (prev)	220 M€ (400 + n.a.)
COPPER-Au (Zn+Pb)[110]	Zarza and San Telmo (Tharsis)	I	Tharsis Mining and Metallurgy		
	Lomero Poyatos		Denarius Silver		
ZINC	Aguas Teñidas Mines (MATSA)	A	Sandfire Resources Ltd	93.000 4.5 Mt/a	Included in the Cu
	Los Frailes - Aznalcóllar	B	Grupo Mexico (97.31%), and Magtel (2.69%)	96,000 Zn 35,000 Pb 4,200 Cu[111]	410 M€ (318 + 1361)
	Toral de Vados	C	Europa Metals Ltd. / Europa Metals Iberia S.L.	16,500t Zn[112] 15,000t Pb 7 t Ag	71 M€ (200 + n.a.)
	PMR[113]	B	First Quantum Minerals Ltd		500 (480 + 420)
LEAD	Aguas Teñidas Mines (MATSA)	A	Sandfire Resources Ltd	12,000 t Pb 4.5 Mt/a	Included in the Cu
	Toral de Vados	C	Europa Metals	See Zn	See Zn
	New Linares	I	Kerogen Energy	25,000 (prev)	40 M€ (180 + n.a.)
NICKEL	Aguablanca	P	Narcea Resources	4,100 t Ni (prev) 3,400 t Cu (prev)	
NIOBIUM - TANTALUM	Penouta	B	Strategic Minerals Europe/ Strategic Minerals Spain	246 t Sn 14t Tantalite 14t Columbite	40 M€
	Doade.	C	Strategic Minerals Spain	-	
TANNUM	La Parrilla	A	Iberian Resources Spain	400	Included in W
	Oropesa	B	Spanish tin mines	2,440 t Sn 0.8 Mt/a	84 M€ (200 + n.a.)
WOLFRAMIO	Los Santos	P	Almonty		
	La Parrilla	P	Iberian Resources Spain	240 t WO_3	90 M€ (160 + n.a.)
	Barruecopardo.	A	Saloro, SL.	2,600 t WO_3[12]	70 M€ (180 + n.a.)
	San Finx.y	B	Rafaella Resources/ Pivotal Metals Ltd.		
	Varilongo	C			
	Valtreixal.	C	Valtreixal Resources Spain S.L.	506 t WO_3 264 t Sn (prev.)	40 M€ (n.d.)
	Abénojar-El Moto	C	Mining Hill's S.L.	-	175+175
LITIO	San Jose	B	Extremadura New Energies (ENE)[114]	19,500 t LiOH 2 Mt/year (prev)	532 M€ (400)
	Las Navas- Cañaveral	C	Lithium Iberia	30,000 LiOH 1.2 Mt/year (prev)	540 M€ (400+1.200)
	Doade-Presqueiras	C	Mineral Resources Galicia		

105 There is also copper production at Orovalle as can be seen below in the table. In 2021, production was 2,858 tons.
106 In phase of stoppage and construction of the new subway project
107 MATSA includes three mines: Aguas Teñidas, Magdalena and Sotiel.

[108] 2013-2021.
[109] Direct plus indirect.
[110] For the case of Cobre las Cruces see the Zn section.
[111] Estimated production when normal operating regime is reached.
[112] Data deduced from the public information of the project.
[113] Refers to Zn production from the polymetallurgical refinery and also includes Cu, Pb and Ag.
[114] Infinity Lithium owns 75 %.

RARE EARTHS	Matamulas	P	Quantum Mining	1,500 t TREO[115]	60 M€ (115)
COBALT	Exploration in Almeria, Granada, Leon, Ciudad Real and Asturias				
GRAFITO	There are small abandoned farms and there is no exploration				
ORO[116]	Orovalle	A	Orvana Minerals Corp,	1.47 t Au	(482 + >1000)
	Salave	C	Cantabrian Mining Explorations	2.43 t Au (prev)	400 M€ 150+(>1000)
	Corcoesto	P	Mineira de Corcoesto S.L.U/ Edgewater		170 M€ (217 + n.a.)
	Isabel	P	Edgewater		
SILVER	Orovalle	A	Orvana Minerals Corp,	2 t Ag	172 M€ 482
	Polymetallics of the Pyritic Belt	A	Recovered in the metallurgy of Cu, Pb and Zn	76 t Ag	
	Toral de Vados		Europa Metals	7 t Ag (prev)	
IRON[117]	Alquife	B	Minas de Alquife S.L.U.	4.500.000 t min iron (prev)	200 (1400 D+I)

Table 37. *Mining projects in the Iberian Pyrite Belt except Touro.*
Source: authors' own elaboration.

Project	Quantity (Mt)				Cu (%)	Zn (%)	Pb (%)	Ag (g/t)	Au (g/t)	Ni (%)
	Proven+ probable	Measurements+ indicated	Indicated	Inferred						
Atalaya Mining. Cerro Colorado 2021	197				0,42					
		258			0,40					
Atalaya Miming New Riotinto Project										
San Dionisio (open sky)		57,4			0,89	1,12	0,23			
San Dionisio (subway mining)				12,4	1,01	2,54	0,62			
San Antonio(subway mining)				11,8	1,32	1,79	0,99			
Atalaya Mining. Other Research Projects										
Masa Valverde			16,3		0,66	1,56	0,65	27	0,55	
				73,4	0,61	1,24	0,61	30	0,62	
Majadales				3,1	0,94	3,08	1,43	54	0,32	
Atalaya Mining. Touro		130			0,39					
				46,5	0,37					
Aznalcollar Los Frailes	115				0,33	4,64	2,83	72		
White Water	3,5				0,6					0,6
Tharsis Mining & Metallurgy										
La Zarza										
Telmo Salt										
Tharsis										
Denarius Metals. Lomero Poyatos				10,7	0,45	1,02	0,41	21	2	
Sandfire. MATSA										

115 Total rare earths contained.

116 There are also the following projects: Lomero Poyatos (C) of Denarius Silver; Alconchel (C) of Atalaya Mining and Narcea Recursos and Dominio de Tharsis (C) of Tharsis Mining and Metallurgy.

117 The Cehegín project (Solid Resources Mines España/ Minework Technologies) is not included due to lack of updated information. This amount is the target recognized by the company. However, the Secretary of State for Energy, General Directorate for Energy Policy and Mines (2022) did not give any production.

Table 38. Projects non-metallic miners in Spain. Note: D = direct, I = indirect. Note: there are other industrial minerals with a high unit value such as quartz that is operated in Galicia, for example. Source: authors' own elaboration.

Mining Project	Status (*)	Property	Annual production 2021 (t)	Investment (M€)	Employment (Direct/ Indirect)
STRONtium (SO_4 Sr)					
Mines of Montevive (Granada) Aurora Mining Group http://minasdemontevive.es/	A	Canteras Industriales, S.L. (Bruno, S.A.)	26,500 SO_4 Sr (2020)	n.a.	8 / 24
Solvay Minerales Minas de Escuzar (Granada). ht- tps://www.kandelium.com/	A	Kandelium Minerals	88,500 SO_4 Sr (2020)	n.a.	n.a.
FLUORITE					
Minersa. Cucona Mine, Moscona Mine (Corvera), Emilio Mine (Colunga), Viesca Group (Siero) and Villabona Group (Llanera). Asturias	A	Minerales y Productos Derivados SA	446,238 ROM 145,000 F_2 Ca (Contents)	n.a.	230 / 900
Orjiva Mining (Sierra de Lújar / Sierra de Gádor)	A	Minera de Órgiva, S.L.	15.5 F_2 Ca (Con- had)	n.a.	90 / 270
PHOSPHATE ROCKS					
Fontenarejos Project	C	Alcudia	800.00t ROM/ year 140,000t of P O_{25} content	n.a.	n.a.
GRAFITO					
Guadamur Mine (1919-1920, 310 t, 1947-1961, 4,500 t) and "La Española" mine (1943-1947, 530 t) (Toledo) (**)					
El Muyo, Madriguera, Becerril and Ayllón (Segovia)					
Peridotites of the Serrania de Ronda (Málaga)					
Almonaster la Real, Cortegana, Aroche and Santa Ana la Real (Huelva)					
POTASSIUM SALTS					
Cabanasses mine (Suria) and Vilafruns mine (Balsareny). Barcelona https://www.icliberia.com/	A	ICL Iberia Súria & Sallent	1,000,000 (prev.)	n.a.	1.100 / 3.000
Muga Mine. Undués de Lerda and Sangüesa (Navarra) https://www.geoalcali.com/muga/	B	Geoalcali S.L.		600	800 / 2.400
MAGNESITES					
Eugui Site (Navarra) https://www.magnesitasnavarras.es (***)	A	Magnesitas Navarras, S.A. Group mult. Roullie	171,000 MgO	n.a.	275 / 1.100
Borobia Site (Soria)	A	MAGSOR	106,400 MgO	34,5	85 / 165
Vila de Mouros site (Lugo).	A	Rubian Magnesites	60,000 MgO	n.a.	50 / 150
RED OXIDES					
Ojo Negros Mines (Teruel) https://promindsa.com/estrenamos-nueva-web/	A	Productos Minerales para la Industria,SA (PROMINDSA)	7,500 ROM 6,700 t Fe O_{23} content (2019)	n.a.	n.a.
La Salvadora Mine, Priego (Cordoba)	A	Óxidos Rojos Málaga, S.A.		n.a.	n.a.
Las Piletas Mines Huéneja (Granada)	A	Óxidos Férricos, S.A.		n.a.	n.a.

3. About Spanish metallurgy in 2021[118]

Closely linked to mining activity is metallurgy, which in Spain is an activity of great industrial and economic importance, as will be seen below. In fact, metallurgy shows a great deal of activity, both primary (obtaining the metal from the ore that contains it) and secondary (obtaining the metal from secondary raw materials, e.g., rock) (see Figure 81).

Figure 81. *Metallurgy in Spain. Source: authors' own elaboration.*

The ferrous metallurgy or iron and steel industry in Spain is represented by 22 plants that produce steel and 50 that laminate it or carry out the first transformation. One of these steel mills is integral (Arcelor Mittal) and the others are electric arc furnaces. Although steel mills are spread over eleven Autonomous Communities, the greatest concentration is located on the Cantabrian coast, mainly Asturias and the Basque Country (UNESID, 2021).

Steel production in Spain in 2021 was 12.7 million tons (9.1 million produced by Arcelor Mittal and 3.6 million by the remaining facilities), which at market prices resulted in a turnover of €23.35 billion and generated some 26,000 direct jobs and 78,000 indirect jobs.

Acerinox produced close to 2 million tons of stainless steel in 2021. Its turnover increased by 45% compared to 2020 thanks to price increases (both base price and alloy surcharge). Ferroatlántica (now Ferroglobe), produced ferroalloys (ferrosilicon, ferro-manganese and silico-manganese) at its four plants in Spain, which generated €370 million in revenues and generated
1,000 direct jobs and 3,000 indirect jobs.

Non-ferrous metallurgy produced in Spain in 2021 aluminum, copper, zinc, lead, tungsten, gold, silver and tin. In addition, other metals were produced in the form of oxides such as alumina (Al_2O_3).

Alcoa, at the San Ciprián metallurgical complex (San Cibrao, Lugo), has a production capacity of 1.5 million tons of alumina per year for the production of primary aluminum at Alcoa's plants and other producers, as well as for external customers (domestic and international) for non-metallurgical applications such as the ceramic and chemical industries. The primary aluminum plant has a capacity of 228,000 tons per year .[119]

[118] The data in this section come from the annual reports of the companies for the year 2021. This is not an exhaustive list, so the data does not have to coincide exactly with those collected by the INE and presented in section 5.1.

[119] Aluminum production in Spain in 2019 was 230,000 tons (according to Statista data).

The San Cibrao complex directly employs approximately 1,050 people, around 450 in the alumina plant and close to 600 in the aluminum plant. San Cibrao has a port, a plant for obtaining Al O_{23} , a plant for obtaining aluminum from imported bauxite, mainly from the mines of Guinea (Boké).

According to Alcoa's website, aluminum production will resume in January 2024, when the electrolysis series will be restarted. Smelting and alumina plant activity will be maintained, for which the company has provided the business plan during these years, at a rate of
65,000 tons of billet per year and forecast sales of 25,000 tons of aluminum plate per year.

In copper metallurgy, we can distinguish companies such as Cobre las Cruces that have an integral process from mining to the manufacture of copper cathodes and those that manufacture cathodes and other products from copper concentrates. This is the case of Atlantic Copper, with a production of 270,000 tons of copper cathodes and an average workforce of 755 people in 2021.

Pyrometallurgical copper production in Spain is carried out by Atlantic Copper, in Huelva. It uses imported and local mineral concentrates from mines in the Pyritic Belt[120] . Total production in 2021 was 275,000 tons of refined (primary) copper (99.99 % purity) which, at prices with an upward trend in the international market, represented a turnover of 2,625 million euros. Direct jobs generated amounted to 1,000 and 3,000 indirect jobs.

To the almost 300,000 tons of copper from Atlantic Copper must be added those coming, in general, from imported concentrates, the mining production of CLC, MATSA, and Atalaya Mining, as well as a small amount from Orovalle. Copper from scrap recycling should also be added.

In 2021, zinc production in Spain was 106,000 tons from imported mineral concentrates and was carried out by the company Asturiana de Zinc, which has metallurgical facilities in San Juan de Nieva in Castrillón (Avilés), with a production capacity of 511,000 tons per year of zinc with a purity of 99.995 %. making it the most relevant zinc metallurgy in Europe. Primary production plus secondary production of 35,600 tons resulted in a total production of 141,600 tons, a turnover of 354 million euros and 900 direct and 2,700 indirect jobs. To the production of metal from concentrates at Asturiana de Zinc must be added the production of MATSA.

In Spain there is no primary production of lead, only secondary lead is produced by pyro-metallurgical processes. Production was 28,000 tons which, at market prices, resulted in 46 million euros, generating 100 direct jobs and 300 indirect jobs.

Tungsten production in Spain amounted to 341 tons which, at market prices, resulted in an annual turnover of 10.7 million euros, with 50 direct and 150 indirect jobs. Gold production amounted to 2 tons, with a turnover of 63 million euros, 60 direct jobs and 180 indirect jobs.

Silver production reached 90.7 tons which, at market prices, represented a turnover of 66.75 million euros, 30 direct jobs and 90 indirect jobs.

[120] Cobre las Cruces produces the metal from Spanish ore from its mine, by hydrometallurgical process. Its production reached 30,000 tons, representing a turnover of 265 million euros and employing 400 people directly and 1,200 indirectly. The company saw a reduction in production (70,000 tons in the last 10 years) when the open pit mine was depleted and the preparation of the future subway mine began. It is currently using ore accumulated from the open pit mine.

Tin production in Spain amounted to 147 tons which, at market prices, represented 6.4 million euros and employed 50 people directly and 150 indirectly.

Overall, metallurgical activity in Spain produces 15.7 million tons of metals, generates 28,287 million euros annually and generates 31,890 direct jobs and 95,670 indirect jobs (i.e. 127,200 jobs in total) (Table 39).

There are currently projects under investigation in Spain that, if put into operation, could, in some cases, be considered with an *ad-hoc* metallurgical activity to obtain metals from the minerals that are extracted. This would result in integration in the value chain with the advantages already discussed in the previous chapter.

	Production (thousands t)	Turnover (million euros)	Direct employment	Indirect employment
Steel	12.700	23.350	26.000	78.000
Stainless steel	2.000	0,37	1.000	3.000
Ferroalloys				
To	494	1.235	2.300	6.900
Cu	335	3.155	1.400	4.200
Zn	141,6	354	900	2.700
Pb	28	46	100	300
W	0,341	10,7	50	150
Au	0,002	63	60	180
Ag	0,091	66,75	30	90
Sn	0,147	6,4	50	150
Al O_{23}	0,00064	256	-	-
Total	15.699	28.287	31.890	95.670

Table 39. *Summary of metallurgical activity in Spain in 2021. Source: authors' own elaboration.*

4. Economic aspects of the mining and metallurgy value chain in Spain. Main economic variables

Table 40 below presents data from the industrial survey of the National Statistics Institute (INE) and information on relevant variables in the analysis of competitiveness[121] for the non-energy mining industry and metallurgy .[122]

[121] For more detail on these variables see (Diaz et al., 2016).

[122] The sectors of the National Classification of Economic Activity (CNAE) selected to cover the metallic mining and metallurgy value chain refer to the categories: 07 (extraction of metallic minerals), 08 (other extractive industries), 09 (support activities for extractive industries) and 24 (metallurgy, manufacture of iron and steel products and ferroalloys).

Table 40. *Main economic parameters of non-energy mining and metallurgy in 2019*[123] *. Source: authors' own elaboration based on (INE, 2022).*

	Employment (no.)	Productivity (thousands of euros/employee)	Labor costs per employee (thousands of €)	Investments (thousands of euros)	Sales (thousands of euros)	Exports (thousands of euros)
071 Mining of iron ores	50	106	44	1.268	9.962	3.780
072 Mining and quarrying of non-ferrous metallic minerals	2.280	180	50	154.474	869.126	356.446
081 Quarrying of stone, sand and clay	10.916	52	33	111.728	1.733.539	169.535
089 Mining and quarrying not included elsewhere (n.e.c.)	3.021	104	50	118.349	899.856	486.014
099 Support activities to other mining and quarrying industries	959	63	47	6.748	163.111	30
241 Manufacture of basic iron, steel and ferroalloy products	23.097	75	53	409.344	12.059.602	5.622.670
242 Manufacture of tubes, pipes, hollow profiles and related fittings, of steel	6.429	58	47	59.375	1.798.114	943.495
243 Manufacture of other products of first steel transformation	3.287	60	40	19.551	1.312.793	353.032
244 Production of precious metals and other nonferrous metals	14.556	88	46	317.438	12.822.289	6.749.349
245 Metal casting	14.174	59	42	125.548	2.988.679	1.652.028
Total Industry	[illegible]	69	38	[illegible]	[illegible]	[illegible]

In 2020, a total of 2,629 exploitations had production in Spain, of which 76.3% corresponded to quarried stone extraction, 16.7% to ornamental rocks, 6% to industrial minerals, and 1% to energy and metallic mining (Secretaría de Estado de Energía, Dirección General de Polí- tica Energética y Minas, 2020). The main drop in the number of companies has occurred in sector 081 Extraction of stone, sand and clay, where 201 companies closed in the period 2015-2019.

4.1. Employment

Since 2005, the Spanish mining sector (Graph 8) has lost approximately half of the employment it generated (38,011 in 2005 vs. 17,350 in 2019) (Statista, 2022a) and (Secretaría de Estado de Energía, Dirección General de Política Energética y Minas, 2020), accounting for 0.75 % of industrial employment in 2019. Between 2016 and 2018, direct employment maintained a slightly increasing trend, to show a decrease in 2019, mainly due to the cessation of coal mining.

In the mining sector there are multinational companies, national state-owned companies, medium-sized companies, small companies and *junior* companies. Each has its own business risk assessment and its own exploration motivations (Regueiro and Espí, 2019).

In the case of Spain, the average size[124] of companies in the industry is small, with just 12 employees on average. However, companies in the industrial sectors associated with the mining and metallurgy value chain are, in general, larger, except in the case of sectors *071 Extraction of iron ores* and in sector *081 Extraction of stone, sand and clay*.

The largest companies are those in sector *241 Manufacture of basic iron, steel and ferroalloy products*, although they lost size between 2015 and 2019. On the other hand, companies in the sectors

[123] Each row represents the totals of the sectors. The last row (Industry total) is the sum of all industrial sectors in the country.

[124] Estimated as the ratio between the total number of employees in the sector and the number of companies.

072 Extraction of non-ferrous metallic minerals and *244 Production of precious and other non-ferrous metals* have grown during the same period. In the case of metallic mining two operations have less than 100 workers, one has less than 500 and the other five have more than 500 employees (Secretaría de Estado de Energía, Dirección General de Política Energética y Minas, 2020).

Around 77 % of mining operations had fewer than 10 workers in 2020, accounting for 28.2 % of employment in the mining sector. In comparison, the five operations with more than 500 workers accounted for 21 % of employment. If the number of hours worked is taken into account, there is a significant amount of part-time employment in quarrying, where many operations operate on a demand-driven basis, thus working intermittently.

Number of workers in the extractive industries in the region. Spain from 2005 to 2018. Source: authors' own elaboration based on (Statista, 2022a) and (Secretaría de Estado de Energía, Dirección General de Política Energética y Minas, 2020).

Most of the employment is concentrated in the communities of Andalusia, with 30 % of the total, followed by Castilla y León (11.3 %), Galicia (10.9 %) and Catalonia (10.7 %). Most of the workforce is self-owned (Secretaría de Estado de Energía, Dirección General de Política Energética y Minas, 2020). In Andalusia, metal mining accounts for 62 % of total employment[125] ; in Galicia, the extraction of ornamental rocks, especially slate, employs 60 % of the total; in Catalonia, potash mining accounts for 28 % of mining employment.

In metallurgy, the number of employees increased, primarily in sector *241 Manufacture of basic iron, steel and ferroalloy products*, which gained 2,512 employees.

If we look at the number of hours worked (expressed in thousands of hours), we can see that there is part-time employment, a very relevant issue in quarry stone mining, where the activity depends, quite markedly, on the evolution of demand. It should be noted that in the case of metallic mining the volume of own personnel (33.3 %) is lower than for ornamental rocks, for example (85 %).

4.2. Labor productivity

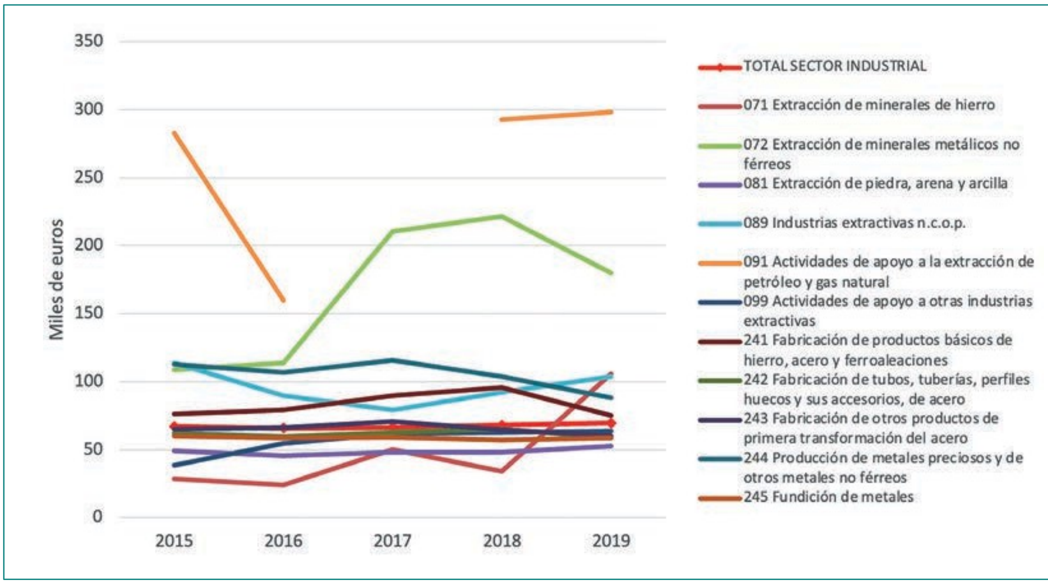
Labor productivity in the industrial sector[126] (Figure 9), measured in terms of sector value added per employee, has remained stable in the 2015-2019 period at around 67,000

[125] Andalusia has a map of key critical minerals for the development of clean technologies (Smartgridsinfo, 2023).

[126] Represents the average of all industrial activity, including that of the sectors analyzed in detail.

euros/person. The sectors *072 Extraction of non-ferrous metal ores*, *244 Production of precious and other non-ferrous metals*, *089 Mining and quarrying* and *241 Manufacture of basic iron, steel and ferroalloy products*, have maintained their productivity above the industrial average, with very high levels, having exceeded in some cases 200,000 euros/ person.

On the other hand, sectors *081 Extraction of stone, sand and clay*, *242 Manufacture of tubes, pipes, hollow profiles and their accessories, of steel* and *245 Metal foundry* are the sectors with the lowest productivity, in economic terms.



Graph 9.
Productivity evolution in thousands of euros per person. Source: authors' own elaboration based on (INE, 2022).

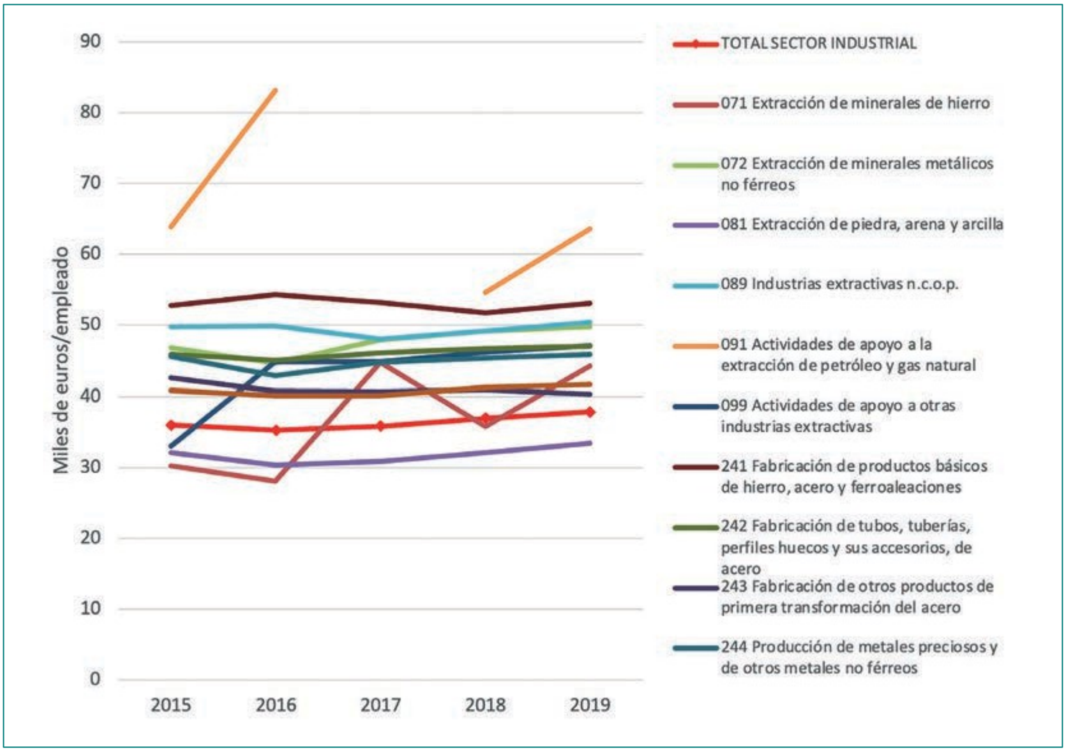
As can be seen, mining has high labor productivity compared to other industries. This is because the sector is intensive in the use of physical capital and benefits from natural capital (Australian Productivity Commission, 2008). Long-term growth in labor productivity is mainly due to higher capital investment.

4.3. Labor costs per employee and unit labor costs

Industry tends to be a sector with a level of labor costs per employee in the vicinity of €35,000-40,000, above Spain's average per capita income in 2020 of €27,057.16. In 2019, only sector *081 Extraction of stone, sand and clay* had labor costs per employee below the industrial average. The rest of the sectors related to metal mining and metallurgy had higher labor costs per employee.

Mining employees are generally better paid than other workers (Figure 10), due in part to higher average skill levels among miners and, in part, to the dangers and difficulties of mine work, including remoteness.

The unit labor cost indicator, calculated as the ratio of labor cost per employee to productivity, shows the cost of employing a worker as a function of the company's productivity. Sectors *071 Mining of iron ores*, *072 Mining of non-ferrous metal ores*, *089 Mining and quarrying* and *244 Production of precious metals and other non-ferrous materials*



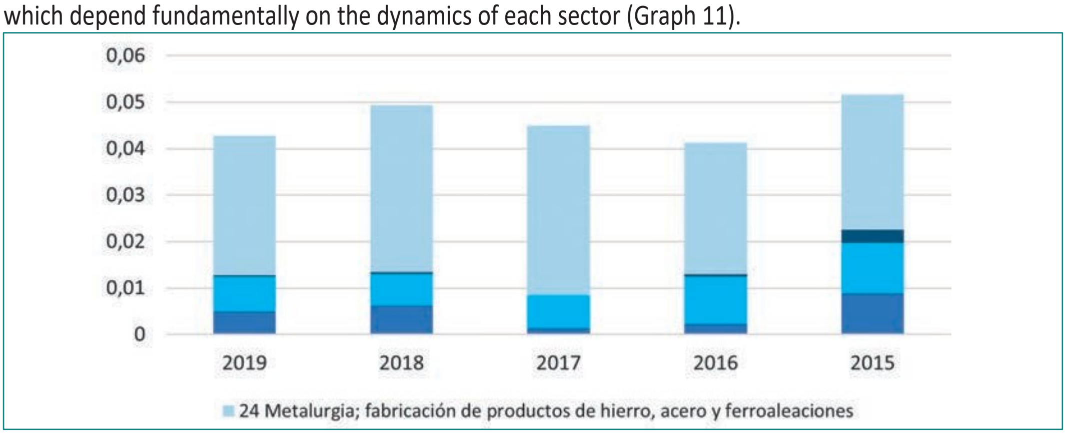
__Graph 10.__ Evolution of labor costs per employee. Source: authors' own elaboration based on (INE, 2022).

are those that are in a better situation than the industrial average. The rest of the sectors should consider the need to improve this ratio in order to guarantee their competitiveness in the long term.

4.4. Investments

Between 2015 and 2019, the main investments made by the sectors under study, which have represented between 4.3 and 5.1 % of the total investment of the industry, have been mainly in tangible assets and, in particular, in technical installations, machinery and tooling and transport elements.

The main investment sector is *241 Manufacture of basic iron, steel and ferro-alloy products,* followed by *244 Production of precious and other non-ferrous metals* and *072 Mining of non-ferrous metal ores*. Between them, they accounted for 66.4 % of investment in the sectors under analysis. In any case, no historical trajectory can be mentioned, as there were increases and decreases throughout the period, which depend fundamentally on the dynamics of each sector (Graph 11).



Evolution of investments by sector. Percentage of total industry .[96] Source: authors' own elaboration based on (INE, 2022).

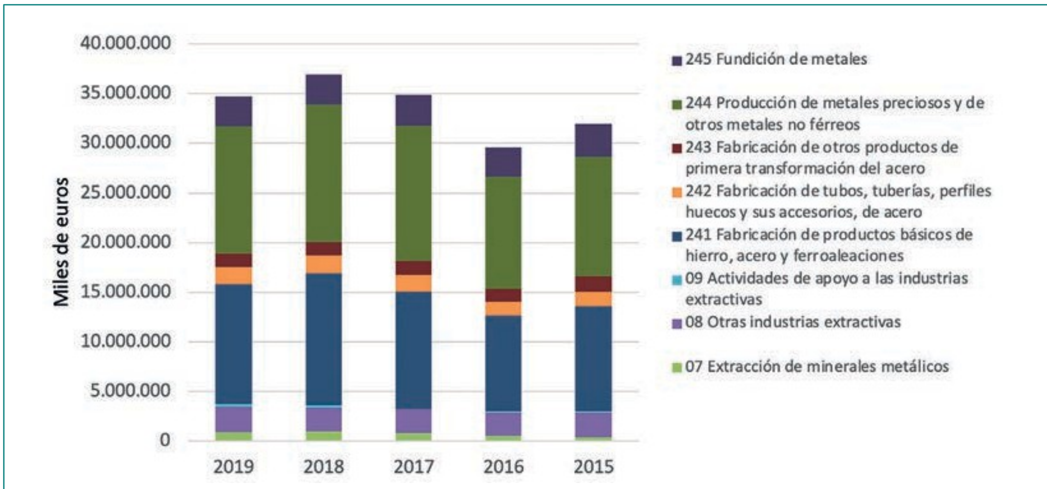
[127] Industry includes all manufacturing activities in a country.

Investments in intangible assets in the sectors under analysis are small. In general, they have only accounted for more than 10 % of the total investment in these sectors. Exceptions in 2019 are sector *071 Extraction of iron ores* and *072 Extraction of non-ferrous metal ores.* However, in the first case the volume of total investments was relatively small (1,268 million euros in total, compared to 31,035 million total investment in the industry in the same year).

In the case of mining, investments were mainly in the metallic minerals sector, mainly copper, gold/silver and wolfram. In the case of non-metallic minerals, investments in potassium salts, glauberite and rock salt stand out. The largest investments are in the mining and processing phases, which accounted for nearly 80 % of the national total in 2019. In the research phase, half of the investments were made in copper mining.

4.5. Sales/Exports

In the last five years, in Spain, between 5.1 and 5.5 % of industrial sector sales came from the metallic mineral extraction, other extractive and support industries and metallurgy sectors. The mining sectors accounted for 0.5 % of industrial sales, with a greater weight of the other extractive industries sector (which includes neither coal, gas nor crude oil mining nor metal mining, but does include stone, clay and sand), compared to 4.5-5 % for metallurgy. As can be seen in Graph 12, the evolution has not been homogeneous, nor has it followed a clear trend.



Graph 12. *Evolution of sales by sector. Source: authors' own elaboration based on (INE, 2022).*

However, it can be said that, in the case of metallurgy, approximately half of the sales are made in the country itself (compared to the industry average of 65-70 %), between 30 and 35 % of the total in EU countries and the rest in third countries. This highlights a greater exporting character of this activity than the rest of the national industry.

In the case of metallic mineral extraction, during 2018 and 2019, sales in Spain were around 60 %, barely 5 % was exported to EU Member States and the rest was sold in third countries. In other extractive industries, the percentages of sales in Spain were much higher (around 75 % and the rest was divided into 14 % sales to other EU Member States and 10 % to the rest of the world). Most of the sales of support activities for the extractive industries were made in the country (around 91-98 %).

Unlike the extractive industry, metallurgy is a clearly export-oriented activity. Situations such as the current situation of significant increases in energy prices affect the competitive capacity that this sector has maintained up to now. They also affect the extractive industry in general.

5. Conclusions

Spain has production and mining experience in base metals (such as copper, zinc, lead), technological materials (such as tin and tungsten) and precious metals (such as gold and silver). There are a significant number of projects in the development phase, pending authorization or in the research phase. The potential for development of mineral raw material mining projects for energy transition (i.e. lithium, rare earths) exists, judging by some projects and preliminary assessments. However, a number of projects are stalled for various reasons. As a result, significant amounts of funds have to be spent on acquiring raw materials abroad, which are sometimes available, with the consequent risk of disruptions in supply chains.

If the current projects in the development or research phase in Spain and the *ad-hoc* metallurgical activity to obtain some metals from the minerals extracted were to be put into operation, this would result in integration in the value chain with the corresponding advantages already discussed in the previous chapter.

The ferrous metallurgy or iron and steel industry in Spain is represented by 22 plants that produce steel and 50 that roll it or carry out the first transformation. Non-ferrous metallurgy produced aluminum, copper, zinc, lead, tungsten, gold, silver and tin in Spain in 2021. In addition, other metals were produced in the form of oxides such as alumina (Al O).[23]

Mining and metallurgy are increasingly automated and capital-intensive industries. Recent years have seen a reduction in the number of employees, which may have been due in part to the decline in energy mining. Compared to industry as a whole, both sectors are highly productive and have average levels of labor costs per employee above the industry average.

The data presented show that both sectors should be able to maintain their productive capacity and expand it, to avoid losing a valuable opportunity to develop industrial activities, in the context of the circular economy, and where environmental and labor regulations establish a rigorous framework that is not applied in other countries from which minerals and/or metal products are imported. Minerals and metals are and will be in demand as a result of the energy transition and digitalization processes.

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ANNEX 1

EU CRITICAL MINERALS

Table 41 shows the evolution of the list of critical raw materials in the EU.

Table 41. *Evolution of the list of subjects critical premiums for the EU. Note: in blue are the new additions to the lists. Source: authors' own elaboration from (European Commission 2020a) and (European Commission, 2023b).*

2011	2014	2017	2020	2023 (proposed)
Antimony	Antimony (stibnite)	Antimony	Antimony	Antimony
Beryllium	Beryllium	Barite	Barite	Arsenic
Cobalt	Boratos	Beryllium	Bauxite	Barite
Fluorite	Coking coal	Bismuth	Beryllium	Bauxite
Galio	Cobalt	Borate	Bismuth	Beryllium
Germanium	Chrome	Cobalt	Borate	Bismuth
Graphite	Fluorspar (fluorite)	Coking coal	Cobalt	Boron
Indian	Galio	Fluorspar	Coking coal	Cobalt
Magnesium	Germanium	Galio	Fluorspar	Coking coal
Niobium	Natural graphite	Germanium	Galio	Copper
Platinum group metals	Indian	Hafnio	Germanium	Feldspar
Rare earths	Magnesium	Helio	Hafnio	Fluorspar
Tantalum	Magnesite	Indian	Indian	Galio
Tungsten	Platinum group metals	Magnesium	Lithium	Germanium
	Niobium	Natural graphite	Magnesium	Hafnio
	Phosphate rocks	Natural rubber	Natural graphite	Helio
	Silicon metal	Niobium	Natural rubber	Lithium
	Light rare earths	Phosphate rocks	Niobium	Magnesium
	Heavy rare earths	Phosphorus	Phosphorite	Manganese
	Wolfram	Scandium	Phosphorus	Natural graphite
		Silicon metal	Scandium	Nickel (batteries)
		Tantalum	Silicon metal	Niobium
		Wolfram	Strontium	Phosphate rock
		Vanadium	Tantalum	Platinum group metals
		Platinum group metals	Titanium	Scandium
		Heavy rare earths	Wolfram	Silicon metal
		Light rare earths	Vanadium	Strontium
			Platinum group metals	Tantalum
			Heavy rare earths	Heavy rare earths
			Light rare earths	Light rare earths
				Titanium
				Wolfram
				Vanadium

ANNEX 2

ENABLING TECHNOLOGIES FOR DIGITIZATION

Table 42 below summarizes a brief description of the enabling technologies for digitization.

Technology	Features
Sensors	Sensors are devices whose purpose is to capture physical or chemical variables in an environment. Sensors that measure variables such as temperature, humidity, pressure, acceleration, forces, distances, magnetic fields or ultrasound are common and well known. Current challenges with regard to sensor technology development relate to size reduction, integration of communication capabilities, in many cases wireless, some processing capability and the availability of an independent power source.
Internet of Things (IoT)	Today, there is no agreed definition of IoT, but it could be expressed as: "the *technological paradigm that makes it possible to provide Internet connectivity to any object on which physical parameters can be measured or acted upon, as well as to the applications and processing of intelligent data related to them*".
Cyber-physical systems	CPS systems encompass technology, *software*, sensors, processors and communication techniques that enable interaction between physical objects and the computational or networked world. To understand this concept, we can use an example: a type of tire developed by Michelin incorporates sensors combined with a system for reading and transmitting information that, through its processing, allows fuel savings. The tires are equipped with a microchip and a pressure monitoring system. The difference between IoT and CPS can be described as follows: IoT is an infrastructure that collects information in the same physical space, i.e. it connects objects with each other, such as a smart watch with a smartphone, but in the physical realm itself. Whereas CPS uses senso- res and cloud connections to actively adjust a physical object to a current state, creating a synergy between physical and virtual space by integrating analog and computational *hardware*.
Connectivity	It is the ability of a device (personal computer, PDA peripheral, cell phone, robot, household appliance, mobile car, etc.) to be connected, generally to a personal computer or other electronic device, in an autonomous manner. Connectivity allows information to be transmitted securely, through fixed or mobile communications infrastructures, at any time (permanently and in real time) and in any place (ubiquitously). Therefore, a fundamental aspect to ensure the proper functioning of the IoT is the communications infrastructure on which it relies.
Augmented reality	It consists of the superimposition of digital information on a real scenario, allowing to project on the reality of the environment or context, both objects (static or dynamic) and any other type of additional digital information. To achieve this visualization it is necessary to have applications and devices such as cell phones or smart glasses. One of the main applications of this technology in the industrial field consists of introducing explanatory texts over augmented reality images, practically constituting a digital and interactive instruction manual.
Simulation	Simulation is a technology that makes it possible to transfer the real world to the virtual world, creating 3D models that can be experimented on. Any object, machine, assembly line, even production plants can have their "digital double".
Collaborative robotics	Collaborative robotics refers to the ability to hybridize the possibilities of a robot with the intelligence and skills of a person. The use of this new family of robots allows to gain in flexibility since it is possible to reconfigure and reuse them for the development of different operations in different places of a production facility.
Additive manufacturing	The term comprises a set of technologies whose operation consists of the successive addition of material on a micrometer scale, precisely depositing and fabricating layer by layer in such a way that the superposition of these layers gives rise to three-dimensional solids.
Big data	It is the set of methods and technologies that refers to the acquisition, storage and processing of data that, due to volume, frequency or typology, require to be treated in a non-conventional way. It implements mechanisms for the optimization of data capture, storage, search, sharing, analysis and visualization. Talking about Big Data implies handling what experts call the 5 Vs, i.e.: (i) *volume*: data collection is becoming increasingly massive, (ii) *variety*: there are more and more sources from which these huge amounts of data come from due to the greater number of connected devices, (iii) *speed*: speed in receiving and managing data is fundamental, since this immediacy is what can enable the processing of this information and decision making, (iv) *veracity*: it is the purity or trust that emanates from the data, avoiding unpredictability, and (v) *value*: it refers to the ability to know which data should be used at any given moment.
Cloud computing	*Cloud computing* is the on-demand availability of computing resources as services over the Internet.
Cybersecurity	Cybersecurity consists of "*the protection of information assets, through the treatment of threats that put at risk the information that is processed, stored and transported by the information systems that are interconnected*".

ANNEX 3

DESCRIPTION OF OPERATING METHODS MINING

A mining method can be defined as the procedure used (spatial and temporal sequence) to carry out the extraction of ore, depending on the characteristics of the deposit and the operating conditions. It should be noted that a distinction is made between mining method and mining system. The mining system refers to the equipment used in the execution of the operations of the production cycle (start-up, loading and transport) and their coupling.

The variables that condition the choice of a mining method can be grouped into three categories (Figure 82): (i) deposit characteristics, (ii) environmental conditions and (iii) mining parameters.

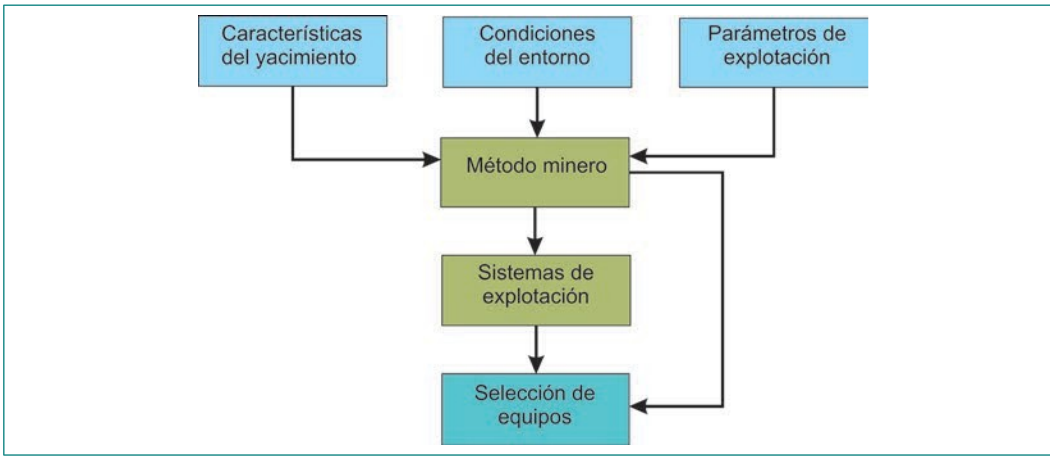

Figure 82. Variables influencing the choice of exploitation method. Source: (López Jimeno et al., 2022).

In relation to exploitation methods and the variables that influence their choice, the ones that most influence this choice are the natural characteristics of the deposit, since they cannot be modified. Figure 83 shows the characteristics of the deposits (shape, relief, proximity to the surface, power, inclination, complexity and distribution of mineralization) according to Rzhevsky (1987), characteristics that condition the choice of the most appropriate mining method.

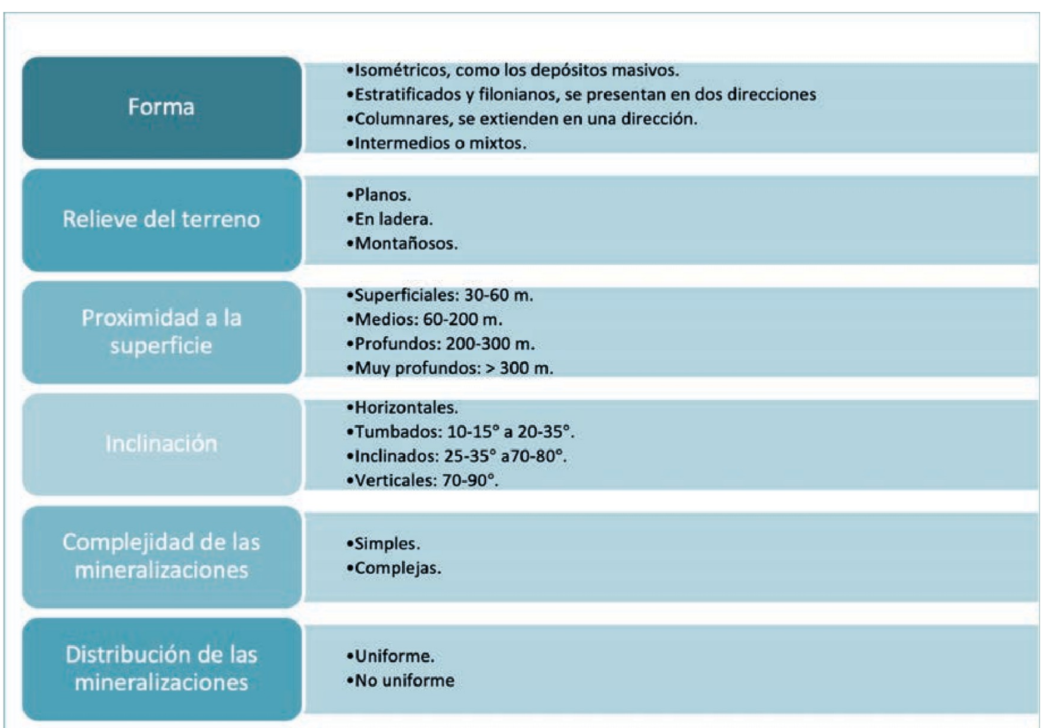

Figure 83. Classification of a reservoir according to their characteristics. Source: authors' own elaboration based on (Rzhevsky, 1987).

The methods of exploitation of solid mineral resources are first classified into three main groups: (i) open pit methods, (ii) subway methods and (iii) methods such as leaching, coal gasification and dredging. This annex describes the most commonly used open pit and subway methods. Reference is also made to the exploitation of marine resources, as this is an area that is currently under research and development.

Open pit mining methods

Open pit mining methods are based on accessing the deposit from the surface[128] . The mining shaft is formed by running the mining benches downwards. In open pit mining it is necessary to extract the material that surrounds the ore or useful rock (material that has no value and is known in mining jargon as tailings from the tailings heap[129]). The variable that measures the amount of tailings that needs to be extracted per unit of ore is the *stripping ratio* and measures the ratio of tailings to ore (in t/t, m^3 /t or m /m^{33}) of a mining operation. Therefore, it is also necessary to apply the production cycle (mining, loading and transport operations) to the tailings, in this case deriving the transport to waste dumps.

Given that the extraction of the tailings (removal, loading and transport to the waste dump) only involves costs (except in cases of revaluation of mining waste), the value of the ratio determines the economic viability of the operation if the amount of tailings to be extracted per ton of ore is excessive. Each mining operation is unique, but, in general, open pit mining has a depth limit: (i) for technical viability (to guarantee the stability of the mining voids), (ii) economic (to assume the cost associated with a greater depth of operations) and/or (iii) environmental (to guarantee an adequate management of an increasing volume of mining waste). If the deposit continues in appropriate quantity and quality at depth, it can be considered to end open pit mining and start subway mining.

The most common open pit mining methods are: (i) cuttings, (ii) open pit, (iii) terraces, (iv) contour mining, (v) quarries and (vi) gravel pits. Figure 84 illustrates different open pit mining methods for different types of deposits.

In the cuttings, the exploitation is carried out by descending benching, so that the mining hole has the shape of an inverted truncated cone. This method is used intensively to extract metallic mining resources, and has been applied since the 1960s in coal and industrial mineral deposits. The depth that these mines can reach is high (the highest in open-pit mining), in some cases reaching a depth of 1,000 m (illustrative examples include the Chuquicamata mine in Chile or Binham Canyon in USA, WHICH AT 1,200 M DEEP IS CURRENTLY THE DEEPEST OPEN PIT MINE IN THE WORLD. USA, which at 1,200 m deep is currently the deepest open pit mine in the world.

As for the equipment used to carry out the start-up operation, if the material is very hard, it is done by drilling and blasting. The explosives used are emulsions and bulk hydrogels and *heavy ampho*, initiated with non-electric detonators with pentolite multiplier and electronic detonators.

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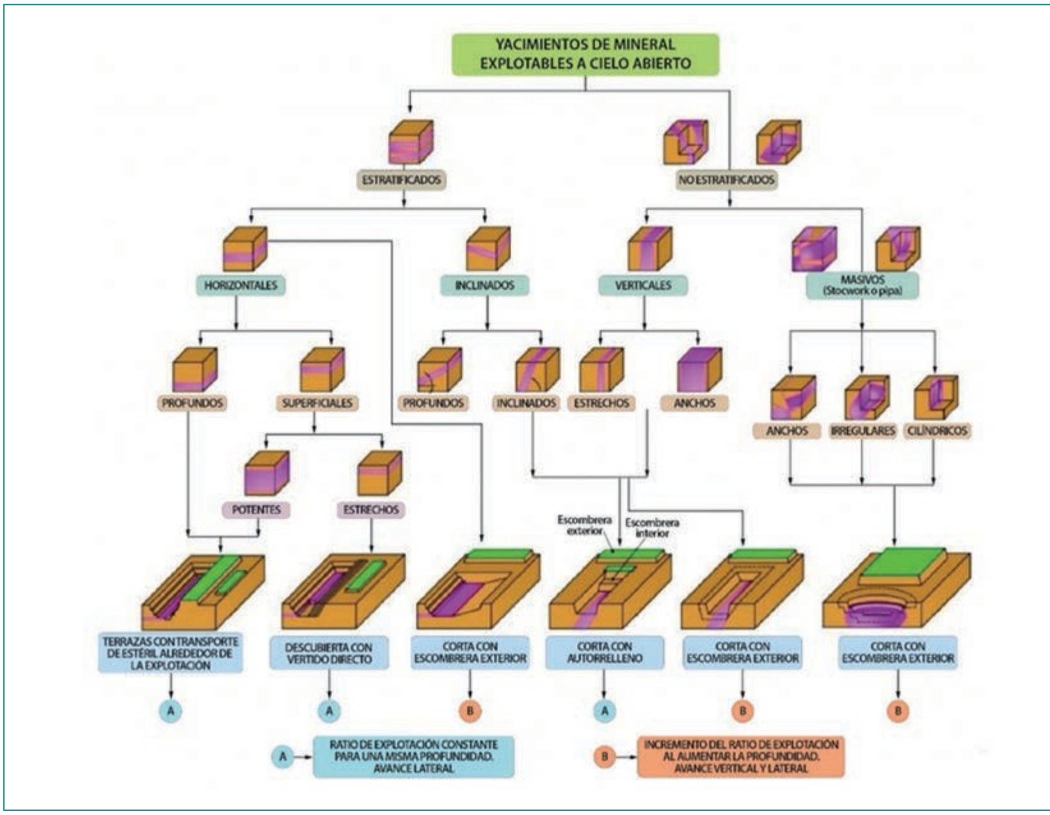
[128] For more details see (Herrera and Pla, 2006).

[129] Gables are the physical contacts of a reservoir with the surrounding material. The upper contact is called the reservoir *roof* and the lower contact is called the reservoir *wall*.



Exploitation methods for different types of reservoirs and their evolution tailings/mineral ratios. Open pit mining manual. Source: (López Jimeno et al., 2022).

cos. Loading is done with cable excavators up to 60 m³, wheel loaders with buckets up to 50 m³ and hydraulic excavators up to 45 m³. Transport is carried out with diesel, electric or mechanical dump trucks. The current trend is to use autonomous dumpers and battery-powered trolleys to eliminate the diesel engine, as well as semi-mobile crushers to eliminate ramp transport in increasingly deeper mines. As auxiliary equipment, tracked and wheeled tractors are used for the maintenance of loading faces and dumps, and motor graders for the maintenance of haulage tracks.

Uncovering is applied in the extraction of horizontal deposits of sedimentary origin (mainly coals), with a cover of less than 50 meters. It consists of the unidirectional advance of a module with a single bench from which the tailings are removed and dumped into the hole generated by the extraction of the previous module, thus *uncovering* the ore. Among the advantages of this method, it should be noted that the rehabilitation of the space affected by the mining is relatively fast, since the tailings that are extracted are transferred to the hole generated in the previous phase, so that it is not necessary to set up dumps outside the mine, except for the tailings extracted in the first module. Depending on the mining system used to start up, load and transfer the tailings, we speak of a continuous system (starting up with a shovel and direct or indirect dumping into the shaft or by conveyor belts, a method also known as terraces) and discontinuous (starting up and dumping of the tailings with draglines).

Terraces are used to extract brown lignite deposits with several layers, typical of Central Europe, India and Australia. In Spain, the method was used in the Puentes de García Rodríguez and Meira- ma mines (both in the province of A Coruña), with productions of 16 and 4 Mt/year, respectively. Both the start-up and the transport are carried out continuously, the former by means of a rotopala and the transport by high-capacity belts, with the transfer of the tailings to the shaft, either directly by means of a bridge, or from the outside, with mobile belts and stackers.

Contour mining is applied to extract coal deposits with the following characteristics: (i) horizontal layers, (ii) increase of the tailings/mineral ratio from outcrop, (iii) reduced layer thicknesses and (iv) single layer deposits. Contour mining is based on performing transfer mining of the tailings to the void generated by the mining.

Quarries are mainly used to extract aggregates and ornamental rock. It should be noted that in the case of ornamental rock (slate, marble and granite) the production cycle is different from the rest of the rocks and minerals, since in the case of ornamental rocks the aim is not to fragment the rock, but to extract large blocks in order to be able to produce slabs of different sizes and surface finishes from them.

In gravel pits, detrital materials such as sands and gravels, stored in valley deposits and river terraces, are intensively exploited due to the demand for these materials in the construction sector. The sands and pebbles are not very cohesive, so that they are removed directly by mechanical equipment. Mining is usually carried out on a single bench, generally less than 20 m deep. When the formations are at high levels, conventional equipment such as wheel loaders and dump trucks are used. However, it is common for the materials to come into contact with the sub-surface or the underlying aquifers, and other mining equipment such as dredges and draglines are then used.

Figure 85 shows two illustrative examples of two methods of open pit mining.

Figure 85. Examples of open pit mining methods. A. Corta Atalaya and B. Mendo aggregates. Source: Atalaya Mining and Áridos do Mendo.

Subway mining methods

When the deposit is at great depth, it is neither technically nor economically feasible to bring the ore from the surface, so the ore is accessed through what are known as *access workings* (inclined galleries, spirals or vertical shafts), without removing the tailings cover that covers the ore. This is the case of subway mining.

A classification of mining methods in subway mining is shown in Figure 86. The criterion for classification is the mechanism used to control the stability of the excavation generated by the extraction of the ore or useful rock. Three geomechanical strategies are considered for controlling the mining void, which correspond to the three groups of methods: (i) leaving part of the ore unmined to ensure the stability of the roof of the excavation, (ii) extracting all the ore and placing the excavation roof in the excavation, (iii) removing all of the ore and placing

(iii) allow the stresses that accumulate around the excavation to be released in the form of deformations, allowing the roof of the excavation to sink (controlled subsidence).

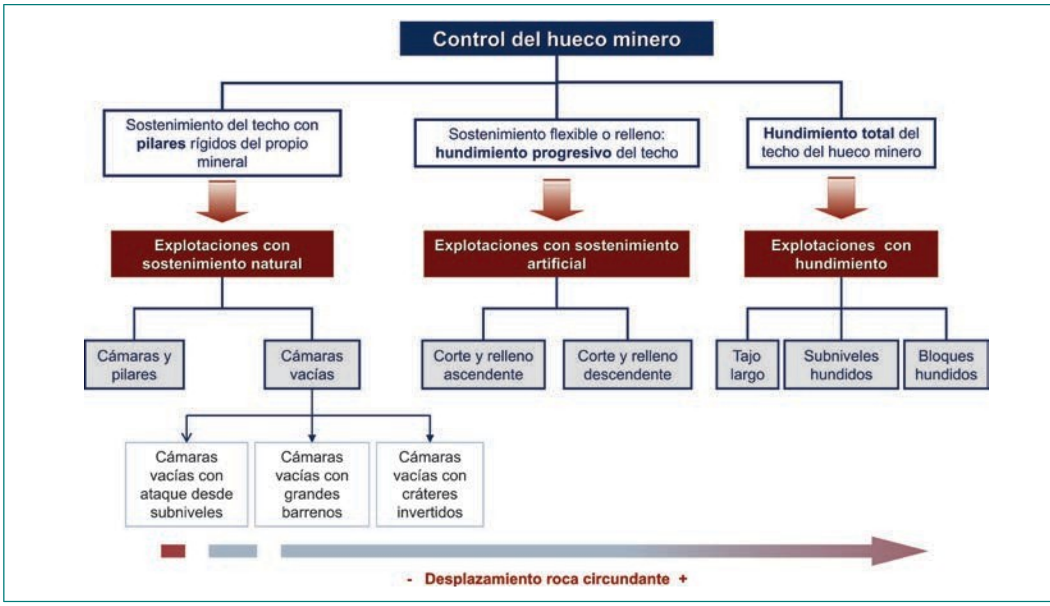


Figure 86. *Classification of the main mining methods in subway mining according to the geomechanical strategy for controlling the mining roof. Source: authors' own elaboration.*

Table 43 below presents a brief description of the main mining methods, some of which are presented in more detail in Table 44.

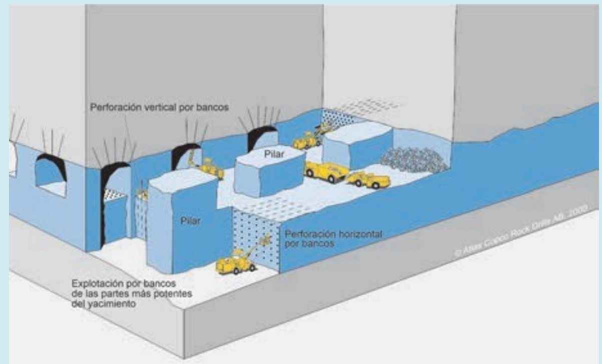
Table 43. *General description and comparison of methods. Source: modified and translated by the authors from (Balt and Goosen, 2020).*

Method	Description
Chambers and pillars / ***Room and Pillar (R&P)***	A mining method that consists of leaving pillars of the ore itself to ensure the stability of the mine. The dimensions of the pillars and the chambers (formed by the extraction of the ore) depend on the characteristics of the ore, the thickness of the overburden and the stresses on the rock. This method is generally applied in layer-type deposits with inclinations of less than 30°. As for the exploitation system, it depends on the material to be extracted. When the material is hard, it is used in the start-up, drilling and blasting. In the case of soft materials (coal), mechanical excavation equipment can be used in the start-up.
A Empty chambers with transverse sub-levels / ***Transverse Open Stopping (TOS)***	This is a variant within the group of empty chamber methods, applicable to powerful deposits of good geomechanical quality. The extraction is carried out from galleries (all the galleries that are on the same level form a sublevel) in retreat from the roof to the wall by means of long blasting shots, drilled from a series of parallel crosscuts in the ore body. The drifts are perpendicular to the direction of the orebody, hence the term *transverse sublevels*. Unlike the sunken sublevel method, here the shaft is supported without sinking, leaving volumes of ore unmined (also called piles), which requires good geomechanical conditions, both of the ore and of the stopes.
2. A. Empty chambers with longitudinal sublevels / ***Longitudinal Open Stoping (LOS)***	It is a variant within the group of methods by empty chambers, applicable to narrow deposits of good geomechanical quality and strong dip. The extraction is made by levels (galleries) in retreat from the ends of defined blocks of ore through long shots, parallel to roof and wall, drilled from the front of the ore in the levels. It requires good geomechanical conditions of ore and gables, since volumes of ore (called pillars) are left to guarantee the stability of the exploitation. The sublevels have the same direction as the direction of the deposit, hence the terminology of *longitudinal sublevels*.

2.B. Inverted craters / ***Vertical Crater Retreat (VCR)***	This is a variant within the group of empty chamber methods used to extract steeply sloping deposits. The ore is removed by upward slicing using blasting with spherical charges. Part of the blasted ore remains in the chamber to prevent the walls from collapsing during the chamber removal process. The extraction of the fragmented material, between 30 and 40 % of the blast, is carried out through a base gallery by means of a system of transversal galleries. Drilling is carried out from a higher level with vertical drills and DTH down-the-hole hammer equipment with diameters greater than 6 inches. After opening the traverses, a suspended charge of explosive is introduced into the drill holes at the lower level to act as spherical charges. The ore fired in slices falls into the chamber, rising successively until a crown pillar is left at the top, which is fired when it leaves the chamber. Deposits must be at least 2 m in depth, have a slope greater than 50° with well-defined ore-waste contacts.
3. Cut & fill (ascending or descending) / ***Cut & fill (C&F)***	The characteristic of this method is the use of backfill as a means of supporting the excavation. The ore is removed by horizontal slices in an ascending or descending direction. Once the ore has been fragmented, it is completely extracted from the chamber through sifters or chutes, and the open space is then filled with material known as *backfill*. The *backfill* can be tailings from the preparation works, surface material or tailings material from the treatment plant. The backfill must have a certain geomechanical quality. There are three types of backfill, of increasing geomechanical quality: manual, pneumatic and hydraulic. Hydraulic backfill is drained to eliminate water, leaving a compact backfill in a few hours (24-48 hours), and the consistency can be increased with the addition of a certain amount of cement. In *overhand cut &* fill mining, once a horizontal slice has been extracted, it is filled and the one above it is extracted. Work is therefore carried out on the backfill material and below the ore *in situ*. In *underhand cut-and-fill* mining, once a horizontal waste has been extracted, it is filled and the one below it is extracted. Work is therefore carried out below the backfill and on the ore *in situ*. In these mines, a good consistency of the backfill is required, through the use of cement. Cut-and-fill methods add one more operation to the production cycle (start-up, loading, transport and *backfill*), making them, in general, the most expensive mining methods. It is therefore necessary to guarantee their economic viability based on a good ore body grade.
4. Longwall / ***Longwall stopping (LW)***	A mining method for narrow, low dip deposits, in which a long mining face (up to 150 m) is excavated. The ore is removed by mechanical means (plows, planers or low profile mechanized equipment). Low strength ores capable of being mechanically stripped and roof materials that sink well are required. The mining roof sinks as mining progresses. The method can be applied for medium or steeply sloping deposits, but in this case it is necessary to fill the gap generated by mining.
5. Sunken sublevels / ***Sublevel Caving (SLC)***	The exploitation is carried out through horizontal galleries at fixed vertical intervals in a descending way. Galleries at the same level form a sublevel. The distance between the sublevels varies between 8 and 60 m. Each of them is developed according to a set of galleries that cover the complete section of the ore and depending on whether the drilling system is fan, ring or parallel. When parallel drilling is used, the distance between sublevels is greater and only two sublevels are worked, one for drilling and the other for extraction, blasting being an open pit bench application to subway workings. This method is applied in deposits with power greater than 3 m and with an inclination greater than 50º, with well-defined contacts between the ore and the tailings. It is one of the most flexible and versatile mining methods that can be successfully employed for powerful ore bodies.
6. Sunken blocks / ***Block Caving Method (BCM)***	Subway mining method for large deposits with particular geomechanical characteristics (deposits that have a certain level of natural fragmentation), in which the ore is fragmented (sinking) by removing the lower part of the ore. The fragmented ore is loaded from the bottom by means of very long controlled blasting shots. It requires a lot of previous infrastructure, but it is very economical since the fragmentation of the material is produced by natural sinking. A disadvantage is the occurrence of strong subsidence on the surface.
Filled sublevels / ***Drift and fill mining (D&F)***	Subway mining for narrow, shallow-dipping deposits that are mined through a series of small drifts, each of which is backfilled before the next is mined. The fact of making small excavations (galleries) and backfilling them means that it can be used in deposits with poor quality ore and stopes.

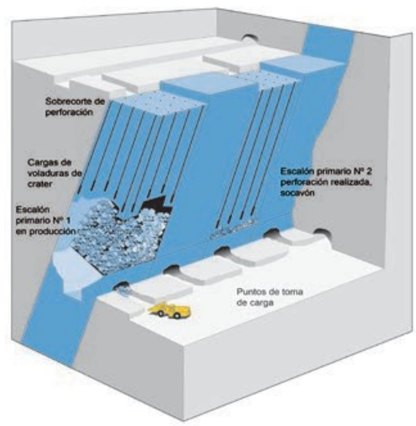
Table 44. *Underground mining methods. Source: authors' own elaboration and figures translated and modified from (Atlas Copco, 2007).*

Chamber and pillar mining method. Application to tabular reservoir with little p e n e t r a t i o n . In this case, the starting operation is carried out by blasting. The diagram shows the jumbos that are carrying out the drilling of augers. Once the material has been fragmented, it is loaded by LDH shovels on low profile dump trucks, which carry out the transport operation. The figure also shows a team placing bolts (elements to support the roof of the chambers that ensure the local stability of the excavations).

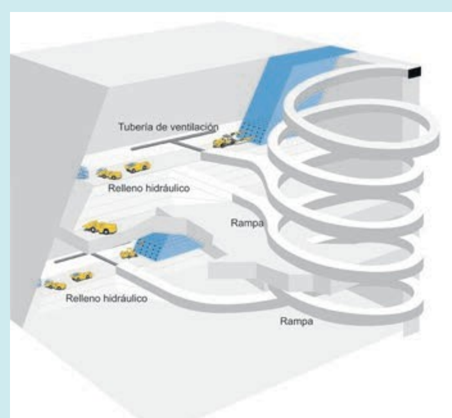


Method of exploitation of empty chambers by *Vertical Crater Recreat* (VCR). The chamber is formed by blasting horizontal slices. To guarantee the stability of the chamber while it is being excavated, the fragmented ore is left inside the chamber for a period of time. The figure shows how two chambers are formed, leaving a volume of ore between them to guarantee the stability of the chamber.

the stability of the farm.



Overhand cut and fill mining method *(overhand cut & fill mining)*. Access to the chambers by a spiral ramp executed at reservoir wall. An example o f integral mechanization of start-up (drilling and blasting), loading (LHD shovels) and transport (low profile dump trucks) operations is shown.



Block caving mining method (*block caving*)

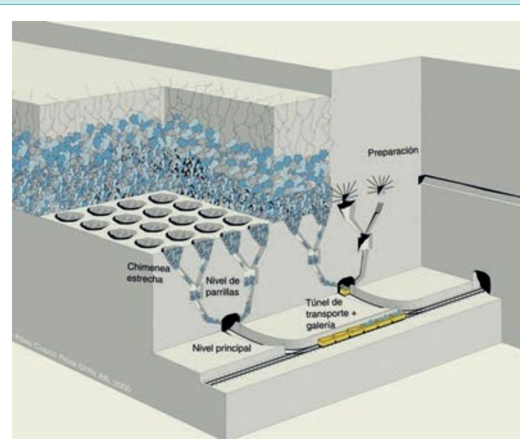


Figure 87 shows an example of a subway mine, showing the access to the galleries and the *ad-hoc* reprocessing plant.

Figure 87. *San José Valdeflorez subway mining project. Source: (Extremadura Energies, n.d.).*

Regarding the choice of the most appropriate exploitation method, UBC (University of British Columbia, Canada) established the classification of exploitation methods and more recently Balt and Goosen (2020) optimized its application in the so-called Method Selection with Analytic Hierarchy Process (MSAHP).

Underwater mining

The increase in demand for mineral resources in the coming years will foreseeably lead to more and more talk of mining in the so-called "peripheral areas", which are those unconventional areas of the planet that could have great potential as a source of raw materials in the near future. In this context, deep water mining, both within and outside national jurisdictions, offers opportunities for the exploration and possible exploitation of metals such as Ni, Cu, Co and rare earths.

The deep sea is the largest ecosystem on earth, but remains one of the least explored due to technological difficulties. Subsea mining faces enormous challenges as it must be carried out in the deep ocean, under extreme environmental conditions using remote technology. The extreme conditions encountered relate to hydrostatic pressure (~500 times atmospheric pressure), total darkness, extreme temperatures (from 2°C at the bottom of the ocean to 400°C, at hydrothermal vents), limited knowledge of the ecosystems and the consequences of mining on them (e.g. potential toxicity of metals to be released into the ocean), variable currents (with time and water depth), variable seafloor characteristics and potential volcanic activity.

In addition, there are knowledge gaps that currently relate to the concentration and size of the resources. Today, commercial interest is concentrated on three types of deposits, to provide metals and TR or REE elements: (i) polymetallic or manganese nodules, (ii) polymetallic hydrothermal sulfides[130] (SMS) and (iii) cobalt-rich ferromanganese crusts. These deposits are distributed along all ocean floors.

[130] *Seafloor massive sulphides*.

To meet the challenges, modern deepwater mining methods are being developed in consultation and cooperation with other sectors involved in deepwater activities, including ocean cable laying, dredging and offshore oil and gas extraction. All are contributing, directly and indirectly, to developing the necessary technology.

Rock and mineral extraction in deep water normally has four main components: (i) remotely operated extraction equipment (excavators to disaggregate the deposits and underwater excavators), (ii) vertical transport system (pipe string or hoist), (iii) surface platform or mining vessel, and (iv) disposal system.

Figure 88 shows the components of a polymetallic nodule mining project. The main components include the seabed collector, the vertical lift system, the surface mining vessel, the bulk carriers, and the onshore processing plant. Multibeam hy- droacoustic mapping with a vessel hull-mounted system provides information on ocean floor topography and water depth (bathymetry), and ocean floor features (hard rock, sediments, nodules). Deep towed systems and autonomous underwater vehicles (AUVs) can get closer to the ocean floor and therefore provide higher resolution (a smaller footprint).

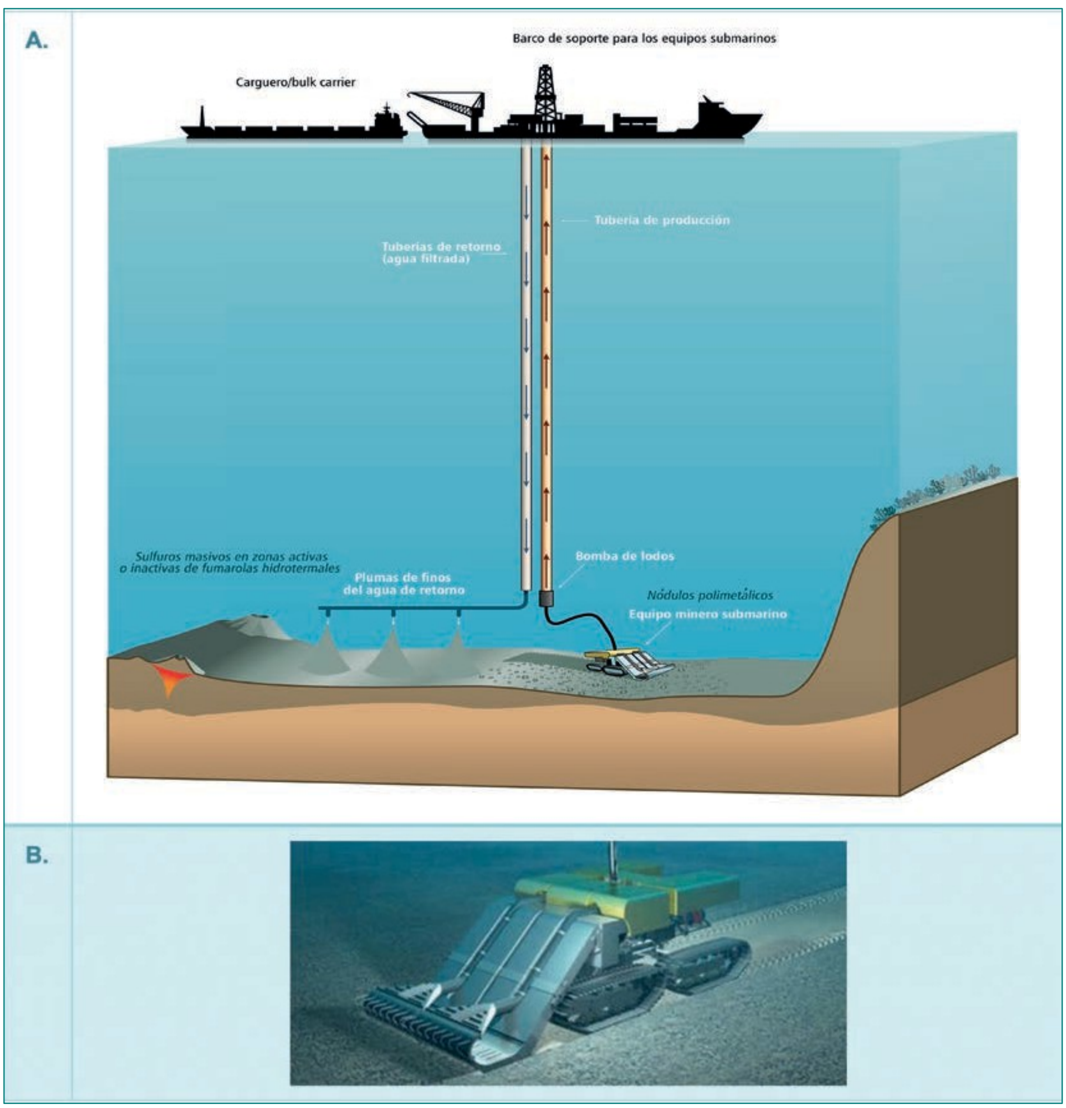


Figure 88. A. *Schematic of deepwater exploration and mining of polymetallic nodules,* ***B.*** *Artist's impression of a scaled-down seafloor nodule collector (or tracer). Source: translated and modified by the authors from (Cuyvers et al., 2018).*

Table 45 shows extraction methods for deepwater mining, indicating their *Technology Readiness Level* (TRL), ranked on a scale from 1 to 9, where 1 is the lowest possible value. As can be seen, all the methods are in the lower range of the scale, indicating that significant technological improvements must be made for subsea mining to become a realistic alternative to land mining.

Deposit type	Technique	Remarks	Development level (maximum value 9)
Extraction			
Massive sulfides	Drum cutters (remote controlled vehicles)	Technology based on that used in surface coal mining. Experiments have been conducted down to 1600 m depth, but no material was collected.	3
Massive sulfides	Auxiliary cutters (remote control)	This equipment facilitates the excavation of drum cutters.	2
Massive sulfides	Rotating cutting head (remote control)	Cutting device consisting of a rotating cutting head, more flexible in handling than drum cutters. Further testing is needed to assess its applicability in deep water.	2
Massive sulfides	Clamshell bucket (remote control)	It is not used to excavate sulfides, but rather to remove the upper layers of deposits. Its applicability for rock collection is uncertain, as is its economic viability.	2
Polymetallic nodules	Passive collectors	It has the advantages of a simple design and low operating costs. However, its use is discarded due to the difficulty to control the quality and quantity of the nodules collected, in addition to the great environmental risks in the form of sediments.	5
Polymetallic nodules	Hydraulic manifolds	It is based on applying (spraying) seawater to separate the nodules from the seabed, which implies a limited environmental impact. Hydraulic collectors have been tested for shallow depths.	4
Ferromanga- neso bark		Due to the difficulties in extracting this resource, it has not proven to be an economically attractive option.	1
Lifting system			
Seabed minerals	Continuous bucket system	The method was first tested in 1972, but was abandoned due to the lack of control of the system and the large environmental impact.	5
Seabed minerals	Pneumatic lifting system	The system is based on injecting compressed air into a pipe to pump the material to the surface. It has been tested in very deep water, but it is a system that is very vulnerable to clogging and requires large amounts of energy.	5
Seabed minerals	Hydraulic pumping lifting system	Simple and reliable system with high lifting capacity, often applied during oil and gas drilling. The concept looks promising for water mining. but more research is needed beyond the current state of the art. the prototype phase	3
Seabed minerals	Cable lifting system	Similar to an earth extraction system, simpler than hydraulic or pneumatic systems The question is mainly whether it will be efficient enough to be commercially viable.	2
Surface platforms			
Seabed minerals	Dehydration	One of the simplest techniques to increase the value of the ore, which is critical to the economic viability of deepwater mining. The system is well known and should be easily applicable to ships or offshore platforms.	7
Deposition			
Waste, tailings		Since large-scale commercial operations have not yet been carried out, this is an unknown area. A clear plan for waste handling is needed.	1

Table 45. *Extraction technologies for deepwater mining and technological readiness level. Note: The level of technological readiness varies from 1 to 9 (the higher the value, the higher the preparation). Source: modified and translated by the authors of Ecorys in (Rademaekers et al., 2015).*

Technological advances could enable the extraction of deepwater mineral resources, but the high level of investment required raises doubts about their economic viability. To date, deepwater mineral exploitation remains a potential rather than a reality.

In addition, it should be pointed out, in relation to the exploitation of minerals in the seabed, that the "*EU Biodiversity Strategy 2030*" establishes that mineral exploitation in the seabed should not be created before the effects have been sufficiently investigated, the risks are known, and it can be demonstrated that the technologies and operating practices will not produce serious damage to the environment. In relation to this point, in March 2022 a Royal Decree has been approved that includes as a new criterion of compatibility with marine strategies the application of the precautionary and precautionary principles mentioned in the European strategy, for underwater mining activities in our country.

ANNEX 4

ENVIRONMENTAL REGULATIONS

After the conclusions drawn from the mining research and, once it has been decided that there are sufficient reserves that can be recovered with the technical improvements available, the environmental procedures are initiated to obtain all the authorizations or "permitting", as the Anglo-Saxons call it. In addition to the technical document describing the resource exploitation project, it is necessary to submit to the Administration, for evaluation, two decisive technical documents: the Environmental Impact Assessment (EIA) and the Restoration Plan. The structure and content of both documents is shown below (Figure 89 and 90).

Figure 89. *Structure and content of the EIA. Source: Official Mining Chamber of Galicia (COMG).*

PHASE 1: DEFINITION OF THE PREVIOUS STATE (BASELINE)

1. Archaeological survey
2. Soil baseline study
3. Socioeconomic study of the environment
4. Baseline carbon balance study

PHASE 2: FINAL PROJECT FOOTPRINT

1. Definition of short
2. Characterize waste
3. Define water management system: water catchment projects, water discharge point authorization project, water charges.
4. Define final cut
5. Baseline hydrogeology and hydrology
6. Geotechnical characterization of the sites chosen to locate ponds and tailings ponds of the system.
7. Definition of the production process

PHASE 3. OPERATION PROJECT AND RESTORATION PLAN

1. Volumes and characterization of mining waste
2. Mineral reserves from resource estimation
3. Definition of the metallurgical process
4. Control and follow-up procedure.
5. Definition of the construction and management project for the mining waste facilities (linked to previous points, as well as a geotechnical investigation).
6. Preliminary project for the closure and decommissioning of mining waste facilities
7. Geomorphological restoration
8. Measures foreseen for the rehabilitation of the natural area affected by research and exploitation
9. Measures foreseen for the rehabilitation of the services and facilities attached to the farm.

PHASE 4: IMPACTS: SPECIFIC STUDIES

1. Noise impact modeling
2. Air quality impact modeling
3. Vibration study
4. Socioeconomic impact study
5. Landscape impact and integration study
6. Environmental risk analysis
7. Carbon Footprint Offsets

Introduction and description of the project

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2. PART II: MEASURES ENVISAGED FOR THE REHABILITATION OF THE NATURAL AREA AFFECTED BY RESEARCH AND EXPLOITATION
3. PART III: MEASURES FORESEEN FOR THE REHABILITATION OF THE SERVICES AND FACILITIES ATTACHED TO THE FARM. Auxiliary buildings and demolitions
4. PART IV: WASTE MANAGEMENT PLAN
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    c. General information on extraction and processing operations
    d. Description of the activity generating the waste and intended handling
    e. Estimated volume of mining waste
    f. Characterization of mining waste
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    h. Impact on the environment and human health due to the deposit of mining waste
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    k. Preliminary project for the closure and decommissioning of mining waste facilities
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5. PART V: CIRCULAR MINING
    a. Valorization of tailings: through the development of RDI projects in applications and recovery processes.
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6. PART VI: IMPLEMENTATION SCHEDULE AND BUDGET
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Figure 90. Structure and content of the Restoration Plan. Source: COMG.

Table 46 shows the state legislation applicable to the development of mining projects. In addition, there are many regional regulations that must be complied with in relation to water, atmospheric emissions, waste, emergency issues, etc.

Date	Designation	Thematic
21-Jul-73	Law 22/1973, of July 21, 1973, on Mines	Sectorial
09-Aug-74	Decree 3025/1974 On atmospheric limitation produced by motor vehicles	Atmosphere (dust and gases)
06-Feb-75	Decree 833/1975 of February 6, 1975, implementing Law 38/72 of December 22, 1972 on the protection of the atmospheric environment.	Atmosphere (dust and gases)
25-Aug-78	Royal Decree 2857/1978, of August 25, 1978, approving the General Regulations for the Mining Regime	Sectorial
Dec 21, 1983	Royal Decree 3255/1983, of December 21, 1983, approving the Miners' Statute.	Sectorial
Dec 26, 1984	Royal Decree 2366/1984, of December 26, 1984, on the reduction of the retirement age of certain professional groups included in the scope of the Miners' Statute, approved by Royal Decree 3255/1983, of December 21, 1983.	Sectorial
02-Apr-85	Royal Decree 863/1985, of April 2, 1985, approving the General Regulations of Basic Mining Safety Standards.	Sectorial
Sep 13, 1985	Order of September 13, 1985, approving certain Supplementary Technical Instructions to Chapters III and IV of the RGNBSM	Sectorial
Mar 19, 1986	Order of March 19, 1986, approving the complementary rules for the development and execution of Royal Decree 3255/1983, of December 21, 1983, Miners' Statute, regarding safety and hygiene.	Sectorial

Table 46. Legislation at the state level, both cross-sectional, and applicable to the development of mining projects. Source: COMG.

11-Apr-86	Royal Decree 849/1986, of April 11, 1986, approving the Regulations of the Public Hydraulic Domain, which develops the preliminary titles I, IV, V, VI and VII of Law 29/1985, of August 2, 1985, on Water.	Waters
Mar 22, 1988	Order of March 22, 1988, approving complementary technical instructions to Chapters II, IV and XIII of the General Regulations on Basic Mining Safety Standards.	Sectorial
Jul 20, 1988	Royal Decree 833/1988, of July 20, 1988, approving the Regulations for the execution of Law 20/1986, Basic Law on Toxic and Hazardous Waste.	Waste
16-Apr-90	Order of April 16, 1990 approving the technical instructions supplementing Chapter VII of the General Regulations on Basic Mining Safety Standards.	Sectorial
03-Sep-90	Order 03/09/1990 on compliance with Directive 88/76/EEC on exhaust emissions from motor vehicles.	Atmosphere (dust and gases)
16-Oct-92	Order 16/10/1992 on compliance with Directive 91/441/EEC on exhaust emissions from motor vehicles.	Atmosphere (dust and gases)
20-Oct-94	Royal Decree 2085/1994, of October 20, 1994, approving the Regulation of Petroleum Installations.	Storage of Chemical Products (APQ)
Nov 08, 1995	Law 31/1995, of November 8, 1995, on Occupational Risk Prevention.	Prevention of Occupational Risks (PRL)
17-Jan-97	Royal Decree 39/1997, of January 17, 1997, approving the Prevention Services Regulations.	PRL
Apr 14, 1997	Royal Decree 485/1997, of April 14, 1997, on minimum provisions for safety and health signs at work.	PRL
Apr 14, 1997	Royal Decree 487/1997, of April 14, 1997, on minimum health and safety provisions for the manual handling of loads involving risks, particularly back and lumbar risks, for workers.	PRL
Apr 24, 1997	Law 11/1997, of April 24, 1997, on Packaging and Packaging Waste.	Waste
May 12, 1997	Royal Decree 665/1997, of May 12, 1997, on the protection of workers against risks related to exposure to carcinogenic agents at work.	Atmosphere (dust and gases)
May 14, 1997	Decree 130/1997, of May 14, 1997, approving the Regulations for the management of river fishing and inland aquatic ecosystems.	Waters
May 30, 1997	Royal Decree 773/1997, of May 30, 1997, on minimum health and safety provisions relating to the use by workers of personal protective equipment.	PRL
Jun 20, 1997	Royal Decree 952/1997, of June 20, 1997, amending the Regulation for the execution of Law 20/1986, of May 14, 1986, Basic Law on Toxic and Hazardous Waste, approved by Royal Decree 833/1988, of July 20, 1988.	Waste
Jul 18, 1997	Royal Decree 1215/1997, of July 18, 1997, establishing the minimum health and safety provisions for the use of work equipment by workers.	PRL
05-Sep-97	Royal Decree 1389/1997, of September 5, 1997, approving the minimum provisions to protect the safety and health of workers in mining activities.	PRL
Sep 15, 1997	Royal Decree 1427/1997 Approval of ITC MI-IP 03 "Oil installations for own use".	Chemical Products Warehouse (APQ)
Apr 30, 1998	Royal Decree 782/1998, of April 30, 1998, approving the Regulation for the development and execution of Law 11/1997, of April 24, 1997, on Containers and Packaging Waste.	Waste
07-May-99	Royal Decree 769/1999 of May 7, 1999, which establishes the provisions for the application of the European Parliament and Council Directive 97/23/EC on pressure equipment and amends Royal Decree 1244/1979, of April 4, 1979, which approved the Pressure Equipment Regulations.	Industrial safety
27-Jul-99	Order 27/07/1999, which determines the conditions to be met by fire extinguishers installed in vehicles transporting people or goods.	Industrial safety
27-Aug-99	Royal Decree 1378/1999 on measures for the elimination and management of polychlorinated biphenyls and polychlorinated terphenyls and equipment containing them.	Waste
01-Oct-99	Royal Decree 1523/1999, of October 1, 1999, amending the Regulation of Petroleum Installations, approved by RD 2085/1994, of October 20, 1994, and the ITC MI-IP03, approved by RD 1427/1997, of September 15, 1997, and MI-IP04, approved by RD 2201/1995, of December 28, 1995, and its correction of errors.	APQ
08-Oct-99	Royal Decree 1566/1999, of October 8, 1999, on safety advisors for the transport of dangerous goods by road, rail or inland waterway.	APQ
06-Apr-01	Royal Decree 379/2001, of April 6, 2001, approving the Regulation on the storage of chemical products and its complementary technical instructions MIE APQ-1, MIE APQ-2, MIE APQ-3, MIE APQ-4, MIE APQ-5, MIE APQ-6 and MIE APQ-7.	APQ

20-Jul-01	Royal Legislative Decree 1/2001, of July 20, 2001, approving the revised text of the Water Law.	Waters
08-Feb-02	Order MAM/304/2002, of February 8, 2002, publishing waste recovery and disposal operations and the European waste list	Waste
22-Feb-02	Royal Decree 212/2002, of February 22, 2002, regulating noise emissions in the environment due to certain outdoor machinery.	Atmosphere (noise and vibration)
02-Aug-02	Royal Decree 842/2002 of August 2, 2002, approving the Low Voltage Electrotechnical Regulations.	Industrial safety
19-Nov-02	Order TAS/2926/2002, of November 19, 2002, establishing new models for the notification of occupational accidents and enabling their transmission by electronic procedure.	PRL
28-Feb-03	Royal Decree 255/2003, of February 28, 2003, approving the Regulation on the classification, packaging and labeling of dangerous preparations.	Waste
Mar 27, 2003	Directive 2002/96/EC of January 27, 2003, on waste electrical and electronic equipment (WEEE).	Waste
23-May-03	Royal Decree 606/2003, of May 23, 2003, amending RD 849/1986, of April 11, 1986, approving the regulation of the Public Hydraulic Domain, which develops the preliminary titles I, IV, V, VI and VII of Law 29/1985, of August 2, 1985, on Water.	Waters
12-Jun-03	Royal Decree 681/2003, of June 12, 2003, on the protection of the health and safety of workers exposed to the risks derived from explosive atmospheres in the workplace.	PRL
17-Nov-03	Noise Law 37/2003	Atmosphere (noise and vibration)
Dec 12, 2003	Law 54/2003, of December 12, 2003, on the reform of the regulatory framework for the prevention of occupational risks.	PRL
30-Jan-04	Royal Decree 171/2004, of January 30, 2004, which develops article 24 of Law 31/1995, of November 8, 1995, on Occupational Risk Prevention, in relation to the coordination of business activities.	PRL
03-Dec-04	Royal Decree 2267/2004, of December 3, 2004, approving the fire safety regulations in industrial establishments. CORRECTION of errors and misprints of Royal Decree 2267/2004, December 3rd, approving the Fire Safety Regulation in industrial establishments.	Industrial safety
14-Jan-05	Royal Decree 9/2005 List of potentially soil contaminating activities and the standard criteria for the declaration of contaminated soils	Environment
Nov 04, 2005	Royal Decree 1311/2005, of November 4, 2005, on the protection of the health and safety of workers against the risks derived or that may derive from exposure to mechanical vibrations.	PRL
Dec 16, 2005	Royal Decree 1513/2005, of December 16, 2005, which develops Law 37/2003, of November 17, 2003, on Noise, regarding the evaluation and management of environmental noise.	Atmosphere (noise and vibration)
Dec 30, 2005	Royal Decree 1619/2005, of December 30, 2005, on the management of end-of-life tires.	Waste
23-Jan-06	Order ITC/101/2006, of January 23, which regulates the minimum content and structure of the health and safety document for the extractive industry.	Sectorial
24-Feb-06	Royal Decree 228/2006, of February 24, amending Royal Decree 1378/1999, of August 27, establishing measures for the disposal and management of polychlorinated biphenyls, polychlorinated terphenyls and equipment containing them.	Waste
Mar 10, 2006	Royal Decree 286/2006, of March 10, 2006, on the protection of the health and safety of workers against risks related to noise exposure	PRL
28-Apr-06	Royal Decree 524/2006, of April 28, which amends Royal Decree 212/2002, of February 22, which regulates noise emissions in the environment due to certain outdoor machinery.	Atmosphere (noise and vibration)
02-Jun-06	Royal Decree 679/2006, of June 2, 2006, regulating the management of used industrial oils.	Waste
Nov 13, 2006	Resolution of November 13, 2006, of the Directorate General for Industrial Development, extending Annexes I, II and III of the Order of November 29, 2001, which publishes the references to the UNE standards that transpose harmonized standards, as well as the coexistence period and the entry into force of the CE marking for several families of construction products.	Sectorial
Mar 23, 2007	Royal Decree 393/2007, of March 23, 2007, approving the Basic Self-Protection Standard for centers, establishments and facilities engaged in activities that may give rise to emergency situations.	Emergencies
20-Apr-07	Royal Decree 508/2007 of April 20, 2007, which regulates the provision of information on emissions of the E-PRTR Regulation and integrated environmental authorizations.	Environment

20-Jul-07	Royal Decree 1027/2007 (RITE) of July 20, 2007, approving the Regulation of Thermal Installations in Buildings.	Air conditioning
30-Aug-07	Order ITC/2585/2007, of August 30, 2007, approving Complementary Technical Instruction 2.0.02 "Protection of workers against dust, in relation to silicosis, in the extractive industries", of the General Regulations on Basic Mining Safety Standards.	Sectorial
19-Oct-07	Royal Decree 1367/2007, of October 19, 2007, which implements Law 37/2003, of November 17, 2003, on Noise, regarding acoustic zoning, quality objectives and acoustic emissions.	Atmosphere (noise and vibration)
23-Oct-07	Law 26/2007, on Environmental Responsibility	Environment
Nov 15, 2007	Law 34/2007, of November 15, 2007, on air quality and atmospheric protection.	Atmosphere (dust and gases)
Dec 13, 2007	Law 42/2007, of December 13, 2007, on Natural Heritage and Biodiversity	Environment
01-Feb-08	Royal Decree 106/2008, of February 1, 2008, on batteries and accumulators and the environmental management of their waste.	Waste
01-Feb-08	Royal Decree 105/2008, of February 1, 2008, regulating the production and management of construction and demolition waste.	Waste
07-May-08	Order ITC/1316/2008, of May 7, which approves the complementary technical instruction 02.1.02 "Preventive training for the performance of the job", of the General Regulations on Basic Mining Safety Standards.	Sectorial
09-Jun-08	Resolution of June 9, 2008, of the Directorate General of Energy Policy and Mines, approving the technical specification number 2000-1-08 "Preventive training for the performance of the position of operator of transport machinery, truck and dump truck, in outdoor extractive activities" of the complementary technical instruction 02.1.02 "Preventive training for the performance of the job", of the General Regulation of Basic Standards for Mining Safety.	Sectorial
09-Jun-08	Resolution of June 9, 2008, of the General Directorate of Energy Policy and Mines, which approves the technical specification No. 2001-1-08 "Preventive training for the performance of the position of operator of machinery for start-up/loading/vehicles, shovel loader and hydraulic chain excavator, in outdoor extractive activities" of the Complementary Technical Instruction 02.1.02 "Preventive training for the performance of the job position", of the General Regulations of Basic Standards for Mining Safety.	Sectorial
05-Sep-08	Royal Decree 1468/2008, of September 5, 2008, which amends Royal Decree 393/2007, of March 23, 2007, approving the basic standard for self-protection of centers, establishments and facilities engaged in activities that may give rise to emergency situations.	Emergencies
10-oct-08	Royal Decree 1644/2008, of October 10, 2008, which establishes the rules for the commercialization and commissioning of machinery.	PRL
Dec 12, 2008	Royal Decree 2060/2008, of December 12, 2008, approving the Pressure Equipment Regulation and its complementary technical instructions.	Industrial safety
Dec 22, 2008	Royal Decree 2090/2008, of December 22, 2008, approving the Regulations for the partial development of Law 26/2007, of October 23, 2007, on Environmental Responsibility.	Environment
20-May-09	Order ARM/1312/2009 of May 20, 2009, which regulates the systems for the effective control of the volumes of water used by water exploitations of the public water domain, of the returns to said public water domain and of the discharges to it.	Waters
09-Jun-09	Order ITC/1607/2009, of June 9, 2009, approving Complementary Technical Instruction 02.2.01 "Commissioning, maintenance, repair and inspection of work equipment" of the General Regulations on basic mining safety standards.	Sectorial
12-Jun-09	Royal Decree 975/2009, of June 12, 2009, on the management of wastes from extractive industries and the protection and rehabilitation of areas affected by mining activities	Sectorial
25-Nov-09	Regulation 1221-2009 of the European Parliament and of the Council of 25 November 2009 on the voluntary participation by organizations in a Community eco-management and audit scheme (EMAS), and repealing Regulation (EC) No 761/2001 and Commission Decisions 2001/681/EC and 2006/193/EC	Environment
Mar 26, 2010	Royal Decree 367/2010 of March 26, 2010, amending various environmental regulations to adapt them to Law 17/2009, of November 23, 2009, on free access to service activities and their exercise, and to Law 25/2009, of December 22, 2009, amending various laws to adapt them to the Law on free access to service activities and their exercise.	Waste
Nov 05, 2010	Royal Decree 1436/2010, of November 5, 2010, amending various royal decrees for their adaptation to Directive 2008/112/EC of the European Parliament and of the Council, which amends several directives to adapt them to Regulation (EC) No. 1272/2008 on classification, labeling and packaging of substances and mixtures.	Environment

Nov 18, 2010	Resolution of November 18, 2010, of the Directorate General of Energy Policy and Mines, approving the technical specification number 2003-1-10 "Preventive training for the performance of jobs included in groups 5.1 letters a), b), c) and 5.2 letters a), b), d), f) and h) of the Complementary Technical Instruction 02.1.02 "Preventive training for the performance of the job", of the General Regulation of Basic Standards for Mining Safety".	Sectorial
Nov 18, 2010	Resolution of November 18, 2010, of the Directorate General of Energy Policy and Mines, which approves the technical specification number 2004-1-10 "Preventive training for the performance of jobs included in groups 5.4 letters a), b), c), d), e), f), g), h), j), k), l), m), and 5.5 letters a), b) and d) of section 5 of the Complementary Technical Instruction. 02.1.02 "Preventive training for the performance of the work position", of the Regulation General Basic Mining Safety Standards".	Sectorial
Nov 18, 2010	Resolution of November 18, 2010, of the General Directorate of Energy Policy and Mines, approving the technical specification number 2010-1-01 "Inspection of wheel loaders" of the complementary technical instruction 02.2.01 "Commissioning, maintenance, repair and inspection of work equipment" of the General Regulation of Basic Mining Safety Standards, approved by Order ITC/1607/2009, of June 9.	Sectorial
28-Jan-11	Royal Decree 102/2011, of January 28, 2011, on the improvement of air quality.	Atmosphere (dust and gases)
28-Jan-11	Royal Decree 100/2011, of January 28, which updates the catalog of activities potentially polluting the atmosphere and establishes the basic provisions for its application.	Atmosphere (dust and gases)
04-Feb-11	Royal Decree 139/2011, of February 4, for the development of the List of Wildlife Species under Special Protection Regime and the Spanish Catalogue of Threatened Species.	Environment
05-Apr-11	Order ITC/933/2011, of April 5, which approves the Complementary Technical Instruction 2.0.03, "protection of workers against dust in soluble sodium and potassium salt mining activities" of the General Regulations on basic mining safety standards.	Sectorial
28-Jul-11	Law 22/2011, of July 28, 2011, on waste and contaminated soils.	Waste
04-May-12	Royal Decree 777/2012, of May 4, amending Royal Decree 975/2009, of June 12, on the management of waste from extractive industries and the protection and rehabilitation of areas affected by mining activities.	Sectorial
04-May-12	Royal Decree Law 17/2012, of May 4, 2012, on urgent environmental measures.	Environment
06-Jul-12	Royal Decree 1038/2012, of July 6, amending Royal Decree 1367/2007, of October 19, which implements Law 37/2003, of November 17, 2003, on noise, with regard to acoustic zoning, quality objectives and acoustic emissions.	Atmosphere (noise and vibration)
19-Dec-12	Law 11/2012, of December 19, 2012, on urgent environmental measures.	Environment
05-Apr-13	Royal Decree 238/2013 of April 5, 2013, amending certain articles and technical instructions of the RITE, approved by RD 1027/2007 of July 20.	Air conditioning
11-Jun-13	Law 5/2013, of June 11, amending Law 16/2002, of July 1, on integrated pollution prevention and control and Law 22/2011, of July 28, on waste and contaminated soils.	Environment
06-Sep-13	Royal Decree 670/2013 of September 6, amending the Regulation of the Public Hydraulic Domain approved by Royal Decree 849/1986 of April 11, regarding water regis- tro and criteria for assessing damage to the public hydraulic domain.	Waters
01-Oct-13	Order AAA/1783/2013, of October 1, which amends Annex 1 of the Regulation for the development and execution of Law 11/1997, of April 24, 1997, on Packaging and Packaging Waste, approved by Royal Decree 782/1998, of April 30.	Waste
Oct 18, 2013	Royal Decree 815/2013, of October 18, which approves the Regulation on industrial emissions and development of Law 16/2002, of July 1, on integrated pollution prevention and control.	Environment
Dec 09, 2013	Law 21/2013, of December 9, 2013, on environmental assessment.	Environment
14-Feb-14	Royal Decree 97/2014, of February 14, regulating the transport operations of dangerous goods by road in Spanish territory.	APQ
09-May-14	Royal Decree 337/2014 of May 9, approving the Regulation on technical conditions and safety guarantees in high voltage electrical installations and its Complementary Technical Instructions ITC-RAT 01 to 23.	Industrial safety
16-Oct-14	Resolution of October 16, 2014, of the Directorate General of Energy Policy and Mines, approving the technical specification number 2005-1-11 "Worker's personal training booklet and record book of courses received" of the complementary technical instruction 02.1.02 "Preventive training for the performance of the job position", of the General Regulations of Basic Mining Safety Standards.	Sectorial

16-Oct-14	Resolution of October 16, 2014, of the Directorate General of Energy Policy and Mines, which modifies the technical specification number 2001-1-08 "Preventive training for the performance of the position of the operator of machinery for grubbing/loading/veillage, shovel loader and hydraulic chain excavator, in outdoor extractive activities", of the complementary technical instruction 02.1.02 "Preventive training for the performance of the job position", of the General Regulation of Basic Standards for Mining Safety.	Sectorial
27-Oct-14	Order AAA/2056/2014 of October 27, 2014, approving the official models for the application for authorization and declaration of discharge.	Waters
20-Feb-15	Royal Decree 110/2015, of February 20, on waste electrical and electronic equipment.	Waste
Mar 13, 15	Royal Decree 180/2015, of March 13, regulating the shipment of waste within the territory of the State.	Waste
09-Jul-15	Law 17/2015, of July 9, of the National Civil Protection System.	Emergencies
11-Sep-15	Royal Decree 817/2015, of September 11, establishing the criteria for monitoring and evaluating the status of surface waters and environmental quality standards.	Waters
21-Sep-15	Royal Decree 840/2015, of September 21, approval of measures to control the risks inherent to serious accidents.	Emergencies
12-Feb-16	Law 56/2016, of February 12, transposing Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, regarding energy audits, accreditation of service providers and energy auditors and promotion of energy supply efficiency.	Energy efficiency
08-Apr-16	Royal Decree 144/2016, of April 8, establishing the essential health and safety requirements for equipment and protective systems for use in potentially explosive atmospheres and amending Royal Decree 455/2012, of March 5, establishing measures aimed at reducing the amount of gasoline vapors emitted into the atmosphere during the refueling of motor vehicles at service stations.	Industrial safety
15-Jul-16	Royal Decree 294/2016, of July 15, establishing the procedure for the management of mining rights and hydrocarbon public domain rights affected by the change of the geodetic reference system.	Sectorial
20-Jan-17	Royal Decree 20/2017, of January 20, on end-of-life vehicles.	Waste
17-Feb-17	Royal Decree 115/2017, of February 17, which regulates the commercialization and manipu- lation of fluorinated gases and equipment based on them, as well as the certification of professionals who use them and which establishes the technical requirements for installations that develop activities that emit fluorinated gases.	Air conditioning
22-May-17	Royal Decree 513/2017, of May 22, approving the Regulation on fire protection installations.	Emergencies
23-Jun-17	Royal Decree 656/2017, of June 23, approving the Regulation on the Storage of Chemical Products and its Complementary Technical Instructions MIE APQ 0 to 10.	APQ
07-Jul-17	Royal Decree 706/2017, of July 7, approving the supplementary technical instruction MI-IP 04 "Installations for supply to vehicles" and regulating certain aspects of the regulation of oil installations.	APQ
31-Jul-17	COMMISSION ENFORCEMENT DECISION (EU) 2017/1442 of 31 July 2017 on. sets out the conclusions on best available techniques (BAT) according to Directive 2010/75/EU of the European Parliament and of the Council for large combustion plants.	MTD
14-Sep-17	Resolution of September 14, 2017, of the Directorate General of Energy Policy and Mines, approving the technical specification 2012-01-17 "Inspection of articulated frame dump trucks on wheels", of the supplementary technical instruction 02.2.01 "Commissioning, maintenance, repair and inspection of work equipment", approved by the Order ITC/1607/2009, of June 9, 2009, on the General Regulation of Basic Safety Standards Mining.	Sectorial
14-Sep-17	Resolution of September 14, 2017, of the Directorate General of Energy Policy and Mines, approving technical specification 2011-01-17 "Inspection of rigid frame dump trucks on wheels", of supplementary technical instruction 02.2.01 "Putting into service, maintenance, repair and inspection of work equipment", approved by Order ITC/1607/2009, of June 9, 2009, of the General Regulations on Basic Mining Safety Standards	Sectorial
10-Oct-17	Order APM/1007/2017, of October 10, on general rules for the recovery of excavated natural materials for use in backfilling operations and works other than those in which they were generated.	Waste
23-Oct-17	Royal Decree 920/2017, of October 23, regulating the technical inspection of vehicles.	Environment
02-Nov-17	Order PRA 1080/2017, of November 2, amending Annex I of Royal Decree 9/2005, of January 14, establishing the list of potentially soil-polluting activities and the criteria and standards for the declaration of contaminated soils.	Environment

05-Dec-18	Law 9/2018, of December 5, amending Law 21/2013, of December 9, on environmental assessment, Law 21/2015, of July 20, amending Law 43/2003, of November 21, on Forestry and Law 1/2005, of March 9, regulating the greenhouse gas emission allowance trading scheme.	Environment
25-Jan-19	Royal Decree 18/2019, of January 25, 2009 GHG Emissions Trading 2021-2030 period	Environment
06-Mar-20	Order TED/252/2020, of March 6, which modifies the Complementary Technical Instructions 02.0.01 "Optional Directors" and 02.1.01 "Health and Safety Document", and which repeals the Complementary Technical Instruction 09.0.10 "assembly, operation and maintenance personnel", of the General Regulations on Basic Mining Safety Standards.	Sectorial
26-May-20	Royal Decree 542/2020, of May 26, amending and repealing various provisions on industrial quality and safety.	Industrial safety
26-May-20	Decree 96/2020, of 29 May, approving the Regulations of Law 7/2008, of 7 July, on the protection of the Galician landscape.	Landscape
02-Jun-20	Royal Decree 553/2020, of June 2, regulating the transfer of waste within the territory of the State.	Waste
22-Dec-20	Royal Decree 1154/2020, of December 22, amending Royal Decree 665/1997, of May 12, 1997, on the protection of workers against risks related to exposure to carcinogens at work.	Atmosphere (dust and gases)
13-Apr-21	Royal Decree 265/2021, of April 13, on end-of-life vehicles and amending the General Vehicle Regulations, approved by Royal Decree 2822/1998, of December 23, 1998.	Waste

ANNEX 5

DESCRIPTION OF METALLURGICA L PROCESSES

Aluminum metallurgy[131]

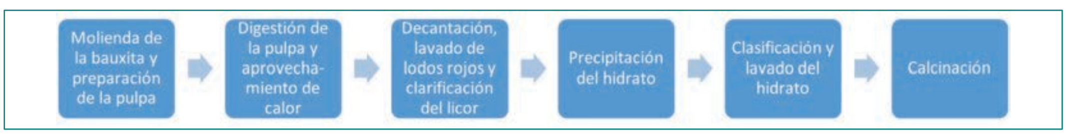
By reserves and content of $Al\ O_{23}$ the ore for obtaining aluminum is bauxite (40-50 % $Al\ O$;$_{23}$
<20 % $Fe\ O_{23}$; 3-10 % SiO_2), which is an earthy, brownish-red, brownish-gray or yellowish material. It is a mixture of aluminum hydroxides: gibbsite[132] boehmite[133] and diaspore[134] ; along with other minerals such as clays, silica, free quartz, hydroxides and oxides of iron and rutile (TiO).$_2$

Currently, aluminum is produced by the Bayer and Hall-Hérault tandem processes. In the former, alumina ($Al\ O_{23}$) is obtained from bauxite, and in the latter, aluminum metal is obtained from alumina by igneous electrolysis. From 4 kg of bauxite, the Bayer process yields 2 kg of alumina, from which 1 kg of aluminum is obtained .[135]

Bayer Process

Patented in 1889 by K. J. Bayer, like all hydrometallurgical processes, the Bayer process is cyclic and is not unique; there are as many as there are aluminum ores. However, broadly speaking, two types can be defined. On the one hand, there is the low-temperature or American Bayer process, which treats bauxites of a gibbsite nature. The high-temperature or European Bayer process treats bauxites with a high monohydrate content, of the boehmite type. Figure 91 shows a flow diagram with the basic stages of the process.

Figure 91. *Stages of the Bayer process. Source: authors' own elaboration.*



(i) Milling and preparation. Once the bauxite is received, it is stored in stockpiles for homogenization. The bauxite with low water content is crushed (<1 cm) and then passed to the ball and rod mills where wet milling is carried out (with the spent or lean liquor from the precipitation stage), obtaining a pulp, which is ground to sizes of 300 µm-2 mm. This pulp is taken to holding tanks where it is homogenized and kept hot and in suspension by injecting steam. At this stage, soluble silica (Si <1.5%) is removed. It is then sent to digestion.

(ii) Digestion. In the digestion process the pulp is attacked with the lean liquor from precipitation, adjusting the soda content so that an alumina/caustic ratio of 0.68-0.70 g $Al\ O_{23}$ / g $Na_2\ CO_3$ is obtained at the outlet. The temperature and pressure of the process is determined by the type of bauxite and the digestion times vary depending on the silica content. The reaction that takes place can be represented as follows:

$$Al\ O_{23}\ .nH_2\ O\ (s) + 2NaOH\ (ac) \rightarrow 2NaAlO_2\ + (n+1)H\ O_2$$

In this way, the alumina is put into solution, leaving as a solid residue most of the impurities that accompany the bauxite (mainly iron and titanium oxides).

[131] This section generally follows Sancho et al. (1994).

[132] Aluminum trihydrate, $Al(OH)_3$, 34.6 % average aluminum content.

[133] Aluminum monohydrate, $\gamma\text{-}AlO$(OH), 45 % average aluminum content.

[134] Aluminum monohydrate, $\alpha\text{-}AlO$(OH), 45 % average aluminum content.

[135] Aluminum production in integrated plants (production of alumina, aluminum and pre-transformation) tries to meet the following requirements, which are difficult to meet all at once: (i) short distance to bauxite mines, (ii) short electrolysis/smelting distance, (iii) (iii) proximity to abundant fuel and electricity, with security of supply and at a competitive price, (iv) proximity to r e a g e n t s (soda, etc.), (v) cheap labor, (vi) adequate infrastructure, and (vii) high-capacity seaports.

The liquor leaving the digesters goes through several stages of decompression and heat recovery in heat exchangers[136] . When the digested and evaporated pulp reaches 100 °C it is transferred to sludge separation (settling).

(iii) Decanting. The pulp from digestion is subjected to separation of the sands, silts and sludges it contains. The sands can be separated in a hydrocyclone type classifier and, once washed, can be used later for certain types of filters. The finer silts are settled in decanters with the aid of synthetic flocculants in small quantities (a few grams per ton of mud). The decanted sludge (25% solids) is pumped to the sludge washing circuit. It works countercurrent, leaving a red sludge that is sent to the red sludge reservoir (where it is consolidated with additives).

(iv) Clarification. After decanting, the remaining or floating liquor, which still contains solids, is sent to a tank for clarification. Clarification is carried out by means of filters. After passing through the sand filters, the pulp is practically free of solids and clarified.

(v) Hydrate precipitation. This is a key stage of the process in which alumina is precipitated from solution[137] . Precipitation is carried out by cooling and dilution. Despite lowering the temperature of the liquor to 75 °C, it is difficult for spontaneous precipitation to occur, so it must be encouraged by seeding the hydrate crystals, thus obtaining the desired grain size. The precipitating hydrate is the trihydrate ($Al\ O_{23}\ .3H_2\ O$). The precipitated product is called hydrargyrite, bayerite or gibbsite.

Equilibration of the reaction takes a long time, and the yield will depend on the operating conditions. One should aim for (i) the highest amount of coarse-grained hydrate, (ii) the highest hydrate yield and (iii) a suitable grain texture.

Precipitation can be carried out discontinuously, in a single step or in a double step. To precipitate in a single step, the coarse and fine germs are added together, the coarse precipitates being separated in the primary classifier, which are dried and calcined. Double-pass precipitation involves two types of germ, coarse and fine. The coarse germ is used to nucleate the final product, while the fine germ is used to produce coarse germ.

The tendency is to precipitation continues using numerous tanks (12-16) through which the liquor circulates. In the head tanks (70 °C) the fine germ is added and in the intermediate ones (50 °C) the coarse germ, being favored in the first precipitators the agglomeration, by means of a high temperature (70 ºC), and obtaining the two thirds of precipitated hydrate. In the intermediate and final precipitators the temperature drops to 50 °C, which leads to an increase in yield.

(vi) Classification and washing. The hydrate is classified in the sedimentation tanks according to increasing diameters: coarse (product to the calciner), medium (coarse germ nuclei) and fine (fine germ). The coarse germ is washed to eliminate the liquor it carries. Filtering and washing are carried out, resulting in a cake containing 10-15% water, which is sent to the last stage of calcination.

(vii) Calcination. The trihydrate, once separated, is dried and calcined in a rotary kiln or in a kiln of

[136] The low thermal costs of the Bayer process today are due, in large part, to the convenient design of the hot pulp heat recovery units for heating the return liquors.

[137] The reaction is as follows: $2NaAlO_2\ (ac) + 4H_2\ O \rightarrow Al\ O_{23}\ .3H_2\ O\ (s) + 2NaOH\ (ac)$.

fluidized bed. Drying is done using the hot gases from the calciner. Then it is sent to a furnace where it is calcined at 900- 1,200 °C obtaining alumina ($Al\ O_{23}$) according to the reaction: $Al\ O_{23}.3H_2O \rightarrow Al\ O_{23} + 3H_2O$; obtaining the product that will feed the electrolysis tanks.

Hall Hérault Process

The method used worldwide in the production of aluminum is the Hall Hérault process (patented at the end of the 19th century in the USA and France simultaneously). It is a process of igneous electrolysis of alumina in a bath of molten cryolite ($3NaF.AlF_3$), which is the ionic medium in which the igneous or molten salt electrolysis is to take place (aluminum cannot be obtained by electrolysis of an aqueous solution of a salt because the normal reduction potential of aluminum is lower than that of hydrogen. Thus, the aqueous solution containing Al^{3+} and H^+ ions, when electrolyzed, the H^+ ions are discharged at the cathode, instead of the Al^{3+} ions, which remain in solution, releasing hydrogen) .[138]

If two electrodes are introduced into the bath and a potential difference is applied, which exceeds the decomposition voltage, the polarizations at the electrodes and the ohmic drops, a series of reactions occur at both the cathode and the anode which constitute the electrolysis process. The approach of the anodes to the cathode forms the electric arc that keeps the bath of solids molten at 1,010 ºC and allows the aluminum to migrate towards the cathode at the bottom of the tank.

Electrolysis is a continuous process[139] , and continuous feeding systems have been developed for both Söderberg and precooked tanks. The feed is discontinuous at hourly intervals in between. Part of the alumina is dissolved and some is deposited on the slope and the cathode or crucible of the vat from where it is progressively dissolved. Periodically, at least once a day, the alumina supply is interrupted until the so-called "anodic or packing effect" occurs, which consists of an increase in the voltage (anode/o potential difference) of the electrolysis cell, indicating that the alumina dissolved in the electrolyte reaches a lower percentage than necessary. After breaking the anodic polarization layer, formed by decomposition of the fluoride salts that make up the electrolyte, by mechanical means (gas bubbling), the alumina supply and the electrolysis process are resumed.

The elementary unit of the aluminum production process is the electrolytic tank. The vat consists of three parts: cathode[140] , anode[141] and electrolyte.

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[138] Aluminum fluoride, calcium fluoride and lithium carbonate are also added in order to satisfy properties such as: good solubility of alumina, solidification temperature as low as possible, lower density than liquid aluminum (which allows to physically separate the electrolyte from the metal, maximum density difference), good electrical conductivity to minimize ohmic losses, low solubility of aluminum, good thermodynamic stability, low viscosity (an increase in viscosity decreases the diffusion and transport of aluminum to the cathode) and low price. For example, LiF and MgF_2 reduce the melting temperature of pure cryolite, but decrease the solubility of the electrolyte.

[139] The current efficiency (or Faraday efficiency), which is defined as the ratio between the weight of aluminum actually produced and that which should be produced according to Faraday's laws, is industrially in the range of 84-94 %, which depends on temperature, current density, interpolar distance, electrolyte composition and tank design. The main mechanism of current yield loss is the redissolution of aluminum in the electrolyte and its subsequent reoxidation with the anode gases.

[140] The horizontal cathode is made of carbon and consists of preformed blocks, joined to each other and to the lateral lining by means of the so-called jointing paste, also made of carbon. In their lower part, the carbon blocks are attached, either by casting or by carbon paste, to steel current collector bars. Above the blocks is the liquid aluminum "pool", which is therefore negatively polarized and whose surface constitutes the so-called effective cathodic surface. It is the vessel containing the metal and the molten bath at a temperature of 950 ºC where the cathodic reaction takes place. Its mission is to be a conductor for the electronic contribution to the cathodic reaction and, at the same time, to be a furnace resistant to aluminum and cryolite-based molten salts.
In the cathodic reaction the aluminum cation is found forming negatively charged Al-O-F type complexes. Na+ is present as a free cation. Since the aluminum is not free, but forms complexes, it must be these that participate in the cathodic reaction: $2AlF^{3-} + 6Na^+ + 6e^- \rightarrow 2Al + 6(Na^+, F^-) + 6F^-$. The excess of F^- ions shifts the equilibrium to the left, so that the reaction total is written as: $AlF_6^{3-} \leftrightarrow AlF_4^- + 2F^-$; and $3AlF_4^- + 6Na^+ + 6e^- \leftrightarrow 2Al + 6(Na^+, F^-) + 2AlF_6^{3-}$

[141] The anode, also made of carbon, is suspended at a short distance from the surface of the liquid aluminum. The distance between both electrodes is 4-5 cm (interpolar distance), with electrical continuity due to the presence of the molten salt electrolyte (mainly cryolite).

There are two types of anodes (Figure 92): (i) precooked tanks: made up of several individual anodes that are manufactured in an area other than the electrolysis area and are already coked, hence the name precooked (the only thing to be done is to replace a worn anode with a new one); and (ii) precooked tanks: made up of several individual anodes that are manufactured in an area other than the electrolysis area and are already coked, hence the name precooked (the only thing to be done is to replace a worn anode with a new one).
(ii) Söderberg vats: the anode is formed by auto-firing in the vat itself. Coke and pitch pellets are added inside an enclosure enclosed by a metal shell. It is the temperature of the process itself that causes the melting, partial distillation of the pitch and firing of the paste, forming the fired anode. The current input is produced by means of steel conductors known as needles that are inserted into the paste.

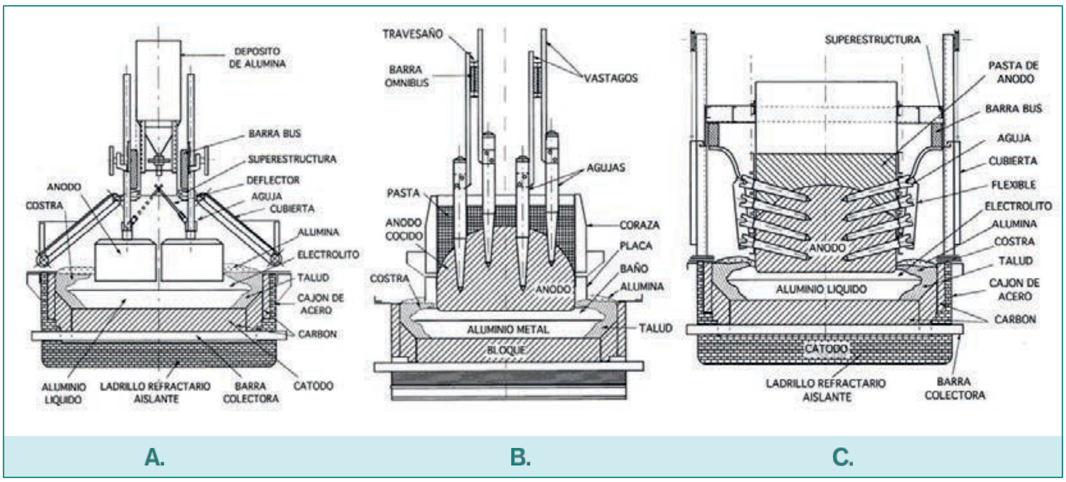


Figure 92. *Types of anodes:* ***A.*** *prebaked* ***B.*** *Söderberg: vertical needles* ***C.*** *Söderberg: horizontal needles. Source: (Sancho et al., 1994).*

Anodes burn out and need to be replaced frequently, so aluminum plants also have an anode factory.

The alumina is dissolved in the electrolyte by periodically breaking the crust by means of pneumatic hammers or cylinder-driven blades. Continuous feeding or spot crushing is also possible.

The aluminum produced is deposited on the cathode because it has a higher density than the bath. The metal height is based on the thermal equilibrium and magnetohydrodynamics of the system, and is maintained stable with periodic extractions of the metal. The overheating of the aluminum with respect to its melting temperature (on the order of 300 °C) ensures that it remains liquid until it is transported to the smelter.

The aluminum metal obtained in the electrolysis tanks must be removed every 24 hours. The casting is carried out by siphoning each vat. The metal is loaded into a common "ladle" which is taken to the melting shop, whose function is to treat and solidify the metal in the best conditions to obtain a semi-finished ingot or a clean, homogeneous ingot, with the right composition and format.

The first phase is skimming, i.e. the removal of impurities and alumina that rise to the surface of the metal in the ladle. The next is to degas the hydrogen (present in the molten metal due to the reaction of aluminum at high temperatures with humidity and ambient gases). This hydrogen dissolves in the metal and its solubility decreases with temperature.

In the anodic reaction there must be sufficient concentration of alumina in the electrolyte (2 % for industrial current densities of 0.7 A-cm²). The only oxygen-containing ionic species is the Al ion $_2OF_{2x}^{4-2x}$, which is the only one undergoing the anodic reaction. The overall anodic reaction for x= 3 is as follows: $3Al_2OF_6^{2-} + 6F^- \rightarrow 3O + 6AlF_4^- + 6e^-$. From the above reaction 3 AlF_4^- are employed in the. cathodic reaction and the other 3 react with the $6F^-$ from the cathodic reaction to give: $3AlF_4^- + 6F^- \rightarrow 3AlF_6^3$ The $3AlF^{3-4}$ from the last reaction bind to another AlF_6^{3-} from the cathodic reaction to give in the presence of alumina: $4AlF_6^{3-} + Al_2O_3 \rightarrow 3Al2OF_6^{2-} + 6F^-$. The oxygen released is combines with carbon from the anode to generate carbon dioxide. The overall reaction is as follows: $Al\,O_{23} + (3/2)C \rightarrow 2Al + (3/2)CO_2$

giving bad properties to the finished metal, making it brittle and oxidizing elements in solution such as sodium and cleaning solid impurities present in the broth.

Particles or inclusions can produce defects or cause problems, both in products and in processes, such as poor surface finish, defects in bright aluminum, internal porosity, difficult machinability, etc. The incorporated particles can be of different nature, oxidation products (alumina and other oxides), or others such as pieces of refractory material or slag. Inclusions can be removed by furnaces at high temperatures, but filtering is the best way to obtain a fine cast product. The filters are ceramics (silicon carbide) that act either by creating a layer of retained particles over the casting time, which makes the filter finer, or by retaining the particles in the filter itself.

Prior to casting, a series of alloying agents, modifiers and refining agents are added to improve the properties of the final product. Two types of properties are sought: properties necessary for the final product (strength, thermal and electrical conductivity, hardness, corrosion resistance, fracture toughness, etc.) and properties necessary for manufacturing (ductility, castability, volumetric shrinkage (shrinkage) or cracking). Figure 93 shows a summary picture of aluminum metallurgy.

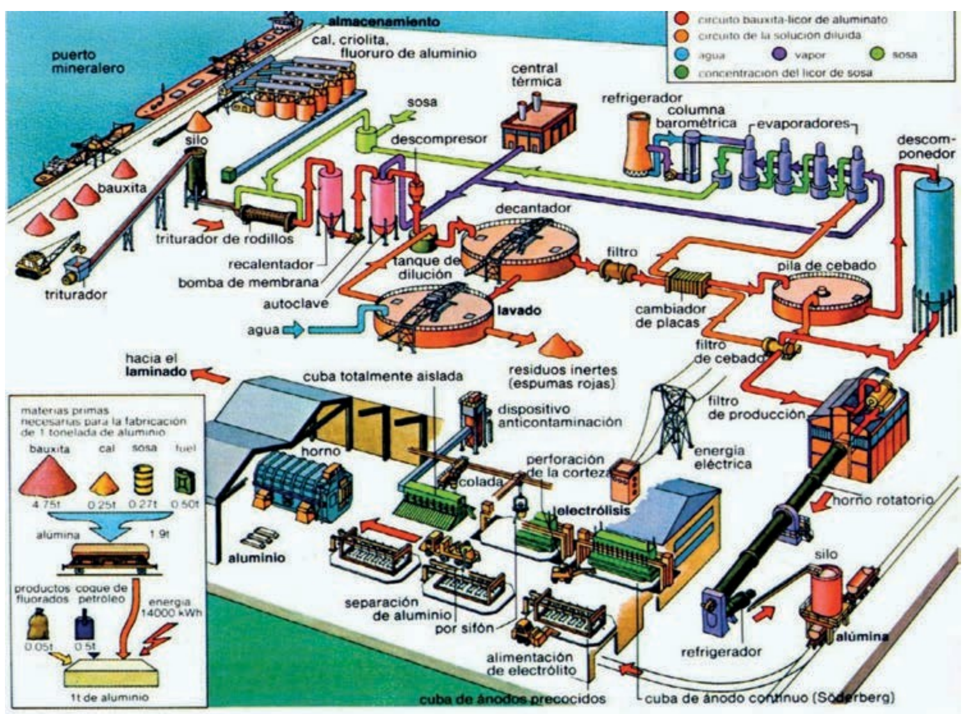


Figure 93. *Aluminum metallurgy. Source: (Aquilar, n.d.).*

Cobalt metallurgy

The essential cobalt production operations are performed according to the following routes: (i) cobalt production in the processing of ores containing copper or nickel, (ii) concentration of cobalt-containing material during hydrometallurgical or pyrometallurgical treatments of copper or nickel, (iii) purification of solutions by liquid separation techniques such as selective precipitation, solvent extraction, ion exchangers, and (iv) cobalt production.

cobalt powder, cobalt precipitated by independent processes such as electrorefining, electrowinning or reductions/precipitations.

The following is a brief description of the process of obtaining cobalt metal from cobalt-copper sulfide ores (carrolite ore, $Co_2\,CuS_4$ and chalcocite, $Cu_2\,S$), which are being exploited in several mines in the Democratic Republic of Congo and Zambia. Cobalt metallurgy has both pyrometallurgical and hydrometallurgical processes. The stages are shown in Figure 94.

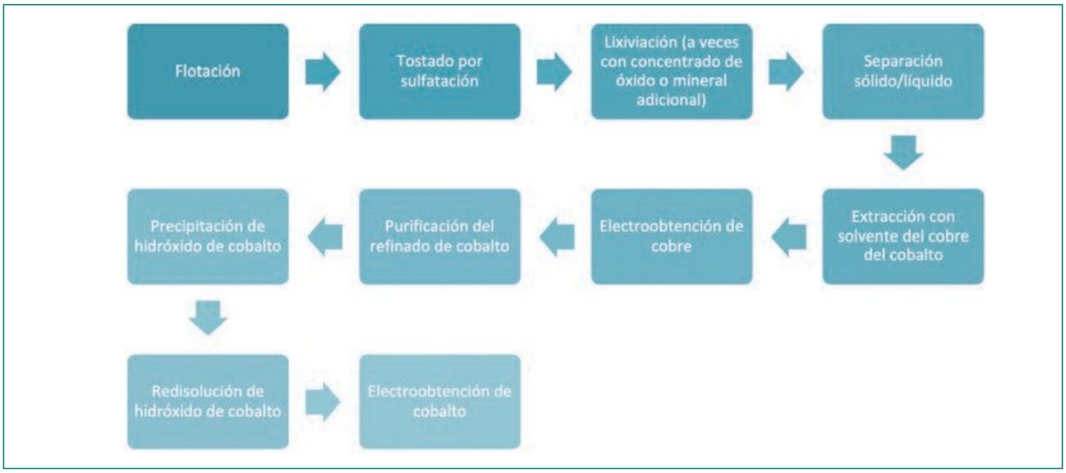


Figure 94. *Phases of cobalt metallurgy. Source: authors' own elaboration.*

Figure 95 provides a flow diagram for a typical process for the production of high purity cobalt from a cobalt-copper sulfide concentrate according to the cited source. The concentrate roasting process is aimed at obtaining a soluble sulfate calcinate, rather than insoluble oxides, for which the temperature chosen in the fluidized bed roasting furnace is 695-705 ºC. About 90% of the sulfides are oxidized to soluble sulfates instead of oxides .[142]

The sulfate calcine is cooled from 700 ºC to 75 ºC and sent to the cobalt-copper leaching plant, which works with open air agitated Pachuca tanks, using as leaching agent copper solvent extraction refining (approximately) ~30 g $H_2\,SO_4$ /l + fresh sulfuric acid (obtained from the roasting gas) .[143]

The product obtained is a sulfate solution containing ~22 g l/Cu , 7 g Co/l and <50 ppm solids (after sedimentation, filtration and clarification), which is sent to the solvent extraction stage, where the Cu^{2+} is separated from the Co^{2+} . The residue formed by the undissolved calcine is sent for washing and final disposal.

For the precipitation of high purity cobalt hydroxide, $Co(OH)_2$, the starting solution is the refining from solvent extraction (~7 g Co/l) (about 30 % of the refining stream, the rest goes back to the calcining leaching stage).

Prior to hydroxide precipitation, "impurities" such as copper are removed,

[142] The process is controlled by the O content$_2$ of the inlet gas (30 % by volume of O_2 , 70 % by volume of N_2 (oxygen enriched air)) and the amount of $H_2\,O$ in the feed suspension.

[143] The pH is maintained below 1.5, which is achieved by adding fresh sulfuric acid as needed.

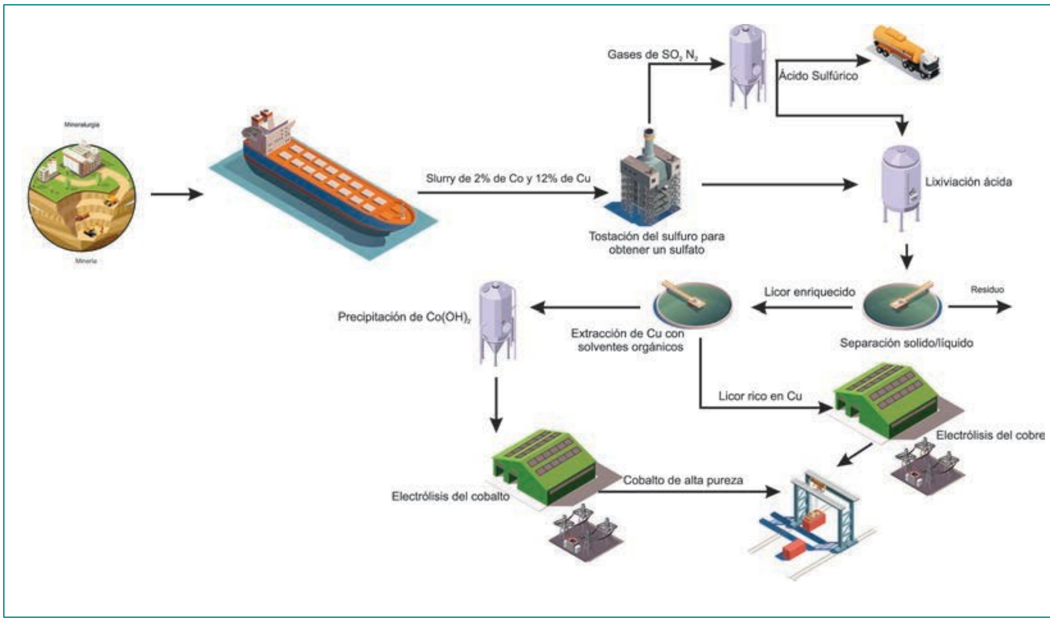


Figure 95. Production of high purity cobalt from sulfide concentrate. cobalt-copper. Source: authors' own elaboration.

zinc and iron (purification of cobalt-rich refining)[144] . Once the impurities have been removed, precipitation of the cobalt hydroxide takes place by raising the pH to 8.8 with quicklime.

Before proceeding to obtain cobalt by electrolysis, it is necessary to prepare the electrolyte using as starting materials the high purity $Co(OH)_2$ prepared as described above and the spent electrolyte recycled from the cobalt electrolysis process itself. The procedure is to dissolve the $Co(OH)_2$ in the spent electrolyte, adding sulfuric acid to control the pH to be between 6.2 and 6.5 (to avoid dissolving the Zn(OH)).$_2$

Clarifiers and filters are used to remove undissolved solids. The removal of soluble sulphides and entrained organic matter is done by passing the filtered solution through carbon columns. For the elimination of nickel, 20 % of the solution is recycled through an ion exchange column. Finally, the product obtained is the cobalt sulfate electrolyte (>20 g Co/l).

High purity cobalt metal (99.65-99.7 % Co) is obtained from the electrolyte by the electrolysis process[145] . Cobalt recovery from concentrate to metal is approximately 62 %. The cathodes are crushed into 0.02 m - 0.04 m flakes in a roller crusher. To obtain pure cobalt metal, hydrogen gas is removed by vacuum degassing at 800-840 °C in electric furnaces of ~1 m diameter and 7 m height.

As discussed, cobalt can also be obtained as a by-product of nickel metallurgy *from sulfide and laterite deposits .*[146]

[144] Copper is removed by secondary solvent extraction with LIX 984N, iron and residual copper by raising the pH to 3.5 with limestone and quicklime. Zinc removal is carried out by recycling 30% of the solution through a Zn solvent extraction plant (using D2EHPA). The final iron removal takes place by raising the pH to 6.7.

[145] The anodes of the electrolysis tanks have dimensions of 1mx1m and are made from an alloy with a composition of 94% Pb, 6% Sb. The cathodes, which have the same dimensions as the anodes, are made of 316L stainless steel. The applied voltage is 4-4.5 V and the current density is 300 A/m² cathode surface area.

[146] For more details see Crundwell et al. (2011).

Uranium metallurgy

Uranium is a gray-colored metallic chemical element of the actinide series and is about 500 times more abundant than gold in the earth's crust. Its most important use is as fuel in nuclear reactors to generate electricity .[147]

To use uranium as nuclear fuel, the ore must undergo a series of physico-chemical processes, since it is necessary to increase the proportion of the U-235 isotope, the only fissile isotope, from the 0.7% found in nature to between 3 and 5%. This process is called enrichment.

After the exploration stage, open pit or subway mining and ore treatment, in which through physical-chemical processes the uranium concentrate U O_{38} , known as *yellow cake*, is obtained from natural uranium, comes the first conversion stage, in which the uranium concentrate is transformed into gaseous UF_6 in order to move on to the next stage of enrichment, which is carried out by diffusion or centrifugation and consists of increasing the proportion of the U-235 isotope from 0.7%, where it is found in nature, to a maximum of 5%.

Once enrichment has been completed, the second conversion stage begins to convert the uranium in its gaseous state to a solid state, specifically in the form of uranium dioxide powder, UO_2 . This is followed by the fuel assembly manufacturing stage, which is the only stage carried out in Spain at the Juzbado mill (Salamanca).

From the UO powder$_2$ by pressing and sintering, ceramic pellets of cylindrical shape of about 8 mm in diameter and 10 mm in height are obtained, which are inserted into tubular sheaths, with an inter-diameter of not slightly more than 8 mm and a length of about 4 m, made of a special zirconium alloy called zircalloy. The rods are grouped into rigid parallelepiped structures forming the fuel element. Their main function is to keep the rods at an appropriate distance for the coolant to circulate between them and receive the heat generated in the nuclear fission chain reaction. Figure 96 shows the first part of the cycle: from nature to the reactor, with the different stages of the transformation of the ore into nuclear fuel.

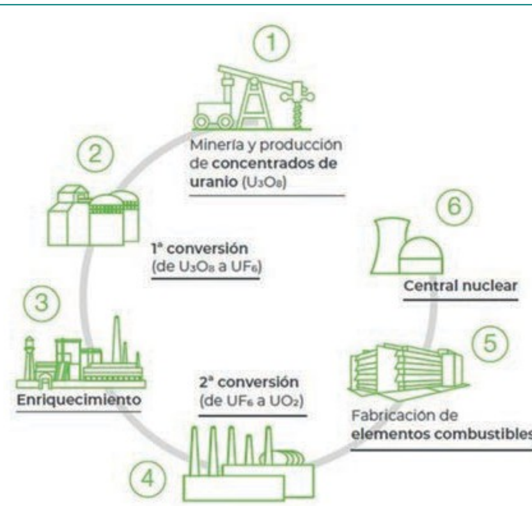


Figure 96. *First part of the cycle: from nature to the reactor. Source: (Nuclear Forum, 2020).*

[147] According to the Nuclear Energy Agency (2020), there are more than 6.14 million tons of recoverable resources identified at prices below \$130/kgU and more than 8 million tons at prices below \$260/kgU. Spain has the largest uranium reserves in the EU, with the capacity to cover its national demand.

Once the fuel has been in operation for three operating cycles (about 5 years) it still contains 95 % of the enriched U-235; 1 % is plutonium and the rest is minor actinides, long-lived and short-lived radioactive products and stable fission products. If the reuse of the remaining U-235 and the Pu-239 generated is considered, the fuel is reprocessed or recycled for use in other types of nuclear power plants, since it retains more than 90% of its initial energy capacity.

The reprocessed fuel is known as MOX (short for Mixed Oxide) and consists of a mixture of natural uranium oxide, reprocessed uranium and plutonium oxide. This operation separates these two elements from the fission products, which constitute the high-level waste. This option, in which the fuel is reused, is known as a closed cycle. If it is decided not to reuse the energy resources contained in the irradiated fuel, it is managed as high-level radioactive waste, since the fission products are confined in it. After an initial stay in the pool of the nuclear power plant itself, it will be initially deposited in an Individualized Temporary Storage (ITS) in dry storage and later, in principle, in a Centralized Temporary Storage (CTS). The final destination of the irradiated fuel is its final isolation in a Deep Geological Storage (AGP). This option is known as open cycle.

GLOSSAR
Y OF TERMS

Alloy: is the mixture of a pure parent metal with other elements to improve the physical and mechanical properties of the parent metal. By varying the composition of alloys, a range of different properties can be achieved for a wide range of applications. Steel and other ferrous alloys are the most widely consumed due to their wide range of properties, ease of production and cost of manufacture. Another example is metallic copper with small amounts of beryllium, which greatly increases hardness and strength.

Algorithm (*algorithm*): An algorithm is a *software* procedure, i.e., a set of instructions designed to perform a specific task. Since there may be more than one path to complete a task, any algorithm can be modified over time to improve its performance, efficiency or accuracy.

Automation: In the industrial field, automation is the use of computerized and electromechanical systems or elements to control machinery or industrial processes.

Big data: all those methods and technologies that refer to the acquisition, storage and processing of data that, due to volume, frequency or typology, require to be treated in a non-conventional way. It implements mechanisms for the optimization of data capture, storage, search, sharing, analysis and visualization.

Biometallurgy is the branch of biotechnology that studies the applications and economic potential between the world of metal-rich minerals and the world of bacteria. It encompasses relatively simple but multidisciplinary processes that enable the extraction, separation, purification and recovery of critical metals in an economical and sustainable manner.

Brownfield: *Brownfield* exploration projects focus on deposits adjacent to an existing mining project. There is usually geological data available on these deposits so that the investment risk in the project is much lower than in *greenfield* exploration.

Calcination: process that aims to decompose a compound (carbonate, sulfate, hydroxide, etc.) into its forming oxides, in order to eliminate any volatile substances it may contain, using heat.

Capex (*Capital expeditures*): expenses incurred by a company for the acquisition of assets intended to remain in the company for more than one year.

Cybersecurity: set of security practices, processes and technologies applied to digital transformation to manage risk. It enables the protection of infrastructures, systems and applications, devices and the transmission of information, preventing access to systems by unauthorized persons, ensuring the availability of resources and information and guaranteeing data integrity. Cybersecurity is necessary for the use, processing, storage and transmission of information in organizations and industrial infrastructures. The evolution of systems (from physical to *cloud*) exposes companies to greater threats, with attacks becoming more frequent, especially in industry, and with a higher level of professionalization.

Clark* or *Clark-(Clarke) Number: is the average abundance of a chemical element in the earth's crust. The term is applied to specific values or average values.

Cloud: The *cloud* is a virtual space for processing and storing data and *software* in geographically distributed data processing centers that are agnostic to the user, who only sees an access interface from his control terminal.

Cloud computing: is the provision of *hardware* and *software* resources, in the form of predefined or parameterized services, over the network, in real time and with the possibility of simultaneous connectivity of users. The services provided range from storage, data computing, accessibility and application building from the *hardware* side, to end-application services. Depending on the level of utility of the *cloud* service, there are infrastructures, platforms or *software* as a service (IaaS, PaaS, SaaS).

CNAE: acronym for National Classification of Economic Activities. It allows the classification and grouping of production units according to the activity they carry out for the purpose of preparing statistics.

Concentrate: final product obtained in mineralurgical processing plants in which the solid all-one ore extracted from the mine is treated in order to separate the ore minerals from the gangue and concentrate the valuable metallic component(s) from the ore.

Connectivity: the ability of a device (personal computer, PDA peripheral, cell phone, robot, household appliance, automobile, etc.) to be connected, generally to a personal computer or other electronic device, without the need for a computer, i.e. autonomously. It is also the degree of connection between social, governmental and educational entities. Connectivity allows information to be transmitted securely, through fixed or mobile communications infrastructures, at any time (permanently and in real time) and in any place (ubiquitously).

Connected factory*:** smart or connected ***factories are made up of a network of connected devices that offer new dynamic ways to detect aspects of demand, reconfigure supply chains and redesign manufacturing processes in a real-time flow of information that affects any element of the value chain, blurring the boundaries between demand, design, manufacturing and supply.

Mineral deposit or deposit: part of the earth's crust in which, due to the action of geological and geochemical processes, an abnormal accumulation of a mineral raw material has occurred, which, due to its characteristics of quantity, quality and conditions, has the potential to be extracted for economic benefit.

McKelvey diagram: is a diagram used to differentiate between resources and reserves and the differences that may exist between them. The parameters used to differentiate between them are the degree of certainty and the profitability of the deposit.

Drone: is an unmanned aircraft or flying robot, controlled by remote control. They usually incorporate cameras or sensors to capture images or data from a specific place or facility.

Electrofining or electrolytic refining: Electrolytic refining is similar to the electrolysis process and is used for the production of very high purity metals. The metal to be refined forms the anode; the cathode consists of a thin film of the pure metal and the electrolyte consists of a solution of a salt of the metal. When electric current passes through the electrolyte, the anode decreases in weight in the same proportion as the cathode increases, while the solution remains unchanged.

Electrowinning: process that consists of recovering the metal from a properly conditioned leaching solution (electrolyte) and depositing it on a cathode, using an electrolysis process.

For this purpose, a low intensity direct electric current is circulated through the solution. Electrowinning is a process of great economic importance, since it allows the recovery of metals such as copper, zinc, gold and silver from leachable resources that would otherwise be unviable.

Electrolysis of molten salts: process that aims to obtain a metal from one of its compounds dissolved in a molten electrolyte and using the passage of electric current through the solution, the metal ions are reduced. For example, it is used to obtain aluminum by electrolysis of alumina dissolved in a bath of molten cryolite ($Na_3\,AlF_6$, sodium hexafluoroaluminate).

Electrometallurgy: branch of metallurgy in which the deposition of a given element is obtained from a solution (aqueous or molten salts) containing it, through the application of an electric current (electrolysis).

Chemical element: each of the fundamental forms of matter. It always appears as atoms (the smallest particle into which an element can be divided without losing its properties) of one and the same type and which, therefore, cannot be broken down into simpler substances by means of chemical reactions.

Tailings: rocks that are extracted in mining operations but do not contain ore or contain ore in quantities below the cut-off grade, and whose final destination is the mine waste dumps.
It also refers to the residues from mineral processing plants (tailings, tailings or *tailings*).

Mining or mining: process or set of processes by which a natural earth material is extracted from which an economic benefit can be obtained: it can range from water to diamonds, for example. It is carried out by means of wells (in the case of water or oil and gas, among others) or mines (subway or open pit).

Concentration Factor (CF): is the degree of enrichment that an element has to present with respect to its normal concentration in the earth's crust (Clark) to be exploitable, that is to say, the degree of enrichment that an element has to present with respect to its normal concentration in the earth's crust (Clark) to be exploitable, that is to say:

$$FC = \frac{Cutting\ \ Law}{Clark}$$

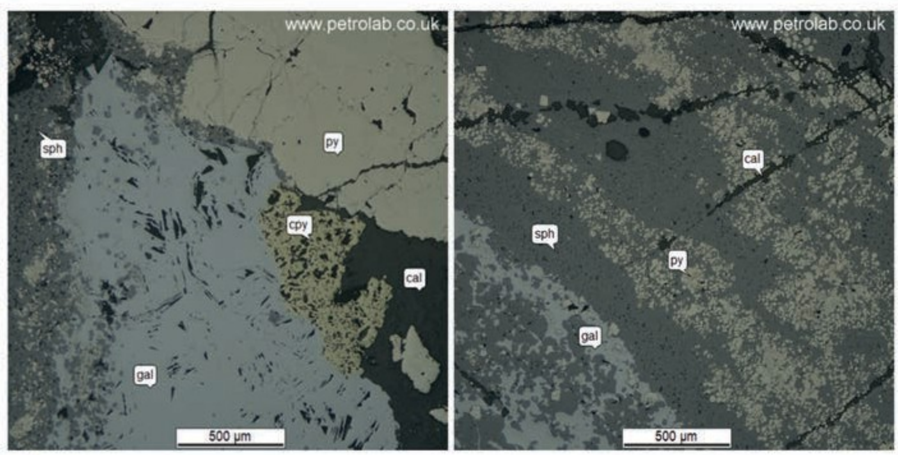
Thus, for example, gold is found in the crustal rocks at an average or Clark ratio of 0.004 ppm, while in the deposits of the Witwatersrand Basin (South African Republic) its cut-off grade is 7 g/t (1,750 times higher).

***Modifying factors*:** are considerations used to convert Mineral Resources into Mineral Reserves. These include, but are not limited to, mining, processing, metallurgical, infrastructure, economic, marketing, legal, environmental, social and governance ("ESG") and regulatory factors (PERC asbl, 2021).

Melting: operation in which, in a suitable furnace working at the required temperature, several molten materials are obtained: metal, slag or matte. It is one of the most widely used operations in extractive metallurgy. For example, it is used to obtain pig iron or dirty iron in the blast furnace (reductive smelting) or as a preliminary step in obtaining copper (neutral smelting: matte smelting). The slag is formed by reacting the gangue contained in the ore with a flux (acid or basic) that is added to the process for this purpose.

Gangue: the concept of gangue is associated with that of ore or ore minerals. Gangue minerals are those minerals that accompany the ore, but have no economic value. Gangue minerals may surround or be finely mixed with the ore minerals and are mainly represented by silicates, carbonates, fluorides, sulfides, etc. For a particular ore body, the concentration of ore minerals in the gangue and the potential for their separation from the gangue determine the economic viability of mining that ore body. It should be noted that minerals considered as gangue at certain times have been transformed into ores when some new application was found for them.

Ore minerals are separated from gangue minerals by mineralurgy processes, by means of which concentrates of the element or elements of interest are obtained. Figure 97 shows an example of the ore and gangue minerals at the San Dionisio deposit (Minas de Riotinto, Huelva).



Microphotographs of the mineralization of the San Dionisio deposit (Minas de Riotinto, Huelva). showing massive galena (gal) together with sphalerite (sph) and chalcopyrite (sph). (cpy) associated minerals representing Pb and Zn ores, and Cu, together with minority calcite (lime) and pyrite (py) as gangue. Source: Microphotographs courtesy of Atalaya Mining SLU.

Geophysics*:* science that studies the physical properties of the Earth. Geophysical prospecting methods are based on a set of non-destructive techniques that allow studying the subsurface to certain depths. These methods study the variations and distribution in depth of the physical properties of the Earth's materials and have traditionally been used for the exploration of materials of economic interest such as water, metals or hydrocarbons.

Geomechanics: science that studies the mechanical behavior of geological materials in response to changes in stress, pressure, temperature and other environmental parameters. In this field, its focus of study is the relationship between stress and deformation, whether elastic, plastic or rupture, and its consequences at each stage of the development cycle of a reservoir, from exploration to abandonment.

Geochemistry*:* science that studies the origin, distribution and evolution of chemical elements (and their isotopes) in the Earth, contained in rock-forming minerals and products derived from them, as well as in living things, water and the atmosphere. Geochemical prospecting is the application of geochemical and biogeochemical principles and data to detect economic mineral, oil and gas deposits.

GPS *(Global Positioning System)*. It is a system that allows locating any object (a person, a vehicle, etc.) on Earth with an accuracy of up to centimeters (if differential GPS is used), although a few meters are common.

***Greenfield*:** basic type exploration in still virgin areas. It focuses on the discovery of new mineral deposits in areas not previously explored and without previous discoveries, but which show favorable geological conditions. In some cases they are subdivided into: (i) *grassroot* exploration projects: these are very incipient exploration projects in which a conceptual idea of the deposit is developed based on indications and investment is made to verify if it is true (these are very high risk projects and the activities usually undertaken are geological, geophysical and geochemical surveys aimed at determining possible targets for drilling) and (ii) advanced exploration projects, which are those exploration projects in which a resource has already been defined with reasonable expectations of being economically viable in the future.

Hydrometallurgy: branch of extractive metallurgy that deals with those processes that use water (aqueous phase reactions) or acidic or basic solvents to selectively extract metals from the minerals that contain them and that work at low temperatures.

Industry 4.0: refers to the fourth industrial revolution, which is based on the real-time availability of all product-relevant information provided by a network accessible to the value chain, as well as the ability to vary the optimal value stream at any time.
This is achieved through digitization and the union of all productive units of an economy. This requires the fusion of technologies such as Internet of Things (IoT), computing and *cloud, big data* and cybersecurity, as well as complementary ones: mobile, *analytics*, M2M, 3D printing, robotics and community/sharing. In short, it is the application of new technological paradigms to digitized industry for its interconnection and the creation of smart factories through the introduction of IoT concepts.

***Public reports*:** technical documents prepared for the purpose of informing investors or potential investors and their professional advisors of exploration results (including exploration targets), resources or mineral reserves. They include, among others, annual and quarterly company reports, press releases, information memoranda, technical papers, website postings and public presentations (PERC asbl, 2021).

***Artificial Intelligence (*AI):** In computer science, AI is the set of systems or combination of algorithms intended to create machines that mimic human intelligence to perform tasks and can improve as they gather information. Artificial intelligence is not intended to replace humans, but to significantly enhance human capabilities and contributions.

Internet: a network based on the IP protocol suite that interconnects equipment with worldwide communication capacity.

Internet *of Things* (*IoT*): technological paradigm that defines the provision of Internet connectivity to any object on which physical parameters can be measured or acted upon, as well as the applications and processing of intelligent data related to them.

Mineral Investigation (MI): a set of techniques (geological, geochemical and geophysical) used to identify and evaluate those places in the earth's crust where the concentration of an element is well above the average value, which occurs where there is mineralization of that element.

***Cut-off grade*:** generally defined as the minimum amount of metal or valuable element that a ton of material must contain for it to be sent to the processing plant.

(Rendu, 2014). Material with a grade above the cut-off grade is considered mineral and material with a grade below the cut-off grade is considered barren.

It is a value that marks an economic threshold (it discriminates between barren and ore), and defines the profitability and also the life of the mine. It depends on geological factors, such as mineralogy and the presence of penalizing elements or impurities in the ore, economic factors, such as the price of metals, political and fiscal factors, interest rates or capital expenditure, and also mining factors such as extraction costs (open pit or subway mining). There are several methods to estimate the cut-off grade taking into account costs and benefits. Currently the most widely accepted method of determination by the industry is the one that aims to maximize the Net Present Value (NPV) of the operation.

Average grade: average concentration of the chemical element of mining interest in the deposit.

Leaching: hydrometallurgical process by which the valuable metal contained in the ore is chemically attacked (dissolved) in the aqueous phase to be recovered in subsequent stages. It can be acidic, basic or neutral depending on the character of the chemical reagent used, which in turn is a function of the gangue. In copper leaching, a sulfuric acid solution ($H_2 SO_4$) is used.

M2M (*Machine to Machine*): a term used prior to IoT and which defines communications between connected devices. Unlike IoT, M2M does not prioritize the openness of data and protocols or the processing provided by *big data* and business intelligence technologies.

Rock mass: the form in which rocks occur in the natural environment. A rock mass is formed by one or more rock types and discontinuities (bedding planes, joints, faults, folds and other structural features).

Matte: is the heaviest semi-metallic phase, containing most of the sulfides, which is the result of the first melting of the ore and is where the metal is concentrated, for example, copper.

Mineral raw material: a substance or element obtained from rocks or minerals to take advantage of their properties and the compounds obtained from them.

Ore: is the part of a mineral deposit consisting of the mineral or minerals of economic interest. In general, it is a term that refers to metallic minerals and designates the mineral from which the chemical element or elements of interest are extracted, which are called ore minerals. Thus, an ore mineral is a mineral from which an element, generally a metal, can be extracted because it contains sufficient quantity to be exploited. For example, in a zinc (Zn) mineralization, the ore would be the set of Zn-bearing minerals: sphalerite, smithsonite, hemimorphite, etc.

Metal: each of the chemical elements that are good conductors of heat and electricity, with a characteristic luster and usually solid at room temperature (except mercury).

Metallogenesis or Metallogeny: branch of geology that studies the genesis of mineral deposits (metallic and non-metallic) in the earth's crust based on their origin, evolution and geo- logical context, so as to show on a map the areas likely to contain mineral concentrations and which are called metallogenic charts. The metallogenic chart aims to show the mineralizations in a particular region and their relationship with geological-tectonic events, grouping and interpreting data to define the rules of its distribution, being its most important utility the definition of mineralization guides and potential areas for exploration.

Metallothermy: a process in which one metal displaces another of its compounds by being more reactive. For example, in the production of titanium, magnesium is used to reduce titanium tetrachloride.

Metallurgy: science and technology of metals and their alloys. It studies the chemical and physical behavior of metallic elements, metallic compounds and their alloys, including all processes and techniques to produce metals and alloys with forms and properties suitable for commercial use. Extractive metallurgy is the branch of metallurgy concerned with the processing of ores for the extraction of metals and their concentration through physical, chemical and electrolytic processes.

Extractive metallurgy encompasses: (i) pyrometallurgy, which involves the thermal treatment of ores, producing a chemical and physical transformation in these so that metals can be recovered through roasting or smelting processes, (ii) hydrometallurgy which solubilizes metals in aqueous solutions, (iii) electrometallurgy, which consists of the production of metal deposits through the application of a continuous electric current, (iv) biometallurgy, which encompasses biotechnological processes involving the interaction of microorganisms and metals or metal-rich ores such as *bioleaching* processes (bacterial leaching for the recovery of metals in ores and tailings), or bioremediation, which focuses on the elimination or extraction of hazardous contaminants such as heavy metals in contaminated areas, and (v) geometallurgy, a combination of geology, geostatistics and extractive metallurgy to create predictive models of an ore deposit during extraction to optimize its treatment.

Mineral: a naturally occurring, inorganic substance of defined chemical composition within certain limits, with characteristic properties and a certain crystalline structure. Minerals are usually solids, although there are exceptions. There are several thousand different mineral species described in nature, although the most economically important ones do not exceed one hundred.

From a mining point of view, it is any substance, extracted for its value, that occurs naturally in or on the Earth, in or under water or in *tailings*, wastes or stockpiles, and which has been formed by or undergone a geological process, but excludes water, oil and gas (PERC asbl, 2021). Examples of these types of minerals are shown in Figure 98.

Figure 98. *Examples of minerals: hematite, bauxite and chalcopyrite. Source: authors' own elaboration.*

Figure 99. *Examples of industrial minerals. Source: authors' own elaboration.*

Within minerals, we find the so-called industrial minerals, which are all rocks and minerals, predominantly non-metallic, that, because of their physical or chemical properties, and not because of the energy generated or the metals extracted, can be used in industrial processes. Industrial minerals have multiple functions, as a raw material, as a special component of a formulation or additive, directly after extraction or after treatment. Examples of industrial minerals are shown in Figure 99.

Mineralization: occurrence of a mineral or combination of minerals in mass or deposit of economic interest. The term is intended to cover all the ways in which mineralization can occur, whether by type of deposit, mode of occurrence, genesis or composition (JORC, 2012).

Mineralurgy: set of industrial operations related to the treatment/transformation of the all-in-one material coming from mining extraction activities for the following processes to which it is destined without altering the chemical composition of the substances of which it is composed.

Concentration mineralurgy: operation of the whole extracted from the mine to the concentrate; it brings together a set of physical-mechanical and physical-chemical treatment techniques aimed at preparing the whole extracted from the mine and concentrating the ore, in order to obtain products with commercial value and transformable by metallurgy. The mineralogical plant is usually located in the vicinity of the mining site.

Transformation mineralurgy: in the mineralurgical operation a substantial transformation of the mineral or rock takes place, obtaining a non-metallic product. The mining product, as it leaves the quarry or the mineral plant, if it is not metallic in nature, often needs other treatments before it can be used. For example, ornamental rocks need cutting and surface treatments of the cutting surface, aggregates need size reduction and classification, perlite or vermiculite need thermal expansion to obtain light aggregates, limestone needs to be calcined to obtain lime ($CaCO_3$ + heat → $CaO + CO_2$). This concept includes the cement, glass, gypsum, magnesite, etc. industries.

***Middlings*:** particles obtained from the grinding/fragmentation of ore that are neither clean liberated ore (concentrate) nor gangue; they are mixed type fragments (ore and gangue). Figure 100 shows the types of particles resulting from the milling process. The objective of grinding is the liberation of the mineral of interest from the gangue at the coarsest possible particle size. If the amount of mixed obtained is very high, grinding to a finer size is required to achieve a higher liberation of the mineral of interest.

Figure 100. *Types of particles produced by ore milling. Source: translated and modified by the authors from (Wills, 2006).*

UNE Standard: UNE standards (UNE, Una Norma Española) are a set of technological standards created by the Technical Standardization Committees (CTN), which include all the entities and agents involved and interested in the committee's work. As a general rule, these committees are usually formed by ENAC (National Accreditation Entity), manufacturers, consumers and users, administration, laboratories and research centers.

OPEX *(OPerating Expense):* is a recurring cost for the operation of a product, business or system. It can be translated as operating expense, operating expenses or operational expenses. It is a key parameter together with CAPEX.

***Competent Person*: a** mining industry professional, registered or licensed by a Recognized Professional Organization ('RPO') on the list of accredited professional organizations, with applicable disciplinary processes, including the powers to suspend or expel a member. A Competent Person must demonstrate a minimum of five years of relevant experience in the type of mineralization or mineral deposit being considered and in the activity being undertaken by that person (CRIRSCO Definition 3.6, 2019).

***Qualified Person*:** a person with a university degree or equivalent accreditation in an area of geoscience or engineering related to mineral exploration or mining. They have at least five years of experience in mineral exploration, mine development or operation, or mineral project evaluation, or any combination of these, that is relevant to their professional degree or area of practice. Has experience relevant to the subject matter of the mining project and technical report and belongs to a recognized professional association (NI 43-401, 2011).

Pyrometallurgy: branch of extractive metallurgy that uses heat, and therefore high temperatures, to obtain the metal from the ores that contain it. It is the oldest metallurgy, although it has evolved constantly. Today it is used with efficiency and advantage over hydrometallurgy in obtaining metals such as copper or lead, although it is losing application to hydrometallurgy, which uses low temperatures.

Mineralogical plant: facility or group of facilities where the treatment of the whole mineral coming out of the mine is carried out. It is also called processing or beneficiation plant, since it refers to the facilities where the operations for the beneficiation of the mineral or of the elements of economic interest take place: mineral concentration plants, coal washing plants, industrial mineral processing plants or aggregate processing plants.

Precipitation: process whose objective is to separate the valuable metal from the solution, in elemental form (almost always) or in oxidized form (rarely).

Purification and/or concentration: process carried out on the solution obtained in the leaching stage. Its objective is to remove certain impurities from the solution.

***Stripping ratio*:** In open pit mining it is the ratio or quotient of dividing the amount of tailings by the ore; it is expressed in m^3 / t or in t /t.

Augmented Reality (AR): term used to describe the set of technologies that allow a user to visualize part of the real world through a technological device with graphical information added by the device. The device, or set of devices, adds virtual information to the existing physical information, i.e. a virtual part appears in reality. In this way, tangible physical elements are combined with virtual elements, thus creating an augmented reality in real time.

Virtual reality: an environment of real-looking scenes or objects, generated by specialized *software*, that allows the user to interact with that environment to a greater or lesser degree. Physical objects are combined with virtual objects in an application that combines real information obtained with virtual information to emulate reality.

Mineral resource: a concentration or occurrence of solid material of economic interest in or on the earth's crust in such form, grade (or quality) and quantity that there are reasonable expectations for eventual economic extraction. The location, quantity, grade (or quality), continuity and other geological characteristics of a mineral resource are known, estimated or interpreted from specific geological evidence and knowledge, including sampling. Mineral resources are subdivided in order of increasing geological confidence into Inferred, Indicated and Measured categories (JORC, 2012).

Indicated Mineral Resource: part of a mineral resource for which the quantity, grade (or quality), densities, shape and physical characteristics are estimated with sufficient confidence to allow the application of *modifying factors* in sufficient detail to support the planning of its extraction and the evaluation of the economic viability of the deposit (JORC, 2012). An Indicated Mineral Resource has a lower confidence level than that applied to a Measured Mineral Resource and can only be converted to a Probable Mineral Reserve.

Inferred Mineral Resource: part of a mineral resource in which the quantity and grade (or quality) is estimated on the basis of limited geological evidence and sampling. The geological evidence is sufficient to assume, but not verify, geological and grade (or quality) continuity. It is based on exploration, sampling and test information collected through appropriate techniques from locations such as outcrops, trenches, excavations, workings and drill holes (JORC, 2012). It has a lower confidence level than that applied to an indicated mineral resource and should not be converted to mineral reserve. It is reasonable to expect that most Inferred Mineral Resources could be upgraded to Indicated Mineral Resources as a result of continued exploration.

Measured Mineral Resource: part of a Mineral Resource for which the quantity, grade (or amount), densities, shape and physical characteristics are estimated with sufficient confidence to allow the application of *modifying factors* to support detailed mine planning and final evaluation of the economic viability of the deposit (JORC, 2012). A Measured Mineral Resource has a higher level of confidence than that applied to either an Indicated Mineral Resource or an Inferred Mineral Resource. It can be converted to a proven ore reserve or under certain circumstances to a probable mineral reserve.

Network: interconnected devices capable of exchanging data in a standardized way.

Rehabilitation: treatment of land affected by mining activities in such a way as to return the land to a satisfactory state, in particular with regard to soil quality, fauna, natural habitats, freshwater systems, landscape and appropriate beneficial uses, as appropriate.

Mineral Reserve: a mineral or ore reserve is the economically mineable part of a measured and/or indicated mineral resource. It includes dilution of materials and allowances for losses that may occur when the material is mined or extracted and is defined by appropriate Feasibility or Pre-Feasibility studies that consider the application of *modifying factors* and demonstrate that, at the time of reporting, extraction could be reasonably justified (JORC, 2012).

Probable Reserve: economically mineable part of an indicated mineral resource and in some circumstances measured mineral resource. The confidence in applying *modifying factors* to a probable reserve is lower than one applied to a proven reserve (JORC, 2012).

Proven Reserve: economically mineable part of a measured mineral resource. A proven ore reserve implies a high degree of confidence in the *modifying factors* (JORC, 2012).

RFID (*Radio Frequency Identification*): near field technology for reading identification devices. It is mainly used in access, payment, *ticketing*, etc. systems.

Rock: solid material formed by crystals or grains of one or more minerals. Their composition and structure is variable. Rocks are formed by essential minerals that allow them to be classified, and accessory minerals. According to their origin, they are classified as igneous, sedimentary and metamorphic.

There are rocks whose value lies in the fact that they contain certain minerals, which is what is intended to be exploited from the rock, and others in which the rock itself has value, as in the case of marble, granite, slate, coal, limestone, or aggregates (limestone, sand and gravel, dolomite). Some examples of rocks are shown in Figure 101.

Figure 101. *Examples of rocks: limestone, granite and slate. Source: authors' own elaboration.*

Sensor: although a sensor is an electronic component capable of transforming a physical measurement into an electronic one, the term is applied more globally to define connected objects equipped with sensors and, sometimes, actuators. Sensor" is often used interchangeably with "connected object" or "IoT device". Sensors are devices that detect physical or chemical characteristics of their environment and their variations. *Wearables*, for example, are a type of device that incorporates a microprocessor and one or more sensors that accompany the user and can interact with the user. Examples include: activity monitors, smart watches or glasses, etc.

Seismic: Seismic prospecting uses the same principle and physical laws of seismology, with the difference that the energy generating source is an artificial disturbance and that it propagates through the subsoil in the form of waves depending on the elastic properties of the medium. The processing and interpretation of the information obtained (different waveforms, travel times, etc.) make it possible to detect the shape of geological structures and their depths.

Smartphone: personal use device with capabilities extended to the basic capabilities of a cell phone (voice and messaging), allowing the execution of applications and the generation and reproduction of multimedia content.

***By-product*:** in mining these are subsidiary materials that are extracted in deposits where other materials are predominant, they are usually minerals of economic interest, but due to their grade, value or difficulty of exploitation they may not be ore in themselves and are not the main object of exploitation (exploiting the deposit by their mere existence) but they facilitate the profitability of the exploitation as a whole by increasing the economic value of the production. The existence of by-products in some deposits makes mining viable, as in phosphate mining, uranium or vanadium, cadmium or mercury contained in sulfide deposits with high sphalerite content, or manganese contained in copper porphyries, are often valuable by-products.

Tailings **(process tailings[148] *or* process tailings):** tailings resulting from the separation of the economically valuable mineral fraction (ore minerals) from the non-economic (gangue) in mineral processing plants. These tailings are mostly made up of silt-clay sized gangue particles and usually contain varying proportions of water depending on the method used for their storage.

ICT: Information and Communication Technologies. Term used to refer to the sector that covers companies dedicated to *software* and *hardware* development in all its aspects.

***Run of Mine* (*ROM*):** in mining, the product of the exploitation of the deposit, represented by the mixture of ore and gangue, characterized by a certain grade, and which is fed to the mineral processing plant or processing plant. It is characterized by the tonnage per unit time and the different grades of the elements of interest.

Roasting: operation by which a sulfide, when reacted with oxygen in the air, is transformed into an oxide. For example, roasting of copper sulfide ores to produce copper oxide or roasting of zinc sulfide ores to produce zinc oxide. This is usually a pre-smelting operation. Sulfate roasting may also be performed instead of oxidizing roasting.

Volatilization: operation leading to a metal (reducing), a compound (oxidizing), a halide (of halides) or a metal carbonyl (of carbonyls) in gaseous form. For example, in dry zinc metallurgy, the metal is obtained as a gas by reduction of the oxide.

***Wearable*:** personal IoT device that can be worn on oneself and assist us with information related to our daily life.

WiFi: wireless interconnection protocol for IP networks defined in the IEEE 802.11 protocol, with different versions depending on the data rate, security mechanisms and frequency of use.

5G: next generation of mobile telephony standards. In the IoT world, the definition of communication classes according to the needs of this sector in terms of device cost, communication and energy expenditure is foreseen.

[148] The name comes from *tailings* and tends to be used mainly in Latin America. Its use in Spain is limited.

ACRON
YMS,
ABBREVIATI
ONS
AND ABBREVIATIONS

ACATECH	German Academy of Science and Engineering
Ag	Silver
AGP	Deep geological repository
AHS	*Autonomous haulage system* / Autonomous transport systems
IEA/IEA	International Energy *Agency* / *International Energy Agency*
To	Aluminum
$Al\ O_{23}$	Alumina
APQ	Chemical Warehouse
AQL	Inspection based on samples
ASEAN	Association of Southeast Asian Nations
ATC	Centralized Temporary Warehouse
ATI	Individualized Temporary Warehouse
Au	Gold
AUV	Autonomous underwater vehicles
B	Boron
Ba	Barium
BCM	*Block Caving Method* / Sunken Blocks
BDG	*Black Dragon Gold*
Be	Beryllium
BOM	Bill of Materials/ *Bill-Of-Materials*
Br	Bromo
C	Carbon
C&F	*Cut & fill* / Cut & fill (ascending or descending)
Ca	Calcium
$Ca_5\ Cl(PO\ )_{43}$	Crolopatite
CAPA	Preventive and connecting actions
CAPEX	CAPital EXpenditures
C.A.	Autonomous Communities
Cd	Cadmium
Ce	Cerium
CH_4	Methane
CIM	*Canadian Institute of Mining Metallurgy and Petroleum*
CLC	Las Cruces Copper
CNAE	National Classification of Economic Activities
Co	Cobalt
CO	Carbon monoxide
CO_2	Carbon dioxide
CODEIME	Mining and Energy Engineering School Directors Conference
COMEX	New York Metal Exchange
COMG	Official Mining Chamber of Galicia
COP	Conference Of the Parties
COVDM	Volatile Organic Compounds other than Methane
cp	Chalcopyrite
CPS	*Cyber Physical System* / Sistemas Ciberfísicos
Cr	Chrome
CRIRSCO	*Combined for Mineral Reserves International Reporting Standards*
Cs	Cesium
CTN	Technical Committee for Standardization
Cu	Copper

3D	Three-dimensional
D&F	*Drift and fill mining* / Sublevel fills
SWOT	Weaknesses, Threats, Strengths and Opportunities
DCF	*Discounted Cash Flow* / Discounted Cash Flow
DESI	*Digital Economy Society Index* / Índice de economía y sociedad digital.
DIA	Environmental Impact Statement
DMAIC	*Define, Measure, Analyze, Improve, Control*
DMLS	Direct Metal Laser Sintering
DOE	Design of experiments
DTH	Down the hole
Dy	Disprosio
EBITDA	*Earnings Before Interest Taxes Depreciation and Amortization* / Earnings Before Interest, Taxes, Dep*reciation* and Amortization
EC	Circular Economy
ECCP	*European Strategic Cluster Partnerships* / European Platform for Cluster Collaboration
WWTP	Wastewater treatment plants
USA. USA.	United States
ef	Sphalerite
EFG	*European Federation of Geologists* / Federación Europea de Geólogos
EGDI	European Geological Data Infrastructure
EHEHPA	Di-2-ethyl-hexyl phosphoric acid-mono-2-ethyl-hexyl ester
EIA	Environmental Impact Study
EIT	*European Institute of Innovation and Technology* / European Institute *of* Innovation and Technology
EMC	Cantabrian Mining Explorations
ENAC	National Accreditation Entity
EO	Electrowinning
EOL	End Of life
ERMA	*European Raw Materials Alliance* / European Raw Materials Alliance
ESG	*Environmental, Social and Governance* / Medioambietal, social y gobernanza
FC	Concentration Factor
Faith	Iron
FE	Enrichment Factor
IMF	International Monetary Fund
FPI/IPB	Faja Pirítica Ibérica/ *Iberian Pyrite Belt*
FQM	First Quantum Minerals
FRX	X-Ray Fluorescence
g/t	Gram per ton
Ga	Galio
GD	Group identifier
GDI	Interest group
Ge	Germanium
GEI	Greenhouse Gases
GeoERA	*European Geological Surveys Research Area*
GIS	*Geographic Information System* / Sistema de información geográfica
GPS	*Global Positioning System*
HCl	Hydrochloric acid
HDEHP/ DEHPA	Di(2-ethyl-hexyl) hydrogen phosphate
He	Helio
HFC	Hydrofluorocarbons
Hg	Mercury

HREE	*High Rare Earth Elements* / Heavy Rare Earths
IA/AI	Artificial *Intelligence* / Inteligencia artificial / *Artificial Intelligence*
ICAMYL	International Center for Advanced Materials and Raw Materials of Castilla y León
ICMM	International Council on Mining and Metals
IGME	Geological and Mining Institute of Spain
IM	Mining Research
IMEB	Iberian Mining Engineers Board
In	Indian
INE	National Institute of Statistics
IoT	*Internet of the* Things
Go to	Iridium
IRE	Indian Rare Earths
ISF	*Imperial Smelting Furnace*
ISP	*Imperial Smelting Process*
JORC	*Joint Ore Reserves Committee*
JRC	*Joint Research Centre*
K	Potassium
KOH	Potassium hydroxide
The	Lanthanum
LBMA	London Bullion Market Association
LCA	*Life Cycle Assessment* / Life Cycle Analysis
LCE	Lithium carbonate equivalent
LED	Light Emitting Diode
LFP	Lithium Ferrum Phosphate
LHD Shovel	*Load-Haul-Dump* / Loading, transporting and dumping shovels
Li	Lithium
LME	*London Metal Exchange* / London Metal Exchange
LOF/LOM	*Life of Mine* / Vida de la mina.
THE	*Longitudinal Open Stoping* / Empty chambers with longitudinal sublevels
LPPM	*London Platinum and Palladium Market*
LREE	*Light Rare Earth Elements* / Light Rare Earths
LTE	*Long term evolution*
LW	*Longwall stopping* / Longwall *stopping*
M€	Millions of euros
M US$	Millions of U.S. dollars
M2M	Machine to Machine
M3	Michigan Micro Mote
MATSA	Aguas Teñidas S.A. Mines.
M.C.	Key message
MCA	Open pit mining
MCC	Best Known Conditions
MCI	*Mining contribution index/* Índice de Contribución Minera
MEM	Microelectromechanical
Mg	Magnesium
MGP/ PGM	*Platinum Group Metals* / *Platinum Group Metals*
Mintell4EU	*Mineral Intelligence for Europe*
m-IoT	*Metaurgical Internet of the Things* / Metallurgical Internet of Things
MITRED	Ministry of Ecological Transition and the Demographic Challenge
Mn	Manganese
Mo	Molybdenum

MOX	Mixed Oxides
MPF	Fundamental Raw Materials
MPS	Secondary Raw Materials
MS	Subway mining
MSAHP	Method Selection with Analytic Hierarchy Process
Mt	Millions of tons
MTD	Best available techniques
Mtpa	Millions of tons per year
MWD	Measuring While Drilling
$N O_2$	Nitrous oxide
Na	Sodium
$Na_3 AlF_{,6}$	Cryolite / Sodium Hexafluoroaluminate
NaOH	Sodium hydroxide
Nb	Niobium
n.e.i.c.	Not covered elsewhere
Nd	Neodymium
n.a.	Not available
NDC	*Nationally Determined Contributions* / Emission Reduction Commitments
NEA	*Nuclear Energy Agency*
Ni	Nickel
NI	*National Instrument*
NIMBY	*Not In My Back Yard* / No en mi patio trasero
Np	Neptunio
NPI	Introduction of new products
NRGI	*Natural Resource Governance Institute* / Instituto de Gobernanza de Recursos Naturales
NYMEX	*New York Mercantile Exchange* / New York Mercantile Exchange
O	Oxygen
OECD	Organization for Economic Cooperation and Development
ODS	Sustainable Development Goals
UN	United Nations
OPEX	OPerating EXpense
Os	Osmio
OSCE	Organization for Security and Cooperation in Europe
NATO	North Atlantic Treaty Organization
OTC	*Over The Counter*
oz.	Ounce
oz/t	Ounce per ton
PACE	*The Platform for Accelerating the Circular Economy*
Pb	Lead
PDA	Personal Digital Assessment
PDAC	Prospectors & Developers Association of Canada
Pd	Palladium
ADP	*Preliminary Economic Assessment*
PERC	*Pan European Reserves & Resources Reporting Committee*
PERTE	Strategic Projects for Economic Recovery and Transformation
CBP	Perfluorocarbons
PHVA	Plan-Do-Check-Act
PI	Industrial Product
GDP	Gross Domestic Product
PMR	*PolyMetallurgical Refinery*

PNIEC	National Integrated Energy and Climate Plan
Pr	Praseodymium
PRL	Prevention of occupational hazards
Pt	Platinum
PVE	European Green Pact
py	Pyrite
QA/QC	Quality Assurance & Quality Control
R&P	*Room & pillar* / Chambers and pillars
RA	Augmented Reality
RAI	Royal Academy of Engineering
RAM	*Random Access Memory* / Random Access Memory
RCD	Construction and Demolition Waste
RETECH	Territorial Networks of Technological Specialization
RFID	Radio Frequency IDentification
RGNBSM	General Regulations for Basic Mining Safety Standards
Rh	Rhodio
RIS3	Smart Specialization Strategy
RMI	*Raw Materials Initiative* / European Raw Materials Initiative
ROM	*Run of Mine* / All-one
RPO	Recognized Professional Organization
S&P	*Standard & Poor's*
Sb	Antimony
SDS	*Sustainable Development Scenario*
See	Selenium
n.d.	No date
SF_6	Sulfur hexafluoride
Yes	Silicon
SLC	*Sublevel Caving* / Sublevel sinking
SLM	*Selective Laser Melting*
Sm	Samarium
SMS	*Seafloor massive sulphides* / Sulfuros hidrotermales polimetálicos
Sn	Tin
SOB	Work instructions
SPC	Statistical process control
Mr.	Strontium
STEM	*Science Technology Engineering Maths*
STEPS	*Stated Policies Scenario*
STRADE	*Strategic Dialogue on Sustainable Raw Materials for Europe*
SX	Solvents
T&D	Transportation and distribution
Ta	Tantalum
Tb	Terbio
PBS	Tributyl phosphate
TCTC	Shredders in Cutting and Conveying with Belts
Te	Tellurium
Th	Thorium
Ti	Titanium
ICT	Information and Communication Technologies
TOS	*Transverse Open Stoping/* Empty chambers with transverse sublevels
TR/ REE	Rare earths / *Rare Earth Elements*

TREO	Contained Rare Earths
TRL	*Technology Readiness Level* / Technology maturity level
TROCl	Rare earth oxychlorides
TR O S_{22}	Rare earth oxysulfides
U	Uranium
UBC	*University of British Columbia*
EU	European Union
UNE	A Spanish Standard
US$	U.S. dollars
V	Vanadium
VAN	Net Present Value
VCR	*Vertical Crater Retreat* / Inverted craters
W	Wolfram / Tungsten
WAAM	*Wire Arc Additive Manufacturing*
WGI	*Worldwide Governance Indicators* / Indicadores de Gobernanza Mundial
XRF	Handheld X-rayfluorescence analyzers
ZB	Zettabytes
Zn	Zinc
Zr	Zirconium
2DS	*2 Degree Scenario*
≈	Approximately
%	Percentage

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