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# Preface

Equilibrium thermodynamics is a revolutionary "young" science (it has only more than 170 years!) because it can change our understanding of planet Earth. It is a science that needs to be known by those who want to quantify the damage and degradation which humans are causing to the planet's capacity to support the human species. Engineers, physicists, chemists, geologists, environmentalists, ecologists, economists, forecasters and policymakers must learn from equilibrium thermodynamics and develop it further. This book focuses particularly on the abiotic (i.e. non-living) resources of our planet and on how they have been and will be affected by human behaviour.

Although this book presents a novel application of thermodynamics for assessing the Earth's mineral wealth, no expertise in the academic discipline of thermodynamics is required to understand the book's main message. A reader who is not well versed in thermodynamics can readily cherry-pick various parts of the individual chapters that (s)he finds illuminating.

Chapter 1 presents the context of the Earth's mineral resources and how this book proposes to assess their degradation.

Chapter 2 provides information on the extraction and use of energy and non-energy mineral resources from the past to the present. It focuses on key raw materials in the decarbonisation of the economy and describes some of the mineral criticality studies that currently exist.

While Chap. 2 focuses on economic demand, Chap. 3 addresses economic supply, analysing the availability of minerals on Earth. Besides, a description of the mining and refining processes of raw materials and the associated environmental and social impacts are presented.

After analysing mineral supply and demand, we outline in Chap. 4 the thermodynamic methodology proposed in this book. It describes a model of an economically degraded planet, Thanatia, used as a reference to assess the current state of mineral resources and their degradation velocity. In addition, the equations for calculating the exergy of mineral resources are provided, and thermodynamic rarity is proposed as an indicator of raw material criticality.

Using the thermodynamic tools presented in Chap. 4, Chap. 5 quantifies the exergy degradation of mineral resources on the planet since 1900. Various minerals' peak-production rates are assessed via Hubbert curves traditionally applied to fossil fuels. The novelty brought is that these can be represented in the same graph, taking into account the quantity and the quality of the resources. A study is also carried out on the mineral exergy balance of various regions of the world. With this approach, it is possible to detect the enormous inequalities between exporting and importing countries immediately. Finally, a monetary assessment of the exergy replacement costs of raw materials is undertaken. The adoption of such an accounting would imply a fairer appraisal of the mineral heritage of nations, taking into account future generations.

Chapter 6 focuses on assessing the potential raw material demand for the energy transition. Data are provided on the expected penetration of clean technologies, as well as on their material composition. Based on International Energy Agency or Greenpeace scenarios, the energy transition's exergy flows are analysed. It then becomes clear that there will be a shift from a dependence on fossil fuels to a multi-dependence on minerals, some of which very scarce, with extraction localised in only a few places of the world. Finally, some likely material bottlenecks in the development of clean technologies are identified.

Yet it is not only renewable energies that are mainly dependent on these scarce raw materials. So are new technologies that increasingly incorporate electrical and electronic components. Chapter 7 analyses these devices' thermodynamic rarity, focusing on probably the most resource-intensive technology: the vehicle.

Chapter 8 provides solutions to slow down the degradation of scarce mineral resources, showing how thermodynamics can help to manage the mineral wealth better. Thus, material substitution possibilities for various resource-intensive technologies are addressed. It also discusses the so-called circular economy and the thermodynamic limits it faces. Eco-design measures to increase the recoverability of raw materials at the end of life of products are also discussed. Finally, an insight into alternative mineral sources is presented: urban mining and asteroid mining.

We finally offer in Chap. 9 some reflections and conclusions drawn from our own research findings, claiming the need for a new humanism that cares about the future of the planet.

Here are some introductory remarks for readers versed in thermodynamics. Let us start with an example of the First Law of Thermodynamics: It is generally agreed that a calorie is a very small amount—just enough to raise the temperature of a gram of water by 1 °C. But if that gram of water were to carry a speed of 329 km/h, it would have the energy, now kinetic, of a calorie! This is surprising because we have not internalised the concept of energy. Moreover, we seem to associate energy with damage rather than heat. Yet in reality, a punch from a boxer can communicate less energy than a gentle caress. Numbers say nothing if they are not internalised. As Protagoras said, "man is the measure of all things", but be careful; the sense of physical damage is not an appropriate measure of deterioration.

Despite these paradoxes, we can make statistics and foresight studies also because energy is additive. We can add electrical energy to thermal energy and to any other energy manifestations without making mistakes, as long as we distinguish between primary and final energy.

However, what is no longer straightforward is to understand the second law of thermodynamics quantitatively. If energy is not lost, where does it go? We know that heat cools, metals rust, the wind stops, water rains, living beings age and die, and the planet degrades. But how fast does Earth degrade? And how fast does it regenerate? If the planet is finite, how long will it take until its exhaustion? And how can we stop this degradation? These are the questions that currently have no scientific answers. There are proclamations, considerations, predictions, but there is no quantitative science behind it. We need a transdisciplinary theory based on thermodynamic criteria, which goes beyond it. We need a science that builds ever more detailed statistics, even if these are initially based on imprecise and fuzzy but objective data, that serves as a rudder and thermometer of the damage inflicted by our civilisation on planet Earth.

From the second law, we know that sooner or later, all quality energy will become heat. Heat is the sink of all energies, so the energy we receive every day from the Sun moves the biosphere. Yet, unfortunately, humankind degrades natural resources faster than the Sun replenishes them. If any degradation can be measured with entropy, we need to focus on understanding what entropy is.

We can easily understand that if energy is conserved and hot bodies cool spontaneously, isolated systems tend to increase their entropy. Unfortunately, entropy has units of energy divided by temperature, making it complex to comprehend and impractical to use. First of all, entropy is not a property that behaves linearly like energy. Losing 1 °C at 5505 °C (i.e., at 5778 Kelvin, the equivalent temperature of solar radiation) is not the same as losing it at 27 °C (300 K) or losing it at −73 °C (200 K). In other words, entropy forces us to live with exponential behaviour, which is difficult to understand for those not used to mathematical thinking. On the other hand, using units such as kWh/K does not facilitate the quantitative explanation of the social consequences of degradation. Therefore, it is not surprising that entropy is often used as a metaphor, moving away from quantitative messages.

The solution to these issues comes with exergy. Exergy is more interesting than entropy because it simultaneously integrates the First Law of Thermodynamics, energy conservation, and the second, the entropy law. In other words, exergy simultaneously condenses information about energy and entropy. Mathematically, it has a straightforward formula: the change in energy minus the ambient temperature multiplied by the entropy change. Its generic formula is:

$$B = \Delta E - T_0 \Delta S$$

where B is the exergy, $\Delta E$ is the energy change with respect to the reference, $T_0$ is the absolute temperature of the reference and $\Delta S$ is the entropy change with respect to the reference. It is therefore easy to see that the exergy property integrates both energy and entropy. It is measured in energy units and is additive, which makes it much more practical and easy to understand. Technically, exergy measures the maximum work obtained from a system when it is brought into equilibrium with the environment. Alternatively, exergy represents the minimum work necessary to bring the system from equilibrium with the environment to a given alternative state.

Note that to define exergy, we have added a new concept, the reference environment, which can open up a new problem rather than providing a solution depending on how we see it. The reference environment is not originated from the convenience of calculations but from observing the physical behaviour of matter. It is the ground if we speak of a ball falling down, it is the absence of wind if we speak of the atmosphere, it is the diluted $CO_2$ in the environment if we speak of a fossil fuel that has been burned, it is rusted metal, it is a dilution of pollutants in the sea and the atmosphere, it is the unavoidable dispersion of materials throughout the crust, it is the irretrievable loss of natural resources, and it is death. It is Thanatia, a planet easily imaginable if we observe Nature's degradation, at temperature $T_0$, slowly increasing if we do not stop climate change.

Thanatia's message flips the way the degradation of natural resources is perceived and assessed. Instead of moving from today to a defined temporal future, Thanatia's thinking suggests time to run backwards. If we accept an end, i.e., the finitude of resources, we can ask ourselves how fast we are approaching it. It is as if we had to take a flight at a fixed date and time. We organise our time backwards, we prepare the luggage, commutes, and all the necessary steps to arrive on time to take the plane. In short, it is forward vs. backward thinking. This change in thinking helps us to find a way to avoid any pessimistic future.

This is, dear reader, what this book is about. It shows that equilibrium thermodynamics can explain how relentless loss of the planet's mineral wealth—a loss which the energy transition will accelerate—can be assessed. However, now we are no longer talking about the equilibrium between bodies as classical thermodynamics does, but about the equilibrium between humans and the planet, which is why the word equilibrium thermodynamics takes on a new nuance. Perhaps to avoid confusion it should be called the thermodynamics of sustainability.

Our work on this topic started in 1998 with several papers and a book entitled "Desarrollo Económico y Deterioro Ecológico" (meaning "Economic Development and Ecological Deterioration"). After three Ph.D.s and more research papers, our studies led us in 2014 to write a book entitled, *Thanatia. The Destiny of the Earth's Mineral Resources. A Thermodynamic Cradle to Cradle Assessment*. Now, seven years later, after five additional Ph.D.s and more than 50 scientific papers, we present this new book, opening up new questions on a crucial issue for twenty-first-century humankind: the conservation and rational management of the planet's mineral resources for future generations.

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# About the Authors

**Alicia Valero** studied chemical engineering at the University of Zaragoza (Spain), where she also completed a master's degree in energy efficiency and industrial ecology. In 2008, she obtained a European PhD from the University of Zaragoza. She is currently an associate professor in the Department of Mechanical Engineering (University of Zaragoza) and head of the industrial ecology group at the CIRCE Institute. Her research activity has focused on the exergy evaluation of the Earth's mineral capital, a subject in which she has been working for 15 years. She has received four international awards. She is the co-author of over 50 publications in scientific journals and book chapters and more than 60 communications to international congresses. She has participated in more than 30 national and international projects related to the study and optimisation of energy and materials. She belongs to various international experts' committees on raw materials.

**Antonio Valero** is the chair in thermal systems at the University of Zaragoza (Spain). He is the director and founder of the Research Centre for Energy Resources and Consumption (CIRCE Institute) belonging to the University of Zaragoza (Spain). Since 1986, when he published the general theory of exergy saving, he has developed various thermodynamic theories, including thermoeconomics and exergoecology, used for the optimisation and evaluation of natural resources. He has directed more than 35 Ph.D.s and has co-authored hundreds of scientific papers, book chapters and communications to conferences on these topics. He is a fellow member of the American Society of Mechanical Engineers. He received the ASME James H. Potter Gold Medal Award 1996 for advancing the theory of thermoeconomics to a new level, as well as the Stanislaw Ocheduszko Medal 2016 to distinguish his contributions to thermodynamics, among other international recognitions.

**Guiomar Calvo** graduated in geology from the University of Zaragoza (Spain) in 2010. She studied a master in introduction to research in geology (2011) and a master in eco-efficiency and industrial ecology (2013) at the same university. In 2016, she defended her doctoral thesis, entitled "Exergy assessment of mineral extraction, trade, and depletion", which consisted of the evaluation of mineral resources and mineral depletion from a thermodynamic point of view. She is the co-author of over 50 scientific papers, conference communications and book chapters, along with three dissemination books related to minerals. She has participated in various national and European research projects related to assessing and optimising raw material use. She has worked as a postdoctoral researcher at CIRCE Institute, where she has carried out the vast majority of her research activity. She has also worked as a lecturer at the International University of La Rioja (Spain).

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# Chapter 1
# What Is This Book About?

**Abstract** Humankind has relied on the extraction of different raw materials for centuries, starting with iron, copper or gold to a large number of metals and fossil fuels currently used in multiple sectors, thanks to technological development. Still, this change has also led to other issues, such as increasing $CO_2$ at a global level and climate change. One way to mitigate these problems is to rely on renewable energy sources that use the Sun or wind to generate electricity instead of burning fossil fuels. However, these technologies need certain elements that are scarce on the planet or very complicated to extract. To assess our planet's mineral loss, in this book, we will use thermodynamics, specifically its second law, that will allow us to explain this degradation process physically. Using Thanatia as a baseline, a hypothetical land where all concentrated materials have been extracted and dispersed, and all the fossil fuels have been consumed, we can assess the cost of replacing minerals through a grave-to-cradle approach and combine it with the more traditional cradle-to-grave approach.

Everything around us is made up of minerals. Dozens of chemical elements are used in smartphones, household appliances, vehicles, concrete, paints, detergents, etc., that come from the extraction and processing of these minerals. We start from the advantage that the natural processes that have been taking place over millions of years on our planet have been concentrating these elements in the form of mineral deposits. Mining becomes then our primary source, from where we extract the minerals that we then use. Since these mines are not infinite, it is legitimate to ask what limitations may exist in the short, medium and long term.

The increase in population, globalisation and the change in consumption trends are causing the use of resources to increase dramatically every year. In fact, the primary extraction of quarry products, metallic minerals, fossil fuels and biomass increase year on year. On a limited planet, are we going to be able to maintain this pace forever? What consequences will this have on future generations and on the planet?

Historically, the extraction and use of raw materials have been closely linked to human development. We have gone from consuming about 3 kg of natural resources per inhabitant per day in prehistory to 44 kg in our current industrialised society

 
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(Friends of the Earth, 2009). Our prehistoric ancestors obtained mineral resources through surface collection, selecting those materials most suitable to serve as cutting tools, such as quartzite or flint. Other readily available materials have historically been used as cosmetics and for decorative purposes. The Egyptians used mixtures of oils with dust from the crushing of lead minerals, such as galena, and copper, such as malachite, among others, to make *kohl*, a thick black substance that they later applied to outline their eyes (Hallmann, 2009).

With the emergence of more complex societies, mining became much more relevant, using materials for own consumption and exchange. Different metals gradually gained more weight, including copper, bronze (an alloy of copper and tin), and gold, highly desired both for ornamentation and jewellery and for its economic value.

A well-known example globally is the ancient gold mine of *Las Médulas*, located in the province of León (Spain), considered the largest open-pit metal mine in the Roman Empire (Fig. 1.1). The exploitation was carried out by the force of water, with the method known as *ruina montium.* Water was channelled and accumulated at the top of the mountain and, as this water was released through steep galleries, and by the force of gravity, the mountain would erode, dragging the gold to the washing sites located at the bottom (Pérez García et al., 1998). It is estimated that the Romans were able to extract between five and seven tons of gold from this location, which has left as an inheritance the characteristic landscape that this area presents. Such is the value of this natural space that UNESCO included it as a World Heritage Site in 1997.

**Fig. 1.1** Ancient gold open-cast exploitation of the Roman Empire of *Las Médulas* (Castilla y León, Spain). *Author* Rafael Ibáñez Fernández. GNU FDL. Wikimedia Commons

Historically, gold that appears in its native state has also been mined manually using pans. This technique, widespread in past centuries, consisted of using a pan filled with sand and immersed in water; through a series of circular movements, and due to the difference in density of the materials, the gold deposited at the bottom while the gravel was washed off (Fig. 1.2). This same technique was also used during the gold rush in the United States in the middle of the nineteenth century, along with the sluice boxes, where the material was washed. During this time, dry gold washing also became popular, driven by the lack of water in many regions. In this case, the mineral was deposited inside a conical wooden pan. Throwing the material into the air, lighter materials dispersed leaving the heavier ones at the container's bottom. However, as can be assumed, this was not a very effective method since only large gold nuggets could be recovered (Taylor Hansen, 2007). The use of pans and decantation in artisanal gold mining continues to this day.

The technological development that has taken place over the centuries has progressively increased the number of metals and other elements that are used, from just a few in the seventeenth century to practically all of those contained in the periodic

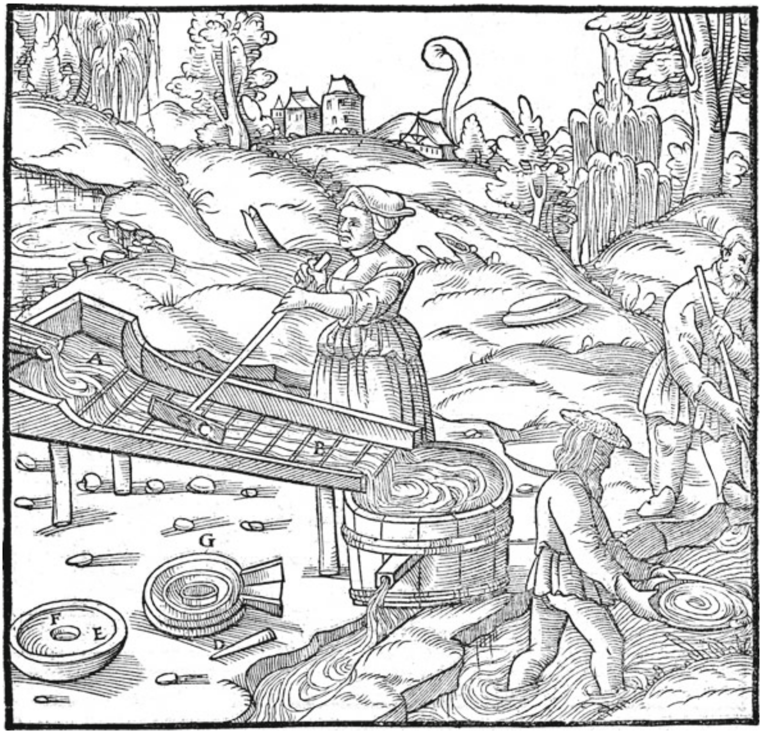


**Fig. 1.2** Engraving from the work of Georgius Agricola, *De re Metallica*, published in 1577, representing gold extraction techniques in Germany in the sixteenth century. The sluice boxes ensured that gold, a denser material, accumulated in the channels. There is also a person panning, a traditional method still used in some places

table today. This is even more evident in the case of elements used in the energy sector (Zepf et al., 2014). Initially, the materials necessary to manufacture mills that harnessed the energy of the wind were few: chiefly iron, wood and stone; the same occurred with candles or oil lamps used for lighting. With the industrial revolution and the steam engine's invention, other elements were introduced in the energy sector: copper, tin, lead, manganese, etc., but they were still few in number. The appearance of motor vehicles changed the situation drastically again, increasing not only the consumption of fossil fuels but also that of other metals that until now had not been very useful.

Today, we use many elements in different applications that increase our convenience and comfort. For instance, in a smartphone, we can find several dozen elements of the periodic table, which include tin and indium oxide in the touchscreen and rare earth elements that produce the colours we see and, of course, lithium in batteries (Merchant, 2017).

Electricity generation is no exception either, since it requires large amounts of elements, some of them very valuable and scarce, to produce wind turbines, photovoltaic panels, etc. For example, to produce one gigawatt (GW) of electrical power equivalent to that which a natural gas-fired power plant could supply would require a total of 200 5-megawatt (MW) wind turbines or 1,000 1-megawatt (MW) wind turbines. This would imply the use of approximately 160,000 tons of steel, 2,000 of copper, 780 of aluminium, 110 of nickel, 85 of neodymium and 7 of dysprosium for its construction. These are not negligible amounts if it is estimated that in the future the energy produced by wind turbines in 2050 could be around 2,200 GW (International Energy Agency, 2019).

Worse still, as can be seen in Fig. 1.3, wind turbines are one of the renewable technologies that require the least variety of elements for their production, but others such as the electric car employ over 40 different elements, and that's before considering the rest of the necessary materials such as plastics, glass, polymers, etc. (Valero, 2018).

Considering the intense use of materials from clean technologies, will the deployment of renewable energy required to achieve the Paris Agreement goal (preventing Earth's temperature rise of over 2 °C before the end of the century) be possible? We want to move from a society based on non-renewable energy sources to one based on renewable sources. However, what has been rarely considered is that these technologies require a greater diversity of materials than conventional energy sources and that, in addition, they are highly voracious in many different elements.

As we currently know, society is completely dependent on many elements, almost all of which come from the primary extraction of certain minerals. In our society, no product exists that does not contain minerals or whose production does not directly involve minerals. Consequently, the global extraction of natural resources has increased exponentially, as can be seen in Fig. 1.4, and the same situation can be observed for other materials.

The amount of biomass that has been extracted, comparing 1900 and 2017 data, has increased fivefold, in the case of fossil fuels 15-fold, and by a factor of 43 and 65 in the case of metallic and construction minerals, respectively (International Resource

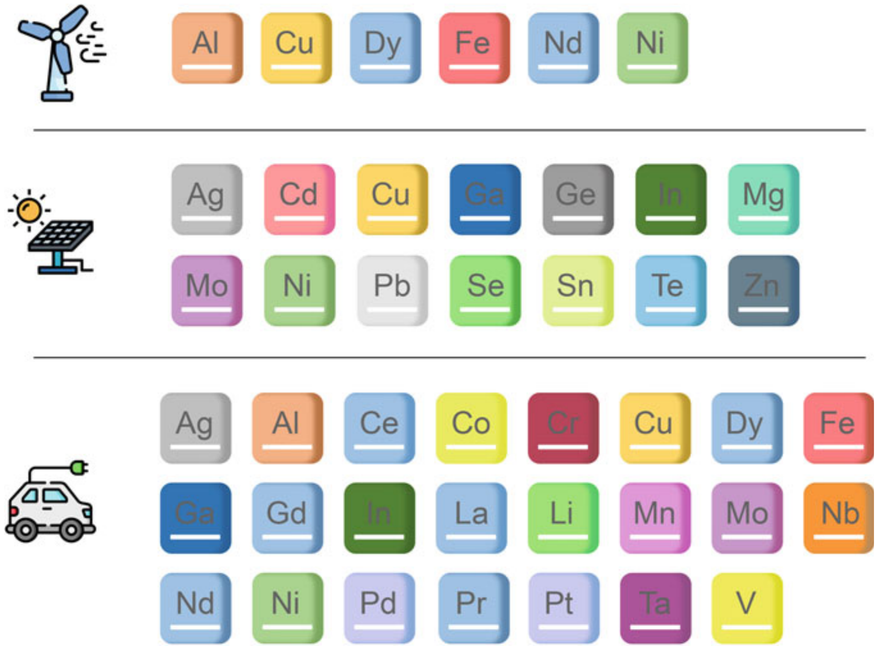


**Fig. 1.3** Some of the elements that are used to manufacture clean technologies (Valero et al., 2018)

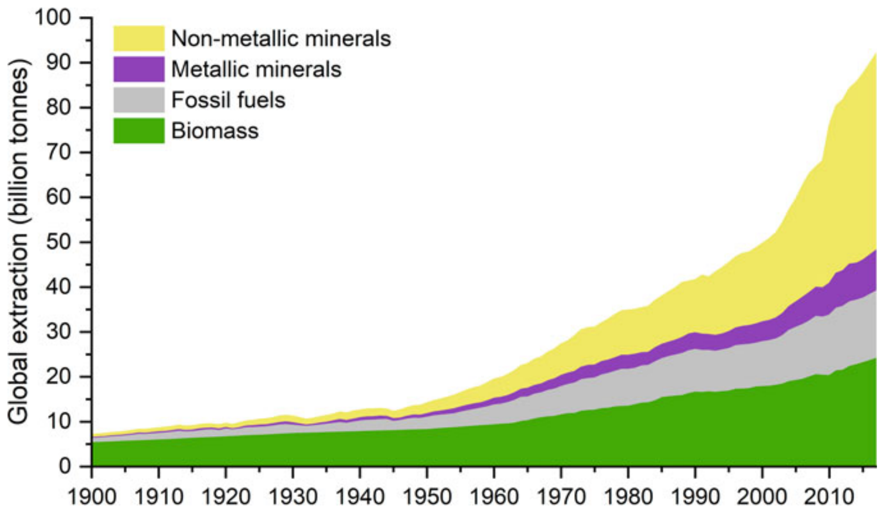


**Fig. 1.4** Global material extraction from 1900 to 2017 in billions of tons (International Resource Panel, 2019)

Panel, 2019). In fact, so far in the twenty-first century (in the last 20 years) we have extracted almost the same amount of copper that was extracted in the entire twentieth century, and this same situation can be extrapolated to many other elements (USGS, 2018).

However, this extraction of raw materials is not equally distributed across the globe. In the case of mineral resources, it is geology that conditions the places where the elements have been concentrating over time. In Australia, for example, there are economically profitable deposits of practically all the elements, while in Spain, despite having a considerable amount of mineral deposits of different elements, only a few basic metals such as copper, lead or zinc can be economically extracted.

If we take as an example some of the elements that are most crucial to our economy, such as lithium, which is essential for electric car batteries, approximately 55% of the total global extraction originated in Australia in 2019. Another representative example of that same year are rare earth elements, used in many technological applications; in this case, China dominated the market with a global extraction quota of over 60% (USGS, 2020).

Furthermore, this unequal extraction of resources is associated with consumption that is also unevenly distributed. For example, in Europe, three times more resources are consumed than in Asia, and four times more than in Africa, and someone born in the United States consumes even more than an average European. For example, a child born in the USA in 2019 will, throughout their life (78.6 years), require a total of 9,129 kg of iron, 937 kg of primary aluminium, 444 kg of copper, 432 kg of lead, 211 kg of zinc, 13,693 kg of salt and 6,503 kg of phosphate rock, among many other elements, in addition to some 1,800 barrels of oil, 150 tons of coal and 7.7 million cubic meters of natural gas (Minerals Education Coalition, 2019). This implies that if all the inhabitants of the planet tried to live today as an average US citizen, we would need to multiply the current copper extraction by two to cover the demand of a single year and something similar would happen with the rest of the raw materials.

The exponential extraction of materials also entails an increase in the required energy dedicated to mining, which in turn can significantly impact the environment. According to studies by the International Energy Agency, the mining industry consumes between 8 and 10% of global energy. As an example of how intensive mining is in terms of energy use, each year, the Australian mining industry consumes as much electricity as Portugal, and if the cost of transport is also factored in, it is equal to the energy consumed in Spain. It is clear that there can be no materials without energy, but neither can there be energy without materials.

So, what does the future hold? Knowing the consumption of mineral resources in the past or the present is relatively simple: we resort to the mining statistics of the different countries to obtain approximate figures. However, of equal or greater importance is trying to predict what future behaviour will be to anticipate eventual shortage problems. To this end, different models have been created based on statistical calculations and trend analysis, among others. Some striking insights can be gleaned from these studies. In the case of silver, gold, copper or nickel, their demand is estimated to increase fivefold by 2050. Taken alone, this figure doesn't provide much value but compared to the known amount of these elements in mines today, it exceeds