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Raw Materials and Materials for Energy

Mineral Resources Economy 1

Context and Issues

Coordinated by
Floriant Fizaine
Xavier Galiègue

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Contents

Introduction

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Why did we write a book on the economics of mineral resources? As economists, we would be tempted to say that the absence of a French title on the subject was the motivation for the very existence of the original French edition of this book. Nevertheless, this answer might seem rather sketchy, since there are so many reasons for the creation of this collective work.

To begin with, there are the foundations and knowledge accumulated on the subject over decades by researchers from different disciplines. This knowledge and these representations conveyed through more specialized articles and books convince us of the issues related to the theme. As we will see later, these issues are of various kinds: environmental, social, economic and so on. This knowledge questions us too. Sometimes by its originality, more often by its gravity, it urges us to deepen the field of knowledge to better understand causes, mechanics and consequences and, potentially, to propose levers of action.

Then there are the gaps, shadows and persistent mysteries around the theme. Some of these disappear with the accumulation of work in a discipline and the renewed interest of researchers in understanding what cannot be easily explained. Others – and this is particularly the case for problems associated with our book – are illuminated thanks to the cross-fertilization of several disciplines, with which we are able to fully grasp the intricacies of complex problems, but above all thanks to the interdisciplinary toolbox that can unravel them.

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These reasons, although important, are not specific to mineral resources. Therefore, a detour through different time horizons may shed some light on the role of these particular resources for human civilizations. We shall then see in what particular context they come into play.

I.1. Why are mineral resources important?

Observation of the past can provide welcome insights. If we had been able to measure the material footprint of *Homo sapiens* in the early days, we would probably have been able to see that they relied only very partially on mineral resources, with the possible exception of the manufacture of tools such as flint or the bifaces inherited from their ancestors. History evolved radically with the passage of the Neolithic revolution. The three characteristics of this revolution – sedentarization, the production economy and the adoption of a new form of social organization – are still debated among researchers, particularly with regard to their simultaneity.

However, this "new stone age" (also called Neolithic) was accompanied by a renewal in the consumption of materials because a sedentary lifestyle, agriculture and the development of denser settlements required more resources. The role played by polished stone (like axes) therefore intensified. Pottery, although pre-dating the Neolithic period, also served as a cornerstone for the development of trade. The surpluses generated by agriculture allowed for a first step towards the specialization of tasks and certain types of resources (tools and other rare resources) could then be distributed where they were lacking via a vast network of exchange controlled by the elites, producing an extension of the human frontier (Barbier 2011). Humans thus generated the first profound modification of their environment. Later, technical innovations based on the mastery of extraction and the isolation of new mineral resources marked history, through the Bronze Age (3000 BCE) and then the Iron Age (1200 BCE).

Although the extraction of these mineral resources became more widespread and was, therefore, an integral part of the development of human civilizations, minerals remained a scarce resource. For example, the price of iron in the eponymous era varied at that time between eight times the price of gold and twice that of silver (Virolleaud 1953). In the 17th and 18th centuries, another revolution, that of industry, was born at the same time as the massive extraction of another mineral resource: coal. The civilizations of Europe then moved from agricultural and artisanal societies to industrial societies, and thus withdrew a little more from the rhythm imposed by the biosphere.

This mastery of a new form of energy from a more abundant and concentrated stock than biomass, accompanied by the development of knowledge (physics and chemistry), gave rise to a new surge in the production/consumption of mineral resources. For example, the production of copper rose from 216,500 tons per year in 1800 (about the level of the Roman period) to more than 500 kt per year in 1900 (Hong *et al.* 1996). This century also marked the discovery of new elements that expanded the seven metals known since Antiquity. Finally, the generalization of industrialization and of the Western way of life spread throughout the world from the contemporary period (since 1945), leading to another leap in the consumption of already existing mineral resources, as well as to a surge in the production of small metals that had hitherto remained confined to the role of curiosities. However, this last period, although recent, brought with it a new and deep mark of humans in their environment. The latter itself became the primary force of change for the geosphere, the biosphere and the climate. Is history moving into a new era – the Anthropocene (Steffen *et al.* 2015)? While the opening of a new era is still under debate, it is clear that a look back leads us to believe that *each time humans free themselves a little more from the constraints and temporalities that their environment places on them, they do so by making more intense use of mineral resources*.

Beyond the past, mineral resources also shape the present. If the climate crisis remains, at first glance, regularly associated with an increasing use of fossil resources (coal, gas and oil), a more seasoned analysis, like that of historian V. Smil (2013), shows that a great part of this energy is dedicated to the extraction, production and provision of material resources for the economy. Thus, according to his book, 20% of the world's primary energy is used for the production of materials, including 13% for mineral resources alone (10% for metals and 3% for construction materials), which is roughly the size of the United States in the world's primary energy consumption. This major role of mineral resources in energy consumption is closely related to their environmental impact in terms of greenhouse gases (GHGs), insofar as the energy used remains predominantly carbon-based (Mudd 2010; Northey *et al.* 2013). *Our relationship with mineral resources is, therefore, not unrelated to the current climate crisis and other environmental issues*. Indeed, the latest UNEP report (2019) indicates that the predominance of metals in the environmental impacts of natural resources. Thus, metals account for 18% of the impacts in terms of greenhouse gases related to resources and 39% of the effects of particles on health and the environment. Other non-metallic mineral materials, although representing the bulk of the mass and experiencing the strongest growth, generate less environmental stress on a global scale (less than 2% of total resources), though there are exceptions here again, particularly when looking at cases of local degradation. Most of the impact of this other important category of mineral resources today comes from their use in cement and fertilizer production.

While the role of mineral resources in today's issues is not disputable, they also appear repeatedly in the utopias of our time, particularly that of the circular economy. Therefore, they are also a part of the future considered (fantasized?) by the new thinkers of sustainable development, alongside renewable resources (biomass and renewable energies). The words change according to the context: circular economy, symbiotic economy (Delannoy 2017) or blue economy (Pauli 2011). What these concepts have in common, however, is that they draw on the circularity present in natural ecosystems to ensure the sustainability of human economic systems. *In this framework, mineral resources, because they are mostly recyclable, clearly fall within these concepts evoking the intrinsic regeneration of future economic systems*. For example, stone paper, a mixture of calcium carbonate and high-density polyethylene is often advanced by Pauli as a practical example of the blue economy (Pauli 2011). This new form of paper does not use water and can theoretically be recycled *ad infinitum* (no pilot factory for the moment). The symbiotic economy is also inspired by industrial ecology, evoking the "Kalundborg Symbiosis", the industrial eco-park of a Danish port city where the unwanted by-products of some manufacturers become inputs for others. Here, again, mineral resources will play a key role as some future activities are expected to continue to mobilize capital, often through the use of metals and other non-metallic resources, as is the case with most mobility solutions, whether or not they fit into the economy of sharing or functionality.

Mineral resources have played a major role in many periods of human history and will certainly continue to accompany it in its development. Made use of in the fight against global warming, the energy transition and the switch to renewable energies are, nevertheless, raising new questions in the scientific community. Indeed, increasingly important evidence seems to confirm the existence of a growing relationship between the consumption of mineral resources and the development of renewable energy.

I.2. Should we fear a new mineral jump caused by the decarbonation of energy?

To our knowledge, the first study to have reported on this hypothesis is that of Lund (2007), a material intensity analysis of the different electric production technologies. Later, other general studies confirmed this hypothesis (Kleijn *et al.* 2011; Phihl *et al.* 2012; Ashby 2013; Elshkaki and Graedel 2013; Vidal *et al.* 2013). At the same time, other analyses have also raised the greater sensitivity of green energy to specific categories of mineral resources like rare metals (Yang 2009; Kleijn and Van der Voet 2010; Elshkaki and Graedel 2013; Fizaine 2013; Moss *et al.*

2013). *Generally speaking, these scientists highlight the greater consumption of materials and metals caused by the use of green energy and also more broadly by decarbonated energy* (we thus compare fossil fuels without CO_2 capture and sequestration and fossil fuels with CO_2 capture and sequestration). This means that, with constant electricity production, the shift towards a greener electricity mix should lead us to consume more metals (and mineral resources).

For example, the latest study to date, that of BRGM (Boubault 2018), sheds an interesting light on the material footprint of electricity production systems. Through a lifecycle analysis, and in contrast to previous studies, it shows that fossil fuel-based electricity production systems are more intensive in raw materials per kWh, on the one hand because they consume large amounts of fossil fuels and also because of the mining waste generated to access these fossil resources. Figure I.1 shows the material footprint of electrical systems in decreasing order of CO_2 equivalent emissions. If we focus on the material footprint, the energy transition appears to be consistent with a policy of resource conservation. Coal is far ahead at more than 2,715 kg/kWh compared to only 0.036 kg/kWh for hydropower. Renewable energies continue to consume fossil fuels for their construction but in much smaller proportions than fossil fuel-based electrical systems. A more specific analysis of the metal footprint reveals a much less clear general pattern (Figure I.2). Here, geothermal energy, followed by wind and concentrated solar power, now appear to be the highest in metal consumption.

Conversely, other renewable energies, such as photovoltaic energy and biomass, and hydropower even more so, do as well as nuclear or fossil fuels. If we follow the results of this study, the metal footprint of the electrical system would not necessarily increase in case of decarbonation; it would all depend on the precise content of the energy transition and in particular the respective shares of each of the renewable energies. An even finer analysis by metal leads to even more disparate rankings (Figure I.3). Thus, Figure I.3 shows the share of metal consumption of the electrical system absorbed by each type of technology. Three main conclusions can be drawn from observing these results. Firstly, what is obvious is the significance of photovoltaics, which concentrates an important part of the consumption of several minor metals (tantalum, gallium, indium, strontium) and also of some major metals (aluminum, copper, zinc and lead). Secondly, nuclear power monopolizes a much more limited range of metals and also plays a major role (uranium, platinum, lithium, titanium oxide, chromium, nickel). Thirdly, the consumption of wind power, also significant, remains rather concentrated on major metals (iron, copper, manganese, nickel, chromium). As things stand, other forms of electricity production consume smaller quantities of metals. This study concludes that the shift to a "clean" mix, as described in the International Energy Agency's *World Energy*

Outlook, should, at a constant amount of electricity produced, increase the electrical system's consumption of iron by 23%, copper by 242%, silver by 633% and tellurium by a factor of 10. Of course, these results must be put into perspective, particularly because we do not take into account the importance of the production of these metals and the potential for production increases, since the current consumption of the electrical system plays a minor role in the consumption of most metals.

Of course, these studies also bring with them other areas of shadow, on the one hand because they often reason in isolation; that is, they consider only the material necessary for the manufacture of the wind turbine but not necessarily the mining waste brought by the extraction of the neodymium incorporated in the permanent magnets of the latter (except for this last study). On the other hand, the environment is often excluded from the electrical production system. So, what about the material footprint of the connection of offshore wind turbines and back-up, smart-grid or storage solutions necessary for intermittent renewable energies to perfectly replace fossil fuels? In the same vein, these studies often ignore the intra-technological complexity of power generation systems by considering only large groups (onshore wind, offshore wind, photovoltaics, etc.), whereas there is a significant intra-technological variability in the material footprint, especially for certain specific metals. It may be added that while the share of electricity in the energy mix is expected to increase in the future, metals used in the energy sector are not limited to the production of electricity alone, but also concern other sectors of energy production or use, which themselves consume metals (LEDs, batteries, electric vehicles, etc.). Finally, reasoning in partial equilibrium, ignoring other sectors, induces large blind spots, for example by ignoring the conflicts of use between the digital and energy sectors for metals such as cobalt and lithium (electrochemical batteries) and also indium and gallium (flat screens, printed circuit boards and thin-film PVs).

However, more than these studies, the awareness of the media, the public and decision-makers has probably taken place through the epiphenomenon of the rare earth crisis (used in many offshore wind turbines). The soaring price of lanthanides quickly triggered deep concerns among industrialists and the general public. And what if, beyond the geopolitical crisis, our world was to enter a mining impasse, sending the boom in renewable energies halfway into limbo for lack of metals?

Moreover, the many reports and photos of workers in artisanal cobalt mines in the Democratic Republic of Congo and in rare earth mines in China remind us that environmental sustainability in industrialized countries is meaningless if it is not also part of a socially just and economically secure support for all citizens of the world.

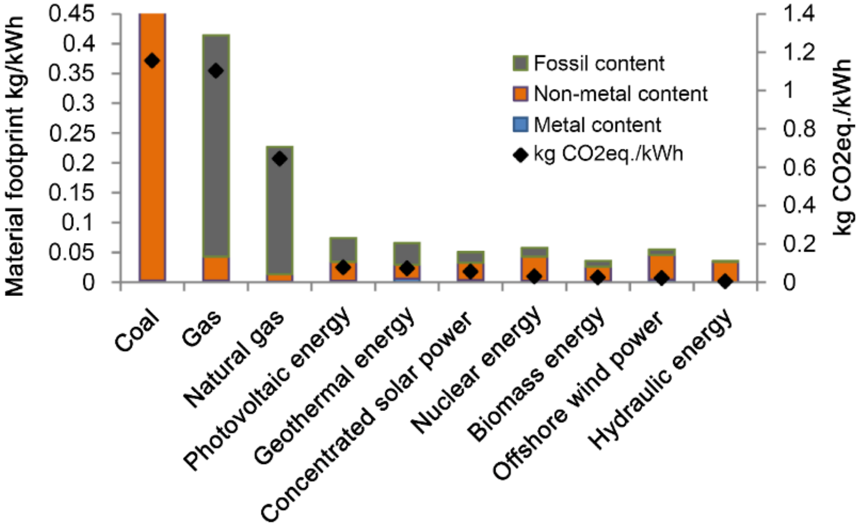

Figure I.1. *Material footprint of various power generation production systems (source: data from Boubault (2018)). For a color version of this figure, see www.iste.co.uk/fizaine/mineral1.zip*

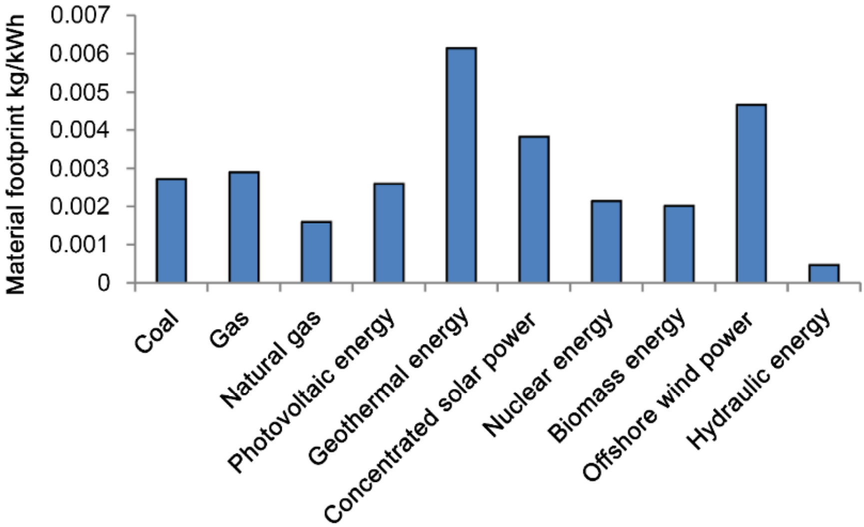

Figure I.2. *Metal footprint per kWh by type of power generation system (source: data from Boubault (2018))*

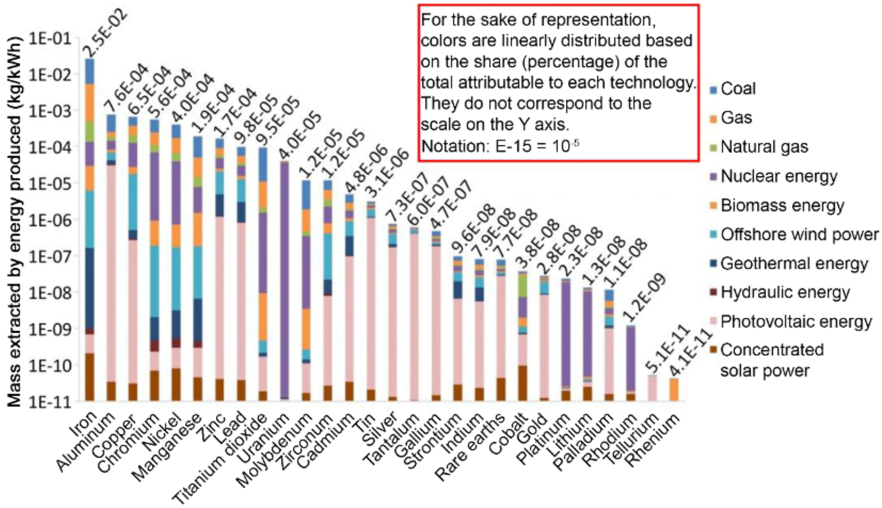

Figure I.3. *Share of metal footprint of the electricity sector by power generation system (source: data from Boubault (2018)). For a color version of this figure, see www.iste.co.uk/fizaine/mineral1.zip*

Although a number of technological impasses have been identified and many points of tension on particular resources must be thwarted with these insights, the realization has nevertheless opened up a lot of thinking on all fronts.

I.3. Systemic mechanics associated with multiple corollaries: insights provided by interdisciplinarity

This book aims to explore, identify and explain the possible bottlenecks associated with the use of mineral resources. *The question of the use of mineral resources does not only arise in terms of the quantities available. An open, prospective and interdisciplinary reflection is, thus, necessary to accomplish this task.* We have, therefore, mobilized a large team of researchers and thinkers on various issues associated with mineral resources. There are economists, of course, and also physicists, engineers, geologists, lawyers and geographers. This book also helps to bring together specialists working on this theme, often still too isolated and without any real lasting connections. Of course, there are many initiatives, such as the *Association française des économistes de l'environnement et des ressources* (FAERE, French Association of Environment and Resource Economists), the team around the "Cyclope" report or the contributions to the mineral-info.fr site, but these are still too fragmented or monodisciplinary compared to other much more unified fields like energy. It is also because energy is already entitled to large interdisciplinary teams that we have chosen to focus on mineral resources and exclude energy minerals from our scope of analysis.

To initiate this reflection, we have decided to adopt a structured approach based on three axes: context, issues and leverages of action, spread over two separate volumes. In Volume 1 of this work, the first axis – context – retraces a few elements that allow for a better understanding of the situation of mineral resources.

First of all, while mineral resources are at the heart of the most advanced technologies, a detailed knowledge of their flows is required in order to assess their demand. This is what Raphaël Danino-Perraud, Maïté Legleuher and Dominique Guyonnet (Chapter 1) focus on in relation to the cobalt market. For example, extraction and refining are highly concentrated in the Democratic Republic of Congo and China, respectively. The assessment of its demand in Europe uses the so-called "material flow analysis" (MFA) approach, which traces these flows and takes into account the multiple forms and uses of cobalt and its recycling possibilities, all the way to the "urban mine". This MFA of cobalt, coupled with a value chain analysis based on European data, makes it possible to question the strategies of European groups that, anxious to position themselves in high value-added segments, end up dependent on operators working upstream (extraction and refining).

Some mineral resources are financialized while others are not and this has important consequences on the transparency and price dynamics prevailing in these markets. With this in mind, Yves Jégourel (Chapter 2) describes the role of the financialization of ore and metals. More specifically, the author reviews the organization and mechanisms of futures and their alternatives. The author also discusses the effect of financialization on the dynamics of mineral prices and also on the transformation of the sectors using them.

Beyond the financial aspects, the supply of mining resources is also part of institutions – in the first place, state policy. As such, not all countries seem to follow the same rules. While many have established a doctrine for the management of energy resources, this is not the case for mineral resources. Didier Julienne (Chapter 3) attempts to deconstruct the myth that countries are genuinely opposed to each other in order to get their hands on metals. In reality, countries such as China, which has a real resources doctrine, are advancing their pawns to secure their future supplies without encountering any real resistance from industrialized countries. The author calls for the reconstruction of a genuine resource strategy in Western countries and for stopping the over-reaction to often truncated economic information.

To assess the amount of mineral resources available to our economies, we use indicators that we rarely question. This is what Michel Jébrak (Chapter 4) does do. In particular, he demonstrates that mineral endowment is a complex concept that can be measured using different parameters: the annual production of a specific mineral and its reserves and their ratio, which can vary in terms of upward or downward trends for different minerals. This endowment can be generalized by the notion of basic reserves, which attempts to assess the overall geological potential of a given metal. If mineral resources are unevenly distributed geographically, their exploitation moves from one country to another according to the movement of industrialization, as in the case of the main copper and tin mines. Ultimately, mineral endowment is a historical construct, dependent on geological data, mineral extraction and processing technologies, and on the economics of mining, which is a capital-intensive industry.

The second part of this book reports on the *challenges* that mineral resources face. They concern the multiple factors that can affect the supply of mineral resources.

In a chapter focusing on the struggle between technical progress and the geological depletion of metal deposits, Olivier Vidal (Chapter 5) shows how two antagonistic approaches (optimistic and pessimistic) can be pooled into a formal approach of dilution–energy and energy–price relationships. Using formal theoretical tools, as well as empirical calibration on past data, he questions the perpetuation of observable price declines for most metals. This downward trend in prices should be reversed by the end of the century if the rate of technical improvement remains the same and if we continue to exploit increasingly less concentrated deposits.

Measuring the environmental footprint of mineral resources is a challenge that Jacques Villeneuve and his co-authors at BRGM propose to take up (Chapter 6). Indeed, the environmental footprint of human activities goes beyond its sole measurement in terms of surface area used to take into account all the environmental impacts on the lifecycle of products. The aim here is to measure this footprint using an extended input–output table (IOT) that determines the consumption of mineral resources and their environmental impacts, induced by final demand with a fine level of disaggregation. These IOTs are then interconnected within a multi-regional model to assess the final impact, including imports, of national demand. In spite of limitations related to the difficulty of obtaining databases comparing data on a global scale, it can be seen that the environmental footprint of the demand for metals required for French final demand is mainly made abroad.

Since the use of mineral resources is part of an economic issue, Romain Debref (Chapter 7) is interested in aspects related to environmental efficiency (energy and material) often implemented in many technologies in order to save resources and energy. He gives an overview of the history of eco-efficiency through the various movements that support it and its limits in terms of the originality and purpose of the concept. In a second step, he details the many forms of rebound effects that still hinder eco-efficiency.

We tend to forget this, but most of our consumption of raw materials requires some countries to specialize in the extraction of these resources. Yet a significant number of these countries have poorer economic health than countries without resources. Audrey Aknin (Chapter 8) shows the main factors that contribute to this resource curse. Far from the simple paradox of abundance, the resource curse is rooted in a variety of channels such as Dutch disease, increased income-seeking behavior, organizational failure, institutional dysfunction, corruption and civil war. The chapter also provides an overview of the recurrent failure of the various tools supported by international organizations to contain these phenomena. The author concludes with a few examples of countries that have successfully avoided the resource curse and the options that are now favored.

The increase in the supply of mineral resources also faces social and legal issues. Thus, Victoire Girard and Agnès Zabsonré (Chapter 9) demonstrate that the exploitation of natural resources can make a major contribution to the process of economic growth and development and that a significant part of the populations of low-income countries depend on the exploitation of mineral resources through artisanal mining. The impact of this exploitation is a controversial issue, leading to a resource curse in some cases, or economic benefits in others. Industrial mining can certainly have some positive local economic impacts, depending on the quality of governance of local institutions and their ability to create economic benefits for related industries. However, artisanal mining appears to have a greater positive effect on the consumption, incomes and well-being of the local population. The long-term impacts on well-being, as well as on health through local pollution, are more uncertain and should be better documented by further research.

In Volume 2, Emmanuel Hache and his co-authors (Chapter 1) review the criticality approaches recently deployed to analyze the new risk caused by the surge in raw material needs for the energy transition. Their overview of the studies leads them to question the absence of a homogeneous theoretical framework and to underline the weaknesses of current indicators (the Herfindahl–Hirschman Index (HHI) and the World Governance Index), particularly with regard to geopolitical aspects. While cartelization attempts in raw materials markets have all failed in the past (with the possible exception of OPEC), this fear is resurfacing today given the significant concentration of metal markets for oil. Researchers are showing what is really going on with lithium, cobalt, copper and rare earths. Finally, the authors discuss the values of different forms of public policy to manage commodity supply risk.

We will also see that more mineral resources uses also mean more extraction. However, the opening of new deposits according to their location does not go without posing legal problems. Stéphanie Reiche-de Vigan (Chapter 2) proposes a review of the different legal regimes affecting mineral resources. She discusses issues related to the domestic law of territorial mineral resources through the French and American cases. The question of the exploitation of mineral resources is posed differently in international law, depending on whether the resources are territorial (in the case of the seabed of the continental shelf) or extraterritorial (the seabed of international waters and the Antarctic). She explains that the current legal regimes are insufficient, often truncated and do not guarantee respect for all aspects of sustainable development.

Finally, Michel Deshaies (Chapter 3) traces how the presence of mineral resources influences the evolution of settlement mechanisms throughout history. In particular, the author shows that settlement mechanisms present historical, regional and material disparities (differences between metal and coal deposits). He also observes that territories where mining activities are carried out have to overcome several obstacles, such as recurrent conflicts with local populations, and also huge reconversion challenges for the post-mining period.

In a third problematic, we propose to explore the major leverage actions often perceived as answers, or elements of answers, to the challenges mentioned above: domestic mining, substitution, decoupling (or material efficiency), recycling and the sobriety associated with the concept of low-tech.

To begin with, Johan Yans (Chapter 4) discusses the interest of domestic extraction on European soil. Although still relevant in Europe, production from European countries that have maintained or developed a mining supply remains marginal in comparison with their needs. This inevitably results in a significant dependence of European industries on imports of mineral resources. As the author reminds us, however, there are inherent gains from the domestic extraction of existing and well-characterized resources: environmental gains linked to short circuits, the stimulation of local employment and the substitution of imports sometimes extracted under disastrous conditions. Nevertheless, major obstacles remain, such as a lack of professional skills (after training that has fallen into disuse since the 1990s) and above all local opposition generated by an often negative public perception (NIMBY syndrome). This is not inevitable and the author looks at the leverage action likely to reduce these dissensions.

Through the analysis of another unavoidable leverage action, Florian Fizaine (Chapter 5) proposes to explore the standard theory underlying intra-material substitution. In particular, he returns to the notions of the demand curve, price elasticity and cross-price elasticity of demand while underlining their shortcomings and limitations when applied to mineral resources. In particular, he sheds light on this lack by evoking the heterogeneity of situations according to the different scales of material sub-constitution. Lastly, he concludes by explaining the multiple technical, economic, socio-cultural and legal constraints that limit material substitution.

Thierry Lefèvre (Chapter 6) reviews empirical studies analyzing the decoupling (dematerialization) between GDP and the various indicators of raw material consumption. He shows that decoupling is at best relative and not absolute, as would be desired by international organizations promoting sustainable development and energy transition. These decoupling indicators also leave aside several important issues, such as inequality and the quality of life of populations. These other dimensions must be taken into account in the future to achieve true sustainable development.

A little further on, Alain Geldron (Chapter 7) describes how recycling activities have been gradually implemented in different countries. Although there are some similarities, traditional mining and urban mining are different in terms of logic and economic model. The author then examines the main factors for the efficiency of recycling through its successive stages (collection, transport, etc.). Finally, he also discusses the most important constraints on recycling and whether they are related to the recycling stage or to the type of metal recycled.

In the final chapter, Philippe Bihouix (Chapter 8) argues that it is impossible to achieve a complete circular economy through recycling and dematerialization. Therefore, frugality and a particular form of ecodesign should be favored, namely the concept of low-tech. He also insists on the importance of choosing the right scale to implement these, on the primary role of humans in their reparability and finally on the need to pursue a new utopia with positive results expected for people in order to achieve this necessary ecological transition.

To conclude, we discuss the main lessons established by these contributions and also the other questions they left open. While the various contributions have shown that the limits to growth no longer lie in the depletion of mineral resources and fossil fuels but in the impact of their exploitation on the environment, all the proposed solutions have their limits, whether it is technical progress, recycling or the circular economy. What remains is the use of greater frugality in our behavior, on the condition that this frugality is not suffered by the most disadvantaged. In any case, we hope that the insights provided by this collective work will call to others on the long road that remains to be traveled to reach sustainability.

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PART 1

Background

Mineral Resources Economics 1: Context and Issues,
First Edition. Florian Fizaine and Xavier Galiègue.

1

Assessment of European Demand for Mineral Resources by Material Flow Analyses: The Case of Cobalt

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1.1. Introduction

The growth of technological innovations in recent decades, especially in renewable energies (REs) and information and communication technologies (ICTs), has led to an ever-increasing consumption of elements of the periodic table used for very specific functions. This has led to concerns about the capacity of their producers to meet demand (Nassar *et al.* 2015). Energy storage systems, especially lithium-ion batteries, are particularly concerned by innovations in ICT and RE. Sold at 4 billion units in 2017 (5.5 billion in 2020) and with a growth of 11% per year (Berthoud *et al.* 2018), the smartphone is the symbol of a digital transition with a high technological content, using an ever larger and more complex combination of metals. For their part, energy transition policies, implemented by most industrialized countries, are also encouraging the use of such systems, whether for transportation (electric or hybrid vehicles) or for stationary use, in order to store electricity production from renewable and intermittent but low-carbon energies. These technologies use a number of raw materials, including lithium, nickel, and cobalt.

Mineral Resources Economics 1,
coordinated by Florian FIZAINE and Xavier GALIÈGUE.

Rising tensions over raw materials, particularly mineral raw materials in the early 2000s, due to growing consumption and a sometimes constrained geographical location, added to the problem of their supply. Criticality studies have, therefore, been carried out in Japan (JOGMEC 2019), Europe (European Commission 2008), and the United States (NRC 2008) to determine which mineral raw materials are essential for the economy but are subject to tensions, whether geopolitical or linked to limited production capacities. Among all these metals, cobalt has always been a concern, regardless of the country under study. This metal in fact represents a summary of the problems related to critical metals. It is essential and hardly substitutable with the same efficiency for key industrial sectors (superalloys for the aeronautics industry or batteries). Its consumption has quadrupled since the beginning of the 2000s, which has led to severe constraints on production. The latter has a limited geographical area, since 72% of mining production is carried out in the Democratic Republic of Congo (DRC), of which 10% to 15% is artisanal production, and 65% is refined in China (Darton Commodities 2019). The instability and corruption prevailing in Congo raise doubts about the country's ability to ensure sustainable production, which encourages price volatility.

The European Union (EU) is particularly vulnerable with respect to its critical metal supplies, as it produces only 2% of its consumption and more than 50% of the 16 of the 27 elements identified in 2017 are produced by China (European Commission 2019). It is for this reason that the Critical Raw Materials Initiative (European Commission 2019) was established in 2008, based on three pillars:

– sustainable production of mineral raw materials within the EU;

– control of EU supply routes;

– a resource efficiency[1] and recycling strategy (European Commission 2019).

While the first pillar is strictly internal, the second and third pillars require a better knowledge of the actors and also of cobalt flows and stocks at the international level.

Due to its ever-increasing consumption in energy storage systems, which are key to the energy transition, the choice of a flow analysis of cobalt at the EU level seems relevant. Combined with an analysis of the value chain at the global level, it would make it possible, as Nuss and Bengini (2018) point out, to understand and anticipate vulnerabilities, thanks to better knowledge of the origin of flows, and also to better

1 "Resource efficiency means using the Earth's limited resources in a sustainable manner while minimizing impacts on the environment. It allows us to create more with less and deliver more value with less input" (European Commission 2019).

manage them at the end of their lives through better knowledge of stocks in circulation. The exploitation of the urban mine could thus partially offset the deficit in primary cobalt production.

According to Brunner and Rechberger (2004), a material flow analysis (MFA) consists of a systematic evaluation, within a system defined in time and space, of the flows and stocks of a given product. It delivers a complete set of information on the latter. As such, it can provide a better understanding of the demand and use of cobalt in Europe. This metal has been less studied than other metals considered more important, such as nickel, copper, and aluminum (Gerst and Graedel 2008). In fact, we can list only seven material flow analyses dealing with cobalt since the late 1980s. In 2013, Asari *et al.* (2013) conducted an MFA of lithium-ion batteries in Japan for the period 2002–2010, revealing the low collection and recovery rate of cobalt. In 2012, through a dynamic method that allows for analyzing stock accumulation, Harper *et al.* (2012) focused on cobalt flows worldwide, then more specifically on their characteristics in China, Japan, and the United States, the three major countries in terms of consumption. For their part, Shedd and the United States Geological Survey (USGS) analyzed cobalt flows in the United States for the year 1992, focusing in particular on the rates of loss and recycling during the various production and use processes (Shedd 1993). Nansaï *et al.* (2012) worked on the origins and destinations as well as the cobalt contents of the different flows worldwide. Chen *et al.* (2019) insisted on the quantification and evolution of cobalt flows in China between 1994 and 2016 by analyzing the vulnerabilities they could reveal, while the consulting firm Deloitte (BIO by Deloitte 2015) carried out a dynamic MFA, but only showed data on incoming and outgoing flows at the EU level for the year 2012.

These various studies enable us to observe that there is no detailed (multiple year) dynamic cobalt MFA for the European Union, which was the third largest consumer of cobalt in the world in 2016 (between 15 and 20 kt), far behind China and in competition with the United States (Roskill 2016). We believe that such a work carried out for the years between 2008 and 2017 will, like the work of Chen *et al.* for China (2019), provide the necessary information for a better understanding of European consumption and vulnerabilities in cobalt supplies. This work is a prerequisite for a more efficient measurement of cobalt consumption and an improvement in the security of cobalt supplies. The first section presents an overview of the cobalt market, while the second focuses on justifying and presenting a combined value chain/material flow analysis methodology. Finally, the third section presents the results obtained and discusses their limitations.

1.2. Cobalt market: structure and operation

Cobalt takes its name from the prankster gnome of the German legends Kobold, accused from time to time of compromising the proper smelting of copper ores. Extracted at the same time as the latter, no process could isolate the cobalt or *a fortiori* prevent it from polluting the copper ore. The development of metallurgy and industrial chemistry from 1730 onwards made it possible to isolate it and then treat it after extraction, thus extending its lifecycle (Bihouix and Guillebon 2010). According to Nuss and Blengini (2018), there are four main stages in the lifecycle of a metal: extraction, transformation and refining, production and use, and the production and use of waste management (collection and recycling). Each step corresponds to one or two segments of the value chain.

1.2.1. *Diverse and highly concentrated resources*

Cobalt (Co) is the 27th element in Mendeleev's table. Fairly scarce in the Earth's crust (25 to 29 ppm), it is of average hardness and has a melting point of 1,495°C and a boiling point of 2,927°C. It is also a trace element essential to living beings, which is included in the composition of vitamin B12.

Cobalt is mainly exploited as a co-product of copper and nickel[2]. It is extracted from four types of deposits:

– stratiform copper deposits (the Copperbelt of DRC and Zambia);

– magmatic copper-nickel sulfide deposits with cobalt and subordinate platinoids (Norilsk in Russia, Sudbury in Canada, etc.);

– lateritic nickel deposits (New Caledonia, Cuba, etc.);

– hydrothermal deposits with cobalt dominant (Morocco), this last type of deposit being the only one where cobalt is exploited as the main metal.

In 2018, the USGS estimated the quantity of reserves at around 7 Mt (million tons) distributed between the DRC (3.4 Mt), Australia (1.2 Mt), Cuba (500 kt (kilotons)), Canada, the Philippines, Russia and Zambia (250 to 300 kt), with the remainder being shared by several countries including China, Indonesia, Madagascar, New Caledonia, and Finland. The resources were estimated at 25 Mt, mostly shared by the Democratic Republic of Congo, Zambia, Australia, Cuba, Canada, Russia, and the United States. According to the USGS, the concentrations of cobalt in polymetallic

2 According to Jebrak and Marcoux (2008), a co-product is "a metal recovered together with another metal in an industrial extraction process".

nodules and certain crusts on the ocean floor contain nearly 120 Mt. Nevertheless, the lack of knowledge of this type of deposit and the difficulties, both environmental and technological, make them unexploitable under present conditions (Shedd 2017)[3].

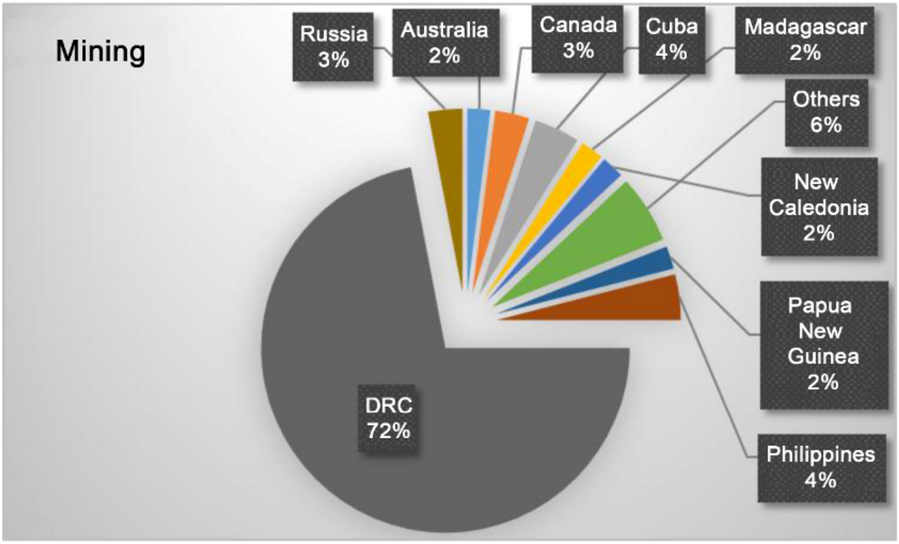
1.2.2. *Production and actors*

In 2018, cobalt mine production (see Figure 1.1) came mainly from the Democratic Republic of Congo (72% of production), while the EU had a small presence (1% of world production in Finland) (Alves Dias *et al.* 2018). Recent years have also seen the emergence of new players such as Madagascar, the Philippines, and Indonesia through nickel mining, while New Caledonia and Papua New Guinea are gaining momentum (Darton Commodities 2019; WMD 2019). When world production reached 140 kt in 2018, Glencore produced around 30 kt tons through four mines (Katanga and Mutanda in the Democratic Republic of Congo, Murin-Murin in Australia, and Sudbury in Canada), while seven Chinese companies (including China Molybdenum, Huayou Cobalt, Jinchuan, etc.) produced approximately 46 kt tons, mainly in the Democratic Republic of Congo through property buyouts or equity investments in projects. Companies such as Vale (Brazil), Implats (South Africa), Nornickel (Russia), ERG (Kazakhstan), Managem (Morocco), and Sumitomo (Japan) shared the rest of the market (Darton Commodities 2019).

Approximately 126 kt of refined cobalt was produced in 2018 (see Figure 1.1), with China accounting for 65% of this production through companies such as Huayou Cobalt, Jinchuan Group, GEM, and Ganzhou Yi Hao. Europe is the second largest player in this segment, producing approximately 15% of the total in Finland at Kokkola (formerly Freeport MacRoan, now Umicore, 12%), in Belgium (Umicore, 1%) and at the Nikkelverk refinery in Norway (Glencore, 3%). It should be noted that the French company Eramet produces a few tons of cobalt from the processing of nickel mattes[4] at the Sandouville plant.

3 Resources and reserves represent “all known deposits that could be exploited when technical and economic conditions permit” and “the share of resources that can be technically and, above all, economically exploited”, respectively (Geldron 2017).

4 The Co production figures held by Eramet are unclear. Darton Commodities and Roskill indicated a few hundred tons in 2017 and 2018, but Eramet’s reference document does not mention this. Elementarium gave the figure of 48 tons of Co contained in cobalt chlorides in 2018. There would have been no production in 2017 due to the restructuring of the production line to process Finnish mattes.



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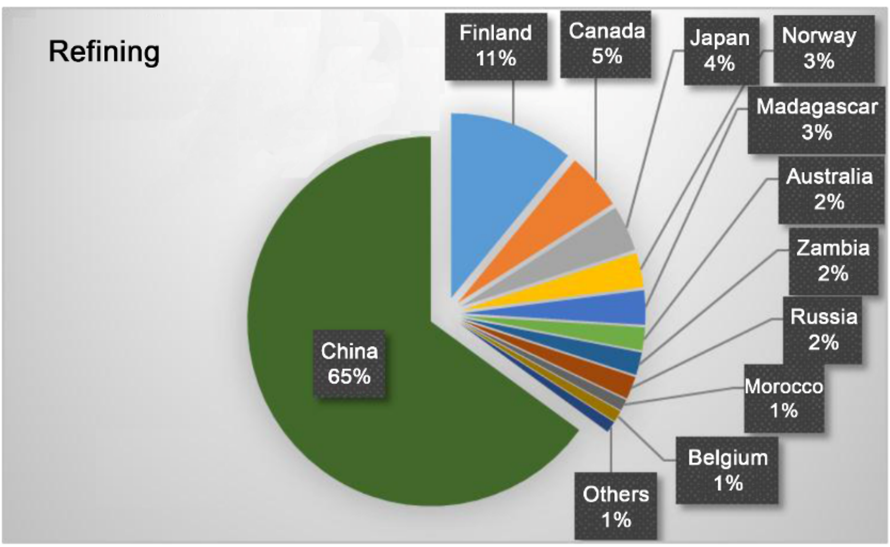


b)

Figure 1.1. *Cobalt mining and refining in 2018 (based on Darton Commodities (2019))*

Cobalt production has more than doubled in ten years from 59.6 kt in 2009 to 126 kt in 2018 (Shedd 2010, 2019). The consumption of cobalt has also changed significantly, with 34% of cobalt used in batteries in 2009 and 54% ten years later. Superalloys (aircraft engines and turbines for power plants) and cemented carbides (tungsten carbides, cutting tools, etc.) were still the second and third largest consumers of cobalt in 2018, although their share had decreased (see Figure 1.2).

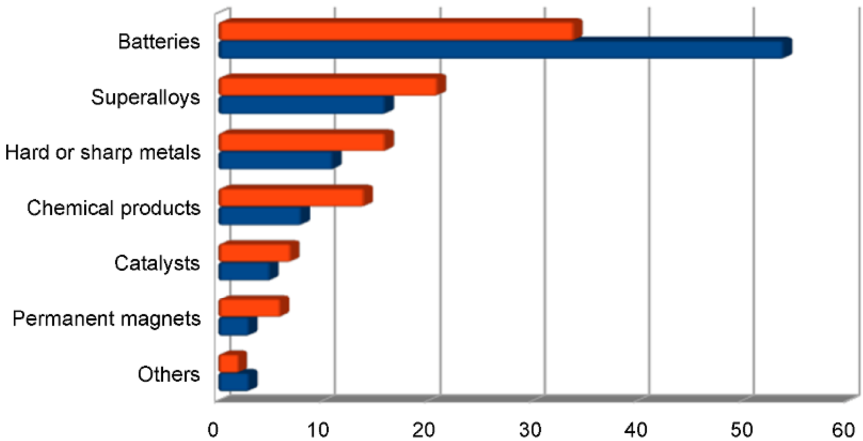


Figure 1.2. *Change in cobalt consumption between 2009 and 2018 (%) (based on Roskill (2016); Darton Commodities (2019))*

In 2013, the United Nations Environment Programme (UNEP) estimated that the end-of-life (EOL) recycling rate for cobalt reached 68% (Reuter *et al.* 2013). However, this figure is debatable since, as we shall see later, batteries are rarely collected and recycled, superalloys are not systematically functionally recycled[5], and dissipative uses (chemicals) cannot be recovered. For their part, Roskill (2017) and Darton Commodities (2018) indicated that the quantity of cobalt recycled was between 10% kt and 15 kt per year, that is between 10 and 15% of world consumption. This corresponds to another method of calculation, the consumption of recycled cobalt over total consumption (recycling input rate or RIR). In 2015, Deloitte gave an RIR of 35.5% for the EU. However, this was the share of recycling at all levels of the value chain (mine tailings, production offcuts, etc.) and not just end-of-life recycling. Finally, Harper *et al.* (2012) gave an EOL recycled content (RC) of 22%, adding 10% degraded recycling, or 68% cobalt lost from all end-of-life products containing it.

5 "Functional recycling is the part of end-of-life product recycling in which metals are separated and sorted to obtain recycled materials that can be used in the manufacturing process of a metal or alloy" (Centre national de la recherche scientifique 2016).

There are, therefore, several ways to calculate and understand the recycling rate, the figures of which are sometimes used without the necessary understanding of their meaning.

1.2.3. *A market undergoing profound change*

The last 20 years have seen a profound transformation of the cobalt market, both in the redistribution of its production and consumption. The Democratic Republic of Congo, which produced only 20% of cobalt in 2000 and 40% in 2009, now extracts 72%. China, which refined only one third of cobalt in 2009 (20 kt), has almost quadrupled its capacity (72.5 kt). China's rise in the cobalt value chain has also resulted in several asset acquisitions by Chinese companies, including China Molybdenum's acquisition in 2016 of the world's second largest cobalt mine, Tenke Fungurume (TFM). Refined production increased fivefold, while batteries accounted for more than half of consumption. This change in the market is leading to an in-depth transformation of refined cobalt production as the production of battery chemicals (sulfates) replaces cobalt metal. In 2019, the latter accounted for 70% of refined cobalt production (for more details on the different types of refined products, see Figure 1.3).

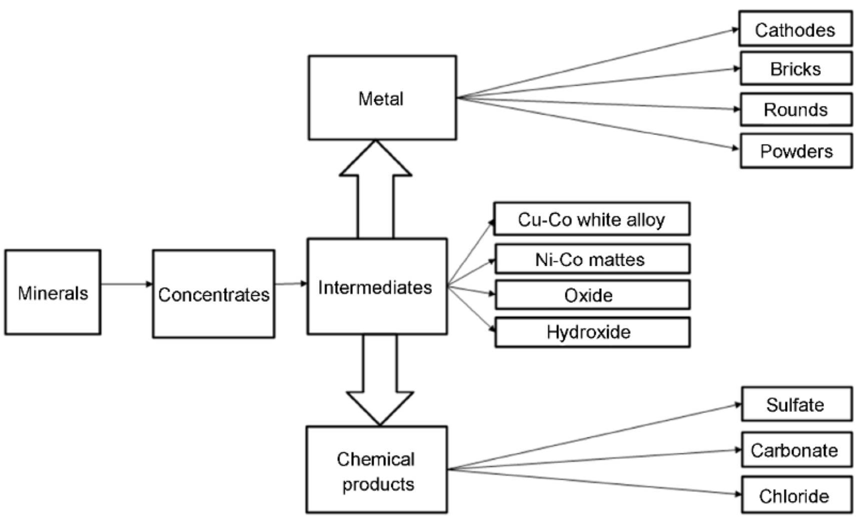


Figure 1.3. *Production of refined and semi-refined cobalt, by product type (according to Aurélie Gaudieux (BRGM))*

As a sign of its importance to the world economy, cobalt has been listed on the London Metal Exchange (LME) since 2010 to improve the transparency of its market and allow commercial players to hedge against price variations. After its price was stabilized at around $33,000 per ton in early 2017, cobalt reached its highest level in March 2018 ($95,000 per ton) and dropped to $55,000 per ton at the end of 2018 and $24,000 in April 2019. However, futures allowing for the quotation of cobalt use aircraft-grade cobalt cathode as the underlying asset (99.8% purity), given the extent of its past use. The increasing use of cobalt sulfate in batteries makes the quotation mechanism less relevant since the exchanges are made on chemicals and intermediate products (cobalt mattes, oxides, hydroxides, etc.) for further processing. The opacity of prices and quantities therefore persists.

1.3. A method combining value chain analysis and material flow analysis

Studying the cobalt market requires a combination of two complementary methods – analysis of its value chain and analysis of material flows. To our knowledge, few authors have explicitly addressed the combined use of these two methodologies. A value chain analysis integrates the quantities produced and the products manufactured, whereas an MFA is based on the different stages of production of an element. These two methodologies have a common basis – the lifecycle of a component or product – from which they draw inspiration to define segments and linkages, flows, and stocks (Dahlström and Ekins 2006; Nuss and Bengini 2018). Value chain analysis focuses on analyzing an object, in this case the market for cobalt, its supply and demand structures, and its stakeholder strategies. It aims to study the creation of value throughout the process of transformation and distribution of a product, from the raw material to the final product. For its part, the MFA highlights the object of the analysis as such and therefore the origins and destinations of the flows, their constitution in different types of stocks, as well as their quantities and their future. It completes the analysis of the value chain by quantifying it while drawing inspiration from the latter's work to understand the evolution of stocks and flows of certain products (Gereffi *et al.* 2005; Dahlström and Ekins 2006; Machacek *et al.* 2017). Many authors are interested in these interactions between actors and materials. Thus, Saurat and Bringezu (2008, 2009) analyzed the constraints encountered by platinoid producers with regard to energy and pollution, while Mudd (2010) showed the determination of the industrial processes of nickel processing by the geological characteristics of the ores. For their part, Schmidt *et al.* (2016) have researched nickel and cobalt extraction and processing sites to analyze their impacts on the production of lithium batteries.

1.3.1. *Value chain methodology*

1.3.1.1. *Value chain and competitiveness*

The concept of the value chain emerged from Wallerstein and Hopkins's (1977) work on primary commodity chains within "world systems" as well as from supply chain research (Dubois *et al.* 2004). Michael Porter created this concept in the context of globalization and increasing competition between developed and developing countries. In his mind, the value chain was to be a strategic tool for understanding and improving the competitive advantages of a company's three components: costs, organization, and technology. The acquisition of information, its analysis, and its application are the central elements of this tool to gain this competitive advantage (Porter 1985).

The value chain is nested within what Porter calls a multi-link value system. Indeed, the different activities within a given segment as well as the support functions are intralinked activities, unlike those between the different activities of a value chain, which are interrelated (Kaplinsiky and Morris 2001). Thus, the raw material extraction function is part of the battery value system, but is itself a value chain. A company can also operate on a single segment of a chain (horizontal operation) or on several segments (vertical operation) (Kogut 1985) (see Figure 1.4).

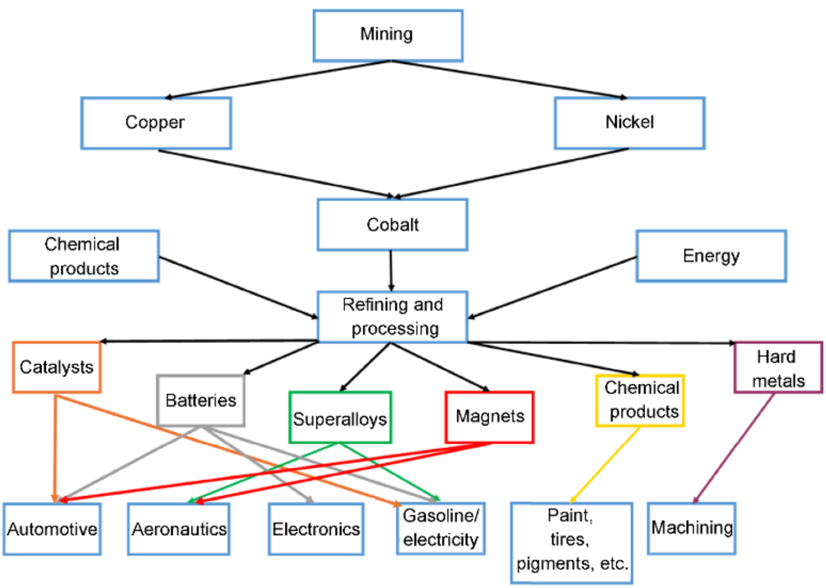


Figure 1.4. *Multi-linked cobalt value chain. For a color version of this figure, see www.iste.co.uk/fizaine/mineral1.zip*

While corporate competitiveness is the central theme of Michael Porter's argument, he does not lose sight of the fact that nations are the main actors in the international system and that they are in economic competition with each other. While the firm creates the economic and strategic value, the nation must somehow give it the competitive advantage by offering it good conditions for development (Porter 1990). Analyzing the rare earths value chain, Machacek and Fold (2014) confirmed the central role of the state in its development.

1.3.1.2. *The value chain as a tool for economic development*

A process of disintegration of global value chains has been observed over the last few years (Gereffi *et al.* 2005). Indeed, companies have concentrated on their core competencies by outsourcing support functions or segments that are less economically profitable. For his part, David Humphrey (1995, 2010, 2013) noted this fragmentation in the mining sector, a consequence of the nationalization processes resulting from decolonization and then of the structural adjustment policies provoked by the raw materials crisis at the end of the 1970s. While it was the rule that refining plants and mines were located in the same geographical area under the same owner, the privatization of assets focused on the most lucrative segments, namely refining and processing (especially in Africa), while many mines, considered less profitable and riskier, remained state owned. The political-economic situation of the states concerned has been a decisive factor in the problem, their instability discouraging potential investors, most of whom are Western. However, the arrival of new Asian and Middle Eastern players has led to a new transformation of the metal industry (Machacek *et al.* 2017).

In a framework of economic development policy, Gereffi and Korzeniewicz (1994) considered value chain analysis as a tool for economic development. After an analysis of the value-added activities of a chain, the authors considered it necessary to focus on the actors and their capacities to appropriate this value even though production is geographically dispersed. This naturally raises the question of chain governance, which can take place at several levels (executive, legal, or legislative) and bring together actors from different horizons (companies, governments, NGOs, etc.) (Humphrey and Schmitz 2001).

While the two visions converge on the analysis of actors' strategies as an integral part of the analysis of value chains, Gereffi and Korzeniewicz (1994) add the notion of added value, linked to the technological mastery of different levels of production.

The latter is illustrated in Figure 1.5 and Table 1.1 (section 1.6), which show that the most advanced products, cobalt cathodes, powders, commercial oxides, and alloy parts (cobalt oxides and hydroxides, or products from cobalt matte flow and other cobalt metallurgy products) are also the most expensive and, therefore, the most value-creating. The degree of purification of cobalt is no longer the sole determinant of added value. This is also the case for the industry's ability to transform it into semi-finished and finished products, thanks to the mastery of specific and sophisticated technological processes.

On the other hand, the less advanced intermediate or primary products (nickel-based products, waste and scrap, certain products from the cobalt matte stream, and other cobalt metallurgy products, as well as ores and concentrates) are also the least expensive.

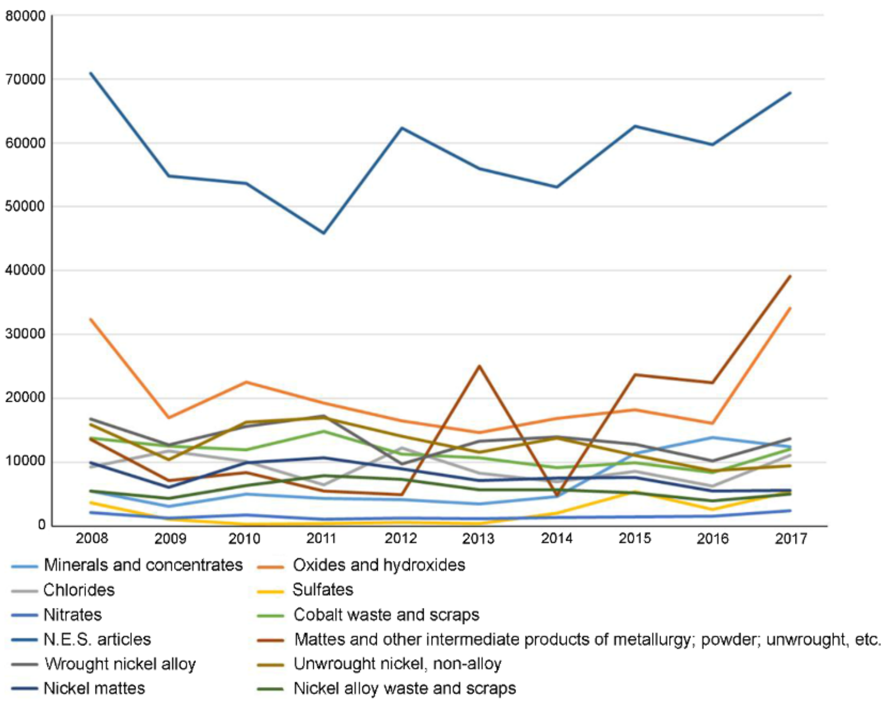


Figure 1.5. *Changes in import prices of intermediate products and refined products containing cobalt; 2008–2017 period (based on Eurostat (dollars)). For a color version of this figure, see www.iste.co.uk/fizaine/mineral1.zip*

1.3.2. *Material flow analysis, for a better understanding of cobalt demand*

1.3.2.1. *Origins and characteristics of material flow analysis*

The origin of the MFA can be traced back to the work of a Paduan physician, Santoro Santoro, in the 17th century, whose aim was to measure human metabolism (Brunner and Rechberger 2004). It was, therefore, originally a tool used by the experimental sciences, as underlined by its constant analogy with biology, the MFA wanting to measure the metabolism of given spaces and in particular anthropogenic cycles (Allenby and Cooper 1994; Chen and Graedel 2012). Thus, the objective of an MFA is akin to examining anthropogenic stocks and flows of material materials at each level of their lifecycle in order to gain a better understanding of their status above ground (Nuss and Bengini 2018). In fact, it has a multidisciplinary vocation because human activities are placed in a larger ecosystem that supports them, notably through the flows of materials and energy that result from them. They must be measured against the political, social, and economic factors that underlie them, but also through their impacts on the environment (Lifset and Graedel 2002).

MFA can be useful in economics because it allows for the incorporation of environmental or resource-related data into economic models (Fischer-Kowalski *et al.* 2011) or for measuring the impact of the economy on the environment (Ayres and Kneese 1969). MFA is also a tool with a geographical vocation, since it is necessary to determine its limits or boundaries, both territorial and between natural and political-economic systems (Fischer-Kowalski *et al.* 2011). This is why it can be used to measure the metabolism of a city (Wolflman 1965), an industry (Ayres and Simonis 1994), an economy (Fischer-Kowalski *et al.* 1998), or an anthroposphere (Baccini and Brunner 1991).

Several terms exist to qualify this methodology. While “MFA” is a generic term that we will continue to use throughout this chapter, substance flow analysis (SFA), applied to an element (chemicals or metal), or the analysis of a material in a system (AMS) are also concepts used (Stanisavljevic and Brunner 2014). In addition, two types of MFA are possible: dynamic when it integrates the temporal variation of flows and stocks (import, export, products, recycling, etc.), taking into account the lifetime of products in use (Guyonnet *et al.* 2014), or static (Müller *et al.* 2014). Thus, an MFA of cobalt carried out between 2008 and 2017 implies the use of commercial data up to 2000, since some products have a lifespan of eight years. This methodology also has to cope with certain constraints such as mass balance (what goes in at one place must come out somewhere or be stored) or model delineation and many uncertainties regarding the data incorporated in the models due to the lack of knowledge on flow compositions and their characteristics. Confrontation with other sources and discussions with experts are therefore necessary.

1.3.2.2. *MFA steps*

Three steps are important to build an MFA and we will illustrate them by presenting the choices made for cobalt.

The first stage involves the selection of the product to be studied, while the second is concerned with the delineation of the study's scope and the third with the collection of the data required to conduct the study. Cobalt, a little-known metal subject to tension and essential for the energy transition, has emerged as a logical choice to conduct an MFA study. Moreover, despite numerous uncertainties about some data, it is a metal for which the quantities consumed are sufficiently large to provide quantified information. Thus, 140,000 tons were extracted in 2018 (according to the USGS), much more than gallium, germanium, or beryllium. Analyzing the state and evolution of stocks and flows, as well as the potential of the urban mine, is also an objective that has been built up gradually, in order to identify vulnerabilities and opportunities for the EU in the cobalt value chain. At the same time, the choice of the EU as a geographical border appeared logical since, apart from the MFA carried out by Deloitte for the year 2012, no MFA of cobalt had been carried out *a fortiori* dynamically and over several years, as we do for the period 2008–2017. We have chosen to deal only with flows entering and leaving the European Union and not with flows exchanged within the European Union by its members. This would have made the model more complex without adding value to the objectives. Finally, the data used for the MFA had to be sought and chosen. The Eurostat trade database provided the flows while several sources were used to estimate the quantities of cobalt contained in primary and refined flows, products, and waste.

A review of these tables shows that many elements are missing, particularly with regard to loss management throughout the process. We know, for example, that some occur during the manufacture of batteries, but we do not know the quantities. Concerning the cobalt content, certain rates had to be calculated from ranges reported in several documents, such as those for nickel and cobalt alloys, nickel and cobalt scraps, as well as the cobalt contained in aircraft engines or turbines for gas power plants. Finally, we have chosen to calculate the quantities of cobalt contained from fixed rates as Harper *et al.* (2012) did for cobalt in 2012 and tungsten in 2005 (Harper and Graedel 2008). Thus, several rates were available for cobalt ores and concentrates (Harper *et al.* 2012; Hannis *et al.* 2009; RMSA 2015; Darton Commodities 2018; Shedd 2019) or oxides and hydroxides (Roskill 2017; Darton Commodities 2018; Shedd 2019).

1.4. Results of and discussions on cobalt flow analysis in the European Union

This section discusses the results and limitations of the material flow analysis (see Figure 1.6). The analysis of the results deals with the evolution of flows, stocks, EU suppliers, and their significance in terms of value. Then, through several examples, the difficulties encountered and the choices made to de-emphasize them are discussed.

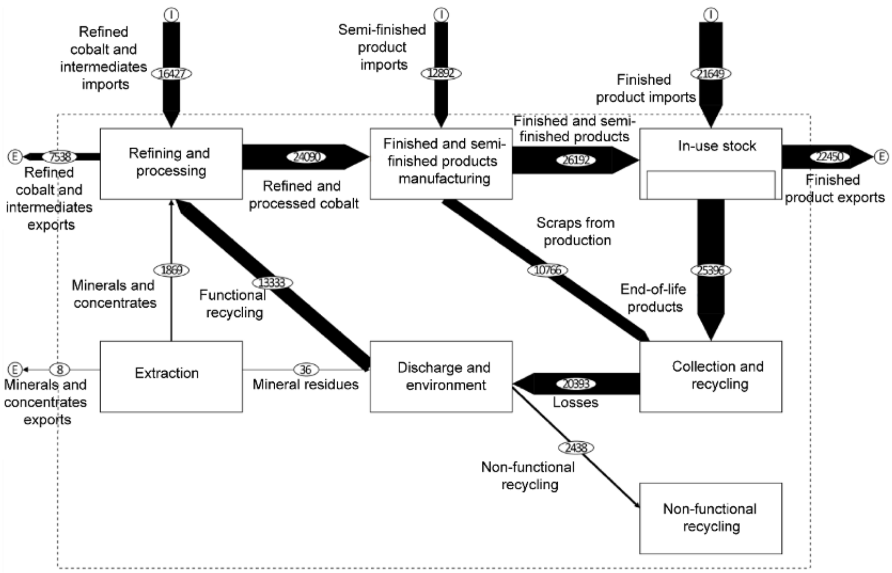


Figure 1.6. *Material flow analysis for cobalt in the EU in 2017 using STAN software (Brunner and Rechberger 2004)*

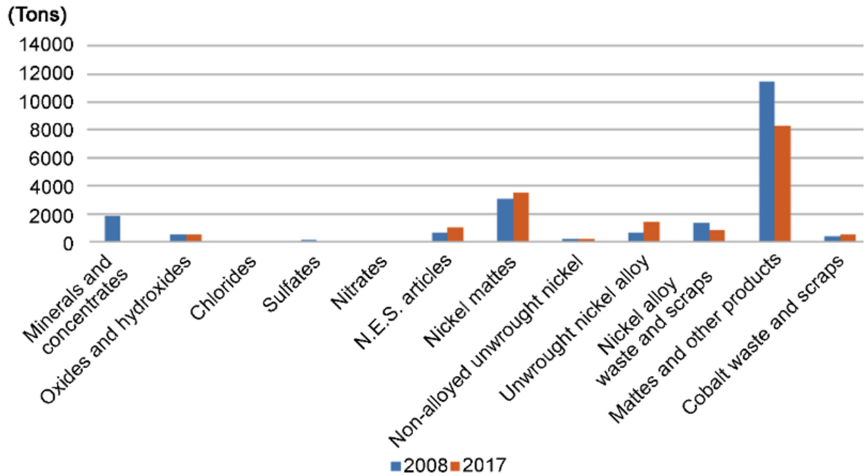
1.4.1. *Changes in flows and stocks: lessons from MFA*

Imports of refined products and finished or semi-finished products showed divergent trends during the 2008–2017 period. In fact, 20,201 tons were imported in 2008 in the form of ores, intermediate products, refined products, waste, and production scraps (23,032–25,396 tons for imports of finished and semi-finished products). In comparison, 16,396 tons were imported in 2017. Decreasing throughout the period, ores and concentrates were largely absent from European imports, while imports of high value-added cobalt items doubled. If the quantity of intermediate products of cobalt metallurgy is decreasing, this is not the case for their average value. Composed of different types of products (oxides, hydroxides, intermediates, concentrates, cathodes, powders, etc.) we see that the average value of products imported through this flow has increased between 2008 and 2017, not only because of the general increase in prices, but also and especially because imported products had a higher value added (disappearance of primary and intermediate products, increase in refined and processed products). While exports increased from 4,699 to 7,656 tons, the distinction is not so clear-cut, since the increase concerned both articles and commercial hydroxides, nickel mattes, or waste and scrap. These last three flows have a value less than half that of the first two (see Figure 1.7).

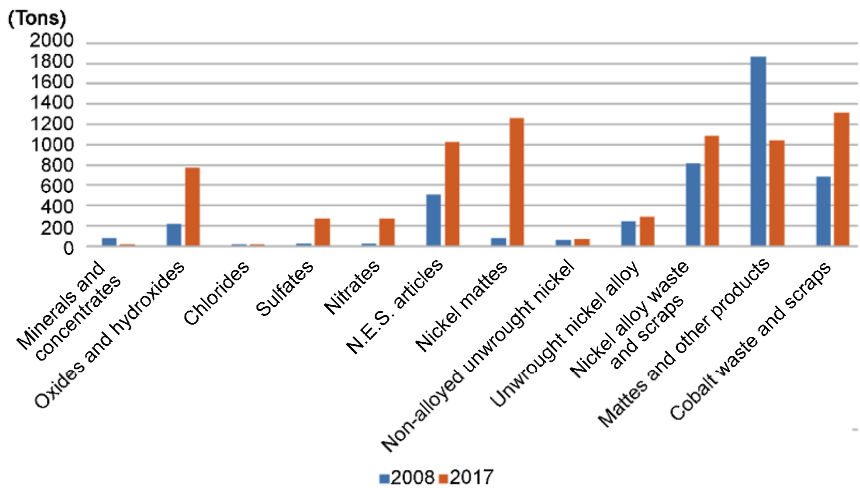
The amount of cobalt consumed by the European industry decreased from 29,210 tons in 2008 to 25,128 tons in 2017, despite the increase in consumption of products containing cobalt. A study of European manufactured production shows a significant drop in the production of semi-finished products (magnets and batteries), as well as finished products with lower added value (electronics). Production with high added value is either maintained (superalloys) or increased (electrical mobility). The case of the production of batteries and cells is singular. Indeed, while Asia produced more than 90% of the world's battery cells (Pillot 2017), Europe has expertise in their assembly, particularly for electric vehicles (Lebedeva *et al.* 2017) (see Figure 1.8).

The quantities of cobalt entering and leaving in the form of finished and semi-finished products have increased (23,032–25,396 tons for imports, 16,140–20,740 tons for exports). The significance of batteries in both exports and imports is still evident. Without data on this subject, but knowing the structures of the battery industry, it is reasonable to assume that the majority of European imports are in the form of cells and battery components, which are then assembled. Battery exports are mainly niche products for specialized industries, while electric vehicles remain an important export item (see Figure 1.9) (Lebedeva *et al.* 2017).

While Deloitte (2015) estimated the cobalt inventory in the European Union at 20,000 tons in 2012, our analysis leads us to suggest 47,717 tons and 54,195 tons of cobalt in use in 2008 and 2017. In 2008, approximately 30% of the European stock consisted of metal (cemented carbides, superalloys), while it only represented 24% in 2017. Even though the increase in electric mobility is visible (1,200 tons in 2008 versus 9,500 tons in 2017), batteries contained in electronic or household appliances remain the majority (see Figure 1.10).



a)



b)

Figure 1.7. *Structures of cobalt imports (a) and exports (b) in the form of ores, intermediate products, refined products, waste and scraps for production in the EU, 2008/2017 (tons). For a color version of this figure, see www.iste.co.uk/fizaine/mineral1.zip*

While exports of cobalt and nickel production scrap and off-cuts increased between 2008 and 2017 (see Figure 1.7), this is not necessarily a good news story for European industry, which simply does not have the industrial or contractual capacity or interest to process them[6]. Furthermore, in 2017, we estimate that 3,532 tons of cobalt were functionally recycled, or about 20% of the end-of-life material. Around 8% was recycled in a degraded manner (1,378 tons) while 72% was lost (12,293 tons). These results are similar to those of Harper *et al.* (2012) and Chen *et al.* (2019). With an RIR of 29.5%, we are below Deloitte's calculation for the European Union in 2012 (34%).

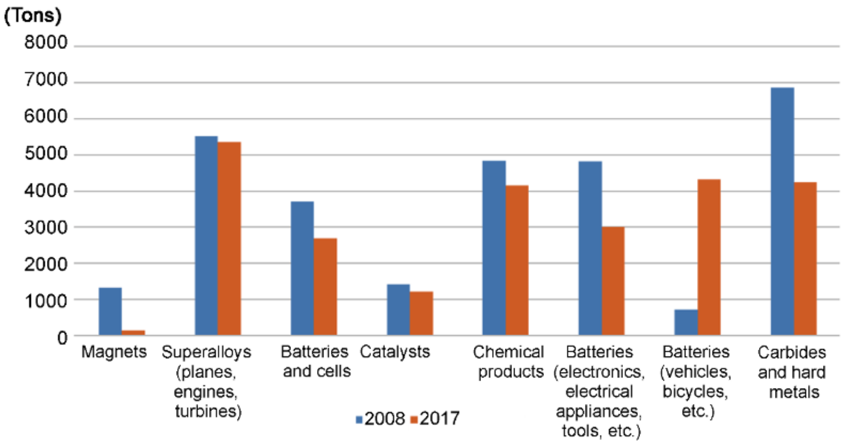


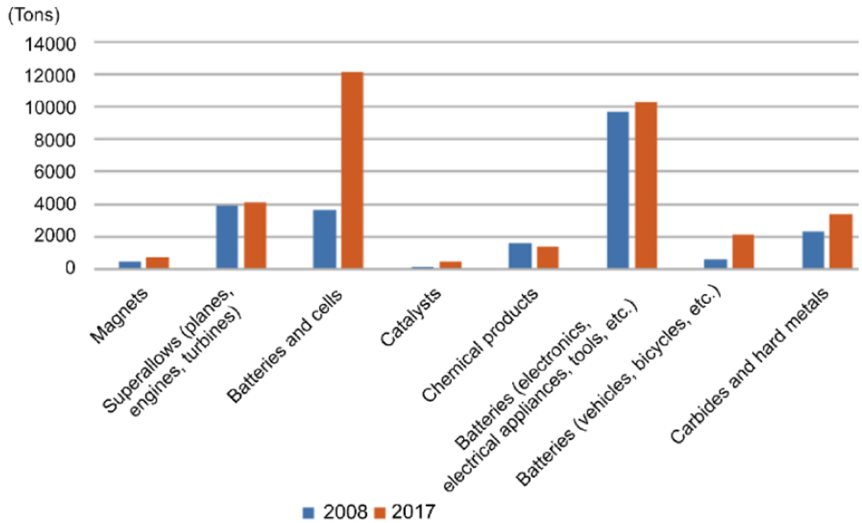
Figure 1.8. *Production of finished and semi-finished products containing cobalt in the EU, 2008/2017 (tons). For a color version of this figure, see www.iste.co.uk/fizaine/mineral1.zip*

Waste management therefore raises questions both in terms of organization and information. For example, production waste and scrap metal are poorly documented. Thus, it is difficult to test their traceability as well as their content; the latter determines whether or not they can be functionally recycled. In the case of the recycling of finished products, there is, for example, an important difference between batteries for electronics and batteries for mobility, both in terms of design and life span and the quantity of metals contained. Collection and recycling are only worthwhile if there is sufficient critical mass to ensure the cost effectiveness of the process.

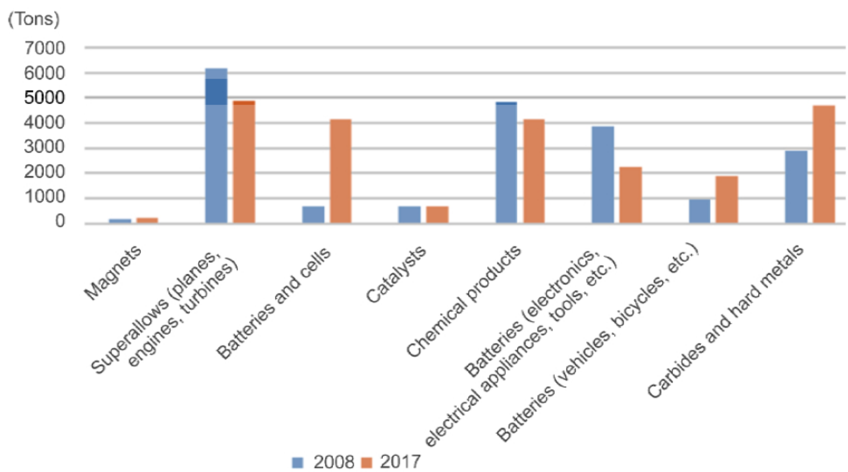
At the moment, due to the battery stock structures in Europe, dominated by electronics with a low collection rate, the recycling system is still too complex. However, the emergence of batteries in electric vehicles by 2020–2025 and the revision of the battery directive in 2021 could accelerate recycling. Also, a solution

6 The market for production scrap containing rare minerals is characterized by return-to-prime-supplier clauses, such as the titanium market (Louvigné 2015).

will have to be found to the volatility of metal prices, which makes any investment in this type of structure uncertain. Better hedging on futures markets could be a solution to this problem (Fizaine 2018).



a)



b)

Figure 1.9. *Imports (a) and exports (b) of finished and semi-finished products containing cobalt, 2008/2017 (tons). For a color version of this figure, see www.iste.co.uk/fizaine/mineral1.zip*

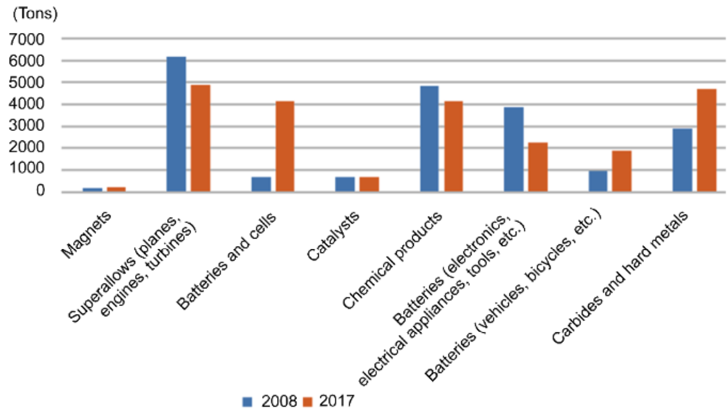
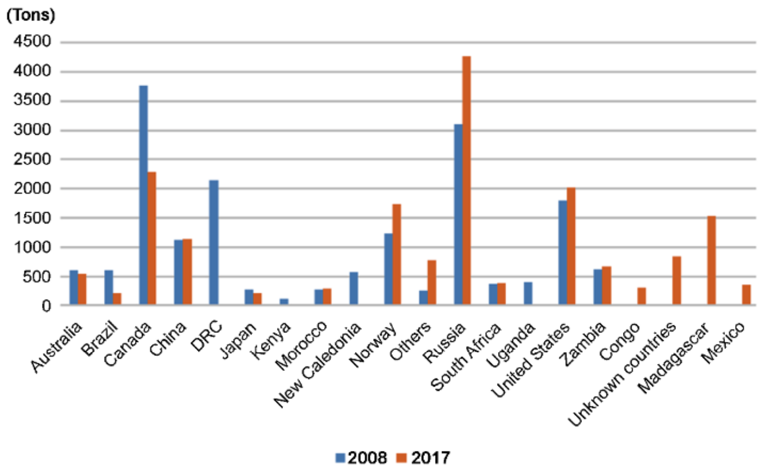


Figure 1.10. *"In-use stock" of cobalt, 2008/2017 (tons). For a color version of this figure, see www.iste.co.uk/fizaine/mineral1.zip*

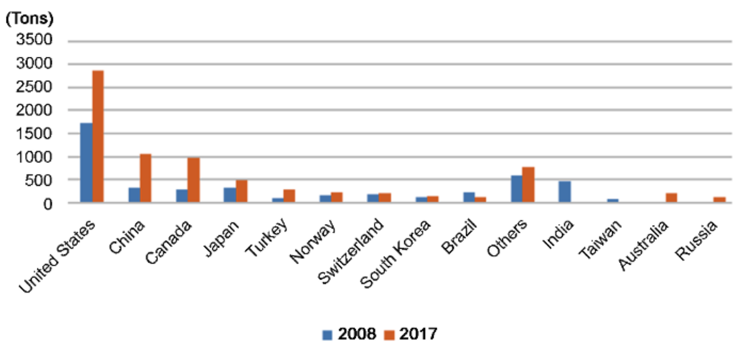
1.4.2. *Value chain partnerships and flow analysis assistance*

The evolution of trade relations between the European Union and its partners in primary, intermediate, and refined products depends on the industrial policies of these different countries. Thus, China has become one of the major players on the cobalt market since the early 2000s, while Madagascar and Mexico have emerged very recently as complementary producers, essential in a strategy of supply diversification. Others, such as Indonesia and the Philippines, are in the process of becoming major producers of nickel with associated cobalt.

These upsurges are often characterized by the implementation of commercial policies that encourage the development of local industry. China has implemented a 25% tax on exports of ores and concentrates, while refined products are taxed little or not at all. Similarly, the Philippines and Indonesia have implemented a quota system on the export of nickel ores that encourages Chinese industries to invest in local processing capacity (Le Gleuher 2017). For their part, the Democratic Republic of Congo and Russia are also looking to move up the cobalt value chain, the former by introducing an export ban on ores and concentrates in 2013, and the latter by building a refinery to produce cobalt ingots (99.5% cobalt content) rather than exporting concentrates to Finland (Roskill 2017; Darton Commodities 2018, 2019). A few years after the Congolese decision, an analysis of Congolese production and exports shows that the Democratic Republic of Congo exports few ores but more intermediate products, such as white alloys and cobalt hydroxides. Russia on the other hand no longer exports concentrates, but ingots and intermediate products (mattes and other nickel-based products).



a)



b)

Figure 1.11. *Main EU suppliers (a) and customers (b) for primary, intermediate, and refined products, 2008/2017 (tons). For a color version of this figure, see www.iste.co.uk/fizaine/mineral1.zip*

In terms of exports, we can note that the four major customers of the European Union are industrialized countries, which confirms the higher value of European exports. On the other hand, in terms of imports, the Democratic Republic of Congo, Brazil, Kenya, and Uganda are no longer among the European Union's major suppliers for various reasons (see Figure 1.11). Brazil, for example, has been hit hard by the decline in the price of nickel and has reduced or stopped production, which has inevitably influenced the production of cobalt. Uganda, on the other hand, stopped producing cobalt due to the depletion of its stocks based on the mining of

Kilembe tailings. Ugandan production could resume in the coming years, but it will be based on copper mining. For its part, the Democratic Republic of Congo now supplies very little cobalt to the European Union (64 tons in 2017). This state of affairs could be the consequence of two different European policies: one a policy of sanctions against Congolese leaders because of human rights violations and the other more coercive on transparency and responsible cobalt production, linked to the European policy on “blood minerals“. However, beyond the lack of data to confirm its assertions, Congolese production transits through certain countries, including Norway, where Glencore has a refinery, which tends to qualify the previous observation.

Understanding the value chain of cobalt-producing countries such as Australia, Canada, Russia, and New Caledonia helps to understand the type of products they can export and their cobalt content. Al Barazi (2018), for example, gave an estimate of the cobalt content of nickel mattes, depending on the country and the type of original ore. He also highlighted the type of products manufactured by the Canadian and Australian mining industries (cathodes or briquettes, 99.5% cobalt content), which allows for a fair analysis of the supplies of these two countries in the flow of “cobalt mattes and other intermediate products of cobalt metallurgy; unwrought cobalt; cobalt powder”, which contains several types of products of different values, without mentioning them.

The lack of data concerning the cobalt content, the imprecision of certain sources, and sometimes even their excessive variety, was a real challenge for the creation of an MFA. This was particularly true for the flow of “cobalt mattes and other intermediate products of cobalt metallurgy; unwrought cobalt; cobalt powder”. As we have shown for some flows (cobalt mattes and other intermediate products of cobalt metallurgy; unwrought cobalt; cobalt powder; as well as the various chemicals containing cobalt), the data for cobalt content were missing, and so they had to be estimated on the basis of assumptions derived from the literature. Some insertion errors in the databases were also found. Between quantities that are sometimes too large to be accurate (cobalt chloride for 2013 and 2014 imported by Denmark) and the lack of clarity and consistency in the indicators (carbides by weight, in kilograms, in tons, or in pieces?), the consequences on the calculation of flows can be significant. Uncertainty about the data led us to choose set limits for the calculation of cobalt content, lifetimes, or recycling rates, rather than variable limits. In our opinion, the latter choice would have made the calculation more complex without necessarily giving additional guarantees in terms of the veracity of the results. This was notably the case for concentrates and cobalt ores with contents ranging from 3% to 10% (Hannis *et al.* 2009; Darton Commodities 2019) or hydroxides ranging from 20% to 72% (Darton Commodities 2019; Shedd 2019).

Further down the value chain, there was a lot of information about the cobalt content of batteries, but barely applicable through the use of Eurostat trade statistics.

Indeed, while the data in the literature provided the amount of cobalt contained per piece or per kilowatt-hour (Kwh) (Buchert *et al.* 2011; Harper *et al.* 2012; Nordic Council of Ministers 2015; Pillot 2017), Eurostat only provides quantities in tons or hundreds of kilograms. Similarly, the database does not indicate the type of batteries (NMC, NCA, LCO, etc.) present in the flows. Concerning the recycling of superalloys, only Shedd (1993) gives useful information on the subject, which was confirmed to us by discussions with professionals. In view of the lack of information available for chemicals, we decided to divide the flows into two: the cobalt and titanium sulfate flows and the barium, beryllium, cadmium, cobalt, nickel, and lead nitrate flows. In the same way, it was not possible to calculate precisely the amount of cobalt contained in manufactured products or imported and exported products. When in doubt, we used data from Deloitte (2015), which indicated that 17% of the cobalt end products manufactured in the European Union were chemicals, as were 7% of the products consumed.

1.5. Conclusion

This MFA of cobalt for the European Union made it possible to identify methodological points and interesting results. First of all, the analyses of value chain and material flows seem to be complementary and allow for a better understanding of stocks, flows, and their evolution through a global vision of the strategies of actors and market transformation. Beyond the strictly quantitative results, MFA also revealed the qualitative aspect of stocks and flows: types of products, types of suppliers, and their evolutions. Through their analyses, we also see that the European industry is increasingly focusing on high value-added segments, which still raises some questions about its industrial strategy. Indeed, activities upstream in the value chain (e.g. extraction, refining, etc.) are decreasing while downstream activities are increasing, which places the European Union in a situation of dependence both in terms of resources for cobalt and battery technologies. This is particularly visible in the recycling segment, which is struggling to take off despite its growing importance and the growing number of questions about it. While there is some interest in the former urban mine operation, transforming the status of waste into a resource, we are still far from its optimal use, in particular because of the many uncertainties as to the revenues from such processes. As shown by the numerous customs barriers on the export of waste of different metals (OECD 2014), waste is gradually becoming a strategic resource but still has little economic value.

Finally, an examination of the evolution of the European Union's trading partners does not make it possible for us to observe, to a certain extent, the effectiveness of the industrial policies pursued in different countries or, conversely, to illustrate the limits they encounter. The case of the Democratic Republic of

Congo demonstrates this clearly. Despite the development of high taxation and tariff barriers, the country is struggling to gain ground because of its overly limited infrastructure and a corrupt political-administrative system. The presence of Russia as the European Union's leading supplier of cobalt also raises the question of the relationships that the latter can establish with its partners. In fact, despite the obvious tensions between the two and the policies of reciprocal trade sanctions, for several years now the latter have not concerned the supply of cobalt as much as other metals such as titanium. It is not for us to answer this question in this chapter; however, this situation illustrates the ambiguities linked to such dependence on a country with which there is no shortage of points of conflict.

1.6. Appendix: quantities of cobalt contained in primary and refined streams, recycling rates, and cobalt waste management

Nomenclatures	Products	Cobalt content (average)
HS 26 05 00	Cobalt concentrates and ores	7%
HS 28 22 00	Cobalt oxides and hydroxides	72.9%
HS 28 34 29 20	Barium nitrate, beryllium, cadmium, cobalt, nickel, and lead	22.5%
HS 28 27 39 30	Cobalt chloride	26.6%
HS 28 33 29 30	Cobalt and titanium sulfate	26.9%
HS81 05 30 00	Cobalt waste and scrap	37%[7]
HS 81 05 20 00	Cobalt mattes and other intermediate products of cobalt metallurgy; unwrought cobalt; cobalt powder	3%–99%[8]
HS 81 05 90	Cobalt, N.E.S. articles	99%[9]
HS 75 03 00 90	Nickel alloy wastes and scraps	7%
HS 75 01	Nickel mattes	1%–5%
HS 75 02 10 00	Nickel alloy, not forged	0.5%
HS 75 02 20 00	Non-alloyed and non-forged nickel	1.5%

Table 1.1. *Cobalt contained in primary and refined flows (%)*[10]

7 Personal calculations based on Shedd (1993), Audion *et al.* (2013); Roskill (2017), Al Barazi (2018), Alves Dias *et al.* (2018), Darton Commodities (2018), Ladenberger *et al.* (2018), and the European Commission (2019).

8 Personal calculations based on the origin and prices of flows as well as Roskill (2017), Al Barazi (2018), and Darton Commodities (2018).

9 Personal calculations based on flow prices.

10 According to Shedd (1993) Audion *et al.* (2013), Roskill (2017), Al Barazi (2018), Alves Dias *et al.* (2018), Darton Commodities (2018), Ladenberger *et al.* (2018), and the European Commission (2019).

Products	Cobalt content (average)	Service life (years)
Superalloys	250 kg/piece	5
Cemented carbides	11%	1
Hard or sharp metals	11%	3
Catalysts	2.75%	5
Electronic batteries: nickel-cadmium (Ni-Cd)	1%	3
Electronic batteries: nickel-metal hydride (NiMH)	3%	3
Electronic batteries: lithium-ion (LIB)	9%	3
Batteries (transport)	30%	8
Magnets (AlNiCo, Sm-Co)	24.5%–66%	5
Chemical products	No data	1

Table 1.2. *Cobalt contained in manufactured product flows*[11]

Products	Collection rates	Functional recycling	Degraded recycling	Untreated
Superalloys	100%	50%	30%	20%
Cemented carbides	100%	15%	75%	10%
Hard metals	100%	55%	20%	25%
Catalysts	90%	75%	No data	32%
Electronic batteries	10%	80%	No data	92%
Batteries (transport)	80%	80%	No data	64%
Magnets	No data	10%	6%	84%
Chemical products	0%	0%	0%	0%

Table 1.3. *Recycling rates for manufactured products containing cobalt*[12]

11 According to Shedd (1993), Buchert *et al.* (2011), Harper *et al.* (2012), Graedel *et al.* (2015), Roskill (2017), Huisman *et al.* (2017), and Ladenberger *et al.* (2018).

12 According to Shedd (1993), Harper *et al.* (2012), Blandin (2015), Roskill (2017), and Heelan *et al.* (2016).

Products	Wear and tear losses	Falls	Collection	Recovery	Degraded recycling	Untreated
Superalloys	No data	66%	70%	70%	20%	10%
Cemented carbides	16%	5%	35%	100%	No data	No data
Metals	16%	5%	35%	100%	No data	No data
Catalysts	6%	No data	No data	No data	No data	No data
Batteries (electronics and transport)	No data	No data	No data	No data	No data	No data
Magnets	No data	No data	10%	No data	No data	No data
Chemical products	100%	0%	0%	0%	0%	0%

Table 1.4. *Management of losses during the manufacturing process*[13]

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13 According to Shedd (1993).

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2

Financialization of the Minerals and Metals Market: Origin, Challenges and Prospects

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2.1. Introduction

The theme of the financialization of commodity markets generated a large scientific literature during the 2000s. While prices soared to give rise to what was to become a commodity "super-cycle", a large part of the empirical work on this question focused on the determinants of this structural increase by distinguishing fundamental factors from "strictly" financial variables (De Meo 2013). The aim was, in particular, to understand the role of index-linked investment funds on the reality of prices. Financialization is, in this precise empirical framework, assimilated to financial speculation or to a particular form of it. For Adams and Glucks (2015) in particular, financialization is a recent phenomenon characterized by a massive influx of capital by institutional investors (mutual funds, pension funds, insurance companies, hedge funds) into the commodity segment. Commodity derivatives have in fact gradually asserted themselves as an asset class in their own right thanks to the expected returns they offered (due in part to the leverage effect inherent in any derivative) and to the low – or even negative – correlation between their returns and those of traditional financial assets (Gorton and Rouwenhorst 2006).

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If we detach ourselves from these recent works to consider an older academic literature, another approach to the phenomenon of financialization can be adopted. This would be characterized by an increase in the economic role played by the financial markets of derivative products in the organization of a commodity sector. Indeed, it should be remembered that the primary function of futures, such as those exchanged since the 19th century on the Chicago Mercantile Exchange (CME) or, among many other examples, on the London Metal Exchange (LME), is to offer a price reference observable by all the operators in the value chain, without cost and without delay. These particular properties mean that this price reference can be used in different ways by the counterparties to a physical exchange as a basis for negotiation to determine the effective price at which this transaction can be carried out. In such a scheme, the physical price of a raw material is, therefore, derived from a financial price; they are not identical due to significant differences in the clauses of the commercial contract and those of futures, but ideally remain highly correlated. This is all the more important since the effectiveness of the price risk protection mechanism (Edenrigton 1979) – the second function of futures – depends intrinsically on the value and stability of the correlation coefficient between these two prices. The third and last function of such an instrument is to improve the efficiency of storage strategies for the material in question (Tomek and Gray 1970) and, more generally, to assist in decision-making with regard to production, consumption, storage, and even productive investment, by offering operators in the value chain different prices for different maturities (Black 1976).

These two approaches to the financialization of commodity markets are naturally not opposed, with the first being ultimately one of the consequences of the second. A financial commodity market cannot be sustainable by satisfying only the interests of the physical operators in the sector, the presence of speculators being one of the *sine qua non* conditions for its liquidity. In this respect, it is perhaps necessary to distinguish between the financialization of *markets* and that of *sectors.* Approaching the question of financialization from a broad perspective and not only from the point of view of financial speculation nevertheless makes it possible to understand in detail the structural changes in the commodity sectors and to deal with the following fundamental questions. Why does a sector become financialized? What are the advantages and disadvantages of such a mutation and what are the conditions under which it takes place? Is it ultimately a desirable development and which operators benefit most from it? What form do the dynamics of financialization take and what will be their next developments? These are all questions that this chapter will attempt to answer by referring to the abundant economic literature on this subject. Although this phenomenon is common to all the major families of raw materials, the analysis proposed here will focus primarily on the international markets for certain ores and metals known as basic or industrial: iron ore and steel, bauxite, alumina and aluminum, copper, zinc, tin, nickel, lead.

2.2. Dynamics of financialization: understanding the heterogeneity of the minerals and metals sector

To understand the phenomenon of financialization, we must first remember that a commodity chain – or supply chain – must be understood as a continuum of economic actors whose common point is to exchange the same product at its different stages of development, and whose price is derived from a reference price, which is usually international. This notion does not benefit from a formally validated definition and, it is easy to understand, has a subjective dimension both in terms of the geographical "perimeter" attributed to it and the "downstream" that delimits it. The "steel" sector, for example, is not easy to define because it would be necessary to determine not only whether it is French, European, or even global, but also whether the production of so-called specialty steels, whose manufacturing complexity and relatively narrow demand, as opposed to crude steel, does not distance it from the very notion of "raw materials". A raw material has indeed the characteristic of being a homogeneous product (Marquet 1993), that is, one for which the possible differentiation by quality does not allow producers to protect themselves in a sustainable manner from competition. In other words, a product cannot be considered a raw material if its marketing can respond to strategies of non-price competitiveness. Although iron ore, like any other mineral, offers different metal grades depending on its geographical origin, it is a commodity par excellence, traded internationally, and traded at a price traditionally expressed with the terms "free on board" in Australia and Brazil or "cost, insurance, freight" in Chinese ports. Regardless of the product in question, a raw materials chain involves producers, processors, and users, as well as physical traders whose economic function is to reconcile these same producers and users in time and space.

2.2.1. *Functions of a raw material chain and outsourcing price risk*

This sector is structured to assume three main functions (Marquet 1993). The first, of an industrial and commercial nature, aims at transforming the product as it appears upstream of the chain (extraction) to adapt it to the needs expressed downstream. Bauxite has, by way of illustration, no other use than to be transformed into alumina, which will then be dissolved in a cryolite bath and subjected to an electrolytic process allowing for the production of primary aluminum. Since aluminum is a global market and because there is no reason why the geographical areas where the ore is extracted should be the same as those where the contained ore is produced for both logistical and economic reasons, this industrial transformation is accompanied by an international transport activity. The second function of a raw materials chain is to add value to the various products in the value chain in question. The resulting prices can be called “transfer prices” when an integrated group assumes all or part of the industrial transformation from upstream to downstream or “market prices” when the exchange of products takes place between different economic entities.

The third and last function of a raw material chain is closely linked to the previous one: risk management and dilution. The physical transfer of a commodity – from upstream to downstream – generates a certain number of risks: industrial, logistical, commercial, and financial. Within the latter, price risk occupies a predominant place. Relating to the product itself and/or the different inputs needed to produce the material desired by the end users, this risk is defined as the fact that the producer (user) does not know at what price he/she will be able to sell (buy) the said material and will take the form of a fall (rise) in prices for the producer (buyer) and a reduction in the intermediation/processing margin for the physical trader and the processor. Whether it is low or high, this risk can be shared between the different players in the sector or partly externalized, that is, borne by players who do not strictly speaking belong to the sector. Two mechanisms that are not mutually exclusive are schematically possible. The first is carried by public authorities through guaranteed prices or subsidies. The second is the development of a market for financial derivatives traded on an organized market. This enables physical operators to develop strategies for hedging this risk and financial operators (index funds, hedge funds, etc.) to speculate, that is, to carry part of this risk in exchange for an expectation of high returns and thus to correct the asymmetry of “hedging” (Gray 1961, 1966). The existence of such a derivative market is a necessary, but not sufficient, condition for financialization. Several futures exist (or have existed) for steel (see Table 2.1) without it being possible to affirm that the steel market is financialized, as is the case for aluminum, copper, nickel, or other base metals. Most of these contracts are not very liquid, are regional, and are based on a liquidation procedure known as “cash settlement”, meaning that the physical delivery of the product is impossible. Over the period from January to December 2017, the trading volumes of the “aluminum” and “copper” contracts traded on the London Metal Exchange (LME) – the two most liquid contracts on the London Stock Exchange – were as follows: 51.43 million and 33.88 million lots, respectively, compared to 307,732 lots and 64,430 lots for scrap metal and rebar alone. The same “rebar” contract traded on the Shanghai Futures Exchange (SHFE) benefits from significant liquidity, but the fact that it is denominated in yuan means that it can only be used for hedging or speculation purposes by Chinese operators. The reason for this financialization is simple; unlike copper, aluminum, or nickel, the steel market is largely segmented both geographically and in terms of the major product families traded, which leads to a "fragmentation" of demand for futures.

Stock exchange	Type of steel	Type of contract
London Metal Exchange (LME)	Hot-rolled coils	By cash settlement (Argus index, with reference to "free on board China")
		By cash payment (Platts, with reference to North America)
	Reinforcing bars	By cash payment (Platts, with reference to "free on board Turkey")
	Scrap (heavy melting steel)	By cash payment (Platts TSI index, with reference to "cost and freight Turkey")
Chicago Mercantile Exchange (CME–Nymex & Comex)	Hot-rolled coils	By cash settlement (CRU index, with reference to "Midwest")
		By cash payment (Platts Index, Midwest)
	Scrap metal (scraps)	By cash payment (AMM Index, Midwest)
	Scrap (heavy melting steel)	By cash payment (Platts, with reference to "cost and freight Turkey")
Shanghai Futures Exchange (SHFE)	Reinforcing bars	By physical delivery
	Wire rods	By physical delivery
	Hot-rolled coils	By physical delivery
Singapore Commodity Exchange (SGX)	Hot-rolled coils	By cash payment (TSI index, import prices, ASEAN)

Table 2.1. *Major steel futures*

If one accepts this "broad" approach to financialization, it is clear that almost all base and precious metals are subject to financial derivatives, while small metals and minerals are little or not at all financialized. Although there are cobalt and molybdenum futures listed on the LME, these are again not very liquid, while the emblematic iron ore contract traded on the Dalian Commodity Exchange, China's second largest commodity exchange after Shanghai, is not accessible to foreign operators[1]. Although we must be careful not to make overly general observations on this issue, two main reasons seem to explain this lack of financialization. The first is that the markets on which minerals and small metals are traded do not drain sufficient financial volumes or "suffer" from too great a concentration of supply for commodity exchanges to be encouraged to experiment with the launch of a future. The second is linked to the prevalence, on these markets, of long-term commercial contracts between companies with a high degree of integration, which limits or even eliminates price risk and therefore makes it completely inappropriate to list derivatives whose role would have been precisely to manage such a risk. Commodity exchanges are, in many respects, companies like any other and profitability is indeed one of the natural determinants of their commercial actions.

2.2.2. *Business practices and the role of futures*

The essential question which then arises is that of the reasons explaining this heterogeneity among metals and minerals and, therefore, that of legitimizing the emergence and then the perpetuation of such a derivative market within a raw materials sector. To this, several levels of response can be made. The first, which is very operational, justifies the launch of a futures by the fact that it meets the needs expressed by the operators of the sector. These needs are twofold: a need for price transparency and price risk management. Thus, the preferred use of spot transactions by the different actors in the sector, combined with high price volatility – two elements that jointly explain why producers and end users are exposed to a significant price risk – are, among other variables, factors that justify the creation of this type of derivative product when the expected transaction volumes are sufficiently large (see Table 2.2). If these needs are confirmed after the launch of the contract and if the contract effectively satisfies them, and also if operators in long or short positions balance out in the medium/long term (Gray 1966), it is then likely that this financialization dynamic will continue.

The "operational" approach referred to above has the advantage of simplicity, but it does not in fact provide a precise understanding of the mechanisms by which a sector gradually opts for a risk management method using futures. As Radetzki (2013) reminds us, several price-setting mechanisms, and therefore commercial practices, can in fact be identified within the value chain and some of them make it possible to avoid price risk – transfer prices practiced between subsidiaries within vertically integrated industrial groups; so-called "producer" prices which, when the market in which they are formed is an oligopoly, allow producers to guarantee their

1 Other iron ore futures are also offered by the Singapore Commodity Exchange, but like their steel counterparts, they are based on cash settlement procedures.

relative stability; prices regulated by exporting countries in order to guarantee the level of their tax revenues or to preserve the income of national producers; and, finally, "pure" market prices reflecting the strict reality of variations in supply and demand.

Launch conditions	Conditions for success
A homogenous product and subject to important exchange flows	A properly defined contract with regard to criteria desired by market operators
A market operating continuously	Low basic risk
A prevalence of cash transactions	Active speculation and a balanced market
A need for transparency on the part of operators in the sector	Operators' knowledge of the hedging techniques sector
Price volatility synonymous with short-term price risk for traders of the sector	A promotional strategy on the part of the commodity exchange
No "substitute" for hedging	A scholarship with the power of international markets
Solvent demand and prospects of profitability for the raw materials exchange	–
An interest of the speculators making it possible to guarantee, in the long term, the balance of short and long positions	–

Table 2.2. *Criteria for launch and success in a future market*

Within these different mechanisms, it is interesting to contrast fixed-price contracts and "price-to-be-fixed" contracts for which only the quantities and the pricing formula are defined (and not the price level)[2]. The first, unlike the second, protects contractors from price risk and it is, therefore, important to specify what has led the majority of sectors to abandon them and accept the rise of derivative markets. Any commercial contract carries a counterparty risk linked to the fact that buyers or sellers do not honor all or part of their obligations. This risk is all the more

2 As part of this last category, an annual contract with intermittent delivery specifies the quantities that will be delivered/received monthly as well as the formula for defining the price – monthly – at which they will be exchanged. This price is traditionally the average of the daily observed prices of the corresponding futures on the reference exchange to which a premium and discount system is applied to take into account the differences between the commercial contractual clauses (product quality, Incoterms, and delivery terms, etc.) and the standardized future prices.

important in a fixed-price contract when the price of the raw material differs significantly from that negotiated by the contracting parties and when the latter are not in a relationship of trust or interdependence[3]. Any deviation of the price of the commodity can indeed be such as to incite the seller (positive deviation) or the buyer (negative deviation) to default in order to benefit from a more favorable market price. This risk is actually known before the contract is negotiated, which encourages the counterparties to the exchange to favor the use of fixed-price contracts which, by their very structure, do not carry such a risk. In this sense, the financialization of commodity chains must be understood as the result of an arbitrage by the operators, who make it up between a counterparty risk and a price risk that is all the easier to manage via hedging strategies, since derivatives can be created for this purpose. Unlike a fixed-price contract, this hedging places the counterparty risk on the clearing house (Carlton 1984) and also allows the divisibility of the risk in time and space, which greatly favors its management[4].

The dynamics of financialization can also be understood as the abandonment of historical producer price systems in favor of a system where market prices prevail. The history of the aluminum industry is probably one of the best illustrations of this. From the 1950s to the end of the 1970s, the industry was dominated by six Western companies – the six majors[5] – which operated according to this particular pricing scheme. As Nappi (1985, 2013) reminds us, the market was then balanced by quantities through variations in the use of production capacities and a policy of (de)stocking. This ensured relative price stability, even if discounting practices were not uncommon (Radetzki 1990; Brault 2008). Nevertheless, several important elements contributed to the fragility of this system and its abandonment. Synonymous with a drop in demand for aluminum and thus a necessary adjustment of supply, the economic crisis of the 1970s first increased the cost for producers to maintain such a practice. Secondly, the boom in recycling eroded their market

3 In the case of the liquefied natural gas (LNG) market, long-term contracts with annual price revision clauses have historically prevailed, but this was due in particular to the infrastructure costs (liquefaction and regasification terminals) imposed by this trade and the resulting situation of strong independence between the producer and the importer. See in particular Chiappini *et al.* (2019) on this subject.

4 For example, an American producer wishing to secure the futures price of 1,000 tons of aluminum will be able to sell 40 futures on the New York Mercantile Exchange (Nymex, a subsidiary of the CME) and find up to 40 counterparties (divisibility in space) without being exposed to any risk on their part because of the principle of subrogation allowed by the clearing house. In accordance with the founding principles of these organized markets, these “buying” counterparties will also be free to cancel their positions at any time they wish, as long as the futures in question have not expired (divisibility in time).

5 Alcan, Alcoa, Alusuisse, Kaiser, Pechiney, and Reynolds.

power. This was all the more true since the existence of superprofits combined with the change in comparative advantages, as the oil shocks had motivated companies, particularly public companies, to compete with them (Mouak 2010). Finally, the increase in the number of producers was not likely to facilitate the implementation of the cooperative strategies that such a system imposes. The launch of a primary aluminum futures by the LME in December 1978 probably accelerated this transition to pure market prices. Faced with the relative opacity of the pricing proposed by the producers, its price gradually imposed itself in commercial contracts, thus mechanically creating the conditions for a strong correlation between commercial and "paper" prices and thus for the success of such a hedging product. The increase in the supply of metal from Eastern European countries during the 1990s, and the ever-increasing assertiveness of Chinese companies, which in 2018 represented more than 56% of world production[6], also played a key role in the decline of the six majors.

Synonymous with a loss of market power, but also with the necessary acceptance of speculation that can sometimes create bubbles and sometimes panic of varying degrees of magnitude, the development of a future is traditionally rarely desired by producing companies. As Arik and Mutlu (2014) pointed out, the launch of steel futures at the end of the 2000s was not well received by the latter, who saw in them a risk of increased price volatility, an assertion that economic theory and its empirical verifications traditionally tend to qualify.

Although iron ore was traded on the LME between 1877 and 1920, it is one of the major non-agricultural "commodities" that has recently been financialized with the launch of a future in October 2013, by the Dalian Commodity Exchange (DCE), in addition to futures offered by the CME and the Intercontinental Exchange (ICE) that do not allow physical delivery, unlike their Chinese counterpart. This future is probably emblematic of what will be the financialization of solid mineral commodity chains over the next decade. It marks, first of all, the affirmation of the Chinese derivatives markets in the face of the dominant position of the historical commodity exchanges that are the LME and the CME. While their national scope requires a nuanced interpretation of their very large transaction volumes, competition from the Chinese financial markets, those of Shanghai and Dalian, should increase thanks to their progressive internationalization[7]. In March 2018, the Shanghai International Energy Exchange (INE) thus launched a contract on oil crude denominated in yuan but accessible to international operators and authorizing the payment of margin calls in

6 Or 36.48 million according to the International Aluminium Institute estimates for a global supply of 64.33 million tons.

7 This being intimately linked to the internationalization of the Chinese currency.

dollars; there is, therefore, no reason to believe that this opening does not ultimately benefit futures on metals listed on the SHFE or the DCE. Secondly, it prefigures a "rise" in the number of sectors that should be operated by the reference stock exchanges. Like any company, these exchanges are engaged in strategies to gain market share. The saturation of the base and precious metals segment should thus push them to launch contracts for raw materials upstream of metallurgy, which, along with fertilizers (phosphate, potash, urea), remain the major non-renewable "commodities" that have not yet been financialized. It is from this perspective that one should understand the launch of an Australian alumina contract by the CME in 2017 and by the LME in 2019 but also, in all likelihood, by the SHFE in the short to medium term.

2.3. Effects of financialization: from price dynamics to value chain change

The financialization of commodity markets is a research topic that is most often part of a vast corpus of research aimed at better understanding the dynamics of their prices. From ancient themes aimed at analyzing, within the framework of the theory of efficient markets, the predictive capacity of prices of futures, to those that attempt to characterize the reality of the trends, cycles, or volatility experienced by these commodities (Jacks 2013), the literature is particularly abundant in this field. Among the most recent works are those that have sought to determine the extent to which the increased presence of investment funds – index-linked funds in particular – could explain the very sharp rise in prices observed between 2002 and 2012–2014. More specifically, their aim was to distinguish so-called "fundamental" factors, linked in particular to the boom in demand from emerging countries, from purely financial or speculative factors.

2.3.1. *Financialization and dynamics of raw material prices*

A significant part of recent empirical studies on raw material prices is organized around three main axes. The first favors a very long-term approach and aims to distinguish between trends, cycles, or super-cycles[8] and short-term volatility,

8 It is indeed important to distinguish between "cycle" and "super-cycle", with the duration of the bullish phase as a classification criterion. A super-cycle would thus initially be characterized by an increase over one or more decades (10 to 35 years) in the real price of a large majority of raw materials, particularly industrial ones, due to a structural increase in demand linked to large-scale urbanization and industrialization phenomena.

whether the resources studied are considered as a whole or by type of product (metals in particular). The second aims to determine the role of financial factors, and in particular speculation, in the surge in prices. This approach is intrinsically complex, as the factors influencing commodity prices are numerous. The rise in the power of investment funds has, moreover, been concomitant with an increase in demand for raw materials from emerging countries, which has made this measurement work all the more complex[9]. The synthesis of work on this issue is naturally beyond the scope of this chapter, but it is interesting to cite the analysis of Irwin *et al.* (2009), which highlights this trend increase, which cannot be due solely to the long positions of investment funds. Using data from the Commitment of Traders (COT) of the Commodity Futures Trading Commission (CFTC), the authors show that the magnitude of speculative bullish positions increased between January 2006 and April 2008 for eight of the nine agricultural commodities considered in their book[10], but that these were overcompensated, for four of them[11], by an increase in short hedge positions from producers and physical traders. In this configuration, it is difficult to conclude on the destabilizing role of investment funds. Other methodological approaches have also been used. Starting from the postulate that this particular form of financialization was rooted in the affirmation of commodities as an asset class, many studies have focused on studying the price movements of a number of products belonging to different sub-categories. Tang and Xiong (2012) thus show that the joint dynamics between the prices of futures on non-energy commodities[12] (grains, “soft commodities”[13], livestock, metals[14]) and those of oil strengthened after 2004 and that this phenomenon was particularly significant for the commodities present in the two major flagship indices of the sector, the S&P GSCI and the Dow Jones–UBS Commodity Index. Among the very numerous studies on the subject is the article by Steen and Gjolberg (2013), which looks at the characteristic sheep-like behavior of speculators and which also concludes that there is an increase in trading between commodities and also between the latter and traditional stock markets.

9 Chen and Wyong (2013) also pointed out that all operators on the futures markets identified as operators in the real sphere can take long or short positions on futures well in excess of their hedging needs, making them de facto speculators.

10 Corn, soybeans, soybean oil, and wheat traded on the Chicago Board of Trade (CBOT) and on the Kansas City Board of Trade (KCBOT), cotton, feeder cattle, live cattle, and lean pork.

11 CBOT wheat, live cattle, feeder cattle, and lean pork.

12 More specifically, it is the price of futures having these commodities as underlying assets.

13 Coffee, cocoa, cotton, orange juice, and lumber.

14 Gold, silver, copper, platinum, and palladium.

The third approach relating to this particular form of financialization sought to determine the effects of such a phenomenon on the dynamics of the commodity prices that were experiencing it. In particular, it was a question of seeing whether the development of a derivatives market (or speculation defined as a corollary) was likely to increase price volatility. Marked by Friedman's (1953) analysis of the stabilizing role of speculation, the question is, of course, not new and has been the subject of numerous studies which, traditionally, conclude that the development of a future does not increase the variability of commercial prices, or even decreases it (Powers 1970; Peck 1976). In the metals segment, Figuerola-Ferretti and Gilbert (2001) have thus measured the impact of the development by the LME of the "primary aluminum" contract on the volatility of commercial prices for this metal. Three sub-periods were considered: from January 1970 to December 1978, that is, before the launch of the future; from January 1979 to December 1985, defined as an intermediate period marked by the coexistence of a producer price system and reference prices derived from the LME contract; and, finally, from January 1986 to June 2000, a period marked by the disappearance of the producer price system. The authors highlighted an increase in volatility over the last sub-period without establishing a causal relationship with the launch of the contract. This would indeed have been due to an abnormally high volatility in the 1980s that disappeared in the 1990s. For this latter decade, volatility seems neither greater nor lower than that measured for the 1970s.

Like aluminum and other industrial metals, iron ore saw a major shift in its marketing in 2010, with the transition from historic annual negotiations between steelmakers and major iron ore producers to spot prices based on "cost and freight" Incoterms (Astier 2010). In line with previous work, Wårell (2014) has thus attempted to characterize the impact of the new pricing system on the price dynamics of this strategic material for the Chinese steel industry.

More specifically, the author examined the influence of spot prices on the volatility of iron ore (Figure 2.1). The period studied was from January 2003 to August 2012 with monthly iron ore import prices in China (62% Fe spot CFR at the port of Tianjin). Unsurprisingly, the author showed that the introduction of a spot price regime has indeed fueled an increase in iron ore price volatility. However, when transportation costs are deducted from these imported prices, it seems that the price volatility of imported iron ore decreased after the change in the pricing system.

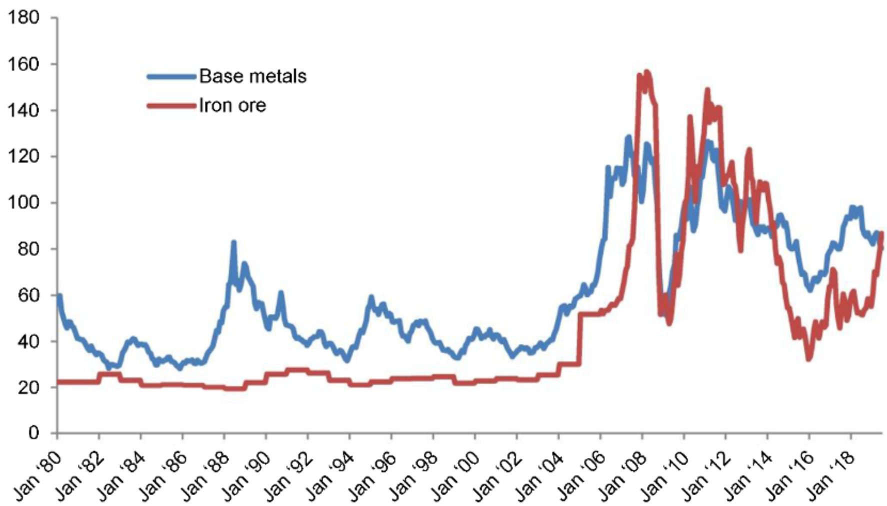

Figure 2.1. *Comparative evolution of iron ore and base metal prices (index, base 100: January 2000) (source: World Bank (pink sheet)). For a color version of this figure, see www.iste.co.uk/fizaine/mineral1.zip*

Among the latest empirical studies on the effects of the launch of an organized commodity market is the econometric analysis of Arik and Mutlu (2014). Focusing on the rebar contract traded on the SHFE (see Table 2.1), it develops measures of steel price volatility before and after the launch of this contract. Based on daily observations from March 27 2009 to March 14 2014, processed by a traditional VECM[15], the authors confirmed, as in the articles on the subject, the existence of bilateral relationships between spot and futures prices, both in the long and short term; while the spot market seems to be the main driver of steel prices in the long term, the futures market sees its role strengthened in the short term. Moreover, the movements between these prices and those of the main indices representative of the industrial metals market have increased. The authors also showed that it is only after the launch of such a contract that the GARCH[16] modeling – a conventional approach to measure the volatility of financial prices – is adapted, suggesting that the dynamics of steel prices saw its speculative component strengthen after this date. Fizaine (2015), interested in the 2010 quotation of two small metals on the LME – molybdenum and cobalt – and also using a VECM with structural rupture and various causality tests, suggested that the launch of the molybdenum future has strengthened the joint dynamics between the

15 Vector error correction model.

16 Generalized auto-regressive conditional heteroskedasticity.

prices of this metal and those of nickel[17], thanks to arbitrage strategies carried out by the operators of the sector.

2.3.2. *Effects of financialization on the structuring of commodity chains*

While the impact of financialization/speculation on the different facets of commodity price dynamics has been widely studied, two important themes should, in our view, be the subject of further research. The first relates to the analysis of speculative bubbles on certain minerals or metals. In a context marked both by a relative inelasticity of supply in the short term – which is combined with a long-term supply risk – and also by a demand that is set to grow due to the boom in electromobility, some investment funds have taken significant long positions on certain metals of the environmental and digital revolution. Cobalt, the flagship product in this field along with lithium, saw its price soar in March 2016 and March 2018 (+310%), before falling sharply over the rest of 2018 and 2019. Therefore, while the existence of a bubble is not in doubt, its measurement, the analysis of its origins, and its consequences on the reality of industrial operators have not, to our knowledge, been the subject of major research work. In this respect, it is important to note that beyond the simple example of cobalt, the history of metals is punctuated by announcements of strong medium-term supply constraints that have sometimes been contradicted by technological developments. The strong endogeneity between the price of a resource and its availability (which naturally depends not only on geological criteria, but also on technological, economic, (geo)political, financial, and environmental criteria) is an essential characteristic of non-renewable resources and must be constantly documented. Marked by an absence of major discoveries despite a resumption of exploratory investments and a structural decline in metal grades, the copper market is today representative of this reality.

Closely linked to the previous one, the second important theme relating to the financing of raw materials requires an even broader vision of this phenomenon than that proposed in the introductory part of this chapter. Many historical mining and/or metallurgical companies are listed on the stock exchange, which has a major impact on their investment strategies and thus on the level of prices in the medium or long term. Concerning the determinants of oil supply, a study by Aune *et al.* (2010) highlights that the rise in crude oil prices during the 2000s could have been due to not only the increase in demand but also to a restriction of supply by international oil groups because of their investment strategies over the past years. Also, often listed on the stock exchange, these companies have in fact reduced their exploratory

17 Nickel has uses similar to molybdenum, particularly in the manufacture of steel, alloys, and super alloys.

investments to improve the return on capital employed (RoACE) and thus support their stock market valuation with the double objective of satisfying their shareholders and limiting the risk of a hostile takeover bid. Although we are not aware of any similar recent analysis of the minerals and metals segment, it is likely that such a dynamic has been at work since 2014, when the fall in prices led many international producers to engage in asset disposals in order to meet their debt constraints, while their Chinese counterparts did not.

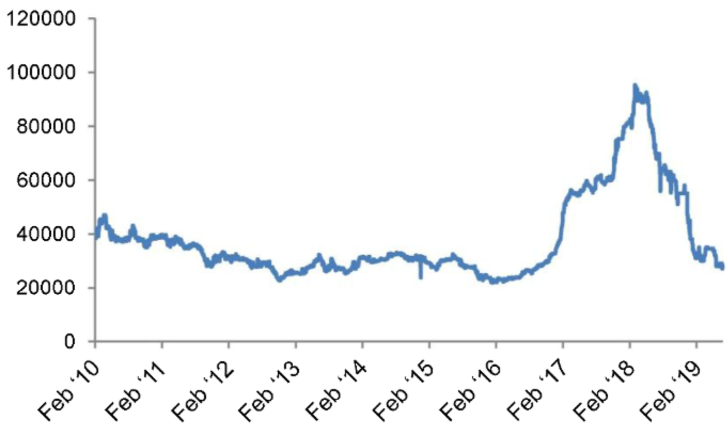

Figure 2.2. *Changes in LME cobalt forward prices (three months) (USD per metric ton) (source: Datastream)*

2.4. Conclusion

The financialization of commodity markets is a complex phenomenon to grasp, both in terms of its precise definition and the measurement of its effects on price dynamics, particularly volatility, and in terms of the reality of the economic players (producers, users, traders) who experience it. If we look at the role played by the financial markets of commodity derivatives, it is quite clear that this role has increased over the past decades. In the solid minerals segment, this trajectory is not expected to change, with an increasing number of "large minerals" or intermediate products being listed. Hitherto confined to a national perimeter, it is also likely that the Chinese reference stock exchanges, particularly the Shanghai stock exchange, will become international in the wake of the yuan.

The abundance of scientific work on the behavior of raw material prices has not exhausted the research potential that such a topic represents. The analysis of the interactions between the so-called "real" and financial spheres remains essential.

From this point of view, it is in our opinion necessary to accentuate the research effort on the financial determinants of mining investment by apprehending broad explanatory variables related to the often negative societal perception associated with this type of activity.

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3

Geopolitics of Metals: Between Strategies of Power and Influence

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3.1. Introduction

Around 2,500 years ago, the Greek strategist Themistocles probably expressed the first natural resources doctrine of our civilization when, within the Athenian democracy of the time, he convinced his fellow citizens to pool the proceeds of the Laurion silver mines. Two hundred ships were financed and the invader Xerxes was defeated in Salamis in 480 BCE. His thought was simple. Nowadays, we understand it as the expression of a strategic solidarity of defense of the city armed with a strategy of power expressed on a deposit of precious metal. It was prolonged by conquests, strategies of influence on its new lands, and a progress of sciences and philosophies, so many facets of a luminous Athenian thalassocracy that maintained its difference compared to the neighboring cities and kingdoms.

3.2. Natural resources doctrine

Like Athens, our states have differentiated from each other because they have each defined in their own natural resources doctrines, that is to say, dependencies, independences, and interdependencies with regard to these resources, and therefore their economies and also their security. Our countries are producers or consumers of

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raw materials and have adopted three doctrines: the national agricultural doctrine and food self-sufficiency, the national energy doctrine and energy independence, the mining doctrine and national industry. The absence of one of these doctrines will mean that a nation cannot harmoniously catalyze a community of objectives and means to sustain its existence in the long term, without relying on foreign territories. The geopolitics of natural resources is this prelude to the political construction and economic development of states, this Great Game in which the national natural resource doctrines of producer or consumer states are elaborated and then collaborate or confront each other. They each have very long-term trajectories and are intergenerational strategic solidarity, which successive governments and administrations at the heads of countries rarely touch, because they shape the particular relationship between the population and its concept of nation.

This reading grid, which is personal to me, sheds light in its own way on how our countries have been built through revolts, revolutions, or more peaceful developments, leading to democracies, constitutional monarchies, or “*democratura*”.

Here, producing countries exercise a strategy of power over their soils or subsoils, and this resource nationalism can be favorable or unfavorable to the consuming country depending on whether it is granted or denied privileged access to these raw materials. Here, the consumer countries exercise strategies of influence in order to obtain supplies from the producer countries, while also committing themselves to the logic of a circular economy through recycling and more economical consumption of resources.

In general, North Asia has an active strategy in all areas, as its local production has long been insufficient:

– Japan and Korea have sought and continue to seek stable supplies of both energy and metals, particularly through long-term relationships with Australia, South America, and South East Asia. The objective remains constant: to diversify supplies, substitute, and recycle.

– Modern China has developed its economy through its own resources, coal, mining, and agriculture. This has taken the form of centralized supply, industrial consolidation, and the fight against smuggling. Regarding the latter, the lanthanide sector is an example of the epiphenomenon revealed in 2010. Over-indebted public companies (China Daily and OECD 2019) are the remnant of this model. Faced with immense needs, insufficient national resources, and the adoption of strict environmental rules, the natural resources doctrine has evolved towards more imports of raw materials, not by exercising a bellicose and misanthropic strategy of resource warfare against other countries, but by exercising its influence. This doctrinaire flexibility was facilitated by the training of Chinese leaders. It is easier to achieve the national goal when one understands the path to it. Of the last six presidents and prime ministers, with the exception of the current prime minister, Li Keqiang, a lawyer, all received thematic engineering training. In power from 1998–2003, President Jiang Zemin and Prime Minister Zhu Rongji were electricians; then, serving from 2003–2012, Hu Jintao was a hydro-electrician, while his Prime Minister Wen Jiabao was a geologist. From 2012 to date, Xi Jinping is a process chemist and knows agriculture well.

This thematic chronology of Chinese leaders corresponds to the stages of the country's development: power plants and coal, hydroelectricity and materials, geology and mining production, which coincide with, among others, the Chinese mining and energy geopolitical advances in Africa, which also concern the agri-food sector. It is, therefore, no coincidence that it is the current president who has decided to renounce the doctrine of food self-sufficiency. China has turned, like other Asian countries, such as Korea or Japan, to the agriculture of other continents. A recent accident proved it right. Following an outbreak of swine fever, which began in the fall of 2018 on its own farms and decimated its livestock, Beijing drastically increased imports of U.S. pork products in the first quarter of 2019. However, the trade deadlock with the United States forced it to tax these flows at 62% as of July 2018 (China Daily 2018). As the conflict with Washington escalated, China turned to other countries, particularly in mid-summer 2019 to Europe and Brazil. As a result, world prices doubled. At the same time, China turned to Russia (Sputnik News 2019) for soybean supplies. As it was freed from a restrictive doctrine of alien self-sufficiency, China overcame this agricultural crisis. However, these imports of minerals, energy, and agricultural products increase the country's dependence on foreign countries. It is, therefore, unavoidable that an embargo on its exportations of certain raw materials, such as lanthanides in response to a crisis with Washington or another allied country on another subject, would risk leading in return to a series of blockades against its imports of other resources vital to its economy: pork, soybeans, lithium, cobalt, nickel, iron ore, gas, etc. The world of raw materials is thus rarely a one-way street.

In the rest of the world, states have selectively active doctrines, but sometimes they do not anticipate events very well:

– Europe has an agricultural doctrine, the Common Agricultural Policy, but it remains without a twin doctrine for energy and minerals because Brussels would have to assemble sometimes contradictory national policies. It would stop at the threshold of definitions of strategic energy and mineral matters. What is there to be done? What does strategic uranium, which is part of the French energy doctrine, have in common with German lignite, Polish coal or that of Eastern Europe? What about the replacement of this European coal by Russian gas or American LNG, each meeting opposite requirements, which is strategic for Europe? Would it be a matter of a Yalta inverted gas, Russian gas in Western Europe (especially in Germany), US LNG in the East with Poland as an entry point for deliveries to Ukraine? No energy geopolitics of the countries of the Union converge between coal, lignite, gas, and uranium. As for the mining doctrine, the problem should be simpler; in spite of Scandinavian production, many metals are in deficit in Europe.

– The United States has largely lost its fears in thinking about natural resources, since it has become the world's leading energy power thanks to unconventional gas and oil. From a strategy of energy independence for a consumer country, they have migrated towards that of energy dominance for a producer country; it is, therefore, tempting for Washington to use this new pressure on Europe (Les Échos 2018a) to counter the gas coming from Moscow; the setbacks of the North Stream 2 gas pipeline around the Danish islands in the Baltic Sea should be read in this light. The American mining doctrine is only the start of apprehensions for some metals of the military-industrial complex. However, resources have been catalogued on the national territory or in friendly countries, notably in Australia for lanthanides; in addition, mining exploration centered on strategic metals is in the making (Le Monde 2019a).

– Some states purchase agricultural commodities under the aegis of a national doctrine: Qatar, Egypt, Mexico, etc.

– Finally, and naturally, oil producing countries in the Persian Gulf and mining countries such as Australia, Canada, the Democratic Republic of Congo, Peru, Bolivia, and so on produce and sell their natural resources through producer doctrines. They encourage investment in their production in order to maximize the national rent. Thus, the South African government and the Platinum Group Metals (PGM) mining companies wanted to create an automotive catalytic converter industry in South Africa for export, as did the Democratic Republic of the Congo when it revised its mining code, which led to the creation of the concept of strategic metals to increase rent: "any mineral substance which, according to the international economic situation at the time, at the Government's discretion, is of particular interest in view of its critical nature and geo-strategic context"; cobalt and coltan in particular have become strategic substances and their royalty increased to 10% (JO RDC 2018). It is also the expressed desire of Indonesia to become an industrial center for electric cars, thanks to its nickel and cobalt mines (Bloomberg 2019).

The geopolitical balance of power between these countries rarely unilaterally favors the doctrines of consumers or producers. On the contrary, the former enjoy privileged geopolitical access to resources and the latter benefit from the influence of consumer countries, in particular to develop their infrastructures or their industries. This influence takes the form of transfers of knowledge and skills, the structuring of industrial sectors, production capacities, and job creation. These are all essential elements for the acceptability of new mining projects.

In general, these two strategies of power and influence rarely oppose each other, a recent exception being the 1973 oil crisis, and then the ones that followed; but in the mining world these two forces often balance each other on the geopolitical map of the Great Game of metals; this is already the case in nickel. For example, this was apparent when Indonesia showcased its power by banning the export of minerals and Beijing's influence made possible the establishment of Chinese factories at the foot of Indonesian mines. An identical movement is not to be excluded for South American lithium: will we see their battery factories adjacent to the Andea salars?

Companies often reflect the doctrines of their own country. In Asia, the stakes are centralized, and companies are active in identifying risk areas and moving up the value chains. Elsewhere, particularly in Europe, the habit is to generally trust the markets and their intermediaries – the traders. Nevertheless, both identify their dependencies and apply their own doctrines to their projects. This is the case for automobile manufacturers, such as Renault for the Zoé, BMW, or Toyota (Usine nouvelle 2018; Actu-Moteurs 2019), who have, or will, eliminate lanthanides from their electric models. It is battery manufacturers who are reducing the volumes of cobalt in their lithium-ion batteries, particularly in the new nickel-manganese-cobalt generations.

However, this win-win game may not work. Due to environmental concerns, the lanthanide producer Lynas has encountered difficulties in stabilizing its ore processing plant in Malaysia and may eventually move some of the refining to Australia. In other cases, the necessary skills are lacking in the producing countries, particularly on the African continent, or industrial porting is prohibited, for example in China where mining sectors are forbidden to foreign companies.

3.3. Abundant, sensitive, critical, and strategic metals

These strategies of power and influence are all the more essential for many countries and industrial sectors after COP21 as the energy transition is shifting from a dependence on hydrocarbons to a dependence on the metals necessary to generate, transport, store, and consume electricity in generators, connectors, battery chargers, accumulators, and motors.

How should states and companies think about the geopolitics of metals (PIR 2012)? We need to go back to the fundamentals again to answer this question and remind ourselves that there are only four types of metals: abundant, sensitive, critical, and strategic.

The tools of a national doctrine of natural resources have been widely used for the production and consumption of abundant metals. These have been sought and discovered by a dynamic industrial fabric and inventive diplomacy. Then a range of technologies proved opportune to extract them from the ground, refine them, and, thanks to ecodesign, consume them in decreasing unit quantities and increasing uses. Finally, they are recycled.

However, these abundant materials can become sensitive if one of the previous steps fails. This can happen, for example, when the demand for a commodity, including for speculative reasons, becomes inflamed and the supply falls behind before catching up. For example, the prices of platinum and palladium in the 1990s, those of some lanthanides in 2011–2012, and lithium, cobalt, and vanadium in 2018: each showed a bell-shaped price curve. Each time a fundamental tension was accompanied by speculation, followed by a decline that the industrial buyer had to be able to manage.

A material is critical if there is a high risk of deficiency without a scientific breakthrough paving the way for substitution. However, it will be critical in one industry and not in another, in one country but not in another, and this evolves over time according to the fundamentals of the market for this metal. This was the case for the downgrading (Le Monde 2019b) of lithium from a critical metal to a sensitive metal.

If the consumption of a resource accelerates (organic agriculture), or if an accident handicaps production (iron ore in Brazil after the collapse of dams), then criticality will persist in the medium term. The cautious consumer with a long memory will regularly wonder about these metals and the balance between real supply and industrial demand; otherwise, the danger is to freeze the critical or, on the contrary, abundant character without giving it a temporal dynamic.

For example, one of the metals that will be critical for the future of the energy transition is without a doubt copper, whereas, as we have just said, lanthanides are losing their criticality for the manufacturers, who are banning them from their electric vehicles.

In addition, if this metal is the byproduct of a major metal, observation of the equilibrium of the latter is essential. Anticipating the fundamentals of the indium market is impossible without evaluating those of its major metal, which is zinc:

– the analysis of gallium must first gauge the bauxite market and, therefore, the aluminum market;

– rhenium is a byproduct of molybdenum itself, like cobalt, a minor metal of copper;

– rhodium follows the platinum market in South Africa and the nickel market in Russia;

– neodymium is interdependent with the cerium market.

On the contrary, despite the simultaneous inflation of their prices in 2018, it is this structural difference between lithium (a major product) and cobalt (a byproduct) that allows for diverging expectations between these two components of electric vehicle batteries.

Finally, a strategic subject moves away from geological or market criteria. It is an indispensable resource for the regalian missions of the State, for national defense, or for the essential political ambitions of a consumer or producer country. Thus, one of the most common materials on Earth – iron ore – demonstrates that an abundant material can become strategic without becoming critical. Indispensable to the steel used in China’s strategic urbanization policy, it had become strategic there since the beginning of the century and reached its peak in 2008–2011. Copper for infrastructures and sand for concrete were of the same order.

In France, with the exception of uranium, which benefits from a law, a decree, and classified directives, there is strictly speaking no other strategic material. On the European scale, without a common policy there are no strategic European metals because one material will be strategic for one European country, but not for the other, and this evolves over time.

3.4. Competitive consumption

If these last two notions, which are critical and strategic, merge, some minds imagine that wars will seize the tensions created around these metals that have become difficult to find; they are looking for insights into past models of the great energy game, particularly the one we have known for oil and/or natural gas for a century. The latter has most often adopted paradigms like that of the Cold War, sometimes leading to real conflicts.

However, this paragon does not apply in metals or in modern agriculture. Our world of metals is not so bellicose that a modern state invades its neighbor with its army and triggers a high intensity war, such as the first Gulf War, or that less vigorous tensions lead to the attack or seizure of oil tankers, as in the summer of 2019 in the Strait of Ormuz, even the drone attacks on the oil sites of Aramco. Metals are multifold, flexible, and substitutable in their uses; hydrocarbons are less so. Metals are everywhere in the earth's crust in varying concentrations whilst hydrocarbon pockets are more concentrated, although the possibilities of unconventional hydrocarbons have revolutionized this industry. They have associations, but no OPEC that operates with the help of OPEC+[1]. Gas opposes two power strategies, those of the United States and Russia on the European market, but copper, aluminum, lithium, cobalt, and lanthanides do not oppose any producing countries.

Moreover, when this fusion between critical and strategic metal occurs, it leads to competitive consumption, that is, competition between different critical consumptions of this metal. The producer favors the user closest to its own strategic objectives: first of all, its national industry. However, this situation can only be ephemeral; such a metal may not have been sufficiently sought in the earth's crust, or it is in ecological over-consumption, or even evolving from a marginal metal to a mature metal.

These situations are generally those of narrow, temporarily poorly managed metal markets that quickly fall into line. This was illustrated by the stratospheric prices of cobalt, lithium, and vanadium in 2018. Their three bubbles have deflated, production, speculation, substitution, and ecodesign having done their work. A similar situation was observed for lanthanides in 2010–2012: tension, then calm once the bubble burst.

3.5. Proliferation of "unobtanium metals"

As it encompasses state and corporate policies, the paradigm that combines the fusion between critical and strategic metals with competitive consumption becomes geo-political and carries the risk of being the target of fake news. In the world of oil, everyone will remember the thundering disinformation that occurred, particularly at the UN, accompanying the Second Gulf War. In this field, the world of hydrocarbons is well ahead of the world of metals. In the past, the "palladium crisis" cost the automobile industry very dearly; Ford (New York Times 2002) lost 1 billion dollars. The "uranium crisis" of 2007 led to the Uramin affair (Le Point 2019) and revealed a financial abyss of 2.5 billion dollars for Areva. In both cases, the market was the victim only of manipulations without any real fake news. More recently, in 2011–2012 (Julienne 2012a), the "lanthanide crisis" began as a production crisis, but it left a stigma in the valuation of stocks of Japanese processors who had bought

1 No more non-OPEC members led by Russia.

against the current and then, following fake news, despite a first warning (Julienne 2015), it concluded with a warning from the AMF (AMF 2016) and a judicial investigation (Le Parisien 2016). In 2017–2019, with an unprecedented vivacity, fake news emerged for a new chapter; "rare metals" or metals that could not be found, such as lithium, cobalt, or vanadium. There was no real real production crisis – on the contrary, their prices rose to historical levels – but once reality was back in control, they collapsed. Perhaps we will later know the harmful consequences of these price movements on strategic stocks.

These fake news phenomena work in cascades, one piece of disinformation causing the next. The first generally takes the form of a fascination: the rare or untraceable metal that could be called "unobtainium". It focuses the attention of the politician of the producer country because he/she imagines it to be a geopolitical element of his/her power strategy, while it hypnotizes the politician of the consumer country because he/she thinks it is a key to his/her strategy of influence. It is simply a myth, an oxymoron, a danger, an illusion that can have damaging consequences on the making of decisions because they will commit the politician to a dead end bordered by deceptive choices between such and such an industrial policy, such and such an energy policy, or such and such an option for national security. The example of the battery airbus is an interesting one. This industrial initiative is undoubtedly an excellent way for Europe to catch up with the three world leaders: China, Korea, and Japan; but why should the relevance of this event be officially linked to "rare metals", as a minister recently did? This statement is strange: "In this sector, we must have the same logic: that of holding it from beginning to end. We are going to work on it, from the search for rare metals (with countries like Chile or Argentina), to the realization of the electric battery, through its integration in the car, details the minister…" (Essor 2019). What are these "rare metals" that are undermined here? Considering the two countries indicated, is it lithium, which, thanks to mining efforts upstream and RD downstream, is very far from rare? Its price has collapsed and there seems to be an abundance! Due to this illusion, the argument of an industrial verticalization of a battery airbus loses its strength considerably. On the contrary, the language of a more ambitious and forceful policy would have been: batteries freed from a dependence on "rare or unobtainium metals".

There are safeguards to avoid such errors and to enlighten the politician: data collection, data analysis, and reporting. However, these lag behind the dissemination of fake news and the actions taken. If a hoax comes from a partial, obscure, disparate, inculpatory or exculpatory extensive search, it is quick, has the coherence and the attractions of purity, and is initially stronger than a complex and constraining truth that requires verification and patience because it is longer and more difficult to establish than a piece of fake news. The politician is generally in a hurry and will be, with few exceptions, a neophyte whose difficulty is to reason truthfully about a virtuality, the "unobtainium", based on false elements. These forms of disinformation, intended to produce over-interpretations and then emotions, provoke errors. Victims of these "fashionable subjects", strategies of power and influence will distance the actions of states or companies from the realities of the markets.

This first hoax of "unobtainium" can generate a second piece of fake news, that of the guilty party who initiated the scarcity. In the "palladium crisis" of 2000, Russia was accused of delaying palladium deliveries in order to provoke a rise in prices, but the latter deflated just after the source of tension, TOCOM, the Japanese futures market, applied restrictions to its palladium contract (Smith 2001).

Today, "rare metals" fake news has a culprit, China, and it takes various forms. Its domination in certain metals, its advances in the metals of the "red batteries" of "green electric vehicles" (cobalt, lithium, lanthanum) (Les Echos 2018b; Le Monde 2019c), and the verticalization of industrial sectors.

First, there is the fake news of the "politically correct" hoax. It teaches that, by dumping its own mining production, Beijing is securing a monopoly of certain punched metals that cannot be found – lanthanides, tungsten, etc. – and then stifling their markets in order to suffocate mines outside China. Then, it would have them bought out by its own companies at a low price. This message has the appeal of sensationalism fueled by caricature – the culprit is China. But which mines would have closed after a real and demonstrated Chinese misanthropic will, what is the proof?

The reality is different. Chile is the world's leading copper producer and it is not the result of a belligerent geopolitical strategy towards competing pro-producer countries, but because its subsoil is rich in copper. Indonesia, the Philippines, Russia, New Caledonia, and Canada share the first places in nickel and this too is for a mineralogical reason and not because they are in a nickel war. Thanks to its petrography, South Africa is first in platinum, and yet the country has peaceful unbellicose relations with the second world producer, Russia. Moreover, the market of iron ore is dominated by the Australia–Brazil couple because the soil is favorable there; the two countries do not war. Guinea supplies so much bauxite not because it has exhausted other producers, but because it has resources. Finally, China is first in lanthanides or tungsten not for a strangely misanthropic geopolitical reason, but again and again for a geological reason: it has rich deposits and it exploits them.

Other countries have deposits as large or as small, richer or poorer, but they do not exploit them. The example of the Salau tungsten mine in Ariège in France is emblematic; it is undoubtedly world-class, but it remains unexplored and unexploited. Why is this? Certainly not because of Beijing!

In conclusion, neither China nor any other country has waged an economic war to bring down the prices of the metals it produces and consequently make mines in other countries disappear. This original idea of misanthropic Chinese domination is a piece of fake news, but no one is saying it.

Second, the Democratic Republic of Congo has recently been, and probably also for a while, another terrain of untruths (Le Monde 2019c). China imports much of the cobalt production of this country, the world's largest producer. But how did the Chinese company China Molybdenum become the owner of the Democratic Republic of Congo's largest cobalt mine? Did it go to war? Did it ask its army to intervene? Did it colonize or invade this territory? Did it use underground networks to bury the entire chain of decisions? None of the above. In 2016, China Molybdenum simply bought this giant mine from a mining company, an American one based in Phoenix, Arizona. A peaceful sale took place between two companies that had two different strategic visions of development, but again no one says that this factual information contradicts the fake news of a Chinese cobalt war. Conversely, if there really was a cobalt war, why would the United States have left one of the world's leading mines in Chinese hands instead of friendly hands?

The situation was identical when, in the midst of the trade war between China and the United States at the end of 2018, the world's leading lithium producer, Chile's SQM, saw 24% of its shares held by the Canadian Potash Corporation bought out by China's Tianqi for more than 4 billion dollars. Tianqi thus became the world's leading producer thanks to investments in other producers in China and Australia. Since it is recognized that the Canadian mining strategy has been in decline since the disappearance of Inco, Falconbridge, and Noranda, we could ask ourselves why, if there had been a lithium war, would we not have witnessed a fight between a Western company and Tianqi for SQM? Why didn't Washington or Europe intervene? Again, the facts tell us not of a lithium war, but a peaceful private sale between two companies; the opposite is to elaborate on a hoax until no state has countered Chinese advances.

Another false truth is the war of the lanthanides. China produces about 70% of the world's ore and processes it in its refining plants. Of the remaining 30%, only about 5% is refined outside China, the rest is exported to Beijing and processed in Chinese factories. If there were a rare earths war, what is this model of confrontation that would leave 95% of the world's materials to one of the belligerents? The fact that one of the minority shareholders of Mountain Pass is Chinese does not explain in any way the fact that this Californian mine exports its production to China, with customs duties raised to 25% since the trade war launched by Washington. Following the Molycorp episode of 2011–2015, if there had been such a conflict of lanthanides, would the United States have been unable to finance a "war effort" of less than half a billion dollars and 300 jobs to produce permanent magnets on its soil from Californian ore or from deposits located in Texas, Colorado, Wyoming, and Alaska ? It was only at the end of May 2019 that a statement by the US Defense Ministry envisaged freeing up funds to reduce dependence on lanthanides of Chinese origin, particularly for military applications, and then President Trump put forward the idea of buying Greenland (Julienne 2019).

As for the European future, if this lanthanide war existed, how would the same Chinese company that invested in Mountain Pass have succeeded, without European opposition, in signing a supply contract with the future Greenland mine when the French plant in La Rochelle, which is closer by, could process it? If there was a battle in this area, it was fleeting. It is necessary to go back to 2009 to see that Australia protected its Lynas mine against an attempted takeover by a Chinese company, but conversely in the same country the Australian mining project of Yangibana contracted for the processing of its future production to Chinese companies. Once again, China is exercising its strategies of power and influence to obtain supplies of lanthanides, while no country is exercising a mining doctrine to counter its access to mines or its technical advances in ore processing.

Following a domination in certain metals, the subsequent fake news is verticalization, the hegemony over a sector of activity. It is however based on an industrial reality practiced by all, the sector. If they give themselves the means, the one who controls the access to the production of the metal dominates the downstream industrial sector. For 30 years, China's huge leap forward has required large quantities of metals and China, like other powers before it and for centuries, has exploited its territory. Then, it has imported by taking industrial and commercial positions in metallurgy and mining from foreign countries at the risk of running up against local economic policies. This verticalization, far from clashing with the nationalisms of the resources of the producing countries, influenced their power strategies to reach compromises.

In 2009, Indonesia passed a law prohibiting the export of its mining resources without transformation from 2014, notably to China. The latter has not gone to war with Jakarta. On the contrary, it turned the crisis into an opportunity; five years later, in 2019, competitive Chinese metallurgical companies set up operations downstream of Indonesian mines. Crossing borders, Chinese industrialists have verticalized overseas, from extracting minerals to marketing manufactured products within the same group, or even within an international supply chain, as in the case of CATL, LG, and Tesla in Indonesia (Telsarati 2019). Thanks to the alliance between Indonesian and Chinese mining doctrines, Indonesia is and will be a major global player in nickel for stainless steel and batteries.

As fake news does, is this strategy of verticalization strategy to be blamed on China, even though it is not new? Arcelor-Mittal operates in this way, from iron or coal mines to steel marketing, as does Korea's Posco also, by securing the loyalty of New Caledonia's nickel ore, and Finland's Outokumpu by operating its own chromium mines for its steel. Norway's Norsrk-Hydro operates in the same way with its bauxite for its aluminum. Michelin cultivates its rubber plantations for its tires. Bonduelle buys farmland for its vegetables. Russia's Rostec groups together the metallurgy of armaments and operates its own copper, gold, niobium, and lanthanide mines. Nestlé builds loyalty with coffee producers for its capsules. The electrical company RWE consumes its lignite production in its power plants and Engie does the same with its natural gas. For their part, Chinese or Japanese car manufacturers do nothing but control the industry, from the mining company exploring for lithium or cobalt to the marketing of electric cars. Controlling upstream to better play a role downstream, the reality of verticalization contradicts the fake news of Beijing's innovative hegemony, especially for the electric vehicle. Here again, China is filling the void left by the absence of mining doctrines and can lower the country's overall production costs. Moreover, critical and strategic metals professionals have long observed that Chinese initiatives in this field are provoking "capitalist competition" among Chinese private companies themselves, sending the conspiracy of a misanthropic Chinese strategy back to its origin, the hoax.

Various pieces of fake news followed, such as the one opposing the circular economy, which seeks to harm the electric car by claiming that the "Chinese red batteries of green electric cars" are not recyclable. On the contrary, in Europe, the collection circuits for these batteries of Asian origin equipping European vehicles are almost all perfected (Les Echos 2017); the incentive is normative rather than economic, and the dismantling of the modules is labor-intensive and requires a minimum of automation. Secondly, as metal refining is widely known, the sector will become more profitable as the volumes to be recycled become available.

Let's stop here with these fake news questions. They show that China has not initiated a metal war, and that, on the contrary, it has peacefully and commercially gained access to mines because of the vacuity of our own mining doctrines; but the question that arises is why this fake news, which has played on ignorance and emotion and is celebrated among neophytes who wish to receive information that only confirms their established beliefs, has been grouped together in a “metal war” myth. Whatever the causes, this legend reinforcing the belief of a conflict has settled in the brains as in the nests of birds absent for the wrong reasons and we investigate three of them.

The first hypothesis is that of the resolutely anti-Chinese myth; it is a small facet of the immense trade war between the United States and China. The danger is that it calls for a bellicose response. Fortunately, no war has been declared over lithium or cobalt, and it is salutary that, with regard to the lanthanides, the recent declarations of the Chinese president about the establishment of an embargo on its “important strategic resources” following the Huawei sanctions by the United States have remained only declarations. Beijing has not responded to the accusations with an embargo on rare earths. The best we can hope for is a reversal of the fake news, so that the beneficial effect of this return to reality will curb anti-Chinese sentiments and appease the youth imprisoned by the feeling that nothing will be possible to save the planet in the area of natural resources since China is an enemy that has already won. As a result, the other benefit of the return of the truth would be a softening of anti-democratic feelings. Indeed, the models advocating 100% renewable energy in Europe, or the Green New Deal of the US Democratic Party, are of such magnitude that they would be impractical in a climate of real or virtual war for natural resources. However, the great danger is that ideologies, and the political promises that support them, like the ecological transition, are in danger of excluding themselves from real life, of no longer understanding their impact on populations, and of losing the link with the industrial world. If it becomes impossible to keep these promises because they would lead to conflicts built on a myth such as the “metal war”, it is democracy in the broadest sense that suffers.

Words have a meaning, and to use the word war without ever having known it is deplorable; we do not need fake news about a “metals war, whether they are abundant, critical, strategic, rare, or untraceable” to save the planet, but on the contrary a truth about “metals peace” to negotiate without emotion. Only inclusive cooperation between Beijing, Moscow, and other producers of technology and natural resources, as Indonesia and China have achieved, will fulfil the promise of a European energy transition that will no longer confuse rhetoric with reform.

The second hypothesis is contiguous to the first. The “metal war” is a dangerous myth because it causes an anesthetic effect. Each state stands still because each believes that China’s mining doctrine is being fought by another, since the fake news indicates that a war would exist between China and another country. However, this war is nowhere and this other country does not exist; no battle, not even economic, has taken place recently specifically for copper, nickel, iron, PGMs, rhenium, beryllium, cobalt, gallium, germanium, graphite, indium, niobium, lithium, or lanthanides. No one opposed their influence and mining advances. This metallic war is a decoy and it never took place.

Here, lists of strategic or critical metals constructed by states do not answer the question of a fight or a negotiation. They are neither proofs of a war nor weapons nor offensives, but on the contrary a kind of observation that should remain secret, a foolish intellectual surrender to the extent of a virtual "metals war" for want of a fighter. And while everyone thinks that someone else is fighting China, Beijing has progressed without being countered. No one has opposed its influence and its mining advances. Accusing China of a "metal war" helped to facilitate its advances because by condemning a symptom, the disease continued to flourish, while the cause of the evil remains hidden: the abandonment of our mining doctrines.

Eliminating the anesthesia of a virtual war virtually waged by others includes claiming that China has gained positions because other consumer countries have deserted the mines and industry (Julienne 2009). Less visionary, they have not re-evaluated their strategic metallurgical and mining solidarities (Julienne 2019b) and abandoned their strategy of influence.

If nothing is done, without new mining doctrines, the next accused, the next victims of fake news, may be mining companies, companies in the business of batteries, electric cars, solar energy, electronics, or even under the alibi of socially responsible investment and environmental and social governance criteria in the lithium, cobalt, manganese, nickel, tin, copper, etc. industries. It is, therefore, necessary to build these mining doctrines while protecting ourselves by questioning future fake news linked to metals.

Other theories could be imagined, but let's mention a third one. It is not impossible that the fake news about the "war of rare metals" is the fruit of a desire specific to our age of communication: to want to be the latest fashion, to acquire notoriety, to "make the buzz" with the ultimate goal of being recognized. We will summarize this last possibility under the qualifier of the "vanity of imposture". Of our three suppositions, it is the simplest and perhaps the most probable, without denying that it was chronologically followed by the first or the second as an element of a larger operation, resolutely anti-Chinese and nowadays popular across the Atlantic.

3.6. Strategy of influence, strategic stock, and exploration

The industrial sectors deeply involved in the manufacture of energy transition products such as wind and solar energy, batteries, electronics, 5G, and so on are looking for tools to counter their dependence on metals through their strategies of influence. Several principles are available to them.

One of the first possibilities is based on strategic stocks. It is necessary to separate the stocks useful for the regal needs of the states from those of the companies. Regalian reserves must have clear rules for entry and exit; their composition must evolve over time according to market fundamentals; built for the long term, they are fragile because they have a duty to navigate on sight, anticipating a market environment where speculation reigns. China, the United States, Korea, France, Japan, and other countries have strategic stocks of various energy, metal, or agricultural materials. These government stocks cannot be pooled with those of the private sector. Such management was improvised in France during the 1990s, and resulted in the sale of PGMs to the international market in the aftermath of the first wave of high consumption of platinum and palladium in automotive catalysts by domestic manufacturers.

On the business side, stocks must be guided by their boards of directors. The latter must, therefore, have the necessary skills to handle them. Another option is the use of trading companies to manage the stocks of industrial chains, and nothing illustrates this part better than the observation of the role of Japanese *sogoshosha* for the benefit of Japan Inc.

The second way to meet the increase in demand is downstream of consumption. Metals go around the world several times between the place of extraction, refining, industrialization, and consumption and then they start again this way after recycling. This last subject is also dealt with in this book.

The third way to meet demand is to increase production. The United States is more familiar with the mineral composition of the moon's surface than with the presence in its own subsoil of raw materials useful for electric vehicles. Deposits of lithium or cobalt exist in the United States, as do deposits of lanthanides. Although we are also ignorant of the value of our subsoil in France, we would easily use the contradictory argument of controlling the production of the metal to dominate the downstream industrial sector. This is why securing supply will require increased exploration and national production by revolutionizing our environmental, societal, and governance criteria. This new situation will make it possible, on the one hand, to evaluate the ecological impact of mining projects, and on the other hand, to exploit only strategic and critical metals that are useful for the government's policies and the industries of the future, and thus curb the production of other metals. This new reading grid will be relevant for objectively deciding whether or not a tungsten mine in Ariège, a lithium mine in the Massif Central, a gold mine in French Guiana, or a lanthanide mine in Colorado, Wyoming, or Alaska is of interest.

3.7. Conclusion

In addition to China's ongoing evolution, the geopolitics of natural resources in the 21st century is already evolving around two main axes: first the urbanization of India, as Delhi is the next big consumer of our century. The second axis is conducive to a new Great Game of natural resources of the 21st century, the self-consumption of producing countries. Like Saudi consumers who were expected to consume more than half of the oil produced by their country (EnergyPost 2014; Gulf News 2014; La Tribune 2019), the formula that "when the African consumer wakes up, China will tremble" (Julienne 2011b) expresses the idea that African, Andean, or Southeast Asian countries will consume more than their own natural resources. Consequently, Europe must focus its thinking in two directions: finding a new strategic geological depth, and this geopolitical pivot of natural resources being that of cooperation with Russia (Julienne 2011a). The future will tell us whether the recent warming (Le Figaro 2019) of relationships between Paris and Moscow is one of the premises. The second parallel point is that the link between the geopolitics of metals and the environmental, social, and governance criteria surrounding the exploitation of natural resources must progress, notably to standardize the criteria according to which a decision to exploit a given resource is made and also to standardize good technical exploitation practices that protect the environment and stakeholders.

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4

Mineral Wealth Endowment, a Construct

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Resources are not, they become.

Erich W. Zimmermann (1933)

4.1. Introduction

Mining wealth is unevenly distributed on Earth. Some countries seem to have almost inexhaustible mines, exploited over centuries, while others, less endowed, have always depended on mineral imports.

This unequal distribution of resources has been the cause of many conflicts, from wars of predation between neighbors to civil wars. The invasion of Crimea, rich in hydrocarbons, by the Russians in 2016 is only a recent avatar of the ancient Trojan War for the Golden Fleece, the colonization of the Belgian Congo, or the nitrate war between the Andean countries in the 19th century. However, this distribution is also at the origin of international trade: very early on, rare products such as metals and precious stones had to be transported by land and sea. With the development of American colonization, the Spaniards invented bullionism, the idea that the quantity of gold and silver is the indicator of wealth par excellence (Spector 2003). In this mercantilist approach, a rich country would be a country endowed with precious metals.

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A country's mineral endowment is, therefore, an essential measure of its wealth. It is frequently used in the theories of international trade and comparative advantages (Tilton 1983, 1992). It is still relevant today. It is one of the evaluation tools for the financing of mining projects by development banks, particularly the European Development Bank and the World Trade Organization (2010). "Geological scandals" are mentioned to describe, for example, Guinea or Congo, in order to highlight the contrast between the presumed value of the deposits and the misery of the inhabitants (N'Diaye 2015).

In this chapter, we first discuss the current assessment of mining staffing as provided by international statistics and surveys. Next, the historical evolution of mineral endowment is examined, using the examples of copper and tin, two base metals of both ancient and universal use. This allows us to highlight the main causes of mineral endowment and measure its relativity.

4.2. Mineral endowment, an attempt at clarification

There are several tools for measuring mineral endowment: annual production, reserves as defined by the CRIRSCO[1] nomenclature, resources, and even the perception of mining explorers.

4.2.1. *Production and reserves*

Among the measurement tools used by economists, the value of output in a given year is probably the easiest to measure (Leamer 1984). This value can then be compared with world production and related to the size of GDP. One can also use the evaluation of mineral reserves in all the deposits of a territory, that is, the quantity of metal that can be mined economically. Finally, we can consider the resources, that is, the quantity of metal as evaluated by mining geologists for a deposit. The terms "reserves" and "resources" are now standardized throughout the world[2].

At the dawn of the great acceleration of the resource industry at the end of the 20th century, the positive relationship between annual production and reserves indicated that much of the growth in output of countries was related to their mid-range endowment (Tilton 1983). In a log–log graph, annual production and resources are correlated with a coefficient of 67.9% (Mudd and Jowitt 2018). However, this

1 Committee for Mineral Reserves International Reporting Standards, www.crirsco.com (accessed April 4 2019).

2 *ibid*.

diagram does not make it possible to estimate the temporal evolution of the relationship between reserves and production. USGS data allows for calculating the reserves to annual production ratio (R/P) for the major producing states for copper and tin over the last 20 years (Figure 4.1). In the case of copper, the R/P has been around 40 for over a century (Schodde 2010). It has experienced some sharp variations (1921, 1931) due to sudden drops in production linked to financial crises.

In the long term, R/P declined throughout the second half of the 20th century. It then increased after 1998, from 28.2 to 46.3, in 20 years. This ratio thus correlates with the general trend in copper prices (in constant dollars). The decline in the ratio between 1950 and 2000 indicated a trend of declining reserves, reflecting a decline in exploration activity due to a lack of sufficient price levels. Conversely, the increase in the R/P ratio since 2000 reflects the resumption of consumption, the increase in prices, the increase in exploration activity and therefore the increase in reserves. On a global scale, the R/P ratio therefore reflects the anticipation of demand (Monnet *et al.* 2017).

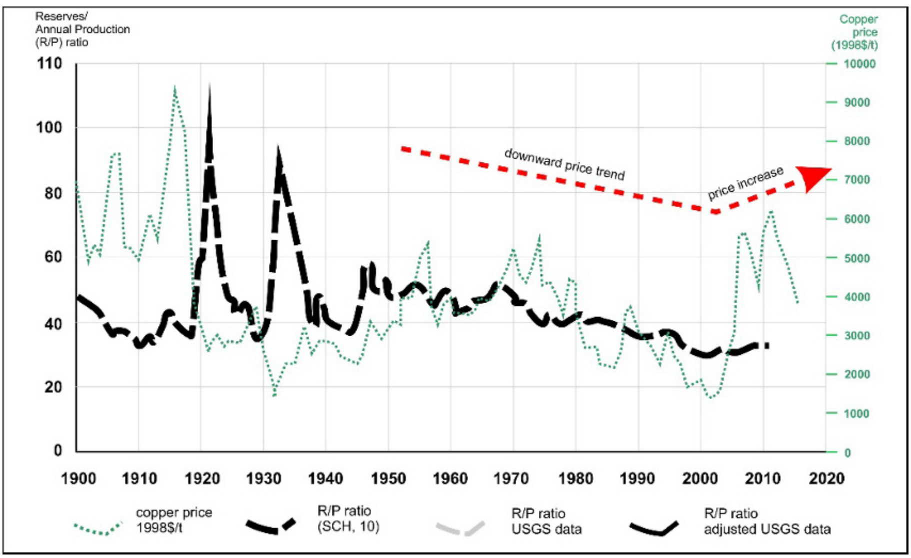

Figure 4.1. *Change in R/P ratio (based on Schodde (2010) and USGS (1998–2018))*

COMMENT ON FIGURE 4.1. – *Peaks in the R/P ratio in 1921 and 1932 are associated with a decline in production. Schodde's (2010) data differ slightly from the USGS data used here for after 1998, justifying an adjustment in the ratio in 1998–2000.*

The ratio also varies by country, ranging from a minimum for Canada, Chile, China, and the Democratic Republic of Congo to a maximum for Mexico, Peru, and Australia (Figure 4.2).

These variations can be explained in part by the nature of the deposits and the volume of investments: large copper deposits, particularly porphyry, represent considerable volumes and require investments that can exceed US$1 billion. There is, therefore, some early concern for long-term reserves.

Conversely, smaller deposits, such as volcanogenic sulfide clusters, are not suitable for establishing long-term reserves due to their size and greater variability in copper grades.

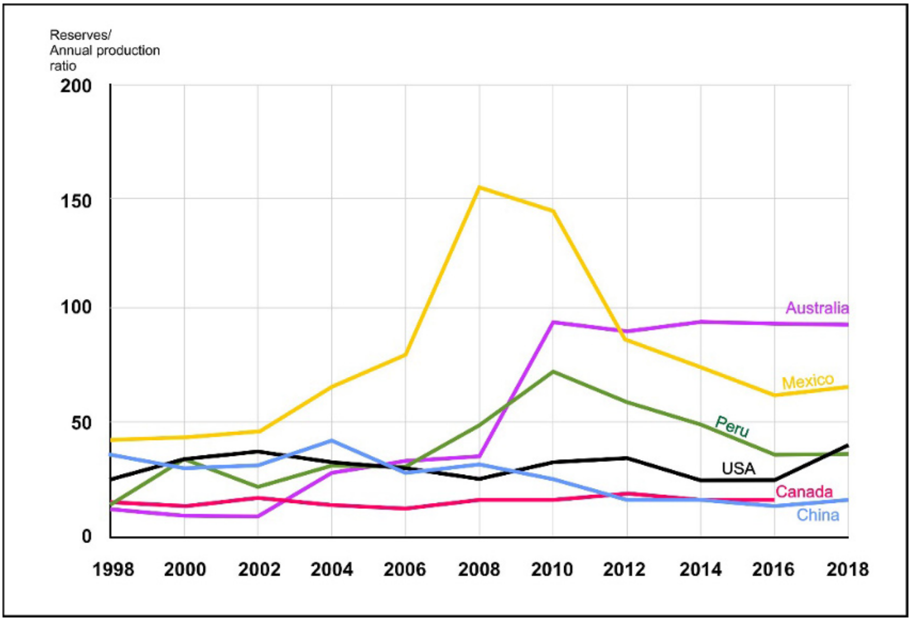

Figure 4.2. *Change in R/P ratio for copper by country (USGS 1998–2018). For a color version of this figure, see www.iste.co.uk/fizaine/mineral1.zip*

In the case of tin (Figure 4.3), R/P variations are much more significant, ranging from 17 (average for China, the world's largest producer) to almost 1,000 (average for Thailand). It is clear that these variations largely reflect statistical uncertainties in both production (much illicit trafficking) and metal reserves.

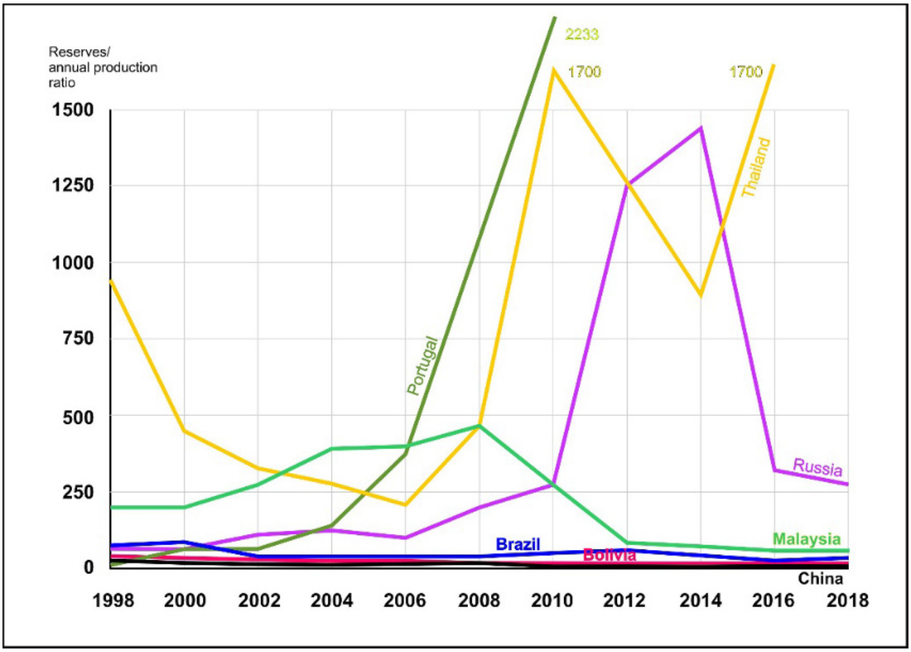

Figure 4.3. *Variation in tin R/P ratio by country (USGS 1998–2018). For a color version of this figure, see www.iste.co.uk/fizaine/mineral1.zip*

The R/P ratio has often been used to represent the number of years of mine production, a theoretical life of operations. It has been used as a support for the promotion of a peak mineral (Prior *et al.* 2012), the hypothesis of maximum production before an inevitable depletion in the short term. This hypothesis is based on the idea of a fixed stock, without variations in price, market, or innovation, an idea that is far removed from the self-regulating economic reality (Tilton and Guzmán 2016). The R/P value of around 40 for copper is simply an indication of the limitation of the calculation of mining reserves beyond 40 years, an economic period of the order of one generation. Beyond that, there is no point in investing for an unpredictable world.

Both production and consumption of copper and tin have increased over the past 20 years with the Asian economic boom. The increase in the R/P ratio over the past 20 years indicates that reserves have grown even faster than production worldwide. This increase is probably due to the production of increasingly large, low-grade deposits; this is particularly the case with the large porphyry copper deposits in the Andes. Thus, reserves have tended to increase, quite the opposite of a predicted shortage!

These data show that mineral endowment, measured at the scale of a deposit, depends on geological factors (type of deposit), but is also related to factors that depend on production: the grade of a deposit is a function of, among other things, capital, labor and energy costs, as well as technological capabilities. It is also sensitive to the competitiveness of public policies and the international market (Tilton and Guzmán 2016). Mining countries are adopting policies favorable to the production of several mineral products (Wright and Czelusta 2004). The notion of mineral endowment is thus largely constructed.

4.2.2. *Resources and perception*

On a regional scale, American authorities developed, in the 1970s, the notion of a reserve base*,* going beyond the notion of mining reserves (U.S. Bureau of Mines and U.S. Geological Survey 1980): this corresponds to geological resources – therefore economic and sub-economic resources – estimated from geological knowledge. The calculation is made on the basis of Lasky's law, which inversely links grades and tonnages of deposits. The geological resources can represent up to double the mining reserves. More recently, the USGS proposed an evaluation of copper resources not yet discovered (Singer 1993; Dicken *et al.* 2016). The depth of investigation ranged from 1 km for porphyry deposits to 2.5 km for deposits in sedimentary environments.

In the case of uranium, a model for calculating ultimate resources has been developed (Monnet *et al.* 2017) on the basis of geostatistical work (Harris and Verle 1988). For a uranium price of less than US$260 per kilogram, the ultimate resources would be between 36 and 72 million tons, while the resources identified would represent only 8 million tons. These figures are to be compared with the 2.8 million tons produced between 1945 and 2016 (World Nuclear Association 2018).

Finally, for gold, Frimmel (2008) showed that the 311,000 tons of gold identified in deposits (production + reserves + resources) to date represent only a tiny fraction of the 45 billion tons of gold existing in trace amounts in the earth's crust. The absence of economic criteria in this study clearly shows that the perception of a metallic potential requires grade and technology constraints. Thus, this work is fundamentally dependent on price and any evaluation of resources, even just geological, must be re-evaluated to take into account the progress of demand and technology.

Finally, we can consider the assessment of a country's mineral potential as perceived in annual surveys of mining company executives; this is the case for the Fraser Institute survey (2018).

Production (2018)	Resources (Mt Cu)	"Endowment" (production, reserves, and resources) (Mt Cu)	Percentage of respondents indicating that geological potential encourages investment
(USGS 2018)	(Mudd and Jowitt 2018)	(Mudd and Jowitt 2018)	(Fraser Institute 2018)
Chile (5,800)	Chile (896)	Chile (1,052)	United States (Alaska, Arizona) (74%)
Peru (2,400)	United States (330)	United States (446)	Peru (72%)
China (1,600)	Peru (210)	Peru (242)	Chile (68%)
DRC (1,200)	Australia (136)	Russia (175)	Mexico (64%)
Australia (950)	Russia (131)	Australia (163)	ROC (63%)
Zambia (870)	China (128)	China (154)	Australia (59%)
Indonesia (780)	DRC (110	Canada (144)	Indonesia (56%)
Mexico (760)	Canada (101)	DRC (134)	Russia (57%)
Russia (710)	Mexico (81)	Zambia (102)	China (n.a.)

Table 4.1. *Ranking of the richest countries in copper*

Table 4.1 shows that the same countries have the highest annual production, resources, endowment (Mudd and Jowitt 2018), and reputation. There are counter-examples, like the current weight of China in the production of rare earths. It dominates production and does not seem to have resources at the same level. However, it is still a niche market, an emerging market, only very partially obeying the laws of the market.

Thus, while there are difficulties in quantitatively establishing potential, there is a broad consensus of indicators as to the wealth of a country at a given point in time – but what about over time?

4.3. Unequal distribution of resources

Historical analysis of metal production shows that countries' mining endowment has changed significantly over time. We will illustrate two examples with copper and tin.

4.3.1. *Copper*

Copper is a ubiquitous metal, distributed in all geological environments. It outcrops in the form of native copper, and often malachite, a blue-green oxide that is easy to identify. Its sulfide form, chalcopyrite, is its main economic mineral. It is known in sediments, notably in Poland and the Democratic Republic of Congo, as well as in enriched granites, the porphyry deposits of the Pacific Rim Fire Belt. It also forms rich clusters from fossilized underwater thermal springs in Mediterranean Europe and Canada. Finally, it is found in association with mantle rocks (Norilsk, Russia) (Jébrak and Marcoux 2008).

The distribution of copper around the world shows strong contrasts. Based on reserves (USGS 2018), the Andean Cordillera countries, Chile and Peru, show endowments of more than 50 kg of copper per square kilometer (Figure 4.4). Major producing countries – the United States, Canada, and China – show lower endowments than the world average (5.8 kg Cu/km^2). These order-of-magnitude differences have no immediate explanation; they could be the effect of recent exploration for larger deposits or a result of geographic dilution, as Canada's copper concentration, for example, is mostly developed in only one of its provinces. Therefore, this parameter cannot really be used rigorously to reflect the copper endowment of countries.

As a general-purpose metal, copper was first used in the Near East and Southern Europe after the seventh millennium BCE. Mines then developed throughout the Mediterranean basin. Its transportation spread rapidly, as shown by the iceman, Ötzi, crossing the Alps with his copper axe (5300 BCE) or the Uluburun ship, near Bodrum in Turkey (around 1350 BCE), with its 354 copper ingots from Cyprus.

The copper mines were to structure Mediterranean trade; thus, in the Old Testament, it was while taking a boat to the Rio Tinto mines that Jonas met the whale. Cyprus, Chalcos, was at the heart of trade. In the 10th century BCE, the Phoenicians, followed by their Carthaginian colony, controlled the market from East to West. The Chalcolithic revolution did not depend on a few large deposits, but was distributed throughout Europe. The rich European deposits fed the mining activity throughout the Middle Ages until the beginning of the industrial revolution. German mines were the source of the Hanseatic metal trade and copper began to be stored in London as early as the 14th century. Falun in Sweden was mined from the 10th to the 20th century. In 1650, at its peak, it was the richest copper mine in the world, producing more than two thirds of the world's copper (Sundberg 1992).

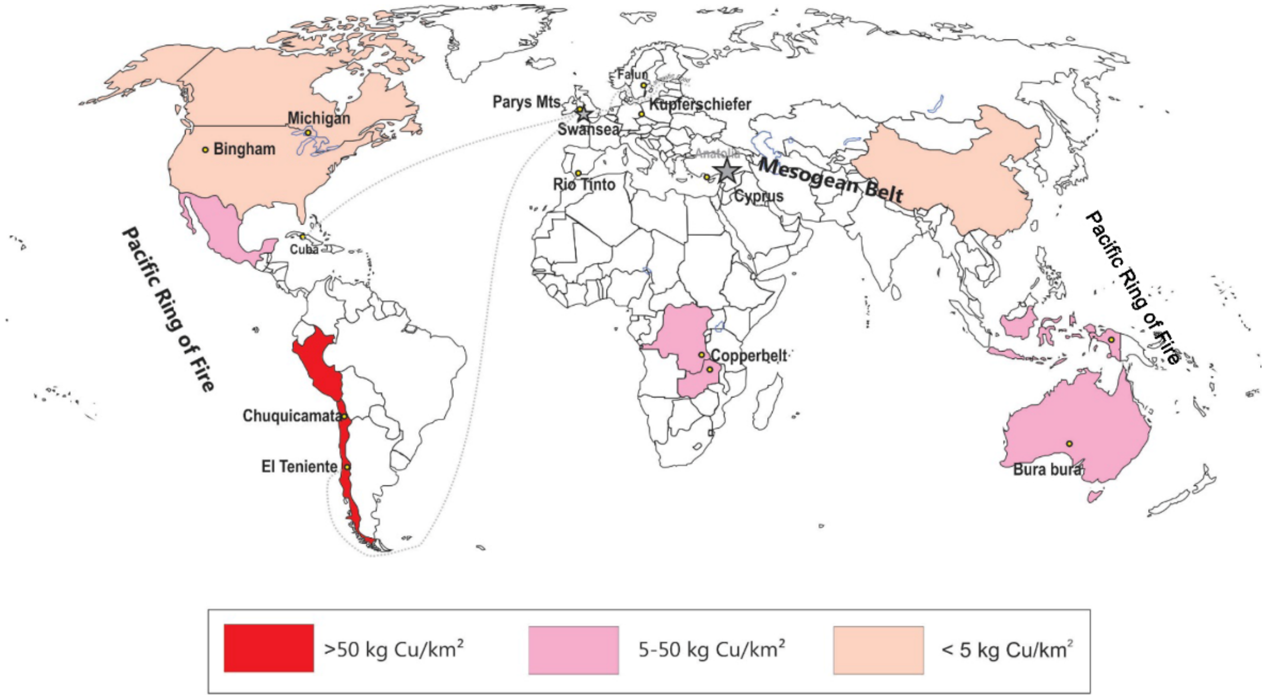

Figure 4.4. *Distribution of copper mining endowment (copper reserves by country (USGS 2018)), divided by country area. Position of somes of the world's major copper deposits. The stars indicate the ancient metallurgical centers of Anatolia (present-day Turkey) and Swansea (UK). For a color version of this figure, see www.iste.co.uk/fizaine/mineral1.zip*

At the dawn of the first industrial revolution, the situation changed drastically. The first copper smelters using a coal-fired reverberatory furnace were built in Swansea on the seafront in 1710, between the mining centers of Cornwall and Wales. The Parys Mountain (Anglesey) copper mine then became the first copper mine in the world.

These smelters then attracted ores from all over the world, first from Cuba, then from Australia (Bura Bura 1845) and Chile (dominant in 1850). World copper production in these smelters increased from 2,500 t in 1,700 to more than 53,000 t in 1850! From 1830 onwards, the metallurgical center of Swansea was technologically and financially ahead of the rest of the world. This was the globalization of copper, the step from a local mining economy, rooted in its geology, to a global maritime mining economy, centered on the Atlantic.

However, this “copper world” lasted only one generation. Development of American copper weakened the Swansea metallurgical center. It was first Michigan that provided more than half of American production in the 1870s; the ore, native copper, did not require complex processing and the company Calumet & Hecla dumped prices (Schmitz 1986). At the turn of the century, the method of copper production changed with non-selective mining methods and the use of flotation to process ore from the large open-pit porphyry quarries of the American West. Metallurgical centers were being set up directly next to the giant mines. The largest copper mine in the world was then Bingham Canyon (Utah), meeting the needs of the North American economic expansion. The United States produced two-thirds of the world’s copper at the turn of the century (Mudd and Jowitt 2018). The large vertically integrated American firms began to develop Chilean porphyries, in Chuquicamata and El Teniente, as early as 1899.

Today, most of the copper is mined in low-grade but high-tonnage copper porphyries. Of the top ten copper mines in the world in 2018, nine are porphyries from the Pacific Ring of Fire, including from Arizona to Chile. The world’s largest copper mine today is El Teniente in Chile, and its copper is widely exported to Asia. As in the Swansea era, copper has once again become a globalized metal transported across the oceans.

Thus, copper endowment, represented by the position of the world’s largest mine, went from Sweden to the United Kingdom, then to the United States, and finally to Chile. These mines had sizes in line with their time. Parys Mountain would be an average mine today; deposit sizes have only increased while grades have declined (Mudd and Jowitt 2018), and world reserves have increased from 95.1 Mt Cu in 1934 to 640.9 Mt Cu in 2010 (Mudd and Jowitt 2018).

The geology of copper has led to the formation of deposits almost everywhere in the world. Thus, while there are indeed large copper-bearing provinces, the position of the largest copper mines primarily reflects demand; at any given time, the largest copper mine is adjacent to the main consumer markets: Cyprus in Near Eastern antiquity, Falun during the Hanseatic Middle Ages, Parys Mountain during the British Industrial Revolution, and Bingham with the American–Canadian boom (Figure 4.5). It is these mines that also explain the increase in production and reserves. Technology plays a secondary but important role. The world's top mines are experimenting with the newest technologies by drawing from the catalog of available inventions, allowing them to expand production.

a) b)

Figure 4.5. *Two large deposits that were the largest copper producers in their time: Parys Mountain, Anglesey, United Kingdom (a), and Bingham Canyon, Utah, United States (b) (photographs by the author)*

Economic and political history has also played a key role. Proximity to markets is an indispensable asset for obtaining investments. It is this availability of capital that makes it possible at a given time to mobilize financing and skills to operate mines in a close environment, with an adequate perception of risk.

4.3.2. *Tin*

Like copper, tin is one of the seven metals of Antiquity. However, it is a much rarer metal, present in oxides, cassiterite, and more rarely sulfides. Cassiterite is a resistant and not very soluble mineral which is found in primary deposits as well as in secondary deposits – placers. Placers are estimated to contain about 80% of the world's resources (Kamili *et al.* 2017). Almost all tin deposits are associated with particular granites, which are derived from the melting of the continental crust. It is a singular geological situation that is found in only a few mountain ranges, hence the rarity of tin deposits.

The current map of the tin deposits shows strong inequalities in their distribution (Figure 4.6). We used the resource and reserves data from the ITRI (2016), which is more complete than the USGS data. Tin poses particular difficulties in terms of complete documentation because almost half of production comes from artisanal or small-scale mines, and a significant proportion is nationalized. Artisanal mines generally do not have assessments of their resources and reserves, while nationalized mines are not required to report their results.

The deposits were identified very early because tin is the indispensable complement of copper in making bronze, the first alloy of Antiquity. Pewter is the secret weapon of metallurgy and the positions of the deposits were kept secret for a long time among the Phoenicians.

Since Antiquity, the map of tin deposits in the world has been progressively enriched; the deposits in Afghanistan, Cornwall, and Central Europe (Erzgebirge) were known to the Romans, while the Chinese were aware very early on of the tin resources of the Gejiu region in the south of the country. Spanish colonizers discovered tin in the Andes (Bolivia, Peru), while African colonization brought tin from Kivu (Democratic Republic of Congo) and Nigeria. Tin from the giant Malay and Indonesian placers was the object of conflicts between the Chinese, Dutch, and English in the 19th century. The Amazonian district of Pitinga was only discovered in 1976 and that of Alaska at the end of the 20th century (Goldfarb and Miller 1997).

Unlike copper, often close to the centers of civilization, tin has remained a metal in the countryside, in specialized mining regions. In addition to its use as an alloy, tin experienced a sharp increase in consumption after the invention of the tin can in 1839 by Isaac Babbit. Today, it replaces lead for soldering. Foundries, initially located in the industrialized European countries, moved to the production sites.

The tin industry originated with Cornish deposits, which provided the bulk of world production until 1870. Indonesia and Malaysia then took over. The name of the first mining company in the world, BHP Billiton, recalled until recently its origin in the island of Belitung, one of the Indonesian tin islands through which Dutch, Chinese, and Singaporean merchants made a fortune. Today, Malaysia has reduced its production because of its oil and tourist resources, while Indonesia continues its production. Tin from Potosi was a source of fortune for Bolivians from 1849 (Daly 2018). Today, regardless of the location of the deposits, the high value of tin makes it possible for it to be transported over long routes to European, American, and Asian centers of consumption.

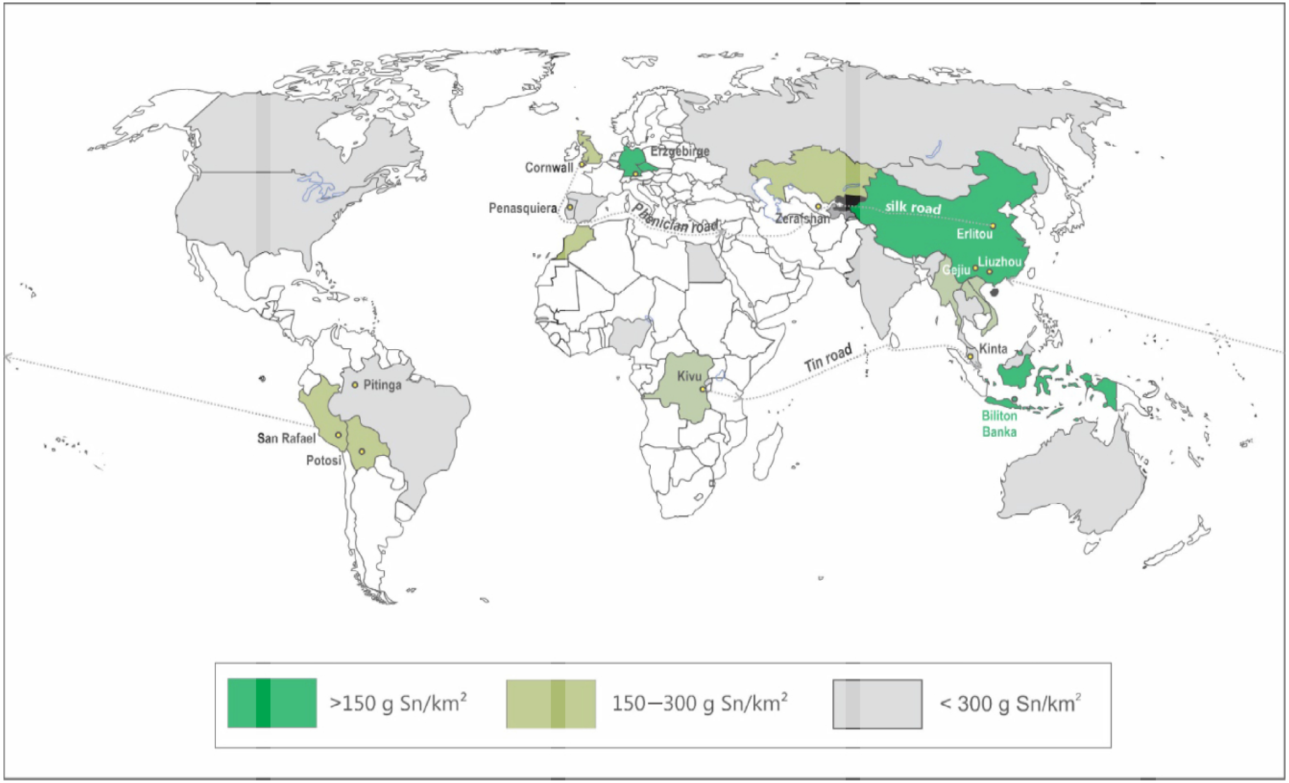

Figure 4.6. *Distribution of tin mining endowment, position of some major world districts and copper and tin routes. For a color version of this figure, see www.iste.co.uk/fizaine/mineral1.zip*

Thus, over time, tin endowment seems to have migrated along with colonial discoveries. Geology has imposed its specific sources, but it is the ease of access that has played a fundamental role: the Afghan deposits along one of the Silk Roads, the deposits in Cornwall accessible to the Mediterranean world beyond the Columns of Hercules, and the placers of Southeast Asia on one of the world's major maritime routes, between Chinese and Western consumers. Deposits located in the heart of continents, particularly in Africa, have been relatively undeveloped. Even more than copper, tin is therefore much more than a geological function; the consumer market, means of transport, and therefore colonial history play a major role.

4.4. Discussion: building mining endowment

Mining endowment appears to be both a robust concept, based on several economic parameters at a given point in time, and a concept that changes over the course of the development of the mineral industry. Mining endowment is a historical construct, originating in various fields:

– the geology of mineral resources;

– the evolution of mineral production and processing technologies;

– mining economy and proximity to consumer markets.

The global distribution of natural resources depends primarily on *geological data*. Mineral deposits are formed through two main types of processes, which are sometimes superimposed: geodynamic processes and climatic processes. Both are very unevenly distributed over the planet. Thus, a large number of mineral deposits are formed at the edges of tectonic plates (Groves and Bierlein 2007); the main copper deposits associated with magmatic rocks are deposited either in the formation zone (accretion) of oceanic plates, along rifts, or directly above subduction zones, in island arcs or cordilleras, resulting from the confrontation of two tectonic plates of which one is oceanic. It is this position that explains the current domination of the Andean countries in copper production (Jebrak and Marcoux 2008), where the South American plate and the Pacific plate meet. Tin deposits are formed in different geological environments; they appear during the collision of two continental plates, a process that occurs more rarely. A second environment is also located behind the subduction zones, as in the case of Potosi (Bolivia). The contribution of geology to mineral endowment is an indispensable prerequisite. However, it is not sufficient: the concentrations produced must be known and exploitable.

The evolution of *mineral technologies* is closely linked to the economy. The production of new types of deposits occurs when there is an imbalance between supply and demand. In almost all cases, the new technologies pre-existed and were only waiting for a sufficient price level to be implemented (Jébrak 2011). Mining innovations can be found in all fields of activity: expansion of exploration areas, increased production efficiency, access to ores that are increasingly complex to process, and reduction of environmental impacts (Jébrak and Vaillancourt 2011).

Each era has a tonnage/grade pair that imposes a type of deposit:

– surface concentrations, with very high contents, in the form of oxides or alluvium. These are the deposits of Antiquity, the colonial period, and the craftsmen of today;

– rich veins, whether hydrothermal or associated with sulfuric volcanic clusters: these are the deposits of the Middle Ages and the Western Renaissance, up to the 19th century;

– disseminated mineralization at low grades over the last century.

Each type of deposit involves an increasing energy intensity, essentially for milling, the use of new mining and processing technologies and a growing environmental impact. Mining innovations have played an essential role in these changes in deposit type, making it possible for the industry to focus on increasingly broad targets. The increase in the size of production equipment thus contributes to operating larger mines. The increasing size of the operations contributes ultimately to increasing the mineral endowment of a territory.

These transitions between deposit types can still be seen today; thus, the transformation of small-scale artisanal mining from subsistence mining to formalized production is based on new technologies: metal detectors, mini-mills of Chinese origin, and artisanal cyanidation; despite the risks, the latter has enabled artisans to develop new fine gold deposits by increasing recovery. Artisanal gold panning is expected to account for more than 10% of global gold production by 2018 (Seccatore *et al.* 2014).

The third parameter is that of the *mining economy*, at the frontier between geopolitics and geo-economics. Mineral exploitation is inherently capitalist, since significant amounts of money must be invested over a long period of time before there is a return, in a context of high risk (and potential return). It is, therefore, always the soundest financiers who have invested, from the Fugger family in the 15th century to today's pension funds. Changes in the types of deposit have led to increasingly heavy investment requirements, partially mitigated by technological innovations. The new deposits, which are larger, less rich, and more complex, require greater capital intensity in terms of purchasing equipment and supplying energy. In addition, these large deposits must be easily accessible to major consumer markets, whether they are directly close to markets, such as tin and copper in Cornwall compared to Europe, or easily accessible by ship, the most economical means of transportation. This is the case for Chile and Peru. With the real or perceived proximity of the deposits comes the availability of capital and advanced mining techniques.

Thus, the dominance of Anglo-Saxon mining countries can be explained first of all by a cultural inheritance. The Angles, supported by Saxon miners, were the first to develop industrial operations; they quickly had the capital (and confidence) necessary for developing mines. Their maritime domination enabled a rapid integration of production and trade processes. This mining culture was expressed by an actual mining ecosystem, including geologists, miners, metallurgists, logisticians, lawyers, etc.

China also has a deep-rooted mining and metallurgical cultural heritage. The Han (206 to 220 CE) exploited iron, copper, and tin; dug the first boreholes for brine; and even nationalized the raw materials. China has thus always been a great mining nation with small-scale mining and state capitalism. Like the British, they have largely projected themselves outside their borders to secure their supplies. The "Belt and Road Initiative" is only the latest version of the Silk Roads, which often lead from land to sea.

Spain, despite its colonial conquests, has never been able to build such an environment, and today Chile represents the best developed mining ecosystem in the Hispanic world.

France has come close to becoming a mining country on several occasions. The mining and metallurgical company of Peñarroya was among the world's leading mining companies in 1920; it had the same turnover as Rio Tinto in 1950, but has disappeared today. The colonial legacy has left some metal deposits from New Caledonia to Gabon. Despite high quality technical expertise, the chronic lack of private capital and the inconstancy of an industrial policy on resources has limited mining capacity both within the country and beyond. France no longer risks revisiting the Viking raids for silver-lead from Poitou (848) or the Prussian invasion for iron from Lorraine (1871–1918)!

Contrary to the locust theory that envisions the exhaustion of fertile mining areas and their abandonment (Bihouix and de Guillebon 2010), production areas have moved relatively little over the centuries. Chile has been a major producer of copper for three centuries and Indonesia a major producer of tin for four centuries. The long-term establishment of mining districts reinforces and perpetuates the comparative advantage; it is easier to open new mines, the logistics are established, and the geology is better known. These countries have widely constructed comparative advantages. This has enabled them to find new deposits after the first discoveries have been exhausted.

4.5. Conclusion

Is mineral endowment a real given?

According to a religious view of the world, mineral wealth is a gift from heaven. In a geological worldview, it reflects the anisotropy of metallogenic processes. In both cases, distribution is a gift that humanity comes to reveal. The analysis in this chapter is at odds with these visions. On the one hand, there are no reliable quantitative criteria for assessing a country's mineral endowment; metal density per square kilometer is largely a reflection of political cuttings; annual production, reserves, and resources show significant variations on a ten-year scale, with sensitive variations in their respective information. On the other hand, on a historical scale, the mineral endowment largely follows economic development, indicating the potential of consumption zones. However, the perception of a mineral endowment is nowadays the subject of a consensus for a given substance; it simultaneously integrates scientific, technological, environmental, and political data.

Thus, mineral resources should not be considered as intrinsic wealth; it would mean considering them as pre-existing elements to humanity. Yet, this is the perception that many governments and non-governmental organizations often have of them. In the 1960s, at the beginning of the "Quiet Revolution" in Quebec, the ministry in charge of mines was called the Ministry of Natural Resources; this is still the French name for Ontario. Countless pamphlets have been devoted to the "plundering of Africa's riches" (for example, Duval (2017)). It is as if the resource economy was seen as remaining a gathering economy where skills, technology, investment, and the market played only a secondary role in relation to the endowment: a very practical simplification to denounce the exploiters, the very people who provide the human, technical, and financial elements that are lacking. In reality, the revelation of potential is an integral part of the construction of the endowment. The map of mineral deposits and the map of mineral endowment thus reflect this combination of geological potential and human capacities.

This is what the government of New Caledonia (2009) emphasized: “a natural resource only becomes wealth according to the use that humans make of it and the techniques that they develop to exploit it”.

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PART 2

Issues

Mineral Resources Economics 1: Context and Issues,
First Edition. Florian Fizaine and Xavier Galiègue.

5

Modeling the Long-Term Evolution of Primary Production Energy and Metal Prices

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5.1. Introduction

Humanity is now using mineral resources at an unprecedented level, with 70 billion tons of material extracted per year and an unprecedented level of resource consumption per capita (Graedel and Cao 2010; Graedel 2011; Wiedmann *et al.* 2015; Elshkaki *et al.* 2016, 2018). The production of mineral resources is very energy-intensive and currently about 12% of global energy consumption and 35% of the energy consumed by industry worldwide is used for the production of iron and steel, cement, aluminum, and non-ferrous metals (International Energy Agency 2013). Various studies indicate that the energy used to produce metals and their long-term prices vary according to the power law of their dilution (inverse of concentration) in the ores mined (Sherwood 1956; Phillips and Edwards 1976; Chapman and Roberts 1983; Johnson *et al.* 2007; Gutowski *et al.* 2013; Daniels 2016). Such a variation implies that, with *constant technology*, the decrease in concentration of deposits over time should induce an exponential growth in production energy. This suggests that the availability of metals could be compromised in the near future by the prohibitive cost of extracting them, as the amount of energy

Mineral Resources Economics 1,
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required for their production would become unaffordable (Valero *et al.* 2013). However, historical data does not support this view; according to Mariscal and Powell (2014), inflation-adjusted commodity prices have actually declined since 1900. This trend can also be observed for many metals like copper, of which the constant-dollar price reported by the USGS has declined from $7,000 $1998/t in 1900 to $3,000 $1998/t in 2005, while the world average concentration of mined deposits has decreased from 4% to 1%. The price evolution over this period is not continuous and strong oscillations can be observed due to cyclical variations (instantaneous relationship between supply and demand, oil shocks and energy prices, conflicts, investments required for production to meet rapidly growing demand, etc.). Nevertheless, the concomitant decline in copper prices and ore grade suggests that technological improvement (improved productivity and energy efficiency) has offset the increase in energy associated with the drop of ore quality. This effect of technological improvement on production costs and price is observed for all resources, whether fossil or renewable. It makes it possible to replace depleted high-quality resources with lower quality but more abundant resources, thus increasing the reserves. Despite the exponential growth in consumption observed for more than a century, metal reserves have never been so high, because the progress of technology allows us to do today what was not feasible in the past. This optimistic view is in total opposition to the anticipated shortage of metals that would result from the depletion of concentrated deposits and the explosion of energy costs and prices. It even gives the impression that perpetual growth would be possible.

In order to better understand the arguments in favor of these two opposing visions, the purposes of the present chapter are:

– to propose a simple formalism based on a reasonable physical approach of the relationships between average ore grade, primary production energy of metals, technological improvement, prices, and reserves;

– to constrain the current parameters of the model using present-day data for a set of metals with highly variable concentrations, production energies, and prices;

– to use long-term historical data to constrain the evolution of the model parameters over time, with the objective of defining primary production energies and long-term prices that reproduce historical developments and give future trends.

Our results suggest that the optimistic and pessimistic views of the effect of decreasing the quality of the resource and technological improvement are reconcilable. Technological improvement has made it possible to reduce the over-consumption of energy due to the decline in ore grade over the last century, but the trend was reversed for many of the metals studied during the 2000s. For these metals, the production energy and long-term prices are expected to increase in the future.

5.2. Relationship between concentration and production energy

The energy for metals primary production (E) can be divided into three parts:

– the comminution energy (Eb) in releasing the metal-bearing minerals from the gangue;

– the separation energy (Es) in separating the metal-bearing minerals from the disaggregated rock;

– the energy of metallurgical processes (Em) in extracting the metal from the mineral.

The comminution energy of an infinite unit of rock mass at a grain size s can be approximated by a power law of the inverse of size (Hukki's law*)* (Lynch 1977):

$$\mathrm{Eb} = K.\left(\frac{1}{s}\right)^{n} \quad [5.1]$$

with n increasing from 0 for $s = 10^5$ µm to 2 for $s = 1$ µm (Thomas and Filippov 1999). For diluted metals with a concentration C less than about 1%, Eb is also a function of the ore grade (Norgate and Jahanshahi 2010; Gutowsky *et al.* 2013; Koppelaar and Koppelaar 2016), which suggests that the liberation size is proportional to the dilution, and that for a metal i:

$$\mathrm{Eb}i\ (\mathrm{J/g\ metal}) = \mathrm{a}i.\left(\frac{1}{Cmetal}\right)^{\mathrm{u}i} \quad [5.2]$$

The minimum energy needed to separate the metal-bearing mineral from the disaggregated rock is proportional to the mixing entropy of an ideal mixture of two components with no interaction (the mineral j and the rock):

$$\mathrm{Es}j\ (\mathrm{J/mol}) = -RT\,(xj\,ln\,jx + (1-xj)\,ln\,(1-xj)) \quad [5.3]$$

where R is the universal gas constant (8.314 J/mol/K), T the temperature (298.15 K), and xj the molar fraction of the mineral j carrying the metal i in the mixture:

$$\mathrm{x}j = \frac{\mathrm{N}j}{\mathrm{N}j + \mathrm{Nrock}} \quad [5.4]$$

where m is the mass and M is the molar mass.

$$\text{Esi (J/gram of metal)} = -\frac{RT}{xj.Mi.ni}.(lnxj + \frac{1-xj}{xj}.ln(1-xj)) \quad [5.5]$$

The minimum metallurgical energy needed to extract the metal from the mineral is proportional to the free energy of formation of the mineral from its constituents (in J/mol):

$$\text{E}mi \text{ (J/g metal)} = \frac{-\Delta G°fi}{Mi.ni} \quad [5.6]$$

The values of Eb, Es, and Em calculated with equations [5.2] to [5.6] for a series of metals covering a concentration range between 50% and 3 ppm are given in Table 5.1 and Figure 5.1. The minimum separation energy is at best an order of magnitude lower than the milling and metallurgical energy. Eb has the highest contribution at C < 0.5%. Above this value, the minimum metallurgical energy becomes non-negligible and exceeds the comminution energy for C > 5%.

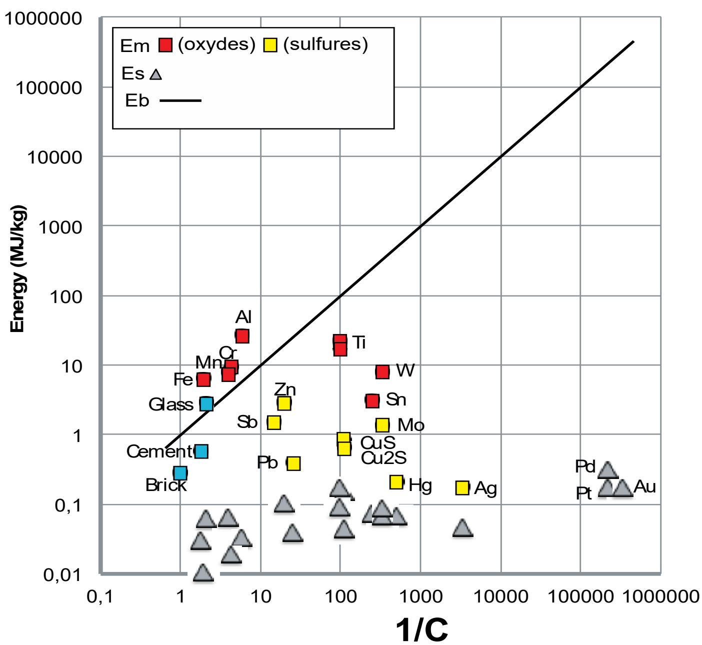


Figure 5.1. *Minimum metallurgical (Em), separation (Es), and mining plus comminution (Eb) energies as a function of ore grade. For a color version of this figure, see www.iste.co.uk/fizaine/mineral1.zip*

		C metal (g/rock)	ΔG°f (k J/mol)	Em (MJ/kg)	Es (MJ/kg)	Eb (MJ/kg)	$\overline{\eta m}$	$\overline{\eta b}$	$\bar{a}$	β (2015)	τ (%)	$\overline{E}$ (MJ/kg)	E obs. (MJ/kg)	P (US$98/t)	Price obs. in 2005 (US$98/t)
Brick		1.0E+00	–	0.30	3.10E-04	1.00E+00	5	1	1	0.92		3	2	57	45
Cement	CaCO3	5.6E-01	–	0.60	3.04E-02	1.79E+00	5	1	1	0.81		5	4[g]	101	91
Glass	SiO2	4.6E-01	–	3.00	6.12E-02	2.15E+00	5	1	1	0.87		17	15	428	300
Fe	Fe2O3	5.2E-01[a]	–742.2	6.75	1.04E-02	1.92E+00	5	1	1	0.70		36	25[b]	741	550
Al	Al2O3	2.5E-01[b]	–1582.3	29.30	2.73E-02	4.00E+00	5	1	1	0.62	2	151	93[g]	3287	1670
Mn	MnO2	2.5E-01[b]	–465.1	8.47	641E-02	4.00E+00	5	1	1	1.23(1.00)		46	57[b]	1440	594
Sn	SnO2	4.0E-03[b]	–519.8	3.34	7.36E-02	2.50E+02	5	1	1	0.78		267	207[b]	7183	8850
Hg	HgS	2.0E-03	–50.6	0.22	6.76E-02	5.00E+02	5	1	1	0.82		501	409[b]	14934	13400
Zn	ZnS	5.0E-02[a]	–201.3	3.08	1.01E-01	2.00E+01	5	1	1	1.27		35	45[b]	1393	1240
Ag	Ag2S	3.0E-04[c]	–40.7	0.19	4.56E-02	3.33E+03	5	1	1	1.23	1.2	3334	4100[k]	177834	197000
Cu	CuS	9.21E-03[d]	–53.6	0.85	1.48E-01	1.09E+02	5	1	1	0.53	1.5	113	60[k]	1898	3190
Cu	Cu2S	9.21E-03[d]	–86.2	0.68	4.46E-02	1.09E+02	5	1	1	0.53	1.5	112	60[k]	1898	3190
Pb	PbS	4.0E-02[b]	–98.7	0.41	3.84E-02	2.50E+01	5	1	1	1.22		27	33[b]	998	1130

		C metal (g/rock)	ΔG°f (k J/mol)	Em (MJ/kg)	Es (MJ/kg)	Eb (MJ/kg)	$\overline{\eta m}$	$\overline{\eta b}$	$\bar{a}$	β (2015)	τ (%)	$\overline{E}$ (MJ/kg)	E obs. (MJ/kg)	P (US$98/t)	Price obs. in 2005 (US$98/t)
Pd	Pd	4.5E-06[c]	0.0	0.00	3.10E-01	2.22E+05	5	1	1	0.81		2.22E+05	1.80E+05[h]	1.03E+07	1.185E+07
Pt	Pt	4.5E-06[c]	0.0	0.00	1.69E-01	2.22E+05	5	1	1	1.22		2.22E+05	2.71E+05[b]	1.60E+07	1.185E+07
Au	Or	3.0E-06[c]	0.0	0.00	1.73E 01	3.33E+05	5	1	1	0.95	0,1	3.33E+05	3.10E+05[h]	1.89E+07	1.190E+07
Cr	Cr2O3	2.3E-01[b]	–1058.8	10.18	1.91E-02	4.35E+00	5	1	1	1.16		55	64[b]	2034	1260
W	MnWO4	3.0E-03[c]	–1544.8	8.40	6.81E-02	3.33E+02	5	1	1	0.95		375	357[b]	12904	24900
Ti	TiO2	1.0E-02[f]	–890.7	18.61	1.74E-01	1.00E+02	5	1	1	1.86		193	360[i]	13020	14440
Ti	FeTiO3	1.0E-02[f]	–1142.1	23.79	9.90E-02	1.00E+02	5	1	1	1.96		219	430[b]	15760	14441
Ni	Nis	9.0E-03[b]	–91.0	1.55	1.56E-01	1.11E+02	5	1	1	1.34	1,2	119	160[j]	5447	12300
Mo	MoS2	3.0E-03[b]	–225.9	1.,41	8.79E-02	3.33E+02	5	1	1	0.77 (1,00)		340	235[k]	12263	26000

Table 5.1. *Observed and calculated energy and price values*

COMMENT ON TABLE 5.1.– *a) Priester* et al. *(2019); b) Fizaine* et al. *(2015); c) www.mining.com/worlds-top-10-silver-mines; d) Vidal* et al. *(2019), equation [5.11]; e) Philipps (1976); f) www.proactiveinvestors.com.au/companies/news/195095/neometals-expands-titanium-vanadium-resource-at-barrambie-195095.html; g) Gutowsky* et al. *(2013); h) Ecoinvent 2.02: http://www.ecoinvent.org/database/; i) Bath ICE v2.02; j) Norgate and Rankir (2000); k) Nuss* et al. *(2014, 2015). For Mn and Mo, the ß (2015) used is not the ratio E obs/E¯ but the value in brackets.*

To take into account the difference between the minimum energy and the actual production energy, it is necessary to multiply Es and Em by $\overline{\eta m}$ and $\overline{\eta s}$, which are corrective factors corresponding to the inverse of efficiency. These factors depend on many parameters such as the type of mines, the type of ore, the maturity, and the type of processing route. The parameters $\overline{\eta m}$ and $\overline{\eta s}$ thus vary from one metal to another, but we first make the assumption that the energy efficiency is identical for all metals. With the additional assumption that a(*i*) and u(*i*) in equation [5.2] are dependent on ore grade, a single equation for the average energy of production can be written for all metals:

$$\overline{E} = \overline{\eta m}.\text{Emi} + \overline{\eta s}.\text{Esi} + \overline{a}.\left(\frac{1}{C}\right)^{-\overline{u}} \qquad [5.7]$$

The values of $\overline{\eta m}$, $\overline{\eta s}$ $\overline{a}$, and $\overline{u}$ were estimated using the present values of production energy and the average ore grade of exploited deposits (Table 5.1).

Figure 5.2 shows that a good agreement between the observed and estimated values is obtained for $\overline{\eta m} = 5$ and $\overline{\eta s} = \overline{a} = \overline{u} = 1$

The difference between calculated and observed energy is less than 30% for all metals except for titanium (–90%) and copper (+45%), and to a lesser extent aluminum (+34%) and nickel (–34%). The reason for these deviations may be an over- or underestimation of the observed average ore grades and/or average energies. For aluminum and copper, another explanation is that the energy efficiency of their production is better than that of the other metals. This efficiency would be lower in the case of titanium and nickel. Finally, the huge differences observed for indium, gallium, and cobalt (about +70%) are due to the fact that these metals are coproducts of the exploitation of another metal that carries the economic value of the mine. The observed energy logically represents only a small portion (about 30%) of the estimated energy, as a significant portion of the mining and comminution energy is already provided to produce the main metal. For this reason, these metals were not used in the estimate of $\overline{\eta m}$, $\overline{\eta s}$, $\overline{a}$, and $\overline{u}$.

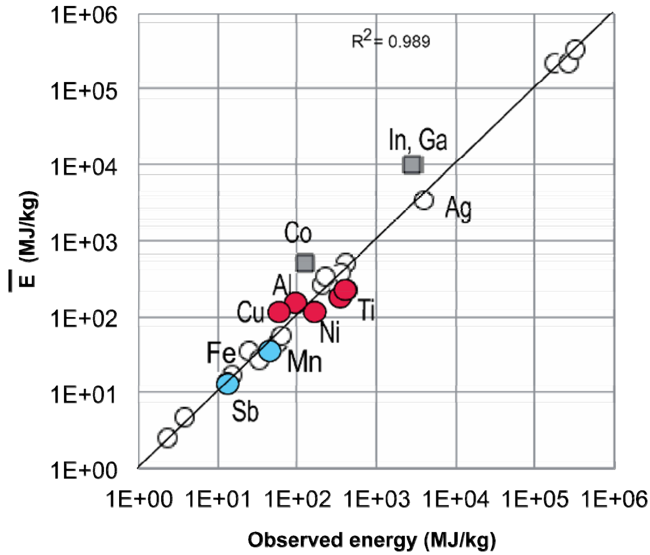


Figure 5.2. *Production energy calculated with equation [5.7] as a function of the observed energy. For a color version of this figure, see www.iste.co.uk/fizaine/mineral1.zip*

COMMENT ON FIGURE 5.2.– *The gray squares are by products and the circles are substances extracted for themselves. The red symbols show the metals with the largest deviation on the regression line. Blue symbols show the metals with the largest deviation on the price versus energy regression line (Figure 5.3).*

Before going any further, it should be emphasized that the parameters $\overline{\eta m}$, $\overline{\eta s}$, $\bar{a}$, and $\bar{u}$ have been estimated in a purely mathematical way to obtain a minimum dispersion between the values $E(i)$ and the observed production energy values. Additional constraints could have been used, like the observed share of metallurgy, mining, comminution and separation energy. In the case of copper, which is detailed below, Norgate *et al.* (2010) estimated that the *primary* energy of the extraction and milling processes is of the order of 60 MJ/kg, while that of metallurgy is of the order of 10 MJ/kg. Metallurgy energy thus accounts for 14% of total production energy, whereas $\overline{\eta m}$.Emi represents only 4% of $\bar{E}$. It is thus possible to improve the consistency between observed and calculated proportions, but this would imply defining values of $\overline{\eta m}$, $\overline{\eta s}$, $\bar{a}$, and $\bar{u}$ by metal rather than as common values for all metals, which seems difficult given the current state of available data.

5.3. Equivalence between energy and price

Several studies have shown that the price of metals is, like the production energy, a power function of its dilution in mined-out deposits (Phillips 1976; Johnson *et al.* 2007; Gutowski *et al.* 2013). This observation is logical if the share of energy in the total cost of production is similar for all metals. The trend is confirmed in Figure 5.3, which represents the energy estimated with equation [5.7] as a function of the price in US$1998 for the year 2005 (according to the USGS). This date was chosen because it is earlier than the 2005–2011 price boom driven by strong Chinese demand and increased speculation. It is thus expected that the 2005 prices are representative of the long-term prices.

Although the correlation between $\overline{E}$ and price is not perfect, Figure 5.3 perfectly illustrates the adage that what is rare is expensive. Irrespective of any economic considerations, the five orders of magnitude between the price of gold, platinum, or palladium and that of iron or manganese can be explained by the five orders of magnitude between their concentrations in the ores. This difference in concentration implies a much higher production energy for the diluted metals and, as long as the energy has a price, production costs will also be higher.

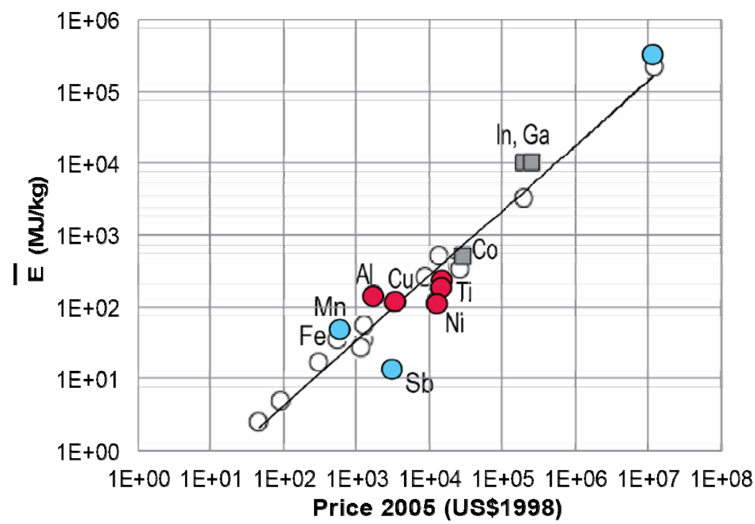


Figure 5.3. *Production energy calculated with equation [5.7] as a function of 2005 metal prices (US$1998). For a color version of this figure, see www.iste.co.uk/fizaine/mineral1.zip*

The production energy of aluminum and to a lesser extent copper in Figure 5.3 are too high relative to the average trend. Conversely, the estimated energy of titanium and nickel appears too low relative to the regression line obtained for all metals. This observation seems to confirm that the energy efficiency of aluminum and copper production better than the average regression estimate for all metals, and that of nickel and titanium is worse. Other metals show significant deviations from the general trend. In particular, the observed price of manganese is low relative to the average trend and that of antimony is very high, while their estimated production energy is in agreement with the observed energy (Figure 5.2). For these two metals at least, it is possible that the price in 2005 was not representative of the long-term price.

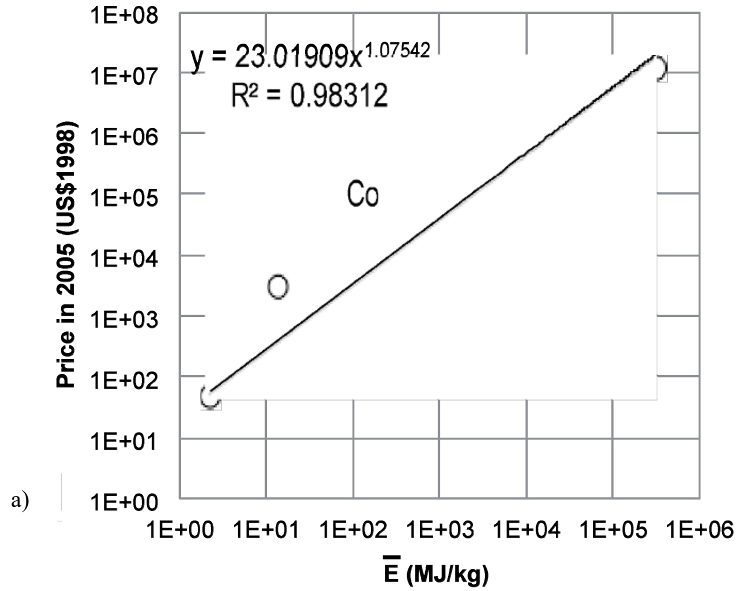
In order to reduce the dispersion of points $\overline{E}$ versus 2005 prices, $\overline{E}$ has been multiplied by a coefficient $\beta = E$ obs/$\overline{E}$, which corrects the average energy efficiency of each metal ($\eta m = \beta i * \overline{\eta m}$, $\eta b = \beta i . \overline{\eta b}$ and $a = \beta i . \overline{a}$), that is:

$$\mathrm{Ei} = \beta i . \overline{Ei} \qquad [5.8]$$

The coefficient of the E versus 2005 price regression (Figure 5.4a) is slightly higher than that obtained with energy calculated without correction when βMn and βMo are assumed to be equal to one. The price recalculated with the values of β reported in Table 5.1 is in good agreement with the observed price (Figure 5.4b), and the equation of the regression line of E versus the 2005 price is as follows (Figure 5.4a):

$$\mathrm{P}i = 23.02 * (\overline{Ei} * \beta i))^{1.0754} \qquad [5.9]$$

This equation can be used to calculate the long-term price as a function of the estimated energy for a given concentration (Figures 5.5a and 5.5b). Figures 5.5a and 5.5b show that the power law relationship between price or energy and 1/C is only valid at concentrations below about 1%, a domain where most of the production energy comes from mining and comminution (Eb). At concentrations above 1%, the share of metallurgy becomes as significant as that of comminution (Figure 5.1), which results in a deviation of energy and price from the power law. Equations [5.7] to [5.9] thus provide a rational (physical) explanation of the empirical relationships of production energy and price that can be expressed as a power law of dilution. This also specifies the domain of concentration beyond which this relationship is no longer valid.



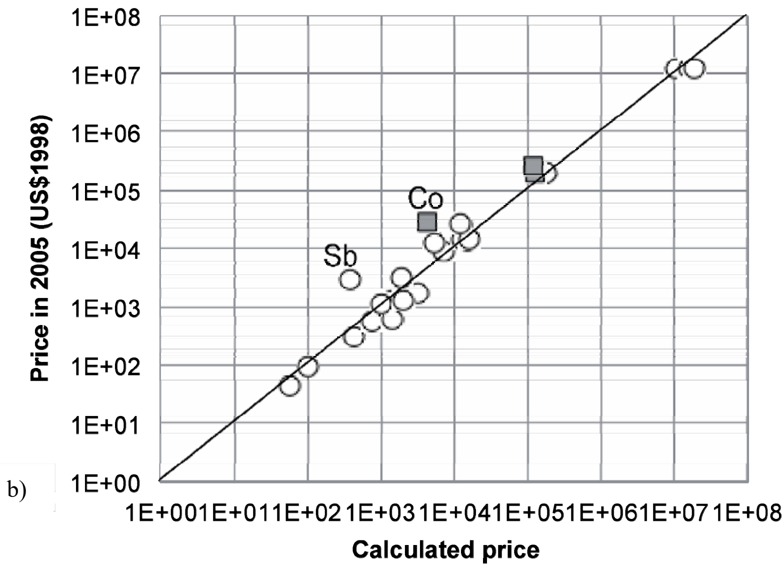
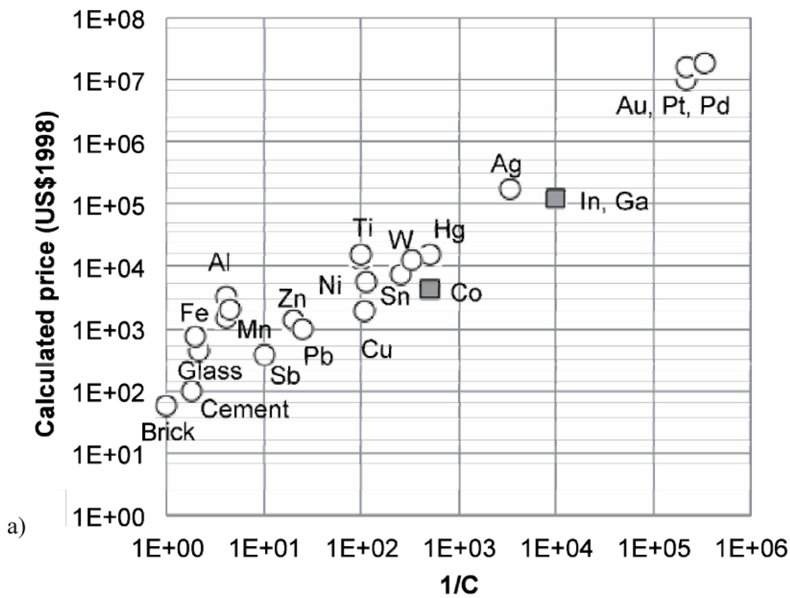


Figure 5.4. *a) Correlation between the energy calculated with equation [5.8] and the observed price in 2005. b) Correlation between the price calculated with equation [5.9] and the observed price*



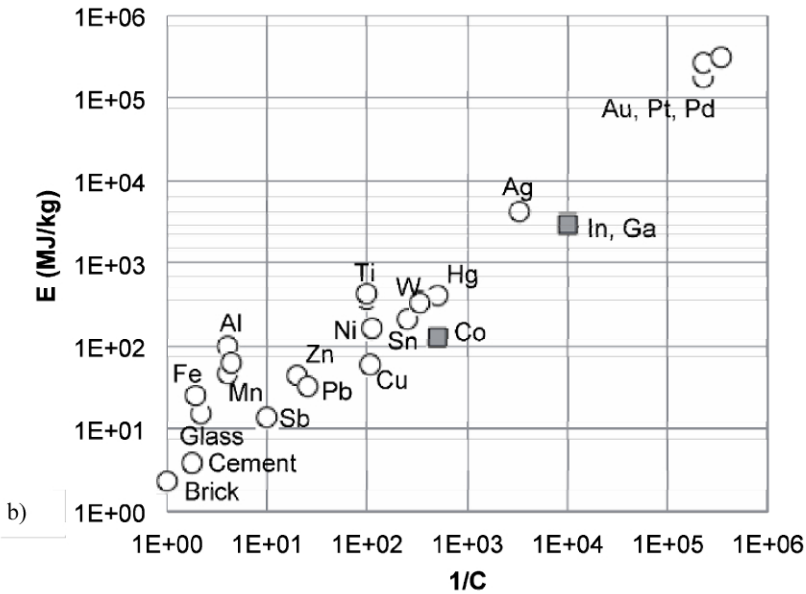


Figure 5.5. *Price (a) and production energy (b) calculated as a function of the dilution (opposite of concentration) of metals in the fields currently exploited*

5.4. Technological improvement and evolution of production energy and metal prices over time

According to Figure 5.5, the decrease in average ore grade over time should necessarily lead to a power-law increase in the production energy and long-term price of diluted metals at C < 1%. As mentioned in the introduction, this point has been repeatedly identified as a major constraint for future metal production. Indeed, the future reserves (the amount of metal that can be exploited at an economically viable cost) are constrained by the costs of production, which depend on the energy of production. However, before drawing hasty conclusions about the future, it is necessary to verify that the historical variations of energy and production costs (prices) are effectively controlled by the concentration of deposits. For copper, for example, the average ore grade of mined deposits has decreased from 4% in 1900 to 1% today (Mudd 2009; Northey *et al.* 2014). Using equations [5.7], [5.8], and [5.9], it can be calculated that 30 MJ was required to produce one kilogram of copper at US$850/t in 1900. However, according to the USGS, the price of copper in 1900 was US$7,000/t, more than eight times higher. This difference is obviously the result of improved logistics and production technologies, which have increased the energy efficiency over time and lowered the production costs. Thus, the relationships between energy or price and dilution shown in Figure 5.5 are valid only under the current conditions of concentration and production technology; they cannot be used to estimate the past or future energies and prices based solely on changes in ore grade. In order to estimate the evolution of long-term price, it is necessary to consider not only variations in ore grade, but also technological advances.

A straightforward approach is to allow a variation of β over time. This can be done by decomposing the production energy in two terms corresponding to:

– the energy of improving technology over time and constant 2015 ore grade ($EC_{2015}(t)$);

– the energy of decreasing ore grade over time and constant 2015 technology ($ET_{2015}(t)$):

$$E(t) = (ET_{2015}(t) + EC_{2015}(t))/2 \qquad [5.10]$$

where t is the year considered and $ET_{2015}(t)$ is calculated with equation [5.9], using the values of βi of the year 2015 listed in Table 5.1 for a concentration C(t) evolving exponentially over time (Vidal *et al.* 2019):

$$C(t) = 8*10^{10}*\exp(-0,0125*t) \qquad [5.11]$$

The long-term price P(t) can also be decomposed in two terms similar to those of energy:

$$P(t) = (PT_{2015}(t) + PC_{2015}(t))/2 \qquad [5.12]$$

For a continuous change in concentration at constant annual rate (equation [5.11]), the value of β over time also varies at a fixed rate (τ) and it can be calculated from the value of β in 2015 (Table 5.1) as follows:

$$\beta(t) = \beta\,(2015).(1 - \tau)^{(t - 2015)} \qquad [5.13]$$

The production energy at constant technology thus varies at the same rate as $(t)_{2015}$:

$$ET_{2015}(t) = \overline{E}.\beta\,(2015).(1 - \tau)^{(t - 2015)} \qquad [5.14]$$

Another reference year other than 2015 could be used, the relationships for calculating eET(t) and eEC(t) for a reference year tR from the 2015 values being as follows:

$$ET_{tR}(t) = \beta\,(2015).\overline{E(C)} \qquad [5.15]$$

$$EC_{tR}(t) = E(tR).(1 - \tau)^{(t - tR)}$$

$$E(t) = (ET_{tR}(t) + EC_{tR}(t))/2 \qquad [5.16]$$

where $\overline{E(C)}$ is the value of the production energy calculated with equation [5.7] for the concentration C(t) and $E(tR) = (ET_{2015}(tR) + EC_{2015}(tR))/2$.

There is an additional constraint that is not taken into account in equations [5.13] to [5.16]: the thermodynamic limit, which sets a minimum value of energy that cannot be overstepped, whatever the technological improvement. For the metallurgy and separation parts, the thermodynamic limits are given by the values of Em and Es (equations [5.5] and [5.6]). It is more difficult to estimate a lower limit for the mining and comminution part, but the United States Department of Energy estimated in 2007 that the minimum energy of production was 30% the present value. For a given metal, this minimum energy must vary over time, since it is proportional to the concentration, which itself changes over time. Assuming that the minimum energy of comminution represents 30% of the present energy of metal production, the minimum limit is given by the following equation:

$$Emin = Em + Es + Eb(C)*\beta(2015)*0.3 \qquad [5.17]$$

with Eb calculated for the concentration at time t. The coefficient β in equation [5.17] is that of the year 2015 because the technological improvement does not change the minimum mining + comminution energy estimated from Eb in 2015. Only the change in ore grade over time needs to be taken into account in the Emin estimate.

5.5. Application to copper primary production

The values of τ (1.5%/year), $ET_{2015}(t)$, $EC_{2015}(t)$, and E(t) (Figure 5.6) were estimated to reproduce the long-term price (P(t)) between 1900 and 2015 (Figure 5.7). Regardless of the reference year, $ET_{tR}(t)$ and $eEC_{tR}(t)$, as well as $PT_{tR}(t)$ and $PC_{tR}(t)$, intersect on the red curves showing the evolution of E(t) and P(t). $EC_{2015}(t)$ plots below the thermodynamic limit at t > 2060 (Figure 5.6a), which indicates that the technological improvement can no longer lead to energy gains beyond this date. According to equation [5.11], the concentration should decrease in the future and E(t) becomes parallel to Emin after 2015. Despite the decrease in ore grade by a factor of 4 between 1900 and 2010, E(t) and P(t) decreased by an equivalent factor because during this period, the energy gain resulting from the technological improvement was larger than the loss resulting from the decrease in ore grade. This evolution is consistent with the observed values of E(t) between the 1960s and today (Figure 5.6a). The trend is reversed in the 2000s, with the gain resulting from technological improvement becoming less than the loss resulting from the decrease in ore grade, and E(t) increases over time. The long-term price follows the same evolution as the production energy and in 2100 will reach the value of 1920.

Similar results were obtained by Vidal *et al.* (2019), who discussed the relative contributions of technological improvement and declining copper resource quality using an independent prey–predator dynamic model linking resource quantity, reserves, annual production, industrial capital, production costs, and price. In both studies, E(t) and P(t) are U-shaped with an early learning phase where technological improvement dominates, followed by a late phase where the declining quality of the resources dominates (Figure 5.7a).

The results reported in Figures 5.6 and 5.7 have significant though hardly quantifiable uncertainties. The uncertainties for the observed average energies used to constrain the parameters of equation [5.7] and β (2015) are difficult to estimate because of the variability in ore grades and production technologies. The reference value used for copper in (2015) (ECu = 60 MJ/kg) is almost identical to that reported by the Chilean Copper Commission (2014) (point 4 in Figure 5.6a), but is higher than that reported by Mardsen (2008) (30 to 50 MJ/kg for a concentration of 0.5 to 1%, point 5 in Figure 5.6a). These latter values suggest that the energy of copper production was reduced by a factor of two between the 1970s/80s and 2010 (E(1975) = 120 MJ/kg for C = 0.76%, according to Gaines (1980), point 3 in Figure 5.6a). Instead, we estimate a stagnation of E(t) at about 60 MJ/kg over the same period of time. This does not mean that our estimates are in strong contradiction with Mardsen's (2008) data. Indeed, a representation of E(t) as a function of concentration rather than time (Figure 5.6b) shows that for a decrease in global concentration from 1.6% (1975) to 0.9% (2015), E(2015) is also half as low as E(1975).

The results shown in Figure 5.7 indicate that the price of copper and, by extension, the price of any natural resource of decreasing quality will eventually increase if the rate of technological improvement remains constant. Therefore, the optimistic view that technological progress will always be able to reduce the production costs and prices is not correct on the long run. The pessimistic view using the current production energies versus ore grade relationships to estimate the future production energies and price is not correct either, as it neglects the role of technological improvement. Indeed, the evolution of the production energy at constant technology $ET_{2015}(C)$ is very different from the evolution at variable technology. The $ET_{tR}(C)$ curves move towards lower concentrations over time as technologies become more efficient with increasing tR. A constrained $ET_{tR}(C)$ curve at a given time tR is, therefore, not representative of past or future production energies. Only the curve E(C) in Figures 5.6a and 5.6b takes into account both variations in average ore grade and technological improvement. This curve indicates that the production energy *increases with ore grade* at C > 1%, whereas the estimates published so far show an inverse trend (stars and the dotted curve in Figure 5.6b), as they are established at a given time, that is, for a constant technology. These published values are in agreement with our estimates of production energy for a constant technology ($ET_{tR}(C)$). However, since the price and production energy of metals both vary as a power law of dilution, the decrease of price observed between 1900 and 2015 implies that the production energy E(C) also decreased over the same period.

On the other hand, the future trends of exponential increase in energy proposed in the literature are correct at very low concentrations, because E(t) and P(t) are U-shaped and because $ET_{tR}(C)$ and E(C) overlap at C < 0.5%. The interest of the model proposed here is that it can predict when the inversion of the long-term price curve appears, for a given evolution of ore grade and for a rate of technological improvement deduced from the historical price evolution.

a)

b)

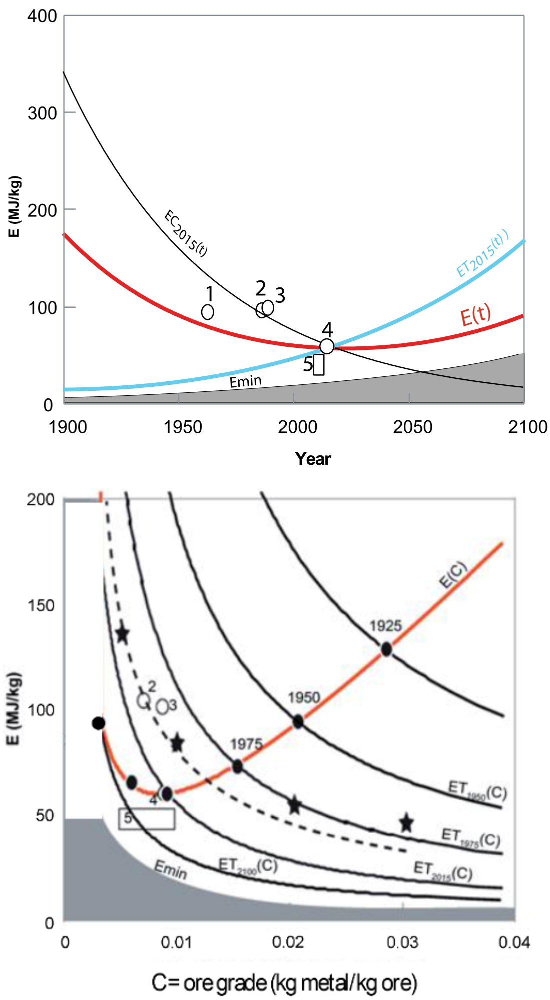


Figure 5.6. *Calculated energy of copper production over time (a) and average ore grade (b). For a color version of this figure, see www.iste.co.uk/fizaine/mineral1.zip*

COMMENT ON FIGURE 5.6. – *The shaded field shows the energy range below the thermodynamic limit (Equation [5.17]). The symbols indicate the historical values observed by Kellogg (1974), Rosenkranz (1976), Gaines (1980), Marsden (2008), and the Comision Chilena del Cobre (2014). The dotted line in (b) shows the values from Norgate and Jahanshahi (2010) and the stars show the values from Chapman (1974).*

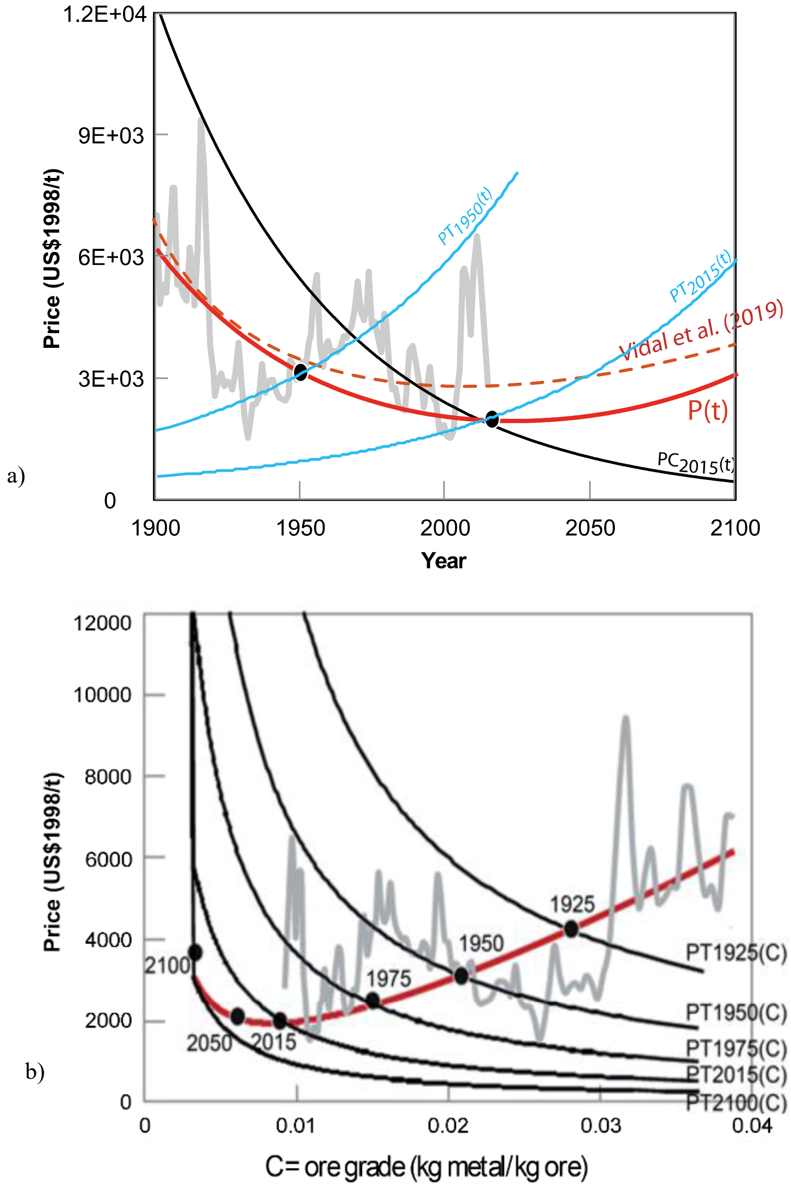


Figure 5.7. *Calculated price of copper over time (a) and ore grade (b). The grey curve shows historical data. For a color version of this figure, see www.iste.co.uk/fizaine/mineral1.zip*

5.6. Application to nickel, aluminum, silver, and gold

In addition to copper, production energies and the long-term prices of aluminum, nickel, silver, and gold were also estimated using the following concentration trends (Mudd 2009): $C_{Al}(t) = 0.3*\exp(-0.002*(t-1900))$, $C_{Ni}(t) = 0.15*\exp(-0.0245*(t-1900))$, $C_{Ag}(t) = 0.003*\exp(-0.02*(t-1900))$, $C_{Au}(t) = 3.10^{-5}*\exp(-0.022*(t-1900))$.

The calculated long-term prices are in reasonable agreement with the historical values (Figure 5.8) for annual rates of change of τ from 1% to 1.5% for nickel and silver (similar to copper) and 0.1% for gold. The long-term prices of silver and nickel increase in the years 2000–2010, faster than for copper. The increase in the long-term price is even faster in the case of gold and it occurs earlier, the rate of technological improvement being very low. Only the price of aluminum will decrease until 2100 because the average ore grade hardly varies. The estimated price of this metal is too high, which suggests that either the share of energy costs in the price or the price of energy to produce aluminum is lower than those of other metals. An improvement of the model to better explain the energy–price equivalence is thus necessary.

The results obtained for aluminum, copper, nickel, silver, and gold show that the proposed method for estimating the long-term variation of metal prices is capable of reproducing the historical trends of metals present in very different concentrations in natural deposits. There is one notable exception that should be mentioned: steel. According to Gutowski *et al.* (2013) and Yellishety *et al.* (2011), the energy used to produce steel has declined at an annual rate of 1–2% since 1950. For a relatively stable ore grade of iron during this period, this drop in energy should be reflected in the price. However, the steel prices reported by the USGS in 1950 and 2005 are quite similar. A possible explanation for this inconsistency between the energy and price evolutions is that the share of energy in price severely dropped between 1950 and 2005.

5.7. Conclusion

An approach based on the evolution of the production energy of metals as a function of ore grade and technological improvement reproduces the prices and production energies observed today for metals in concentrations from 50% to 30 ppm. The proposed approach is capable of reproducing the long-term historical prices over the period from 1900 to today.

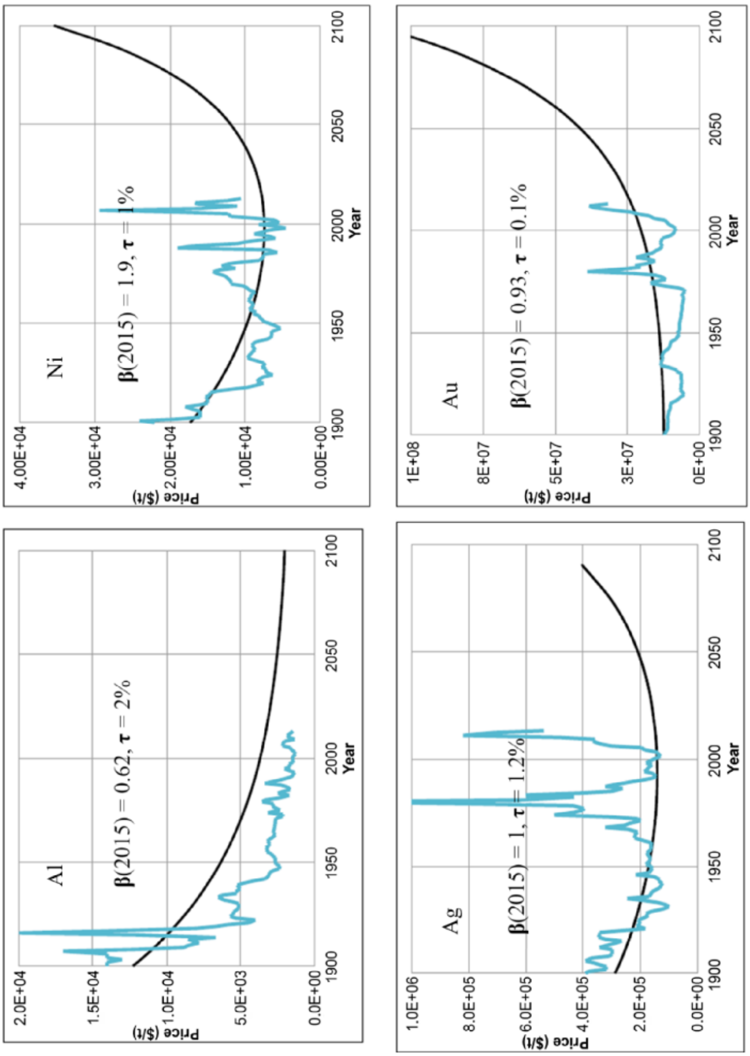


Figure 5.8. *Observed (blue curves) and calculated (black curves) prices. For a color version of this figure, see www.iste.co.uk/fizaine/mineral1.zip*

The question posed in the introduction concerned the arguments in favor of two classically opposed visions: whether the depletion of high-quality non-renewable resources and the exploitation of lower-quality resources will lead to an unaffordable increase of production energy and prices, or whether it is conceivable that technological improvement will favorably compensate for the decline in ore grade? Our results suggest that the evolution of prices associated with a decline in ore quality and constant technological improvement follows a classic U-shaped curve. So far, the energy gain resulting from technological improvement has more than compensated the loss due to the decrease of ore grade. However, this situation is not sustainable because the improvement in energy efficiency through technology is limited by thermodynamic limits. There comes a point when the gain no longer compensates for the loss.

At that point, the long-term price increases if the rate of incremental technological improvement remains constant. The term “progressive improvement” applies to resources whose type varies little over time. The exploitation of new types of deposits, whether oceanic or very deep, could change the situation if decisive technological advances are made in the future. Technological progress to exploit these new deposits is therefore the key to sustainable access to resources. We would not be able to extract copper from today’s deposits with the technologies used in the Middle Ages. Concerns about the ever-increasing exploitation of resources from deposits of increasingly poor quality are not new either. They already existed 50 years ago and prices have not exploded in that time, nor has a shortage set in despite an exponential increase in production. However, the current situation is different from the past and it seems that we are entering a pivotal period, as we are approaching thermodynamic limits where technological progress will not allow us to reduce the energy and monetary costs, nor the environmental costs of primary metal production. This evolution could bring new constraints to the planned increase in production.

Of course, future metal production is not restricted to primary production. An effort to improve recycling is imperative because it would significantly reduce the need for primary raw materials (Vidal *et al.* 2019) and also because recycling is less energy-intensive and impacting on the environment than primary production. That said, even if the energy intensity of recycling is much lower than that of primary production, it is not certain that this has a downward impact on metal prices. This is because, unlike primary production, the base material from which the metal is recycled has a market value. These are end-of-life products whose value is indexed to the price of primary metals. A high long-term price of primary metals will lead to an increase in the value of scrap and, therefore, to a higher recycling cost and a higher price of recycled metal.

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6

Environmental Footprint of Mineral Resources

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6.1. Introduction

According to data made available by the International Resource Panel, covering nearly 50 years (1970–2017) and 191 countries, global natural resource use is expected to reach nearly 90 billion tons in 2017 (IRP 2017). There is strong growth in the extraction of all these resources – biomass, fossil fuels, metals, and non-metallic minerals – which is also closely linked to the quantities of waste and emissions generated. The effects of these quantities on the environment are captured in the form of "environmental footprints", which are assessed in this chapter. For metals in particular, disparities in the locations of extraction, processing, and use also lead to disparities in the geography of the footprints. We will see how multi-regional input–output models provide information on these disparities.

6.2. Notion of environmental footprint

6.2.1. *Beginnings of the footprint*

Commonly speaking, a footprint is a mark left by the passage of an object or a being on deformable ground. Figuratively speaking, a footprint is a "deep and

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lasting”[1] mark. The first usage of the term “ecological footprint” dates back to almost 30 years ago (Rio Summit 1992) in a context of awareness of the possible existence of “limits” to human activity. This gave rise to the hypothesis that the regenerative capacity of the biosphere could be a limiting factor for the human economy. Starting from the observation that a city-dweller uses natural resources (agricultural land, forest areas) outside the city, there is a need to find an indicator capable of measuring this pressure on natural resources by comparing the “supply” to the human “demand” for these resources. In the seminal book *Our Ecological Footprint: Reducing Human Impact on the Earth*, the authors defined a method for measuring the food-producing land and water areas needed to produce the resources that a population consumes and to absorb the waste generated (Wackernagel and Rees 1998).

At the time, the method was strongly oriented around the consumption of food and fossil fuels. The Global Footprint Network[2] took the ecological footprint and refined it over time to account for the appropriation by humankind of the bioproductive capacity of the planet. As a metric, it offers the means to characterize land use according to the demand for food and energy from bioproductive surfaces and also to account for the land needed to absorb carbon dioxide (CO_2) emissions. These results are summed up using the common measure of average global productivity per hectare. The results (the land area needed to support human activity of interest, expressed in global hectares) are “intuitive” and can, therefore, feed into stakeholder debate and engagement. In reality, the communication tool is very well developed and still in the headlines that proclaim that humankind is exhausting the planet’s resources every year a little earlier (2019 ecological debt day: July 29th)[3]. The ecological footprint, in its current form, pays very little attention to mineral resources and does not take into account the full range of environmental impacts. It has the advantage of integrating the results of different human activities into a measure of the load on ecosystems in “global hectares”.

The term “footprint” thus carries this notion of “integrative” measurement, even if, in defining its scope, it does not claim a notion of completeness in taking impacts into account, and focuses essentially on carbon. Other initiatives that lead to the “carbon footprint” follow.

1 *Larousse* dictionary.

2 See: www.footprintnetwork.org/.

3 See: www.footprintnetwork.org/2019/06/26/press-release-june-2019-earth-overshoot-day/.

6.2.2. *Lifecycle assessment and impacts*

Conversely, among environmental assessment methods, lifecycle assessment (LCA) has become widespread, with the aim of covering "as many" environmental impacts as possible. In a deliberately industry-oriented approach, the aim of an LCA is to assess the significance of the various environmental impacts generated by a given product or service throughout its life, that is, from the extraction of the resources needed to produce it to the treatment of the waste it has generated. The advantage of this approach lies in the availability, to practitioners, of standards (ISO 14040 and ISO 14044) that provide rigor and thus achieve a precise quantification of the material flows generated by the production, use, and end of life of various goods and services. This quantification (or inventory) is carried out within the framework of explicit hypotheses, which makes it possible to assess their lacunae. In other words, all the successive chains of elementary flows (materials drawn from or emitted into the environment) are not taken into account, but the lines of sound are known.

From the inventory, a number of impacts can be calculated. Impact assessment methods propose so-called "intermediate" or problem-oriented assessments – that is, on a compartment of the environment where it is possible to measure the biophysical effect of an elemental flow (effect of greenhouse gases on climate change, effect of a metal emission in water on aquatic ecotoxicity, etc.) – as well as "damage-oriented" assessments that correspond to impacts on "protected areas" – that is, on human health, ecosystem health, and natural resources (note that climate change is sometimes considered as a damaging impact, whereas there is no direct relationship with protected areas). Again, not all impacts are necessarily taken into account, but the reasons for the choices are normally stated.

Either way, this multi-impact approach provides valuable results for comparing products or services that produce a benchmark function. It should be noted that there is still a difficulty in weighting impacts with regard to whether they are problem or damage oriented: what is wrong with choosing between air pollution (respiratory illnesses) and water pollution (aquatic toxicity)? In order to overcome this problem, "single scores" have been proposed, as in the "Eco-Indicator 99" method (Eco-Indicator 99 2000), and research is underway on the monetarization of impacts, without a consensus having emerged today on the very basis of expressing impacts of different natures in a common unit (how can the intrinsic value of human life and the productive value of a natural resource be considered in the same way?). Thus, LCA is characterized by the notion of "impact", the calculation of which nevertheless has an integrating character over the entire lifecycle, but without claiming a form of "global mark" underlying the notion of a footprint. However, this semantic distinction is disturbed by changes in language brought about by the standards themselves, such as ISO 14046 for the water footprint and ISO 14067 for the carbon footprint.

6.2.3. *How are impacts translated into a footprint?*

This notion of footprint, as we have understood it, is intended more to support discussion than to provide details on the effects of human activities on the environment. For example, the initiative of the European Commission, which has been working on a new method for rating products since 2013 (the Product Environmental Footprint (PPF)), as well as for organizations (the Organisation Environmental Footprint (OEF)), clearly aims to facilitate understanding of LCA results so that consumers can compare the "environmental footprint" ratings of products in the same range and guide their choices. This method was developed in pilot studies, the results of which were announced in April 2018 in Brussels. It aims to extend the carbon footprint to assess the environmental impact of products consumed in the EU. Work in the pilot phase has shown that the carbon footprint often accounts for only about a third of the overall environmental impact. The objective of the PEF method is to objectively define the environmental footprint of products and to provide a rigorous measurement method common to all EU member countries. It focuses on 15 environmental impacts[4] per product family, covering the entire lifecycle (from manufacture to disposal):

– climate change;

– depletion of resources;

– carcinogenic and non-carcinogenic human toxicity;

– ecotoxicity;

– destruction of the ozone layer caused by the emission of gases such as chlorofluorocarbons and hydrochlorofluorocarbons, emitted in particular by refrigeration systems (different from the carbon impact);

– formation of photochemical ozone from the emission of non-methane volatile organic compounds;

– emission of ionizing radiation, which takes into account the harmful effects on human health caused by radioactive releases;

– emission of fine particles that takes into account the harmful effects on human health;

4 See https://ec.europa.eu/environment/eussd/smgp/communication/impact.htm.

– eutrophication of the seas, soils, and waterways due to excessive nitrate and phosphate emissions leading to algae blooms and oxygen depletion causing an imbalance in ecosystems;

– depletion of water resources;

– acidification of soils and rivers caused by the emission of pollutants, such as nitrogen oxides and sulfur oxides emitted during transport, which leads to the decline of forest areas and human health problems;

– land use.

As with the single score methods in LCA, the 15 criteria can be weighted to obtain an overall score through an approach that was agreed upon in the pilot studies. The consensus-building method was a broad consultation rather than a battle of experts. Both of these methods have been used in the past in the search for the "single score" in LCA. In contrast to these past searches, in this PEF initiative the meaning of the score is not debatable. The next step is to involve more actors in the process and to promote the method to strengthen policies related to environmental information and the circular economy.

6.2.4. *Towards a more integrative impact footprint*

An alternative (and complementary) macroeconomic approach to LCA is input–output analysis extended to the environment. Based on cross-sectoral macroeconomic statistical data and sectoral environmental data, this approach makes it possible to take into account a significant number of basic resource and emission flows across the entire economy of a country or region (whether it is a region of the world, like Latin America, or a territory of a country). Unlike LCA, all stages of production are taken into account, for example, expenditures on banking services through an equipment-producing activity. In contrast, this approach does not consider the "lifecycle" of a product, but rather the flows that result from the recording of economic transactions in a sector (and/or region) over the course of a year. It is, therefore, not a balance sheet of materials exchanged over the entire lifecycle of a product: for example, the production of automobiles and the recycling of automobiles are considered, but it is not the same physical entities of automobiles that are manufactured and recycled during one year. This problem of looping material flows is, however, essential to generating a "dynamic" vision of the economy and anticipating future impacts. It is the topic of current research aimed at integrating inventory accounting into flow accounting. Without going that far, the details of the "input–output" (IO) approach are presented below. In principle, it involves allocating to a "product category" an environmental impact resulting from the impacts of the chain of suppliers who have contributed to this product category. It is, therefore, a systemic approach (of the economic system) which, by its nature, is more in the realm of "footprints" than "impacts". On the other hand, to return to the dictionary definition of "footprint", there is nothing today to qualify the "deep and lasting" nature of the impacts revealed in this way.

6.3. Principles of input–output analysis

6.3.1. *Input–output tables: summary tables of the economy*

6.3.1.1. *What are they?*

Input–output tables (IOTs) are summary tables of national accounts, inspired by international accounting rules (the system of national accounts (SNA)). They are published by Eurostat for all European Union countries based on data compiled annually by the national statistical services (INSEE in France). They are composed of:

– a resource (output) table that accounts for the production of products by domestic activities and imports of these products;

– a table of uses (inputs) that accounts for the use of these resources by the various actors in the economy: the activities themselves (intermediary consumption) and the final consumers (households, institutions, exports);

– a table of "primary inputs" to activities that accounts by activity for labor compensation, capital compensation, and taxes and subsidies, the three components of "added value".

The accounts are drawn up on the basis of administrative data (e.g., VAT or customs duty registration) and company surveys. The data are classified according to nomenclatures that result from a consensus between the actors concerned (administrations, companies, consumers). The nomenclatures concern products (Classification of Products by Activity (CPA)) and economic activities (the Statistical Classification of Economic Activities in the European Community (NACE)).

A system of nested or at least compatible nomenclatures makes it possible to compare data from different countries and at different geographical levels (world, continent, country). Nomenclatures can be reviewed annually by countries, but "international" nomenclatures evolve at the rate of consensus on average every five years.

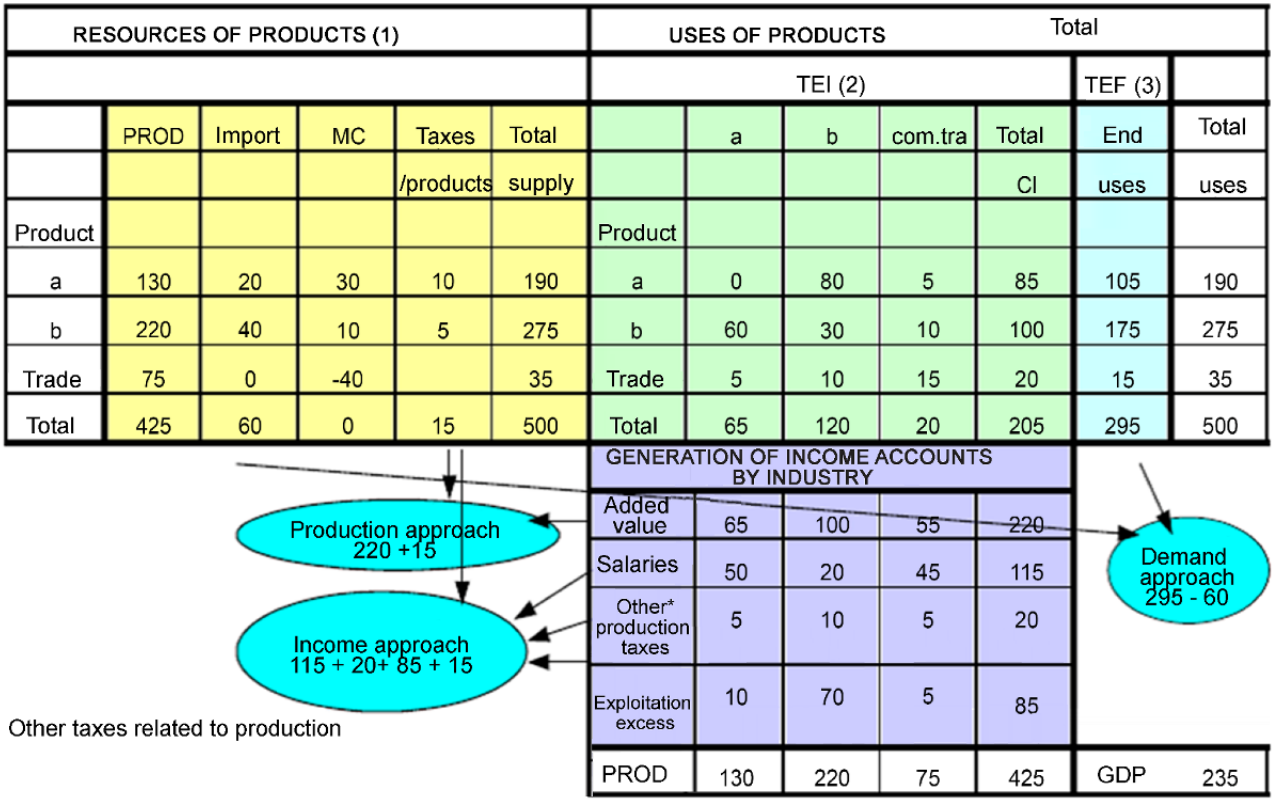

Figure 6.1. *Diagram of the INSEE IOT. MC: transport and commerce margins; com.tra: commerce and transport; TEI: table of intermediate inputs; TEF: table of final consumption.*

The CPA has a parallel structure to the NACE, which allows the publication of "square" tables with the same number of activities (columns) as the number of products (rows). Eurostat tables are typically 60 × 60 in size.

6.3.1.2. *What are they for?*

In particular, IOTs make it possible to derive an approximation of GDP using three calculation methods (see Figure 6.1):

– the "demand" approach: total final jobs minus imports;

– the "production" approach: total added value minus taxes on products;

– the "income" approach, equivalent in principle to the "production" approach, but which differs in the method of calculation: total compensation, taxes on production, gross operating surplus minus taxes on products.

In addition to this major interest, which makes it possible to obtain the main aggregate of today's economies – GDP, by cross-checking the accounts of several origins – this entry highlights the production "induced" by final demand. A brief explanation of this is that the final demand represents the consumption of products and the formation of fixed capital, which in a certain way "leaves" the economy to be used immediately by households, governments, and in exports. For certain intermediate products (typically metal plates or tubes), it is conceivable that the uses are in economic activities rather than in households because they require further processing before their final use. These products are more likely to be found in "intermediate consumption" than in "final consumption". Similarly, some products such as cars are not all intended for households, institutions, and exports, as many vehicles are purchased by companies to contribute to their production. This implies that the economic system must produce "more" than just final consumption. This "more" is actually a "less" for GDP. It is the share of production "lost" both in terms of final consumption and added value. It is, therefore, also this "more" that the IOTs are used to monitor.

IOTs have thus been used for almost 50 years (from 1950 to about 2000) to study the effect of "demand shocks" in order to guide economic policy choices (taxes and subsidies) on sectors and products.

6.3.2. *IOTs and redistributions within the economy*

6.3.2.1. *From the IOT to the technical coefficients (IO) table*

At the level of a country, intermediate consumption is the result of a permanent optimization of the factors of production. Each company, and each aggregate of companies called an "activity" or "industry", seeks to minimize its purchases and maximize its sales and added value. Depending on economic policies, the maximization of added value will be in favor of the remuneration of labor or capital (primary factors of production). In any case, intermediate consumption represents the cost of the unavoidable purchases of products, which are the minimum necessary to ensure production. Thus, they reflect the "technological" state of economic activities, that is, the share of total production mobilized *a minima* to achieve this production.

By normalizing intermediate consumption through production, for each activity, we obtain a table (noted A) called the "technological matrix" that represents the ratios of intermediate consumption for all activities. A column of this matrix thus represents the "recipe" of the intermediate products and primary inputs needed to produce one unit of the activity linked to the column.

By construction, we have:

$$A.p + f = p \qquad [6.1]$$

where p is production and f is final consumption.

The total production must satisfy intermediate consumption and final demand. We can deduce the so-called "Leontief inverse" relationship between production and final demand, which makes it possible to determine the impact in terms of production of the branches p of final demand f:

$$P = (I\text{-}A)^{-1}.f \qquad [6.2]$$

Note that the impact of demand on branch output can be determined recursively from the matrix A:

– A.f means the "direct" intermediate production of activities that produce f;

– A.(A.f) means the intermediate production of the first subcontractors;

– A.(A.A.f) means the production of second subcontractors;

– as these increases decrease, we finally obtain: $I + A + A^2 + A^3 + \ldots A^n = (I\text{-}A)^{-1}$.

6.3.2.2. *Transfers of added value between industries*

One of the main points of interest of IOTs is that they can model the productive system of a country as a system of reallocation of primary inputs (added value) to products sold (final consumption). Via the technology matrix, the model allows us to "go up" the value chain of a consumed product and to calculate the sum of the direct and indirect effects of its consumption.

OBSERVATIONS.

1) Each product consumed does not induce the same production. It is, therefore, possible to determine the profiles of added value in the different activities for the consumption of a product, simply by multiplying the production of the activities by the coefficients of added value. It can be seen that (by construction), final demand equals the total added value, and that the consumption of the different products does not take part in the same way in the distribution of this value in the various activities.

2) The technology matrix "transforms" primary inputs into consumer products by redistributing values: the added value of activities is distributed among consumer products and, conversely, the consumption of products creates added value in all activities. In reality, of course, it is consumption that creates added value, but at the level of national accounts, it is the way in which added value contributes to consumption that also guides economic policies. There is, therefore, a "volume" effect of consumption that predominates and also a "distribution" effect that is less visible but with potentially just as significant consequences. Thus, the final consumption of one product can have a significant importance on the added value via the effects induced by the consumption of other products. Thus, a policy that pushes the consumption of one product may have significant effects on other activities because a *transfer of added value* takes place within the economy. This ability to analyze "transfers" on primary inputs is also very relevant to "environmental extensions", which are the subject of the following chapter.

6.4. Towards IOTs extended to the environment

Environmental considerations in IOTs can be aggregated from inventories and nomenclatures, or at a finer level of disaggregation. They must also integrate imports, the environmental impact of which is far from negligible.

6.4.1. *Current extensions*

"Extensions" are tables that are compatible with the nomenclature of IOT activities. They do not all have the same level of relevance in view of recent changes in regulatory reporting obligations on environmental quality. They concern emissions, natural resources, and waste.

6.4.1.1. *Emissions (NAMEA)*

Atmospheric emission inventories are filled out for quantities of substances emitted into the atmosphere and for different economic activities. The main inventories available are the UNFCCC greenhouse gas inventory and the UNECE inventory of transboundary pollutants.

These inventories are carried out according to a nomenclature (NFR09) built according to a logic that makes it possible to identify "polluting" activities. The activities related to the energy sector are thus very detailed. This nomenclature also focuses on activities recognized as polluting, such as cement production, waste management, and dry-cleaning activities, for example. This nomenclature also includes non-economic categories related to land use or volcanism.

The data are published by Eurostat in a format compatible with NACE[5].

6.4.1.2. *Resources*

Statistics on natural resources are scattered because they are produced specifically by type of resource. With advances in the compilation of economy-wide material flows accounts (EW-MFAs), strongly driven by the needs of efficient resource management policies, data are generally available at a level of aggregation compatible with that of IOTs. Natural resources are exploited by a small number of activities (primary sector), making the work of constructing the "resource" extension relatively easy.

6.4.1.3. *Waste: "products" or environmental extension?*

In Europe, there is a nomenclature that describes the categories of waste (the European Waste Classification (EWC)). This is constructed according to the type of waste, its recyclability, its dangerousness, the sector of activity from which the waste originates, and so on. This nomenclature has the disadvantage of having no connection with the product nomenclature.

The inclusion of waste induces significant changes in the IOT. Waste requires the inclusion of physical flows in the matrix insofar as recycling substitutes primary materials for their "mass" equivalent and not for their "monetary" equivalent.

5 See http://epp.eurostat.ec.europa.eu/portal/page/portal/environmental_accounts/documents/eeSUIOT%20TechDoc%20final%20060411.pdf.

6.4.2. *Inclusion of direct environmental extensions in IOTs*

The extensions are thus presented as attributes linked to activities (emissions from activities, resources consumed by activities).

This involves constructing a matrix B that determines the ratios of emissions or resources consumed per unit of production of the activities, that is:

$$BA.p + f = p \quad [6.3]$$

Calculating $b = B.(I\text{-}A)^{-1}.f$ gives the total emissions and resources consumed induced by the final demand f.

By diagonalizing f, one can calculate the distribution of these environmental pressures in the different activities.

In the same way as for added value, the Leontief matrix makes it possible to allocate emissions (resources) related to activities to emissions (resources) related to products. The impact of the final consumption of a product can, therefore, be obtained in all sectors of the economy.

The IOT with its environmental extensions makes it possible to analyze environmental pressures from two perspectives (EEA 2013):

– a "production" perspective: the mapping of direct pressures from all production sectors makes it possible for us to determine which industry(/ies) cause(s) the most significant pressures;

– a "consumption" perspective: what are the products consumed that directly and indirectly cause the greatest pressures? From this perspective, it is possible to differentiate final consumption: domestic consumption and exports.

According to the "consumption" perspective, the input–output approach forms the basis for a "lifecycle analysis" of the (categories of) products consumed. It carries out a complete inventory of the elementary exchanges with the environment related to the production of products. This approach makes it possible to, in particular, analyze "*impact transfers*". While the "vehicle manufacturing" activity, for example, consumes few resources and, therefore, causes few direct emissions, its production "induces" resource consumption and, therefore, emissions in its supplier chain.

Input–output analysis can be used to calculate the distribution of environmental impacts along the product value chain.

6.4.3. *Imports and environmental extensions*

So far, we have avoided the question of imports/exports. IOTs have a long history and have been used mainly for analyses of national economies and for cross-sectoral transfers of added value or impacts (on employment, for example). To the extent that imports represent only a small share of domestic production, they can be considered to be produced using a technology that is “similar” to domestic technology. However, this assumption is generally incorrect today and imports must, therefore, be specifically considered.

In fact, the final demand of households induces domestic production and also production abroad. On the one hand, the latter is necessary in response to direct final demand for imports. On the other hand, this final demand for domestic products also “indirectly” induces production abroad, since domestic economic activities require the consumption of imports.

The consideration of imports in input–output analysis presents multiple points of interest:

– the location of the “impacts” (in the broadest sense, from an economic or environmental point of view) induced by a given final demand. The consideration of imports in input–output analysis can thus be exploited to determine the domestic added value (produced in a country) in response to a given final demand, the waste generated in a country, etc., as opposed to its production abroad. This dimension is more particularly exploited by Beylot *et al.* (2015) in the article “Assessing the national economic importance of metals: an input output approach to the case of copper in France”;

– with the possible consideration of the specific characteristics of the productive systems of each of the countries exporting to the country where the study is done, the variability, from one country to another, of the coefficients of the technological matrices extended to the environment can thus be taken into account, within the limits of the availability of the associated data.

Thus, Beylot *et al.* (2015) calculated that, to satisfy €100 of the final demand in France (in 2006), about €184 must be produced. This production comes from €162 of domestic production (88%), €14 of imported products for intermediate consumption (7%), and €9 of imported products consumed directly (5%). The total imports (€14 + €9 = €23) require a local production of €37 from the countries that export them.

The impacts (e.g. gaseous emissions, consumption of resources) of French final consumption should, therefore, be calculated for €162 of domestic production and €37 of foreign production.

A limitation of this approach is that, often due to lack of data, it is assumed that the foreign countries taken into account have a technology matrix identical to that of France, which implies that the production abroad of products imported into France is done with a similar technology. Since the early 2000s, with the intensification of international trade and the growing interdependence of economies, multiregional representations of IOTs have emerged. Based on the fact that imports from country A of products from country B correspond to exports from country B to country A, multi-regional input–output (MRIO) tables with global purviews are now available.

6.5. Calculation of environmental footprints of metals by MRIO analysis

6.5.1. *Basic principles of MRIO analysis*

Starting in the 2000s, MRIO models began to emerge to model the economic, social, and environmental impacts of global trade (Arto 2014). The MRIO databases are a response to the limitations of the classical input–output models (focused on a particular economy) presented above. Thus, these databases make it possible to describe the interdependencies of industries within a regional economy as well as within the interregional economy. Figure 6.2 shows the contents of a MRIO database.

Just as in the input–output model based on Leontiev's (1966) input–output tables, the MRIO databases contain a matrix (known as the "technology matrix") modeling economic trade of dimensions n products × n products or m activities × m activities for "p" various regions of the world. Each column lists the intermediate consumption of a unit of production of the product or activity in that column, whether domestic or imported. Basically, it is a matrix expressed in monetary units. The methodological advance of this MRIO approach is to have been able to harmonize in a homogeneous way domestic intersectoral exchanges and international exchanges: the same sector in different countries represents as many sectors that exchange with each other and with others at the world level. The world is thus composed of n (or m) × p sectors.

Solving Leontiev's equations makes it possible, for a given final consumption vector, to calculate the production vector for all sectors in all countries. *For example, what is the production of metals in the world induced by French final consumption?*

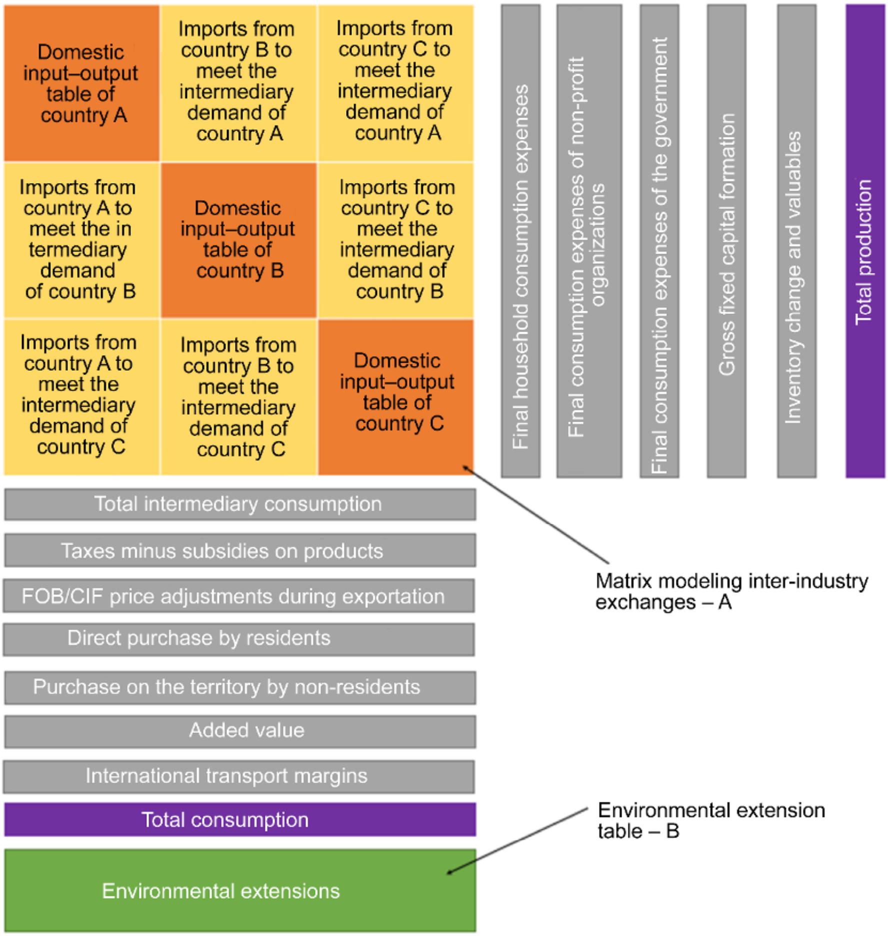

Figure 6.2. *Representation of MRIO databases*

COMMENT ON FIGURE 6.2. – *Note that "imports from country B for intermediate consumption in country A" correspond to "exports from country A for intermediate consumption in country B". A share of country A's exports is destined for final consumption in country B. This share appears in the "final consumption expenditure" columns, which are not detailed here by country, but which do appear as such in the tables.*

An environmental extension, matrix B, may accompany matrix A. Matrix B lists, for a production unit of a product or activity, the emissions to the environment, the resources extracted, or the variations and waste related to this production.

Thus, MRIO models can be used to determine, for example, *the carbon or material footprint induced by a country's consumption* by taking into account all the impacts taking place in the entire supply chain of the products and services consumed.

It is important to realize that this approach includes the entire chain of suppliers involved in the final consumption of a product or service. Thus, virtually all activities in all regions are involved in the realization of each product.

Due to the generalization of the writing of input–output tables to countries/regions, there is a conceptual equivalence between sectors, countries, and sectors by country, and Leontief's analysis is generalizable. Thus, it is possible to determine the production (by region) necessary for the final demand (consumption) of a country (e.g., France), the added value (by region) linked to a country's final demand, and the environmental impact (by region) of this demand.

From the outset, IO models have been used to estimate the effect of consumption shocks. Indeed, certain policies can be put in place to favor or penalize products. With MRIOs, we can also estimate the effect on the environment of a change in the share (or origin) of imported products in final consumption.

However, remember that the model is not predictive. It is not capable of estimating, for example, a qualitative adaptation of production according to consumption. The technology matrix is rigid and does not represent any limits, for example, those in production capacities. Similarly, there is no automatic adjustment of production to variations in consumption in a region.

The emblematic example of application to policy support is that of regions with low added value and high environmental impact and other regions with high added value and low impact.

6.5.2. *Available databases*

Different MRIO databases currently exist; they differ in the granulometry used in modeling, in their modeling assumptions, in the environmental impacts they cover, and in their accessibility. Table 6.1 provides a summary of these different elements for databases with global geographic coverage.

	WIOD	EORA	Exiobase v3	GTAP	TiVA
Website	www.wiod.org/home	www.worldmrio.com	www.exiobase.eu	www.gtap.agecon.purdue.edu/	oe.cd/icio
Time series	1995–2009 (2000–2014 for the updated version)	1990–2015	1995–2011	2004, 2007, 2011	1995–2014
Geographical coverage	43 countries modeled, including one "rest of the world" region.	187 countries modeled	44 countries modeled, including five "rest of the world" regions	140 countries modeled including 20 regions	60 countries modeled
Number of industrial sectors	35 (56 in the updated version)	15,909 sectors (individually per country – 26 sectors in a harmonized version)	163	57	48
Environmental extension	Greenhouse gases, material use, land use, energy use, energy use, other air emissions (not available in the updated version)	Greenhouse gases, material use, land use, water use, specific emissions (N and P)	Greenhouse gases, material use, land use, water use, water-specific emissions (N and P), other air emissions	Greenhouse gases, energy use of land	Greenhouse gases (via data from the International Agency of Energy)
Accessibility	Free access	Between €1,999 and €24,999 depending on the use for the full version	Free access	$5,940 for the private sector	Free access for economic data

Table 6.1. *MRIO database comparisons*

It should be noted that these databases were developed on a project basis and are not produced according to statistical regulations. There are currently no international regulations at the global level that would allow for the standardized and regular production of such databases.

Due to the large amount of both economic and environmental data that needs to be collected in order to set up a MRIO database, often not all countries are modeled and the granulometry of the industrial sectors taken into account remains relatively coarse. Often, in the case of geographic modeling, most countries representing smaller economies are represented in "rest of the world" regions. Although EORA and GTAP say that they model more than 100 countries, proxies are used in a practical way for some of these countries. For example, EORA has economic data for 74 countries; more than half of the remaining countries are modeled using assumptions. As far as the industrial sectors are concerned, Exiobase arrives at a fairly fine granulometry, for which the modelers have worked on the disaggregation of the agricultural sector, the extraction and transformation of raw materials and energy in particular. In terms of environmental extension, the set of databases determine the carbon footprints of a given final demand. Access to other types of environmental extensions depends on the databases; WIOD and Exiobase allow for a relatively complete calculation of the environmental footprint of a given final demand. Finally, Table 6.1 shows that the most recent data modeled vary from one database to another and are subject to the length of time that national economic statistics are made available by the various statistical agencies.

6.5.3. *Metal requirements for French final demand*

We will take Exiobase v3 for the following calculations because of its capacities in terms of the number of sectors taken into account, which make it possible to represent metals in a fairly fine way (see Box 6.1), and due to the availability of relatively recent data (2011).

There are 48 countries/regions (Table 6.2).

The production of metals (all metals in Box 6.1) required for French final demand is obtained as above by:

$$p = (I-A)^{-1}.(y_{FR} + y_{FR\rightarrow exp})$$

where y_{FR} is the vector of final consumption in France and $y_{FR\rightarrow exp}$ is the vector of final consumption exported from France to the rest of the world.

Production of steel and iron, iron alloys, and other primary products.

Reconversion of used steel into new steel.

Production of precious metals.

Reconversion of used precious metals into new precious metals.

Aluminum production.

Reconversion of used aluminum into new aluminum.

Production of lead, zinc, and tin.

Reconversion of used lead into new lead.

Copper production.

Reconversion of used copper into new copper.

Production of other non-ferrous metals.

Reconversion of other non-ferrous metal uses into new non-ferrous metals.

Box 6.1. *Metal production activities in Exiobase v3*

Code	Country	Code	Country
AT	Austria	JP	Japan
AU	Australia	KR	South Korea
BE	Belgium	LT	Lithuania
BG	Bulgaria	LU	Luxembourg
BR	Brazil	LV	Latvia
CA	Canada	MT	Malta
CH	Switzerland	MX	Mexico
CN	China and Taiwan	NL	The Netherlands
CY	Cyprus	NO	Norway
CZ	Czech Republic	PL	Poland
DE	Germany	PT	Portugal
DK	Denmark	RO	Romania
EE	Estonia	RU	Russia
ES	Spain	SE	Sweden
FI	Finland	SI	Slovenia
FR	France	SK	Slovakia
GB	Great Britain	TR	Turkey

Code	Country	Code	Country
GR	Greece	US	United States
HR	Croatia	WA	Rest of the world – Asia and Pacific
HU	Hungary	WE	Rest of the world – Europe
ID	Indonesia	WF	Rest of the world – Africa
IE	Ireland	WL	Rest of the world – America
IN	India	WM	Rest of the world – Middle East
IT	Italy	ZA	South Africa

Table 6.2. *Countries and regions in Exiobase v3*

For the French final demand in 2011, about 60 billion euros of metals are produced worldwide, of which about 10 billion euros are exports. The distribution is shown in Figure 6.3. It was obtained from Exiobase 3.4 monetary data. It shows that most of this production takes place in France (19%), China (14%), and Germany (12%). The metals most widely produced to satisfy French final demand are iron and various steels.

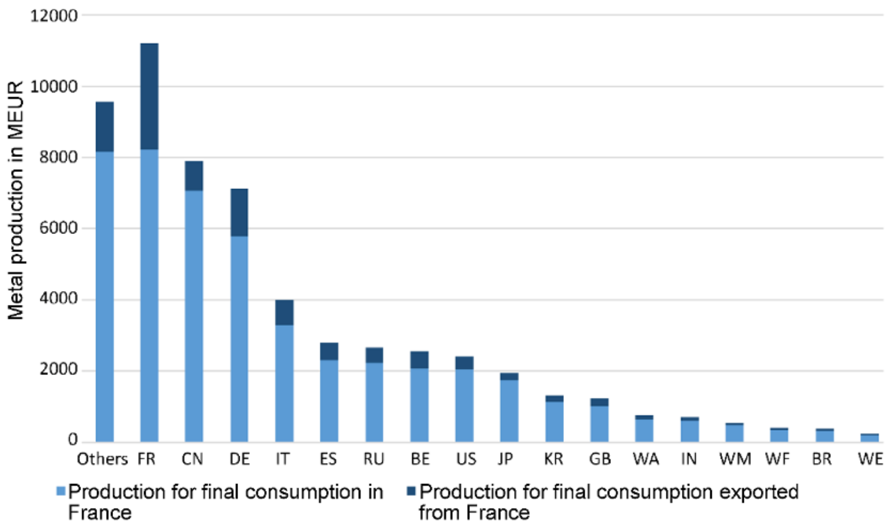

Figure 6.3. *Distribution of world metal production for final consumption in France in 2011. For a color version of this figure, see www.iste.co.uk/fizaine/mineral1.zip*

6.5.4. *Environmental footprint of metal production*

While the MRIO analysis provides a regionalized production inventory of the activities mobilized to meet a given final demand, the environmental extensions associated with the MRIO databases make it possible to transform this production inventory into regionalized environmental impacts.

Figure 6.4 illustrates this regionalization of the production inventory and associated environmental impacts for the specific case of the production of metals required for final demand in France. When analyzing the environmental impacts associated with this production, it can be seen that the most significant contributions do not necessarily take place in the country in which production is most significant.

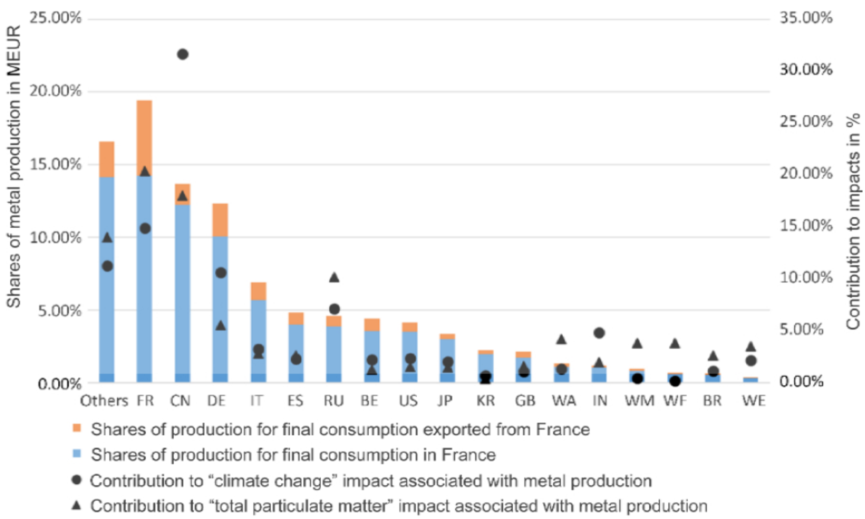

Figure 6.4. *Distribution by country of metal production required for final demand in France and associated environmental impacts (calculations with Exiobase 3.4). For a color version of this figure, see www.iste.co.uk/fizaine/mineral1.zip*

While the contribution to the climate change impact of the production of these metals amounts to 32% in China, this contribution is only 15% in France, while an additional €3,000 million is produced in France.

While the impact on climate change is a global impact (wherever a greenhouse gas is emitted, it will have an effect on global climate change), fine-particle emissions are related to local problems (e.g., worker health). Here again, regionalization makes it possible for us to point out the most significant contributors and the countries for which the relative contribution is significant (e.g., Russia contributes 10% of the total particulate matter impact while Germany contributes only 6% and produces twice as much metal).

Figure 6.5 presents a similar graph obtained using the Exiobase 3.3 database, which contains non-monetary but hybrid data (material and energy exchanges are expressed in physical units). The shift from monetary to physical flows does not change the main metal-producing countries needed for final demand in France, namely France, China, and Germany. On the other hand, there are changes in the order of contribution for other producing countries, such as the United States and Brazil, which has a greater contribution when we look at physical exchanges. Belgium's contribution to metal production for final demand in France increased to 1.5%. These changes can be explained by the differences in price per quantity of metal produced that exist both between producing countries but also between metals considered (between steel and precious metals for example).

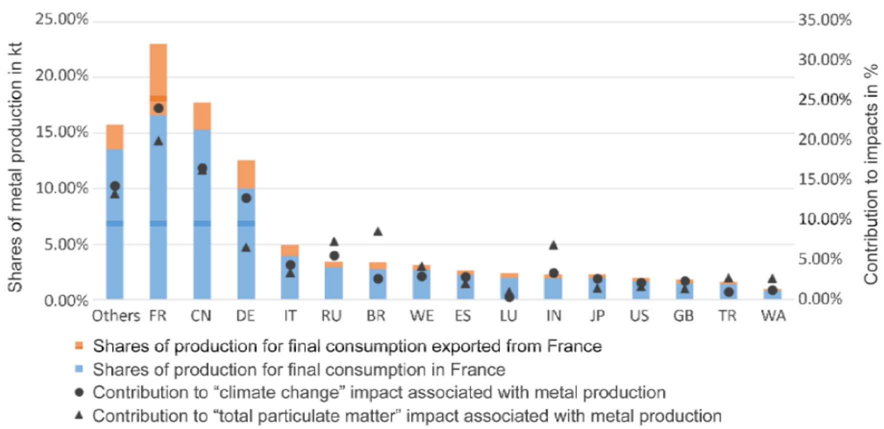

Figure 6.5. *Distribution by country of metal production required for French final demand and associated environmental impacts (calculations with Exiobase 3.3). For a color version of this figure, see www.iste.co.uk/fizaine/mineral1.zip*

6.6. Conclusion

MRIO analysis therefore makes it possible to compare the location of the impacts for a given final demand and the production sites of the products and services required for this demand. In this sense, it can be used for the implementation of public policies aimed at reducing the environmental impacts associated with consumption and for monitoring these impacts.

Nevertheless, in its use, certain limitations should be considered. First of all, access to recent data is an issue for the use of MRIO databases. Thus, in 2019, the most recent data available in the databases were from 2014. This can be explained by the time required between the moment when the data are made public on a territory, the moment when they are transformed into IOTs, and finally the moment when these are compiled in the form of MRIO databases.

A second issue related to the knowledge of the metal sector via the MRIO databases is associated with the disaggregation of this sector; indeed, while the so-called base metals are well-covered, this is not the case for the so-called technology metals, which are aggregated in the categories of "precious metals" and "other non-ferrous metals", which makes the precise composition of these two categories uncertain. The reduction of these uncertainties is being investigated (Beylot 2019).

Finally, while some impact categories are relatively well covered by the environmental extensions of the MRIO databases, this is not the case for others, such as toxicity and ecotoxicity, for which, for example, metal emissions to water and soil are not taken into account.

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7

Why Should We Fear Energy and Material Savings? Deconstructing a Sustainability Myth

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7.1. Introduction

The 1970s remain a paradoxical period, to say the least. Indeed, humanity had never been more successful in using the laws of nature, for instance with the conquest of space and the mastery of the atom and the genome. And yet, it had never been so close to its decline.

This period of questioning was an opportunity for some scientists to come together around a common cause and to advocate for a society in tune with the biosphere. The "Menton Accords" in 1971, which brought together 2,200 scientists, testified to this alarming situation by addressing the rest of the world (UNESCO 1971). The United Nations Conference on the Human Environment, organized the following year in Stockholm, was to remind the world of the magnitude of the situation. Economists were mobilized in the scientific sphere with an anthology of publications testing the relevance of economic growth and our modes of development (Cole *et al.* 1974; Georgescu-Roegen and Passet 1979; Sachs 1980). One of the main challenges was to envision a post-petroleum world while taking

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First Edition. Florian Fizaine and Xavier Galiègue.

into consideration the issues related to nuclear energy[1]. The following decade met with general mobilization with the publication of the Brundtland Report in 1987, which laid the foundations for "sustainable development". Among its recommendations, Chapter 8 of the report highlights "producing more with less" in order to exert less pressure on the biosphere. This principle is found 10 years later in the report *Facteur 4 – deux fois plus de bienêtre en consommant deux fois moins de ressources : rapport au Club de Rome* (Lovins *et al.* 1997). It became one of the cornerstones of environmental innovations considered as a vector of "green growth" (OECD 2010; Debref 2018). These efforts have not been in vain since, at the scale of the global economy, the latest figures show that resource productivity increased by about 30% between 1980 and 2010 (OECD 2015, p. 66). However, material use per capita remains high and has been accelerating over the last 15 years (OECD 2015). Indeed, a closer look at the situation reveals that energy production rose by 120% between 1976 and 2016. In addition, oil and coal extraction is now reaching new heights. In other words, the virtues of "producing more with less" are far from being identified.

The marginalist economist Sir William Stanley Jevons (1865) was the first to discover this paradoxical phenomenon in the midst of the Industrial Revolution. He demonstrated that reducing energy consumption with more efficient machines, such as the steam engine, leads to an acceleration of coal depletion in the long run. This phenomenon, which he called the "rebound effect", has made a triumphant return among environmental and technical change economists over the last 10 years (Berkhout *et al.* 2000; Polimeni *et al.* 2008; Font Vivanco *et al.* 2016). However, if we look at a recent OECD report (2015, p. 75), we note only a low level of interest. Indeed, only a few lines mention it, not to mention its absence during a workshop organized by the European Commission and the G7 dedicated precisely to resource efficiency (European Commission 2019). This chapter is presented as a warning to demonstrate that "producing more with less" is at the origin of a series of failures that could go against its initial objective.

Our demonstration is divided into two parts. First, we will look at the principles and conceptual limitations of "producing more with less", better known as "eco-efficiency". Then, we will see how they contribute, at a more global level, to its increasing complexity due, for example, to the emergence of environmental innovation, of the circular economy in the digital age.

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1 This period was the era of publications dedicated to the "anti-nuclear" movement and the emergence of a "solar" world. See, for example, Dickson (1975) and Lyons and Solar Action (1978).

7.2. Conceptual critique of the "eco-efficiency" principle

This section focuses on the goal of "producing more with less", more commonly known as "eco-efficiency". This point is significant in our analysis since it is at the origin of the rebound effects, as understood by William Stanley Jevons. We will first see (section 7.2.1) how this concept fits into the perspective of sustainable development and green growth. We will then analyze its implementation and observe its conceptual evolution (section 7.2.2). Finally, we will discuss its interactions with the biosphere (section 7.2.3).

7.2.1. *Historical review of the rise of eco-efficiency, or how to "produce more with less"*

7.2.1.1. *The 1970s, a period faced with the resource crisis*

The oil crisis and the end of the *Trente Glorieuses* (the 30 years following the end of World War Two) heralded the decline of our "thermo-industrial" world, although, at the time, the scientific and political community considered disasters as epiphenomena. Their recurrence, however, revealed to the world that a great upheaval was underway. Scientists were the first to mobilize both civil and scientific society. This is evidenced by the international publication of the *Message de Menton* (Message from Menton) (UNESCO 1971) presented the following year at the United Nations Conference on the Environment in Stockholm (UNEP 1972). The resulting publications revealed the importance of saving energy and resources, which could be the responsibility of governments (ecological planning) as well as of industrialists through pollution control tools and recycling. These events were a milestone for economists at the time, to the point that new theories of development emerged, including the life sciences and the waste of energy and materials.

Three major currents of thought contributed to these developments. First, the famous Meadows report, resulting from the Stockholm conference, entitled "The Limits to Growth", was the first step in this questioning (Meadows *et al.* 1972). It uses systemic analyses to identify scenarios that future generations would have to face. Chapter 3 is dedicated to technologies, resources, and the effects of our dependence on fossil fuels. We learn that if, at the time, nuclear energy could have freed us from our dependence on fossil fuels, much to the chagrin of the anti-nuclear movement, the boom in recycling would still come as a reinforcement to for the preservation of "virgin" resources (Meadows *et al.* 1972, p. 133). However, although these technical solutions may seem innovative, they are only one element among others, since population growth plays a significant role in this Malthusian-inspired analysis[2] .

2 The model is based on the IPAT model.

Researchers at the University of Sussex, originating in the Neo-Schumpeterian trend, expressed their disagreements in their book *L'Anti-Malthus : une critique de* "*Halte à la croissance*" (Cole *et al.* 1974). They consider that another form of growth is possible provided that technical change and innovation policies are reinserted at the heart of the problem. Combining environmental preservation and economic growth would be compatible as it would encourage, for example, recycling, waste reduction, and resource and energy savings in industries (Cole *et al.* 1974, p. 81). Here, one of the key issues is who would be willing to pay and take risks to initiate these energy transition initiatives.

Finally, the economist Nicholas Georgescu-Roegen (1979) proposed his own analysis, although he wanted to collaborate with the Meadows team (Levallois 2010). He argued that the evolution of the human species depended on our capacity to adapt to entropy – the second principle of thermodynamics – and on the principles of irreversibility. The evolution of our societies depends on our ability to innovate in order to cope with these laws of physics and biology. History testifies that this capacity for adaptation was made possible by the emergence of so-called "Promethean" technologies (Georgescu-Roegen 1984). They serve as a medium for the socioeconomic development of societies by exploiting the abundant and accessible energy resources[3] of various ages (Vivien *et al.* 2019). As an example, organic resources such as wood enabled humans to control fire – *Prometheus I*. Then, the growth of energy needs led more advanced societies to find more calorific resources by choosing to exploit mineral resources: the starting point of the steam engine and the industrial revolution – *Prometheus II*. According to the author, the last stage would be the return of a new "age of wood" – *Prometheus III* – but in a perspective of "decline" to prevent us from reaching the point of no return too quickly. What interests us here is to note that within each of these Promethean technologies there is a new typology of innovation, with the presence of "economic innovations"[4]. In other words, humans have always been imaginative in saving energy and materials, but it all depends on the basic resource.

7.2.1.2. *1980–1990: eco-efficiency, a means of collective mobilization to operationalize sustainable development*

A decade later, the Brundtland Report (1987) heralded the birth of "sustainable" development. Energy and resource savings were presented as an objective to be achieved, as Chapter 8 of the report, entitled "Producing More with Less", shows. The latter directly targets the industrial world and reassures it by pointing out that

3 It is called "low entropy".

4 It seeks "[…] more complete combustion, less friction, more intense light from gas or electricity, substitution of materials with less energy-intensive ones, and so on".

"[…] these efficiency trends are not the *result of a decline in manufacturing industry* in favor of service industries, because during these periods, manufacturing output has continued to increase" (Brundtland 1987, section 36, italicized by us), and adds that "productivity and efficiency of resource use are steadily improving and industrial production is gradually shifting away from products and processes that consume large amounts of materials" (Brundtland 1987). Moreover, in addition to being an opportunity at the individual level, this objective becomes indispensable for "maintaining the momentum of production at the global level" by adopting "policies that integrate resource efficiency considerations into economics, trade, and other related areas…" (Brundtland 1987, section 38). Thus, contrary to what we observed in the previous decade, energy and resource savings remain compatible with the idea of economic growth and industrial mass production.

Companies took advantage of this situation after the Rio de Janeiro Earth Summit in 1992 by describing their operating methods in detail (Schmidheiny 1992)[5]. This was the moment when the term "eco-efficiency" was officially coined (Schmidheiny 1992, p. 10). This exists thanks to recycling and the saving of energy and materials. It is also a source of competitiveness, thanks to new types of managerial behavior that are more in tune with the preservation of the environment[6]. This is why this strategy is strongly encouraged[7]. In the late 1990s, eco-efficiency became an essential part of company strategies as well as in those of public authorities through the application of the *Facteur 4* principle – advocating decoupling (Lovins *et al.* 1997). Its objective is to reduce fossil energy and material consumption by a factor of four by 2050 by improving production methods. This is why some states have made combating global warming a priority.

7.2.1.3. *2000–2010: eco-efficiency at the root of environmental innovation and green growth*

The subprime crisis and rising oil prices marked the beginning of the new millennium. Public authorities and industrialists intensified their efforts to make eco-efficiency an environmental performance indicator. We find it, for example, in the granting of public subsidies for the energy efficiency of buildings as well as in

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5 A large scientific literature was published on corporate strategy on this occasion. See Porter *et al.* (1995a, 1995b), Fussler *et al.* (1997), Boiral (2005) and Debref (2018).

6 Let us also recall that this period is also that of the emergence of industrial ecology (Frosch and Gallopoulos 1989).

7 We can, for example, for Schmidheiny (1992), mention the section "Increasing Energy Efficiency" (p. 40) and a whole appendix dedicated to the "priorities of a rational energy strategy" (p. 334).

the foundations of HEQ[8] standards since France's *Grenelle de l'environnement* in 2007. Plastics chemistry industrialists are also in favor of this objective, putting in place roadmaps to encourage material savings and "deepen knowledge of the eco-efficiency of PVC and find ways to improve it further" (VinylPlus 2001, p. 8). These few examples alone show that this desire to "produce more with less", this ode to "eco-efficiency" or the improvement of "material intensity"[9], is becoming essential to solving the ecological question through the implementation of environmental innovations (Huppes 2007; OECD 2010, 2012a, 2012b, 2015, p. 27; Debref 2018). The ultimate objective is to steer advanced societies towards a system "that creates more value with fewer natural resources and does not compromise the needs of future generations" (OECD 2012c, p. 3).

7.2.2. *Conceptual evolution and broadening the boundaries of eco-efficiency*

7.2.2.1. *An individual approach*

The literature on eco-efficiency has been extensive since the 1990s (Lovins *et al.* 1997; Ayres *et al.* 2001; Bleischwitz 2003; Ehrenfeld 2005). Huppes and Ishikawa (2005, p. 3) paid tribute to it by proposing a simplified definition. They emphasized that "The most modest position in eco-efficiency is that, setting aside the question of optimality, we do know that achieving environmental improvements for a lower price is to be preferred over more expensive options." In other words, it responds to environmental issues while offering an opportunity for value creation. Its calculation method is very simple, since it is based on a ratio with input as the denominator and output as the numerator, which makes it possible to evaluate the material intensity of production and the productivity of raw materials. This method of calculation is ultimately an accessible starting point for industrialists who would like to take this route. It also has two other points of interest. On the one hand, it is able to calculate the productivity of material resources from a division between two physical variables; for example, by dividing the necessary energy by the weight of a commodity (j/kg). On the other hand, it makes it possible to observe the productivity gains, translated into monetary terms, with a ratio of the cost of the resource divided by the weight of the same commodity (€/kg). Ultimately, this method of calculation enables the identification of the values added as a function of the quantity of a resource in order to increase economies of scale: we can speak here of decoupling (OECD 2012b, 2015). However, production costs cannot decline indefinitely despite the increase in eco-efficiency (Polimeni *et al.* 2008, p. 65). Some technologies have their limitations

8 High environmental quality.

9 Material intensity is also a synonym used by the OECD (2012a, p. 12).

and do not have immediate alternative technologies, and some resources cannot be reused, such as hazardous and radioactive substances and ultimate wastes. In other words, although the intensification of production through eco-efficiency is allowed, and remains promising, its potential can be greatly limited depending on the resources that are exploited (Debref 2016).

7.2.2.2. *Towards a structured holistic and systemic approach to the circular economy*

From the 1990s onwards, the analysis of eco-efficiency took on another dimension as part of a systemic approach (Allenby and Cooper 1994). The boundaries of the system continue to evolve. Indeed, rather than focusing only on the level of a company or a machine, economic and engineering sciences studied the lifecycle of energy and material flows. This new approach generated new opportunities for optimization in all areas of production. The exploitation and transformation of biomass[10] in various sectors remains one of the first subjects of study. This concept, better known as "cascade utilization" or "cascade chaining", makes it possible to identify and plan the major stages of resource transformation (Sirkin *et al.* 1994; Keegan *et al.* 2013; Essel *et al.* 2014; Ciccarese *et al.* 2015). Its principle is that products and by-products, transformed at various stages, are redistributed in the following stages (see Figure 7.1). Initially, users aimed to link the process only according to the intrinsic quality of the resources (Sirkin and Houten 1994). However, as Olsson and colleagues (2018, p. 3) pointed out, the fluctuating market prices sharpen this distribution process; the trade-off between economic and environmental impact could thus cause economic agents to deviate from their initial objectives.

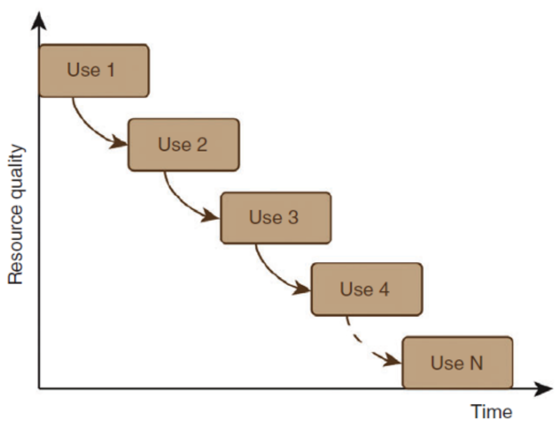

Figure 7.1. *Modeling cascade utilization (Olsson* et al. *2018, p.2)*

10 Such as forestry and the paper and biomaterials industry.

Furthermore, if one positions oneself in the world of industrial production, everyday consumer products can also be designed based on this eco-efficiency logic. Michael Braungart and William Mcdonough (2002) are the main contributors to this idea, with their “Cradle-to-Cradle©” logic, which has become a point of reference in product certification (Debref 2018). It is still highly valued by industrialists who, rather than moving towards the design of eco-industrial parks – or industrial symbiosis – aimed at exchanging energy and material flows, can individually, with the help of certification and the “Cradle-to-Cradle©” label, establish mechanisms that reduce energy and material wastage. The economic and environmental benefits that companies can derive from this can be understood by adhering to the following expression word for word: “doing more with less”[11] (Braungart *et al.* 2002, pp. 51 and 53). However, James Jenkins and Paul Knight (2009, p. 28), remind us that this objective “[…] only works to make the old system a little less destructive […] there is still much to be done and the industry needs to go further.” Also, the principles defended by this practice are far from unanimous among experts.

Finally, the circular economy presents itself as a new dimension offered to this eco-efficiency logic. Industrialists, citizens, and public authorities see it as a robust solution to link the environmental sphere with the industrial world while providing opportunities for growth. A study by the Ellen MacArthur Foundation (2015, p. 12) points out that its implementation could increase resource productivity by 3% per year, or even 7% by 2030 according to certain scenarios. This is becoming institutionalized in France, as evidenced by the appearance in 2013 of the *Institut de l’Economie Circulaire* (French Circular Economy Institute) (Gallaud and Laperche 2016). It also has legal recognition in the official gazette of Article 70 relating to the energy transition for green growth, published on August 17, 2015[12]. Moreover, it is part of the main lines of CSR strategy of *France Stratégie*[13]. At the European level, we even find a strategy for a “circular bioeconomy”, which shows that there is a will to link two universes that have long been separated (European Commission 2018). This circular economy is officially represented in Figure 7.2 and integrates the two eco-efficiency logics that we have just mentioned above. On the one hand, in the environmental sphere (left), we find exchanges of “biological nutrients” with the industrial world, where we observe “cascade production”. On the other hand, we find in the industrial world (right), exchanges of “technical nutrients”[14] that may belong to the “Cradle-to-Cradle©” logic.

11 This expression is not unlike the one used in the Brundtland Report (1987).

12 Relating to the French law no. 2015-992.

13 For example, to create new jobs.

14 Both types of nutrients are specifically mentioned by Braungart and McDonough (2002).

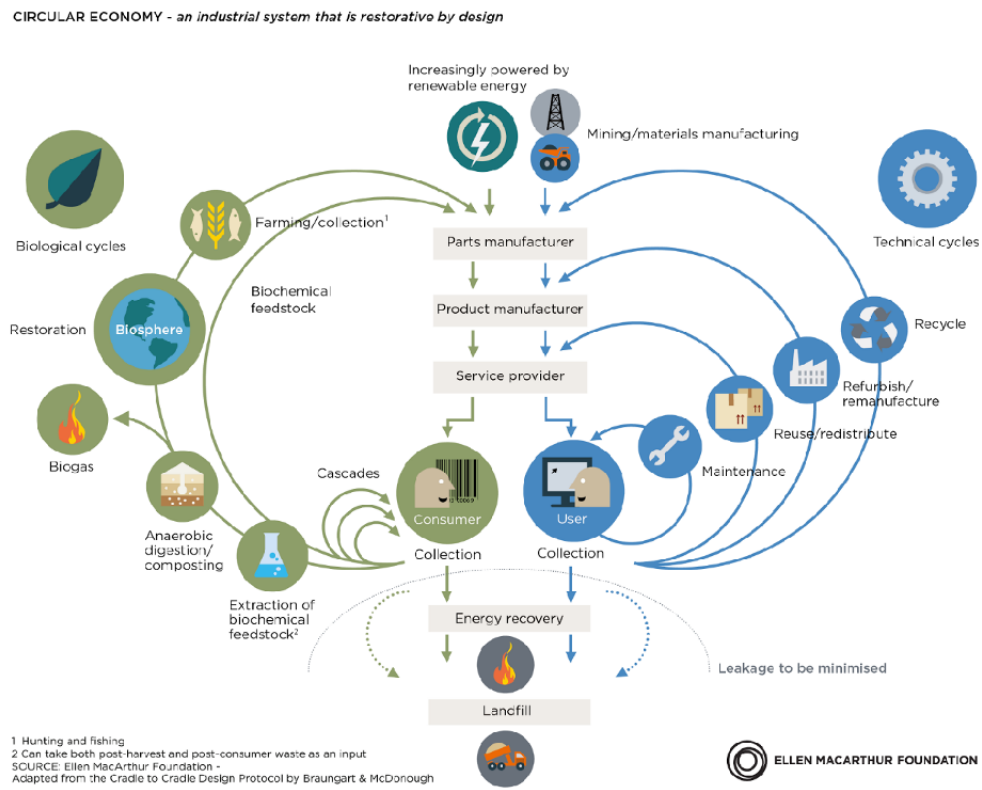

Figure 7.2. *Schematic representation of the circular economy model (Ellen MacArthur Foundation 2015, p. 24). For a color version of this figure, see www.iste.co.uk/fizaine/mineral1.zip*

However, this systemic level, within which eco-efficiency is integrated, has flaws. For example, the diversity of scientific communities and the methodologies used generates very different interpretations of the results (Korhonen *et al.* 2018b, p. 547). This conception is also far from being original, since we find in it the founding ideas of Kenneth Boulding (1966) and in Barry Commoner's (1971) desire to "close the loop". We also find it in practice in the production methods implemented during the Soviet productivist and Fordist era (McCarthy and Sathre (2006) and Grdzelishvili (2006)). Finally, other points deserve further study, such as the management of incentives, the consideration of spatial-temporal boundaries (distances), as well as the dead ends regarding the principles of irreversibility of energy conditioned by entropy (Korhonen *et al*. 2018a, 2018b; Giampietro 2019). Thus, we observe that at all levels of analysis, whether on an individual or systemic scale, the virtues of "producing more with less" are equivocal.

7.2.3. *Eco-efficiency and environmental preservation: an equivocal synergy*

7.2.3.1. *Efficiency, productivity, and wealth creation: a feeling of déjà vu*

We show here that "eco-efficiency" – "producing more with less" – and efficiency – a symbol of productivism – are similar, and that adding the suffix "eco" makes no sense. In order to realize this, it is necessary to go back to the fundamentals of economic theory. William Petty, the famous physiocrat of the 17th century, already studied this question by comparing the energy efficiency of production from flour mills. His method also relied on calculations of the ratio between physical and economic flows in order to compare the relevance of the modes of transport of goods by sea and land. We also find this subject in the work of Robert Thomas Malthus in the following century (1798). With the physiocratic footprint of the time, he emphasized that humans exploit the resources offered by Mother Nature and must equip themselves with a large number of machines : "When a machine in manufactures is invented, which will produce more finished work with less expenditure than before, if there be no patent, or as soon as the patent has expired, a sufficient number of such machines may be made to supply the whole demand, and to supersede entirely the use of all the old machinery. The natural consequence is, that the price is reduced to the price of production from the best machinery, and if the price were to be depressed lower, the whole of the commodity would be withdrawn from the market" (Malthus 1820). In other words, humans must equip themselves with the means for increasing performance to ensure wealth and well-being.

Jean-Baptiste Say considered that this capacity to improve things was the symbol of a new stage in our modes of development[15], synonymous with progress (Polimeni *et al.* 2008). Finally, Karl Marx showed that the quest for eco-efficiency, which can even be linked to the circular economy[16], is at the center of capitalist economics (1865). Indeed, after taking up the example of the performance of flour mills under Louis XIV[17], he noted that "the economies of industrialized countries developed while the resources and energy needed to produce each unit of growth declined". One of the reasons for this was the ability to "perfect the machines so that they can give originally unusable materials a form that makes them suitable for new production". According to him, this could only be possible with the participation of the chemical industry, which is capable of "discovering the useful properties of residues". This is why, he said, "capitalist production has the consequence of giving more importance to the use of the residues of production and consumption". This point is all the more revealing when we return to the recommendations presented in the book edited by Stephan Schmidheiny (1992, p. 97). He expressly invites us to draw inspiration from the German chemical industry, which "succeeded in reducing heavy metal emissions by 60 to 90% between 1970 and 1987 while increasing production by 50%". So, to which paradigm does the concept of (eco-)efficiency belong? Does it not finally fit into a traditional paradigm that we think we have managed to overcome?

7.2.3.2. *Are the principles of eco-efficiency (ultimately) based on the environmental dimension?*

The need to reintegrate the socio-economic sphere within the limits of the biosphere has been part of the research program of development economists for several decades (Georgescu-Roegen and Passet 1979). These authors demonstrate that standard economic theory is not capable of integrating the complexity of these issues. For this reason, they each present their own conception of the bioeconomy[18]. Among these different meanings[19], Vivien *et al.* (2019) recall that these authors define it as a

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15 "The knowledge of the civilized human, compared to that of the savage or barbarian, gives him the power to build a greater number", according to Say (Polimeni *et al.* 2008).

16 For more details, see the chapter "*Utilisation des résidus de la production*" in Book III of *Capital* – Chapter V: "*Économie dans l'emploi du capital constant*".

17 "Parmentier has demonstrated that the art of grinding grain has improved very materially in France since a none too distant epoch, for instance the time of Louis XIV, so that the new mills, compared to the old, can make up to half as much more bread from the same amount of grain" (Marx 1865).

18 It was discussed during the 1980s (Theys and Mirenowicz 1980) until it became a polysemous term (Vivien *et al.* 2019).

19 Other meanings of this term are also used by economic actors. For more details, the reader may refer to the article by Vivien *et al.* (2019) identifying the existence of three forms of bioeconomy.

long process of evolution of our societies that must adapt to the constraints imposed by the laws of nature. Nicholas Georgescu-Roegen insisted on the fact that our energy dependency and the fight against entropy led us to climb different stages of development according to the resources available at the time. Today, our “thermo-industrial” society based on mineral resources prevents us from thinking our actions according to immutable limits. René Passet also shares this point of view by emphasizing that our mode of development based on mineral resources has led us to establish an “economy of dead things”, that is to say, an economy detached from its support in order to remain viable. Finally, isn’t the confusion over the goals of “eco-efficiency” due to the fact that it is based on this narrow approach to economics?

Recent research work presents four forms of eco-efficiency (Debref 2016, p. 89; Polimeni *et al.* 2008). This result is based on the observation that the optimization of resources and energy is achieved both in the industrial sphere (machines, industry) as well as in the bio-industrial sphere (wood, plants, agricultural resources), since organisms also function in this way (Lotka 1924). For these two forms, we are at a static level, like a photograph that would come to study the structure of the entity consuming resources and energy. Insofar as it is a question of preserving the environment and adapting our societies, thinking long term seems quite relevant to studying how production systems optimize their adaptation processes as well as the ecosystems that support them. In this perspective, two other forms of additional eco-efficiency become identifiable, which are in constant interaction with their own rhythms and limits of adaptation.

Finally, the purpose of eco-efficiency, to “produce more with less”, can easily be re-discussed when the biosphere and the constraints it imposes are not taken into account in the analysis. This goal only applies in and for the industrial sphere, as if the biosphere – the very support of the viability of our social systems – had been set aside. We will, therefore, see in the following section the consequences that this conception can have at a macrosystemic level.

7.3. Rebound effects or unintended consequences of “producing more with less” at the macrosystemic level

This section highlights the consequences of “producing more with less” at a macrosystemic level, especially the *rebound effects*. As a first step, it is worth recalling the warnings issued by some economists as to the appearance of a possible “flashback” caused by energy and material savings (section 7.3.1). We will observe a diversity of determinants and also different dynamics according to the development stages of societies. Moreover, we will demonstrate that operationalizing sustainable development is also at the origin of new forms of the rebound effects caused by the circulating economy, with public authorities still on the sidelines (section 7.3.2).

7.3.1. *Optimizing to "burn" better, returning to the origin of rebound effects*

7.3.1.1. *Rebound effects, a new challenge posed by the Marginalist school of thought*

The expression "producing more with less", presented in the Brundtland Report, suggests that it is a robust solution for reducing the impacts of our activities on the biosphere. However, this idea is far from unanimous. Proof of this can be found as early as the industrial revolution in the book *The Coal Question* written by the marginalist economist William Stanley Jevons in 1865. Drawing on statistics and the Malthusian thesis on the population principle, he demonstrated that the performance of coal-fired machinery (steam engines) paradoxically contributed to the acceleration of coal depletion (1865) (see Table 7.1). This paradox, known as the "rebound effect", is largely visible in the following results. He discovered that machines consumed 70% less coal between 1830 and 1863 to produce 1 ton of cast iron. Paradoxically, an acceleration of production of more than 3,000% in the same period can be observed. This phenomenon can be explained, according to him, by the fall in production costs, generating a drop in prices that is reflected in the elasticity of demand. Also, he concluded, "It is wholly a confusion of ideas to suppose that the economical use of fuel is equivalent to a diminished consumption. The very contrary is the truth" (Jevons 1865, p. 103).

Year	Weight of coal required for 1 ton of pig iron	Pig iron production (t)	Total consumption of coal (t)	Evolution of coal consumption (%)	Evolution of pig iron production (%)
1830	7 t	37,500 t	262,500 t	– 71.43%	+ 3,000%
1863	2 t	1,160,000 t	2,320,000 t		

Table 7.1. *The eco-efficiency paradox*
(source: Jevons (1865, p. 293), adapted by the authors)

7.3.1.2. *Rebound effects, a new topic of discussion in the midst of the oil and ecological crisis*

It was in the early 1970s, in the midst of the oil crisis, that this paradox resurfaced. At that time, two conceptions were contrasted. On the one hand, Amory Lovins (1984, 1988) presented the benefits of energy optimization, a postulate that can be understood in context. On the other hand, Daniel Khazzoom (1980) defended the idea that, despite all the efforts made in the fight against the waste of energy and matter, global energy consumption had not been able to reduce the impact on resources, but rather quite the contrary. He inferred from this that "the massive upgrading of the efficiency of the stock of appliances […] will result not in a reduction of demand, but rather in an increase in demand that will require a major price hike to arrest it"[20] (Khazzoom 1987, p. 85). This failure is explained by the dual function of a technology – it can operate with fewer resources, but its use is likely to increase due to the savings achieved. This phenomenon fades away when price elasticity becomes almost zero, but the arrival of new, more efficient technologies is reviving this process (Khazzoom 1987, p. 86). This postulate was taken up again and then criticized by Amory Lovins (1988), who considered that the price elasticity of demand for a service was very difficult to evaluate and that the rebound effect was not generalizable, an argument that was later be challenged by Leonard Brookes (1990). Nevertheless, let us remember that this paradox amounts to a consensus among both neoclassical economists (Saunders 1992) and the ecological economists we shall presently examine.

7.3.2. *A compilation of rebound effects according to the development levels of our societies*

7.3.2.1. *A theoretical explanation of the diversity of rebound effects…*

The publications of Saunders (2000), Alcott (2005), Herring and Roy (2007), and Polimeni *et al.* (2008)[21], all of which fall within the field of ecological economics, reveal the desire to confirm an acceleration in energy consumption despite the arrival of less energy-intensive technologies. They propose a typology to better understand the determinants of this complex phenomenon. Let us take the example of Sorrell and Dimitropoulos (2008, p. 637). Their study identifies two families of rebound effects. The first is a direct effect resulting from consumers wanting to maximize their utility through an income and substitution effect. For example, an engine that consumes less energy encourages people to drive more. The

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20 This observation is also found in Jevons, who wondered about the relevance of incentive taxation for containing rebound effects (Jevons 1865, chapter XVI).

21 We can also cite Greening *et al.* (2000) and Binswanger (2001).

other is an indirect effect where the consumer consumes something else thanks to lower prices and lower operating costs: for example, buying a second vehicle.

Polimeni *et al.* (2008) took the analysis a step further by identifying six causes of rebound effects, the first half of which are direct and the other half indirect. First, we find a cause similar to the one presented by Sorrell and Dimitropoulos. Second, taking up the Malthusian thesis, lower costs give access to technologies for a population that could not afford them previously; an acceleration of energy demand is felt. The third effect comes from the income and profit opportunities that energy savings can offer. In a context of competition, industries are engaged in a frantic race to resist. The consequence of this intensity is the lowering of production costs and, in fact, the offering of more profitable prices for end consumers; they are thus able to consume more with the same income. The indirect causes of rebound effects are more complex to identify. Fourthly, the authors argued that the increase in productivity generated by more efficient technologies allows capital-labor (e.g. employees) to devote more time to consumption and leisure. Zero elasticity would also be a fifth reason. Here, price variation does not change consumer behavior. This is why it is necessary to study the rebound effects caused by specific goods. Finally, the sixth form of rebound effect comes from the effects of falling commodity prices that affect the process of energy substitution. Discovering new oil reserves ensures that the paradigm remains in place until there is no alternative.

Impacts	Principles
Direct	More efficient technologies, but increase in their use (1)
	Population and income growth (2)
	Dynamics of branch industries and substitution (3)
Indirect	Substitution of human labor by machines with the same quantity of energy required (4)
	Elasticity of demand equal to 0 (5)
	Decrease in raw material prices (6)

Table 7.2. *Diversity of rebound effects (based on Polimeni* et al. *(2008); compiled by Debref (2018))*

7.3.2.2. …and its empirical confirmation according to the different development levels of societies

Although the evolution of prices and population remains at the heart of this paradox, more qualitative criteria also come into play. Recent empirical studies focus primarily on the most advanced societies because they are part of a mass consumer society.

Greening *et al.* (2000) analyzed the American market by studying energy consumption according to various actors (consumers and firms). They also made a detour at the level of world production in order to compare their results. In all three cases, these authors identified, from their samples, energy rebound effects, but they remain highly variable. For example, for everyday consumer goods, the size of the rebound effects varies from 0 to 50% depending on the use of air conditioning, heating, transportation, and appliances. For firms, an increase in production would increase the size of the effect by 20% in the short term, but the wide variety of results and the complexity of the interactions over the long term prevent any premature conclusions[22]. Finally, effects at a more global level are identified in areas where increases in living standards and consumption of "luxury" goods are significant (Greening *et al.* 2000, p. 399).

Polinemi *et al.* (2008, p. 169) explored the singularities of the rebound effect by studying countries at different levels of development. With caution, their study includes, in addition to national primary energy consumption[23] and energy intensity, more qualitative criteria, such as purchasing power parity, rural exodus, urban concentration, birth rate, type of imports and exports, and GDP. The analysis begins with primary energy consumption in the United States between 1960 and 2004. The authors found an increase of almost 100%, despite an increase of about 115% in energy intensity (Polinemi *et al.* 2008, p. 152). This trend can also be observed in the countries of the euro area over the last 25 years, with the exception of Germany, but also in some Mediterranean countries[24] (Polinemi *et al.* 2008, p. 154). In this zone, one of the main explanations for these rebound effects is the growth of the population, although the birth rate is constantly falling[25], and also changes in travel patterns, an "energy-intensive" agricultural sector, and exports of products requiring high energy demand (Polinemi *et al.* 2008, p. 159). We find similarities in some Asian countries between 1980 and 2004, except for the strong influence of rural exodus and energy dependency from heavy industry demand. As for Brazil, a similar situation can also be observed, although energy intensity remained lower during the same period. Finally, the study of these geographical areas confirms the presence of rebound effects, although the causes are different. New research is exploring this

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22 They point out that "there is no theory comprehensive enough to predict these effects that could result in more or less energy consumption" (Greening *et al.* 2000, p. 391).

23 Expressed in British Thermal Unit (BTU).

24 Such as Spain, Portugal, and Greece.

25 With the exception of the United Kingdom and France.

avenue by proposing more precise evaluation methods. However, they have discovered that the implementation of strategies dedicated to sustainable development poses new problems (Font Vivanco *et al.* 2015, 2019).

7.3.2.3. *Sustainable development at the origin of new paradoxes: "circular economy rebound effects"*

We saw in the previous section that the eco-efficiency principles present in the circular economy roadmap remain questionable. Our comments make more sense of this roadmap by pointing out that it would also be at the origin of a new form of rebound effect, the Circular Economy Rebound, which Trevor Zink and Roland Geyer (2017) were the first to observe, signaling a possible drift in the system[26].

These authors believe that the circular economy is nothing more than a system of interconnected markets in which the price system drives the exchange of energy and material flows. The rebound effects, for their part, are the result of an insufficient substitution effect between resources. Rather than being complementary, secondary resources compete on prices with primary resources[27]. Some materials are not substitutable because of their unique ability to make certain products work, such as rare metals (Zink *et al.* 2017, p. 598); fluidity in the circuit is then hindered. A few examples may support this thesis. For example, the weakness of the substitution effect is found in the reuse and recycling of smartphones on the US market (Makov and Vivanco 2018). These authors estimated that "about a third, if not all, of the emissions savings resulting from the use of smartphones could be lost due to the rebound effect"[28].

In addition, there are irreversible substitution effects on the biosphere; this is the case of entropy as well as of the disappearance of certain forms of biodiversity (migrations) (Korhonen *et al.* 2018a, p. 43). From our point of view, one should also add to this the distances and modes of transport that allow for the transfer of energy and material flows. Indeed, irreversibility is also found in the energy and resources mobilized to accelerate recovery cycles. Finally, like Polimeni and colleagues

26 "[…] we caution that simply encouraging private firms to find profitable opportunities in the circular economy is likely to cause a rebound and reduce or eliminate the potential environmental benefits that merely link waste streams between one process and inputs to another and do not automatically reduce their environmental impact" (Zink *et al.* 2017).

27 We can cite the confrontation between the acquisition of "pure" petro-sourced plastics and those of recycled petrosourced plastics that can be inserted into a product. The drop in prices triggers incomplete substitution strategies that may be characterized by mixtures of these two resources; these two resources become complementary.

28 To be more precise, this imperfect substitution of recycled and reused products would generate a rebound effect of 29% on average and up to 46% depending on the brand.

(2008), Zink and Geyer (2017) showed that income and substitution effects do not have the same influences depending on the level of development of countries (Zink and Geyer 2017). In fact, developing countries that are making efforts to promote the circular economy must at the same time manage the increase in household purchasing power and the arrival of new resources in large numbers, which automatically accelerate the phenomenon (Geng and Doberstein 2008). This is why Korhonen *et al.* (2018a) encouraged a greater focus on changing consumer behavior in favor of sobriety.

7.3.2.4. *Towards the awareness of public authorities?*

Sir William Stanley Jevons (1865) proposed the introduction of a tax on coal to modify demand behavior and thus avoid "backlash". More than a century later, ironically, the UK's Energy Research Centre published reports on the subject. We are thinking, for example, of the report entitled "Evidence of the Rebound Effect from Energy Efficiency Improvements", based on Khazzoom's postulate (Sorrell 2007). Sorrell, a member of the University of Sussex, posed a new challenge to his fellow critics of the Meadows report (Cole *et al.* 1974). The European Union was inspired by this work in publishing the report "Coping with the rebound effect" (Maxwell *et al.* 2011). In turn, it is based on the Malthusian thesis, but has the originality of studying a set of case studies[29] while insisting on the psychological dimension of the consumer. Finally, the European statistical center Eurostat notes that "resource productivity in the EU increased between 2000 and 2007, but the decoupling of material consumption from GDP was only relative" (Eurostat 2011). In other words, there is no confirmation so far that increased eco-efficiency is the solution to reducing resource use (Debref 2018).

Finally, Font Vivanco, Kemp, and van der Voet (2016) identify several actions that governments could use to contain this phenomenon; these are mostly incentive-based. The authors insist on the introduction of new support policies and the establishment of mechanisms aimed at modifying consumer group behavior. Other recommendations include the willingness to adapt innovation processes while relying on regulations and incentive taxes. Other actions are also present, particularly those designed to encourage companies to change their business models. Although these levers can be studied independently, the major contribution of these authors is their ability to combine them to identify three possible strategies (Font Vivanco *et al.* 2016, p. 118). The first proposes "consuming more efficiently". Here, the public authorities take the path of economic and accounting incentives by proposing evaluation tools to estimate economic and physical impacts, while introducing taxes and subsidies. The second strategy aims to change consumption behavior by

29 For example, heating, dematerialization, and the telephone.

"consuming less" by targeting consumer communities influenced by labels and shared values. Finally, the third strategy is based on the desire to "consume differently" by relying on consumption patterns that promote frugality and autonomy of needs.

7.4. Conclusion

The publication of the Brundtland Report in 1987 is still the starting point for sustainable development today. It also left a set of recommendations for achieving it, notably that of wanting to "produce more with less". Although this suggestion presents itself as an opportunity for those wishing to operationalize it, this chapter deliberately positions itself against this concept, which has now become common knowledge. A systemic approach helps to nourish this questioning. First of all, we presented the principles and limits of the expression "produce more with less", better known as eco-efficiency among economists. After showing how this concept has become established since the 1970s, we presented its conceptual evolution, and then how it fits into a perspective of circular economy, considered as a new stage in the development of advanced societies. We expressed doubts about its originality and purpose by comparing the proposals of the first economists with those proposed by the precursors of the bioeconomy. In a second step, we studied the macroeconomic consequences of eco-efficiency, taking note of the warning of the marginalist economist Sir William Stanley Jevons on the existence of rebound effects. Since then, the fear and the studies regarding this subject have never been as significant as they are today, and they raise new points that we discuss below.

Let us retain the following results from our reflection. At first glance, the objective of "producing more with less" appears to be a model that should be followed, encouraged, and respected if we want to contribute to the ecological transition. Paradoxically, its theoretical foundations are far from belonging to a new model of thinking; they are based on principles that we are trying to challenge at the same time. To demonstrate this, we have re-inserted this quest for eco-efficiency in a bio-economic perspective to note that its process rests on a model that does not integrate the limits of the biosphere. At a macrosystemic level, we have seen that the literature cautiously demonstrates the existence of rebound effects, but this is not the only point that we will retain. Indeed, their appearance is not only due to price variations caused by more efficient machines. They are also due to the specific characteristics of developments of countries, such as in Asia, Brazil, and Europe. Therefore, we deduce that the rebound effect is a phenomenon that is quite present, but which is the subject of a complex process. Finally, a new challenge is added to this paradox with the introduction of a strategy relating to the circular economy. Although this concept presents itself as a solution for entering the era of sustainable development, we conclude that this new stage is creating its own new form of rebound effect.

Therefore, we invite future contributions to explore the rebound effects from new perspectives: first, from the perspective of the bio-economy in its various meanings (Vivien *et al.* 2019); second, from the theory of development economics, which will identify qualitative variables to determine its emergence, including the psychological dimension of consumer behavior. Finally, it will be necessary to come back to the emergence of new mechanisms that public authorities should mobilize to contain this phenomenon (nudges, information, taxes, and regulations).

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8

The "Resource Curse" in Developing Mining Countries

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8.1. Introduction

International trade theories based on the analyses of Smith (1776) and Ricardo (1817) assert that natural resources, especially mining resources, are the source of an absolute or comparative advantage for the country that holds them. Moreover, the exchange value of these resources can make it possible for their holders to generate additional profit (a rent) because of their scarcity as long as it is impossible to produce a substitute, for technological reasons, or as long as the consumption and social organization patterns that made these resources indispensable (for example, gasoline for the automotive industry) remain unchanged. Historically, it cannot be denied that the coal-rich regions of the United Kingdom and France contributed to the European economic boom of the 19th and 20th centuries. The same was true for the United States, Canada, Australia, and the USSR over the same periods.

During the colonial period, most of the future developing countries were already inserted in international trade through the trading economy, particularly in African and Latin American countries. In the aftermath of independence, this insertion had to be modified and, in most cases, the states took control of the savings and led them to national development financed by domestic savings. However, international integration could not be achieved in autarky, as Chenery and Strout (1966) showed in the "double deficit" model; exports were used to generate income to finance

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capital goods purchases that would enable economic growth. The Ricardian argument of comparative advantage or Heckscher-Ohlin's theses encouraged governments in Sub-Saharan Africa and Latin America to specialize in primary products where they had a comparative advantage.

Most of the countries that were able to do so opted for development based on the extraction, processing, and export of their raw materials. However, "countries richly endowed with natural resources have, almost without exception, stagnated in their economic growth since the early 1970s" (Sachs and Warner 2001, p. 837). This is confirmed by Auty: "the median per capita income of resource-rich developing countries has fallen below that of resource-poor countries, whereas a generation earlier, in 1960, it was 50 percent higher" (Auty 2001, p. 5).

To qualify this counter-intuitive situation, the phrase "resource curse" has been used very often since the 2000s. It covers a reality that is broader than the "paradox of abundance" (Karl 1997), which only concerned oil-producing countries. The "resource curse" is invoked when the exploitation of exhaustible natural resources (minerals and hydrocarbons) hinders economic and human development, while irreversibly degrading the environment. In other words, the "resource curse" poses a serious threat to the sustainability of development.

How can the "resource curse" be identified? What are the ways to do it? What solutions can be considered to avoid it or ward it off?

In order to provide some elements of response and reflection, we will begin by showing how economic analysis takes into account the contribution of exhaustible natural resources to sustainability by emphasizing the importance of rent. We will then set out the macroeconomic and sectoral issues related to the management of this rent. In a third point, we will analyze the problematic link between rents and states, emphasizing governance and conflict issues. Finally, we will present some of the mechanisms put forward by international institutions and non-governmental organizations (NGOs) to counteract the "resource curse".

8.2. How to take into account the contribution of exhaustible resources to sustainability and measure the "resource curse"

The "resource curse" is defined as an inverse relationship between the accumulation of capital per capita and the contribution of natural resources to growth, so we must briefly review the history of the economic analysis of exhaustible natural resources.

8.2.1. *From natural resources to natural capital*

It is from the 1970s that the neoclassical economic approach developed a theory of natural resources. These resources were central to the physiocrats, who understood production as an activity of extraction and transformation of natural resources, particularly in agriculture. In classical theories of production, because of their abundance, natural resources are not economic goods but free goods. From the beginning of the 19th century, Say (1817) asserted that natural resources "cannot be multiplied or exhausted" and were therefore not concerned by economics. In 1865, Jevons alone was concerned about the depletion of coal reserves in Great Britain but he did not mention it again in the rest of his work.

Generally speaking, the neoclassical approach to production considers that natural resources, reduced to land, are perfectly substitutable for other factors, such as capital and labor[1]. Moreover, land and natural resources are assimilated to productive capital on the grounds that they are transformed and maintained by humans and, therefore, associated with capital and labor to become a resource[2]. Neoclassical analysis has thus ignored natural resources, especially growth theory, which is based solely on capital and labor. In its elementary version, Solow's (1957) canonical model considers that capital accumulation is the source of medium-term growth and that, in the long term, growth is hampered by the increase in labor power, since the marginal return on capital is decreasing.

It was with the publication of *The Limits to Growth* in 1972 that natural resources regained a place in economic analysis. When we arrived at the conclusion that further growth is impossible because of the depletion of natural resources, essentially energy, and also because of the waste and pollution it generates, the Meadows Report invited us to broaden the analysis of growth. In 1974, Solow proposed a model of optimal growth with exhaustible natural resources by introducing for the first time the concept of natural capital, which brings together stocks of energy and mineral assets (Dasgupta and Heal 1979; Solow and Stiglitz 1974). In this capital-based approach, derived from Fischer (1906), natural capital is a stock generating an income flow called rent. The latter is defined on the basis of Hotelling's (1931) approach, which speaks of scarcity rent because the dynamic nature of the depletion of mineral resources requires that operators (who want to maximize their profit) take into account the entire extraction trajectory up to the

1 On the relationships between nature and the economy in the history of economic thought, see Passet (1979) and Faucheux and Noël (1995).

2 For example, it is known that mineral deposits can be discovered and become resources but this knowledge is the product of scientific and geological research.

exhaustion of the resource and not just current production. Thus, the scarcity rent is the difference between the marginal income and the marginal cost of extraction.

The productive base is, therefore, made up of all capital (produced capital, human capital, natural capital) and it must be preserved over time to allow present and future levels of well-being to be maintained:

> The explained variable is no longer GDP, but the welfare derived from the consumption of goods and services and the services rendered directly by natural capital. The explanatory variables are no longer labor and capital alone (augmented by technical progress), but an 'inclusive' set of capital, a source not only of market goods and services, but more generally of intergenerational well-being. (Thiry and Roman 2016)

8.2.2. *Natural capital, sustainability and the "resource curse"*

Thus, economic and environmental accounting, which extends national accounting to include natural resources, proposes to measure the relative contribution of natural capital to economic growth with the scarcity rent and to assess the sustainability of economic growth with the help of macroeconomic indicators, the best known of which is true savings or adjusted net savings.

This approach was prompted by the World Bank's desire to quantify the impact of environmental constraints on long-term economic growth. In 1999, Hamilton and Clemens produced an indicator that broadens the national accounts measure of net savings by taking into account elements related to the evolution of natural and human capital stocks in the assessment of countries' wealth. The depletion of natural resources is analyzed as a process of liquidation of natural assets that contributes negatively to net income and net savings. On the contrary, spending on education contributes positively to a country's wealth by increasing total investment. For wealth to be maintained for future generations, and thus for development to be sustainable, savings must be sufficient to at least cover the decrease in total capital, with the different types of capital being assumed to be perfectly substitutable.

We find "Hartwick's rule" here, which stipulates that as the resource is depleted, the stock of physical capital must increase by an amount equal to the scarcity rent. According to Hartwick (1977), if the overall capital stock is constant or increases in order to maintain or raise welfare over time, then sustainability is ensured. Genuine savings also establish a bridge with the national accounting aggregates from which they are derived. The methodological framework of this approach, the most recent of which is presented in the United Nations System of Economic and Environmental Accounts in 2014, makes it possible to calculate true savings over a large sample of countries and can, therefore, give rise to international comparisons.

Using this indicator, Auty (2007) established that many countries with a mining economy have negative true savings, meaning that their growth depletes their natural capital stock without compensating for this degradation through sufficiently large investments in produced or human capital. According to Atkinson and Hamilton (2003), the share of rents in GDP is negatively correlated with GDP per capita growth. A 10% increase in the share of scarcity rent in GDP reduces the growth rate of GDP per capita by about 0.5%. While they confirm that negative true savings translate into lower GDP, they show that countries richly endowed with natural resources have low or negative genuine savings. This book established the empirical reality of the hypothesis of the “resource curse”. They also concluded on the need to implement economic policies aimed at a more optimal allocation of natural rent.

The natural income appears to be the key element in that it affects the economic structure and because the significance of the “resource curse” depends on its management by the states. As Ross (2012, p. 4) wrote, “geology is not destiny”; identifying the effects of natural income and the channels of transmission of the “resource curse” is indispensable if we want to understand and remedy it.

8.3. Mining activity and the “resource curse”: macroeconomic and sectoral issues

The extractive sector (mining, oil, and gas exploitation) presents specificities that can prove to be a real macroeconomic handicap. As the mining sector is mainly export-oriented, it is a significant source of foreign exchange. The latter can be used to import capital goods and equipment, thus contributing to productive capacity and, in the long run, to economic autonomy. While the extractive sector provides undeniable access to world markets, it creates little domestic added value because it does not, or only to a very limited extent, mobilize national capacities (capital and labor). Mining companies have developed a significant trading activity, particularly in intra-firm trade, which does not contribute to the creation of added value in the minerals before they are exported. Locally, mining companies mobilize fixed and long-term assets, such as equipment and infrastructure necessary for extraction, processing, and export. Therefore, they have significant needs for very specific capital goods that they import because the domestic economy does not produce them or does not produce them sufficiently. Auty (2001) also pointed out that the low share of local labor engaged in the mining sector undermines downstream linkage effects[3] and final demand linkage effects[4], thus contributing to a large enclave effect. This term refers to the notion of enclave dualism (Higgins 1956; Myint 1964), which emphasizes the fact that there is little interaction between the “modern” (extractive) sector and the “traditional” sector (the rest of the economy) and results in the development of a “modern” sector that is highly dependent on its export opportunities.

8.3.1. *Mining economics and Dutch disease*

For Giraud and Ollivier (2015), the extractive sector and the income it generates have three negative consequences on the economy:

– the development of a local non-agricultural and non-extractive private sector that is not an exporter and is more interested in benefiting from part of the income that is distributed by the state via public procurement while continuing to import what it consumes without relying on domestic production;

– an agricultural sector, mostly rural, and food-producing, which lives in quasi-autarky with few economic relationships with other sectors, since most food products are imported;

– an income that can encourage corruption, the misuse of public funds, and the generalization of behaviors that are more income-like than productive.

By favoring the extractive sector to the detriment of other sectors of the economy (industries and services) whose potential growth is nevertheless higher because with higher added value, natural resource rent can give rise to the most well-known symptom of the “resource curse” known as Dutch disease. The exploitation of mining resources usually generates high profits that lead to the development of mining activity to the detriment of other sectors. This intersectoral imbalance is accompanied by economic destructuring caused by a reallocation of resources between different sectors of the economy and by income effects (Corden and Neary 1982; Corden 1984). At the macroeconomic level, rising national income and demand lead to inflationary pressures, while capital inflows result in a trade surplus and are accompanied by an appreciation of the real exchange rate. The overvaluation of the exchange rate relative to what would otherwise be induced by the country’s performance reduces the competitiveness of other exporting firms. Their profits then

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3 This inolves the induced investment in domestic industries using the outputs of the export industry as inputs.

4 Here, we are talking about domestic investment induced by the demand for consumer goods to satisfy the needs of the labor force engaged in export industries.

decrease, which strengthens the incentives to develop the mining business. This affects the competitiveness of the non-extractive sector(s) and leads to a decline in production and employment.

8.3.2. *A long-term economic handicap*

The decline in the weight of the manufacturing sector or the absence of this sector can also be the cause of a strong amplitude in the economic cycle; in the event of a drop in the price of raw materials, the output of the manufacturing sector may be insufficient to compensate for the decline in the output of the raw materials sector. In general, economies that are highly dependent on raw materials are characterized by fluctuations in economic activity that are highly correlated with fluctuations in commodity prices. Once natural resources are depleted, the atrophy of the productive base and the overvaluation of the exchange rate will have led to a lasting stagnation of economic activity. Since the second half of the 1990s, a growing number of studies have highlighted that a strong dependence on natural resources can jeopardize long-term economic growth in certain situations and under certain conditions:

– in the presence of insufficient regulation of property rights, imperfect markets, and/or non-existent regulatory frameworks;

– depending on whether conflicts over the appropriation of rents from the exploitation of natural resources and the concentration of democratic and political power are obstacles to democracy and growth;

– in resource-based industries employing a high proportion of low-skilled labor.

The implications of this work are significant: strong institutions (with the capacity to manage sovereign funds, invest rents outside the country, and avoid corruption and embezzlement) and an education system aimed at improving human capital (allowing for the development of new, higher value-added industries) can thus prevent the negative effects of the Dutch disease (Kronenberg 2004; Papyrakis and Gerlagh 2004).

8.4. Mining income: an unstable and toxic income for States

As we have just explained, the rent is an income that is inherently unstable, since its amount depends on world commodity prices. However, these prices are characterized by high volatility, the effects of which are all the more significant as the economy is open and little diversified. We find here the model of the “small dependent economy”, which has no market power and is in fact in a vulnerable situation. The end of the Bretton Woods Agreement and the generalization of the floating exchange rate system exacerbated the instability of raw material prices; while the 1960s saw a rise in the prices of raw materials, especially extractive materials, going as far as a real "boom" in the 1970s, the following decade was the decade of the backlash. At the end of the 1990s, prices rose rapidly before stabilizing in the first decade of the 2000s and collapsing again in 2014. In real terms, however, prices remain high compared with the period 1986–2006, which remains the period of historically low real prices.

8.4.1. *Hypothesis of a deterioration in the terms of trade*

In most developing countries exporting their raw materials, the boom of the 1960s boosted production, and production continued to increase despite falling prices as declining rents had to be compensated for. It is a fact that developing countries have remained extremely dependent on their primary exports (CNUCED 2015) and the evolution of the terms of trade is a crucial determinant of their economic development (Collier and Goderis 2012). The hypothesis of a long-term deterioration in the terms of trade is often used to characterize this dependence. Elaborated by Prebisch (1950) and Singer (1950), it predicts that primary specialization can only be translated by poor long-term economic performance. In its usual sense, the Prebisch–Singer hypothesis states that increases in the prices of manufactured goods will exceed increases in the prices of primary products and thus worsen the terms of trade. This deterioration is not only due to a price gap, but also to the fact that world demand for primary products is relatively rigid to world income, whereas world demand for manufactured goods is more elastic.

Moreover, since productivity gains are more significant in the production of manufactured goods, they reinforce price differentials. As a result, commodity-exporting countries see their revenues decline in value terms, while their imports of manufactured goods become more expensive. Thus, by participating in world trade, commodity-exporting countries become poorer. Prebisch and Singer concluded that developing countries, rather than exploiting their comparative advantage in primary products, should protect themselves from international trade by establishing tariff and non-tariff barriers that would allow them to protect the development of their local industry. It is on the basis of this argument that import substitution industrialization strategies developed in most Latin American and African countries in the 1970s. As Bikoué (2010) showed, in the case of African countries, these strategies did not live up to the hopes raised. Moreover, the Prebisch–Singer hypothesis is far from being empirically verified. Long-term changes in commodity prices are characterized by structural breaks that may express dynamic regime changes (Geronimi and Taranco 2018).

> Governments are probably no better than individual agents at knowing whether a rise in commodity prices is temporary or permanent. But governments cannot dismiss the issue of volatility by leaving it to the markets. When it comes to exchange rate policy or fiscal policy, governments are forced to take a position on the question of the possible permanence of shocks. (Frankel 2012)

8.4.2. *Weight of history*

Developed in the 1930s by Innis (1930) and Mackintosh (1953), the staples thesis argues that the export of a country's raw natural resources (staples) to more developed countries affects not only the economy, but also society as a whole. Using Canada's economic history as an example, the two authors showed how the exploitation and export of raw materials (including minerals) from Canada to the United Kingdom and the British West Indies have shaped Canadian economic and political institutions. In their view, Canada's economic development is the consequence of a certain conception of international trade. Peguin and Talha (2001) explained that rent is not related to a country's resource endowment and that it exists only because resources have an exchange value. In the case of most developing countries, natural resources are exploited by foreign companies that pay part of the rent to the states. This is the result of a long history that has determined the way these countries have been inserted into the international division of labor and international trade, which has not allowed them to exploit their resources themselves and has oriented them towards a high degree of specialization in the export of their raw natural resources. It is then easy to understand, according to Magrin (2013), why mining states have seen their functioning largely conditioned and shaped by the external and unstable origin of their financial resources. The expression "neopatrimonial state" (in reference to Weber's patrimonial state) is often used to designate those states that organize the appropriation of rents from the export of products for their own benefit (or that of their agents), which destructure these economies in favor of these resources and to the detriment of non-mineral productive activities.

8.4.3. *Sharing the rent*

The major economic contribution of the extractive sector lies in corporate taxes and the share of the mining income captured by the state through the collection of royalties or other special taxes. Indeed, it is difficult and costly to raise the capital needed for mining exploration and development and a clean tax system encourages this type of investment. At the same time, the negotiation of the tax system almost always results in lower taxes collected and higher public expenditures (especially infrastructure expenditures), significantly reducing the government's share of the mining income (Clark 1999; Mansour 2014).

The empirical work carried out by Laporte and his FERDI team[5] is particularly rich in lessons. As income is difficult to define and measure, states multiply fiscal and parafiscal measures that ultimately depend only on their own objectives. It is, therefore, very delicate and complex to draw general and definitive conclusions on the question of income sharing (Laporte and de Quatrebarbes 2015). By extension, it is difficult to disentangle what, in the appropriation of the value created in global production chains, corresponds to the land rent available to landowners, the mining or oil rent, and the profits that arise from the search for and exploitation of resources and their transport and distribution (Aknin and Serfati 2008). Moreover, the amount received by states depends on the control they exercise, the position of global oil groups, and the more or less recent exploitation of reserves. There is also evidence that reforms of mining codes in favor of foreign industrial and financial groups, which resulted from World Bank recommendations (1992), have increased the share of value captured by global groups in several Sub-Saharan African countries (CNUCED 2005). In fact, in the recent period, privatization of domestic firms combined with tax incentives for foreign investment have increased the relative share of income captured by foreign groups (Campbell 2004).

8.4.4. *Institutional weaknesses*

While some states – such as the Democratic Republic of Congo – are, as Pourtier (2007) wrote, victims of the "mining syndrome" by organizing the plundering of the resources whose fruits they share according to a neopatrimonial logic, others have been more redistributive, such as Gabon before the 1990s. Nevertheless, in a context of liberalization of the mining sector, fiscal pressure has remained low, averaging 10 percent of GDP in Africa (Magrin 2013). Indeed, governments systematically favor taxation on mining revenues to the detriment of other sources of tax revenue, so that the structure of tax revenues reflects neither the economic structure nor the structure of household incomes[6]. As a result, the budget deficit is often persistent, with unproductive expenditures aimed at maintaining social peace multiplying in a

5 All of the work on mining taxation is presented at: www.ferdi.fr/fr/programme-projet/fiscalité-minière.

6 See the work of Ross (2012) on oil countries.

context of growing inequality (Carbonnier 2007, p. 85). According to Di John (2002), developing countries with natural resources are more prone to violence; natural resources generate higher levels of corruption and lower growth rates. Governments rely on “unearned resources”, and, therefore, do not seek to develop a contractual framework of reciprocal obligations upon which to develop a democratic tax system. In sum, they are prone to poor governance (Moore 2004). This institutional weakness may take the form of a lack of democracy or even an authoritarian regime based on clientelism (Collier 2005). The existence of rents has allowed authoritarian governments to gain and/or maintain power over the last 30 years because they have the ability to hide a large part of revenues while buying social peace through, among other things, advantageous tax policies, large public subsidies and social programs, and widespread corruption.

Nevertheless, Ross (2012) and Karl (1997) pointed out that not all oil or mining countries were authoritarian or dictatorial regimes, even if the correlation between authoritarian regimes and mining or oil economies was strong. Furthermore, Ross (2012) found that economic growth based on oil or mining resources limits economic and political opportunities for women, as public transfers to households remove the economic incentive for women to work and “Dutch disease”, by hindering the development of non-oil sectors, reduces employment opportunities. In this context, women have little presence in the economy and, therefore, have very little political weight, particularly in North Africa and the Middle East.

8.4.5. *Armed civil conflicts*

Angola was in a state of civil war from its independence in 1975 to 2002. This conflict, which resulted in 500,000 deaths, pitted the socialist Popular Movement for the Liberation of Angola (MPLA) against the anti-colonialist movement União Nacional para a Independência Total de Angola (UNITA) and had its roots in the Cold War. Nevertheless, the end of the Cold War did not mark the end of hostilities, because in the country’s first multi-party elections in 1982, UNITA refused to recognize the electoral victory of the MPLA, plunging the country back into armed conflict. Losing its main international support, UNITA found a way to finance its military effort through diamonds. In the early 1980s, UNITA established its operational bases in the north of the country, a region rich in diamonds, receiving revenues from the extraction and sale of the stones to the tune of \$3–4 billion over the period 1992–2000. The diamond trade thus became one of the major levers of UNITA’s political leadership, which succeeded in obtaining the Ministry of Mines in 1994, at the time of the Lusaka peace protocol. At the same time, the government's MPLA made extensive use of oil revenues to finance the war. The Angolan civil war is often seen as the war for resources, as the course of the conflict has followed fluctuations in the relative price of oil to diamonds.

In the 2000s, a group of economists gathered around Collier, the then Chief Economist of the World Bank, and, using statistical data for the period 1965–1999, observed that of the 161 countries in the sample, 47 had experienced civil war. Table 8.1 provides some examples of these conflicts. This study identifies five factors that contribute to the outbreak of armed civil conflict. These statistical factors are, in decreasing order of importance; a country's dependence on raw material exports[7], the geographical dispersion of the population, the past occurrence of civil conflicts and the size of diasporas, a low level of schooling accompanied by high population growth and a fall in per capita income, and finally the ethnic and religious composition of the population[8].

This approach, which is intended to renew the economic analysis of civil wars, argues that these conflicts should not be examined as a manifestation of recrimination against an existing regime but as the "ultimate manifestation of organized crime" (Collier 2000, p. 3). Civil wars are thus the result of "large-scale predation" (Collier 2000, p. 3) on economic and income-generating activities in order to finance a criminal rebellion in its motives. The studies by Collier and his colleagues at the World Bank (Collier 2000; Collier and Hoeffler 2001) all emphasize the importance of the predation motive in triggering civil conflict, as this greed-driven predation is to be distinguished from peaceful protest based on grievance. Collier pointed out that extractive activities are the most vulnerable to this predation because they mobilize fixed and long-term assets such as the equipment and infrastructure necessary for extraction, processing, and export. Civil wars are thus explained by the selfish and calculating behavior of agents. In the final analysis, conflicts are caused by the misallocation of property rights (Garfinkel *et al.* 2006). Since greed may be enough to trigger civil war, the way to prevent it lies in removing the object of predation. Paul Collier therefore advocated reducing dependence on raw materials by diversifying economic activities, thus reducing the burden of rent.

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7 This is a nonlinear relationship that resembles an inverted U-curve. However, the validity of this relationship and its theoretical foundations are debated. See Humphreys (2003) and Aknin and Serfati (2005).

8 Paul Collier does not consider the criterion of income inequality to be relevant.

We can only note that the situation does not encourage optimism about the prospects for developing oil and mining countries. The existence of the "resource curse" is the subject of a broad consensus in the economic literature (Al Mamun *et al.* 2017). It can affect the economy as a whole by making it highly dependent on "toxic" rents that fuel opacity, corruption, and even some armed civil conflicts. How, then, can a more sustainable development of mining or oil economies be envisioned? How can we protect ourselves from the "resource curse"?

Country	Duration	Resources
Angola	1975–2002	Diamonds
Democratic Republic of Congo	1996–1998, 1998–2003, 2003–2008	Copper, coltan, diamonds, gold, cobalt, tin
Liberia	1989–2003	Diamonds, iron, gold
Sierra Leone	1991–2000	Diamonds

Table 8.1. *Some examples of civil wars fueled by mining resources in Africa (source: UNEP (2009, p. 11))*

8.5. Is the "resource curse" inevitable?

Botswana (Box 8.1) is often presented as a country that has been able to escape the "resource curse", but it remains an exception.

Botswana, a former British protectorate, gained independence in 1966. That same year, it was one of the poorest states in the world with a per capita income of USD 90 per year. As the main source of cheap labor for South Africa, Botswana's destiny was transformed following the successive discovery of three diamond mines: Orapa in 1967, Letlhakane in 1973, and Jwaneng, commonly referred to as "the prince of mines", one of the ten richest mines in the world.

The second largest diamond producer in the world, Botswana also contains copper, nickel, soda ash, potash, salt, coal, iron, and silver. Some economists explain the success emanating from diamond mining by the political stability and prudent management of the mines. Existing since 1971, the partnership between Botswana and De Beers had provided 85% of diamond revenues to the government and 15% to the De Beers conglomerate by 2017.

From 1974 to 1994, diamond exports grew by an average of 30% per year in value terms, while the mining sector accounted for almost 40% of gross domestic product (GDP) from 1984 to 1994. Equally active in 2017, the diamond industry produced 20 million carats, while its annual production averaged 10.6 million carats, or 2,100 kilos. Moreover, the difference between the 1960 GDP of just over USD 30 million and the 2017 GDP of USD 17 billion is a sign of significant economic progress.

Using data from Botswana's National Statistics Agency, it is interesting to note that the diamond sector provides nearly 89% of the country's export revenues, equivalent to 36% of GDP. In recent years, 2016 appears to have been a more favorable year for diamond production with an increase of 0.3% compared to a decrease in production of 15.6% the previous year. This can be explained by, among other things, the prices of rough and polished diamonds, which rose by 13.2% and 2.1% respectively in 2016.

The reinvestment of a portion of diamond revenues in health and education allowed more than 80% of the population to have access to a health care facility located less than 15 kilometers from their homes as early as 1985. There was also a significant increase in elementary school enrollment between 1970 (59.4%) and 2014 (105.4%). In 2017, Botswana continues to prioritize education, spending 9.6% of GDP on it. With more than one-third of GDP coming from the diamond industry, the economy is vulnerable to the end of the diamond industry, which is expected in less than 15 years. In recent decades, there has been a decline in economic activity in several sectors. At the time of independence, agriculture accounted for more than 40% of GDP, and averaged only 2.2% of GDP in the decade 2000. As for livestock farming, which has become marginal, it accounts for 4% of GDP.

Despite the good health of the current diamond industry and the creation of new jobs generated by the establishment of approximately 20 processing plants, including the most recent one in Garabone in 2016, the unemployment rate in 2017 remains high (17.7%). Although classified as the least corrupt country in Africa, Botswana also has one of the widest disparities in the world. To address the problem, several options are being considered, such as creating a skilled labor force and reforming Botswana's tax revenues. The International Monetary Fund emphasizes the need to accelerate these reforms.

Box 8.1. *Botswana's diamonds (Exama 2018)*

One of the sources of the "resource curse" lies in the great instability of raw material prices. While nothing can change these initial conditions, solutions are possible to mitigate their effects. They can be implemented by states as well as by international institutions and even mining companies:

– limiting oil revenues "at source" by reducing the rate of extraction, developing barter agreements, and distributing mining revenues directly through specialized funds;

– privatizing resources;

– implementing stabilization mechanisms;

– lifting the secrecy on revenues, learning how to manage these revenues effectively with more transparency, and an active fight against corruption.

A series of schemes have attempted to reduce the impact of price instability on producing countries. Abandoned during the period of structural adjustment, they were replaced in the 2000s by actions oriented towards transparency and international cooperation. Under pressure from donors and non-governmental organizations, several measures were then proposed to fight against the “resource curse” and commit countries to a less unsustainable development path.

8.5.1. *(In)effective public policies*

At the time of independence, most developing countries intervened in the markets by implementing fiscal and budgetary policies to stabilize prices. The aim was to support both development and international integration. Policies to control the prices of certain standard commodities date back to colonization. In the 1970s, the argument of deterioration in the terms of trade has prompted UNCTAD to develop and implement instability management tools[9]. This stabilization[10], particularly in sub-Saharan Africa, has been ensured by public (or para-public) bodies: cereal and food production boards on the domestic market and marketing boards for products intended for export. These boards had three objectives: to control the collection and disposal of products on the markets, to guarantee purchases and the stability of prices to producers, and, finally, to manage the reserves necessary for stabilization that had to be mobilized for public investment and debt repayment. Marketing boards soon proved to be inefficient and condemned by the World Bank and the IMF; they attracted rent-seeking in the form of a fiscal surplus appropriated by the government or squandered on lavish spending and corruption (Helleiner 1964; Berg 1981), or encouraged market-dominant practices by large producer states (Newbery 1984, 1989). They did not survive structural adjustment policies. Ross (2012), in an extensive review of recent work, revealed that assumptions about rentier behavior and the failure of states to manage resources efficiently are not systematically validated. This is, firstly, because these studies focus on the very particular period that ran from the 1970s to the 1990s and, secondly, because implementing appropriate fiscal policies to deal with the volatility of oil revenues is extremely difficult politically and economically, even for countries with “good” institutions.

9 On the links between these instabilities and development trajectories in sub-Saharan Africa, see Hugon and Geronimi (1995).

10 Calabria (1995) presented the regimes of regulation of commodity markets.

8.5.2. *Promoting traceability and transparency*

Initially, these initiatives focused primarily on resources related to armed conflict. In December 2000, the UN General Assembly passed a resolution that led in November 2002 to the creation of a certification scheme, known as the "Kimberley Process", designed to regulate the diamond trade. Following a series of investigations conducted between 2000 and 2003 by the UN that highlighted the responsibility of companies in the wars in the Great Lakes region, the OECD also took a series of initiatives aimed at promoting a responsible spirit on the part of companies in mineral-related conflicts. Companies, whose culpable involvement in conflicts is not mentioned, should have as the "triple bottom line principles of beneficence, social responsibility and good governance" (OECD 2004). The OECD Declaration on "Multinational Enterprises and Investment", an important OECD document, includes a passage entitled "Guidelines for Multinational Enterprises" devoted to these issues. Other initiatives have been taken such as the Voluntary Principles on Security and Human Rights and the UN Global Compact Dialogue on Private Actors in Conflict Zones. However, what is possible with diamonds is not possible with most raw materials, which are not easily traceable from the place of extraction to the point of sale due to the very functioning of the markets. Labeling products, particularly those of the mineral industry, would nevertheless make it possible should make progress by giving a more significant role to consumers in a context where a limited number of producers account for 80% of world production; but it would require the active support of distributors and traders. Ross (2012) also argued that the buyer countries to take responsibility, since oil and gas resources are intended to meet a demand that comes essentially from Northern countries and the industrial and financial groups that are often at the heart of their extraction and processing come from Northern countries and more recently from China. He proposed that buyers (countries and firms) should turn away from oil extracted in a dictatorship or a corrupt state.

Global Witness was one of the first NGOs to promote transparency in the management of natural resource revenues. In its 1999 report, "A Crude Awakening", widespread corruption in Angola and its deleterious effects on economic development were widely denounced. This report was the basis of the Publish What You Pay (PWYP) campaign in 2002. In the same year, the Extractive Industries Transparency Initiative (EITI) was launched by Tony Blair at the World Summit on Sustainable Development in Johannesburg. PWYP calls itself "the leading global network of grassroots civil society organizations working for transparency and accountability in the oil, gas and mining industries"[11]. It brings together more than 700 member

11 See www.publishwhatyoupay.org.

organizations around the world and beckons governments and companies to make public what they receive and how much they pay for oil, gas, and minerals. These revenues should include royalties collected on the value of production, bonuses paid on signing of exploitation contracts, and corporate income tax. This information should be made available to civil society, expressed in local language and currency. The objective is to influence the practices of extractive industries and governments by taking up the argument that “clientelist practices can be limited by institutions that hold politicians accountable” (Collier and Hoeffler 2005, p. 108).

The EITI[12] is an international organization that aims to develop a standard to assess the extent to which a country’s oil, gas, and mineral resource revenues are managed in a transparent manner. Companies participating in this initiative are required to publish all payments made to governments in connection with their extractive activities. Governments must also publish payments received from private companies and state-owned enterprises. In addition, the EITI standard requires that sub-national payments, transit payments, and the commercial activities of state-owned companies be published. For each EITI member country, all of this information is under the guidance of a multi-stakeholder group with representation from business, senior government officials, and civil society. Information on the work of these national multi-stakeholder groups is publicly available. Created in 2007 by the United Nations, the International Resource Panel brings together independent scientific experts to help countries use their natural resources with a sustainable development perspective. In its latest report on the governance of mineral resources (GIER 2019), it lists nearly 90 voluntary approaches that have been implemented either by companies or by NGOs, forming a set of good practices and frameworks for conducting mining activities.

These initiatives have led to progress, but most of them only focus on one aspect of sustainable development and/or only address a specific problem (corruption, conflicts, etc.). For example, the EITI, by focusing more on government revenues than on expenditures, does not really measure corruption and, therefore, has a limited scope, especially since economic specialization is not questioned (Kolstad and Wiig 2009). Moreover, and this is where the major weaknesses of these systems lie, they are strictly voluntary and are not legally binding (Carbonnier 2007).

8.5.3. *Necessary governance of mining industries*

As these few examples point out, participation and democracy have been invoked jointly to combat the destructive effects of the mid-term industry. However,

12 See https://eiti.org.

transparency alone is not enough to ensure sustainable mining and preservation from the "resource curse". Governance of extractive activities is a necessity that can be achieved, in particular, through the control of transnational mining companies and international financing agencies. The authorities of some of the countries where mining companies are listed on the stock exchange (Australia, Canada, South Africa) have developed an obligation to report on prospecting, exploration, and mining project design activities, under the nominative signature of experts who are members of recognized professional associations[13].

The NGO Global Reporting Initiative has worked with the industry to develop guidelines for reporting the sustainable development performance of mining and metallurgical companies. There are specific guidelines for the mining and metallurgical industry, with 104 indicators[14]. In 2001, the Mining, Minerals and Sustainable Development project[15] gave birth to the International Council on Mining and Metals, which has 27 members representing a significant share of metal production, but only a small share of industrial mineral production[16]. However, these efforts are often hampered by the economic and institutional situation in resource-rich countries, especially if these countries are "developing". The political powers are often embedded in a long history of corruption and institutional weakness that makes it very difficult to change course, as indicated in the book by Acemoglu and Robinson (2012), which has led to a broader understanding of the persistence of developmental "traps", without addressing the challenge of "the absence of strategies to change political cultures" (Cartier-Bresson 2018, p. 97). For this reason:

> The actors of international cooperation would be better advised to support endogenous processes of institutional transformation. […] The strengthening of counter-powers requires support for the media, the judiciary, and the organizations of civil society, which must be able to exert effective pressure for greater transparency and better allocation of revenues. (Carbonnier 2013, p. 47)

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13 The NI 43-101 (Canada), JORC (Australia), SAMREC (South Africa) and PERC (Europe) codes. The NI 43-101 code is the only one requiring that mining companies make public the exploration and mining development reports (up to and including feasibility) of companies listed on a Canadian stock exchange.

14 See www.globalreporting.org.

15 See www.iied.org/mining-minerals-sustainable-development-mmsd.

16 See www.icmm.com/.

8.6. Conclusion

At the end of this chapter, it appears that abundant mineral and oil resources can be a serious handicap to the economic development of countries that are endowed with them. By reintroducing the role of natural resources in the theoretical analysis of growth, through the rise of clear advances in statistics and in economics and environmental accounting, a great deal of work has made it possible to put exhaustible natural resources back at the center of concerns related to the sustainability of economies and to produce indicators, imperfect though they may be, that are nevertheless useful for identifying and assessing the extent of the “resource curse”.

The abundance of raw materials is, therefore, no longer a vector of development; it is quite the contrary: Dutch disease, economic addiction to rent, institutional dysfunctions, corruption, civil wars, and so on. The picture is very bleak and the proposed solutions may seem very naïve in view of the difficulty of states engaging in more sustainable development while remaining dependent on their natural resources. Despite some encouraging initiatives in favor of transparency and the fight against rent-seeking, the endemic weakness of institutions is without a doubt their main pitfall. How, though, can good institutions be built on the basis of low and unstable tax revenues? Moreover, the desire to moralize extractive activities may conflict with the national sovereignty of producing countries, the growing needs of importing countries in the North, and geostrategic issues. The case of the management of oil revenues by one of the world’s poorest countries, Chad, is edifying from this point of view.

Chad’s recently exploited oil resources were the subject in 1999 of a law adopted by the parliament, Law 001, under the insistent pressure of leaseholders[17], to ensure transparency in the management of petrodollars and to allow the local population[18] to benefit from them. It established the distribution of oil revenues, with 10% deposited in an escrow account for future generations, 15% for the general budget, 5% for the local communities of the region, etc. The project focuses on the Doba oilfield and 70% on the priority sectors (education, health, water, transportation, rural development, and the environment). The law was followed in 2003 and 2004 by implementing decrees, including the decree establishing the *Collège de Contrôle et de Surveillance des Revenus Pétroliers* (CCSRP). Barely five years after its promulgation and two years after its entry into force, the law was amended in December 2005. The new bill eliminates the fund for future generations and increases from 15 to 30% the share of revenues paid, without any control, to the Chadian public treasury. It also adds justice and security to the priority sectors.

17 Notably the World Bank, in exchange for financing the Chad–Cameroon pipeline.

18 See the very detailed presentation and analysis of Massuyeau and Dorbeau-Falchier (2003).

Finally, it changes the composition of the college – no longer truly “independent” – responsible for approving investments made with the oil windfall.

President Idriss Deby responded to the many criticisms raised by this amendment by putting forward the argument of national sovereignty. In an interview on RFI, he even stated, in essence, that Chad was free to dispose of its oil money as it wished, even if it involved the purchase of arms to defend the integrity of its territory. On January 6 2006, World Bank President Paul Wolfowitz responded to N’Djamena’s violation of his commitments by announcing the termination of all financing programs in Chad, freezing $124 million in loans. Through its Managing Director, the International Monetary Fund, which was supporting Chad through a $36.4 million Poverty Reduction and Growth Facility (PRGF)[19], declared its support for the World Bank’s action. After the first failure of a World Bank mission on April 7, an interim agreement was finally signed on April 26 between the two protagonists[20]. On July 15 2006, Chad made a final commitment to adopt, before the end of the year, a new budget law stipulating that 70% of its oil revenues would be allocated to priority programs to fight poverty and to contribute to growth through the creation of a stabilization fund. This agreement put an end to six months of disputes between Chad and the World Bank and the freezing of credits to the country. Could the reasons for this compromise lie in the fear of seeing Chadian power fall into the hands of pro-Khartoum rebels who are strongly hostile to Western powers[21], particularly the United States, in a context where the major importing countries are seeking to diversify their sources of supply at all costs?

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19 The PRGF is the window through which the IMF provides low-interest loans to low-income countries. PRGF-supported programs are based on comprehensive, country-led poverty reduction strategies.

20 See Simonet (2006) for a discussion of developments in the law and the relationship between the World Bank and the Chadian government.

21 In April 2006, the Chadian capital was attacked by rebels and the country almost fell into civil war.

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9

Industrial and Artisanal Exploitation of Natural Resources: Impacts on Development

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Great wastes arise from the suddenness and unexpectedness of mineral discoveries, leading to wild rushes, immensely wasteful socially, to get hold of valuable property.

Harold Hotelling (1931, p. 144)

9.1. Introduction

Fifty-one countries and their 1.4 billion inhabitants are considered rich in natural resources by the International Monetary Fund based on the composition of their exports and tax revenues over the period of 2006–2010 (Venables 2016)[1]. The endowment of natural resources is a *de facto* geological inequality between rich and

1 For the IMF, a country is resource-rich if at least 20% of its exports, or 20% of its tax revenues, come from non-renewable natural resources.

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poor areas in terms of resources. What are the links between this geological inequality and the socio-economic development of countries or regions endowed with natural resources?

The idea that a resource-rich land could impoverish its inhabitants instead of enriching them is undoubtedly counterintuitive. Yet, during the 1980s and 1990s, resource-rich developing countries grew less rapidly than the other developing countries. During the 2000s, marked by a high phase in the resource price supercycle, resource-rich developing countries grew slightly faster than others, although median per capita growth was the same in both groups of countries (Venables 2016). There is, therefore, a large literature on the so-called "resource curse" (Auty 1990), although the latest studies point rather to a resource "blessing" (Smith 2015).

Behind these figures are heterogeneous experiences. For example, Zambia, the largest copper exporter in Africa, saw its poverty rate increase from 42% to 57.5% between 1998 and 2015 (share of the population living on less than $1.90 a day, (World Bank 2019). Many other countries, such as Nigeria, the Democratic Republic of Congo, Venezuela, and Sudan, do not seem to have benefited from the exploitation of their resources. On the contrary, this exploitation seems to have fueled political instability and corruption to the detriment of economic growth.

On the other hand, Botswana is an example of success in natural resource management. The country has been able to turn the abundance of diamonds into an economic blessing for its entire population. Not only did the country experience the world's fastest growth in gross domestic product from 1965 to 1990, but also the policies implemented have made it possible for the population to benefit from this economic growth. Between 1970 and 1990, the infant mortality rate halved and the school enrolment rate doubled (Tyrell *et al.* 2001). Countries such as Chile and Norway are also commonly considered as other examples of success.

Here, by natural resources we mean the exploitation of non-renewable and non-perishable natural resources by humans. Although this chapter looks primarily at studies that are focused on mineral resources, such as gold, copper, diamonds, and so on, the definition also includes hydrocarbons and coal. This chapter leaves aside the question of renewable resources (such as forests and water). Renewable resources raise fundamentally different questions for economic analysis, especially since the intensity of their exploitation has a direct impact on their renewability. Conversely, non-renewable natural resources rather raise the question of their management during the exploitation phase and of their depletion potential.

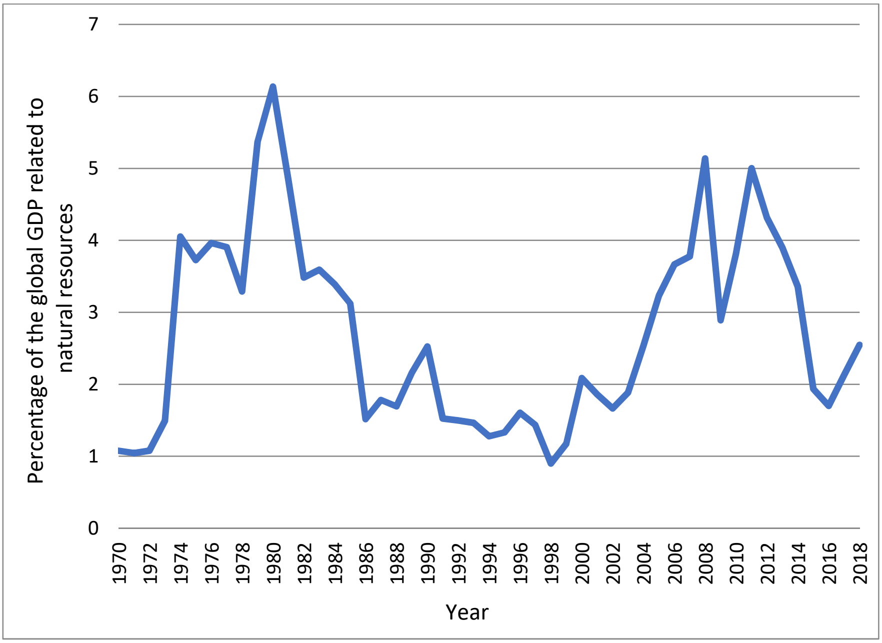

Figure 9.1. *Share of annual rents from natural resources in global GDP*

COMMENT ON FIGURE 9.1. – *Here, total rents from natural resources are the sum of rents from oil, natural gas, coal, minerals, and forests. Estimates of resource rents are the difference between the price of a commodity and its average cost of production. This is done by estimating the world price of specific commodity units and subtracting estimates of the average unit costs of extraction or harvesting (including a normal return on capital). These unit rents are then multiplied by the physical quantities that countries extract or harvest to determine the rents for each product expressed as a percentage of gross domestic product (GDP) (source: World Bank).*

Three observations make an analysis of the socio-economic consequences of the exploitation of natural resources crucial. First of all, the exploitation of natural resources represents a considerable financial windfall. The magnitude of this financial windfall is shown in Figure 9.1; natural resource rents have accounted for 1 to 6% of the wealth produced annually since 1970 worldwide. For resource-rich countries, it is not uncommon for them to account for more than 50% of their exports (Table 9.1). Second, resource-rich countries are primarily concentrated in the southern hemisphere. By 2030, nearly two-thirds of the world population living in extreme poverty is expected to be in resource-rich countries in Sub-Saharan Africa (Cust and Zeufack forthcoming). This chapter, therefore, pays particular attention to the issue of natural resource exploitation in developing countries. Finally, a supercycle affecting the price of resources, which began in the 2000s, has resulted in an unprecedented increase in the number of new mining sites being opened. Focusing on mining resources in Africa alone, a maximum of twelve mines per year opened between 1980 and 2004. In comparison, there were about 60 industrial mine openings on the continent in 2013 (Chuhan-Pole *et al.* 2017).

Country	Type of natural resource	GNP per capita[a]	Share of natural resources in exports[b]	Share of natural resources in tax revenue
DRC Congo	Minerals and oil	180	94	30
Liberia	Gold and iron	210	–	16
Niger	Uranium	360	–	–
Guinea	Minerals	390	93	23
Mali	Gold	600	75	13
Chad	Oil	710	89	67
Mauritania	Iron	1,000	24	22
Lao PDR	Copper and gold	1,010	57	19
Zambia	Copper	1,070	72	4
Vietnam	Oil	1,160	14	22
Yemen	Oil	1,160	82	68
Nigeria	Oil	1,170	97	76
Cameroon	Oil	1,200	47	27
Papua N. Guinea	Oil, copper, and gold	1,300	77	21
Sudan	Oil	1,300	97	55
Uzbekistan	Gold and gas	1,300	–	–
Ivory Coast	Gold and gas	1,650	–	–

Country	Type of natural resource	GNP per capita	Share of natural resources in exports	Share of natural resources in tax revenue
Bolivia	Gas	1,810	74	32
Mongolia	Copper	1,870	81	29
Rep. of Congo	Oil	2 240	90	82
Iraq	Oil	2,380	99	84
Indonesia	Oil	2,500	10	23
Timor Leste	Oil	2,730	99	–
Syria	Oil	2,750	36	25
French Guiana	Gold and bauxite	2,900	42	27
Turkmenistan	Oil	3,790	91	54
Angola	Oil	3,960	95	78
Gabon	Oil	7,680	83	60
Equatorial Guinea	Oil	13,720	99	91

[a] US$ 2001; [b] averages over the period 2006–2020.

Table 9.1. *Low- and middle-income countries dependent on natural resources (source: translated from Venables (2016))*

The presence of natural resources is an inequality not only between countries but also between regions within countries. A complete analysis of the phenomenon requires that both types of inequality be taken into account. This chapter, therefore, proposes to begin with a presentation of the literature that analyzes the macroeconomic link, at the country level, between resources and development, before moving on to the most recent advances in the economic literature, which focus on the local impacts of resource exploitation, particularly mining. The increasing availability of detailed information on the socio-economic conditions of households, coupled with their geo-localization, allows for an increasingly detailed analysis of the local impact of natural resources. These data also allow economic analysis to shed light on ancient phenomena that it was unable to identify until recently, such as the issue of artisanal mining, the second largest source of income in rural areas of Sub-Saharan Africa, to which the end of this chapter is dedicated.

9.2. Impacts of industrial extraction

9.2.1. *Presentation of industrial extraction*

Industrial mining is a worldwide activity that affects almost every continent. The largest producers are China, the United States, and Russia. However, there is also an increase in industrial mining production in some African countries. Indeed, most resource-rich African countries have turned to developing their mining sectors to achieve sustained economic growth. These sectors underwent reforms in the late 1990s (in this case, the development of new mining codes) to attract foreign direct investment to boost mining[2]. As a result, several foreign mining companies have established operations in Africa. The largest, such as BHP Billiton and Anglo American, are present in South Africa for the exploitation of several minerals, including iron, coal, and precious metals. Anglo American is also present in Botswana and is the largest shareholder in the diamond mining company De Beers. In Central Africa, the Democratic Republic of Congo holds the world's largest cobalt reserves (US Geological Survey 2019). It is also home to the largest number of foreign mining companies, with more than 20 active foreign mining companies (KPMG 2014). Mining in West Africa is dominated by gold production and is mainly conducted by Canadian mining companies, such as Asanko Gold in Ghana and IAMGOLD in Mali and Burkina Faso. East Africa is not to be outdone, where Canadian mining companies such as Barrick Gold in Tanzania are active in gold mining. All of these foreign mining companies operating in these countries are engaged in large-scale exploration, research, and mineral production activities[3]. With the increase in resource prices since the 2000s, the exploration and production of several deposits in Africa (excluding South Africa) by mining companies has led to a rapid increase in production. The most striking example is gold mining. Its production increased from 171 tons in 2000 to nearly 558 tons in 2017. This led to an increase of more than 200%.

Industrial mining activity first requires the acquisition of mining permits and the consent of chiefs of land or customary notables in countries where their authority over land is recognized by the state (such as Botswana, Burkina Faso, and Zambia). It also results in settlement on land, which sometimes requires the relocation of a previous activity (generally agricultural or sometimes artisanal mining). In addition, industrial activity in Africa generally takes the form of giant open-pit excavations,

2 These reforms have been promoted by the World Bank with the aim of contributing to poverty reduction through the expansion of the mining sector (Campbell 2004). The main objective was to implement fiscal and legal provisions to improve the business climate.

3 Alongside these large multinational companies are several dozen small companies qualified as junior.

which create social and environmental challenges for the neighboring states and communities. Another key element of industrial exploitation is the participation of states in the capital of mining companies. This varies from 5% in the Democratic Republic of Congo to 20% in Ghana and Mali (Laporte *et al.* 2016). In addition, they are granted tax incentives to facilitate their installations and investments[4].

The abundant literature on the impacts of industrial resources exploitation can be divided into two broad categories. The first concerns studies carried out at a national level or involving several countries, the second refers to studies on the heterogeneous effects of the presence of resources within countries[5].

9.2.2. *Macroeconomic impact of industrial extraction*

Natural resources can contribute to the development of countries by being an engine of economic growth. However, case studies of Bolivia, Nigeria, and Venezuela give cause for some pessimism. Moving on to an analysis of all resource-rich countries, a debate persists on the possibility of natural resources enabling economic miracles such as that of Botswana (Sachs and Warner 1995, 2001; Smith 2015). What mechanisms can help us understand this difficulty in transforming resource exploitation into a source of development? Theoretical explanations of the resource curse can be grouped into three broad categories (suggested by Aragon *et al.* (2015)).

First, the "Dutch disease": this is the idea that a boom in the extractive industries can lead to the crowding out of other industries, particularly those in the manufacturing sector, as a result of an increase in the prices of non-tradables relative to tradables (Corden and Neary 1982; Corden 1984). This mechanism, which seems to be empirically verified primarily in OECD countries (Harding *et al.* 2020), is not intrinsically negative. However, it can have an impact on growth. The economic

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4 For example, in Burkina Faso, from 2003 to 2014, foreign mining companies benefited from favorable taxation with exemptions of up to 1.1% of the GDP. While the income tax rate applied to mining companies was 33% in Ghana, 25% in Mali, and 35% in Niger, it was 17.5% in Burkina Faso (ITIE 2014). However, following pressure from civil society and local populations, the government promulgated a new Mining Code in 2015 that abolishes certain exemptions and also requires mining companies to contribute to local development through the creation of a fund dedicated to local communities.

5 The article by Gamu *et al.* (2015) is an excellent review of these different studies. In addition, they analyzed the various channels through which mining affects poverty and inequality. In a similar vein, Cust and Poelhekke (2015) survey the literature examining the local and regional impacts of natural resource extraction.

growth will be more likely to be sustained if the tradable goods sector, crowded out by the extractive industries, is more conducive to sustaining growth. This is the case if the tradable goods sector benefits from agglomeration effects and other positive externalities, such as human capital externalities (Torvik 2001), or if the tradable goods sector shows increasing returns to scale (Murphy *et al.* 1989).

Second is the question of price volatility. Dependence on the extractive sector makes an economy vulnerable to changes in resource prices. Natural resource prices have been increasingly volatile over the last few decades. It has been shown that resource price volatility is likely to contribute to macroeconomic fluctuations and the uncertainty of foreign investors (van der Ploeg and Poelhekke 2009). For countries whose revenues depend heavily on resource exploitation, such volatility poses problems in forecasting long-term investment (Table 9.1 provides an overview, noting, for example, that 76% of Nigerian government revenues are derived from oil).

Third is the notion of a so-called “political” curse of natural resources. This line of literature, which is in full expansion, is interested in the institutional mechanisms that can help us understand the curse of natural resources by highlighting, for example, the risk of rent-seeking phenomena (Mehlum *et al.* 2006), corruption (Brollo *et al.* 2013), and even conflict (Collier and Hoeffler 2005). The heavy dependence of budget revenues on natural resources, as opposed to taxation of citizens, weakens, for example, governments’ incentives to establish or strengthen quality institutions. In addition, some studies argue that abundant mineral resources are linked to over-indebtedness, as resource-rich states use their natural resources as collateral for their debts on international markets (Manzano and Rigobon 2001; Sarr *et al.* 2011). Another institutional aspect of the resource curse is the issue of education. Some authors argue that investment in human capital (represented by the share of education expenditure in GDP or by school enrolment rates) is negatively correlated with mineral abundance (given that extractive industries often use less human capital: see Birdsall *et al.* (2001), Gylfason (2001), and Papyrakis and Gerlagh (2004)).

The importance of institutions in countering a possible natural resource curse, and the risk that resource abundance perverts institutions, is both the mechanism that has emerged most recently in the literature and the one that has received the most empirical support (with abundant studies since the pioneering papers of Robinson *et al.* (2006), Andersen and Aslaksen (2008), Brunnschweiler and Bulte (2008), and Lei and Michaels (2014)). It can be noted that this problem seems to be exacerbated when the resources are easily appropriable (such as oil, minerals, and diamonds (Boschini *et al.* 2007)).

9.2.3. *Local impact of industrial extraction*

Beyond the question of the macroeconomic impact of natural resources, what consequences do they have for local populations? This question, which places human development at the heart of the analysis, also has the advantage of turning to high quality microeconomic data that allows for a detailed study of causal links.

According to Aragon *et al.* (2015), we can consider four main families of mechanisms linking natural resources and local development: (1) a direct transformation of the local economy through a transformation of local markets (for labor and goods and services) and a local multiplier effect; (2) attempts at fostering a positive local impact of mines through corporate social responsibility initiatives or local content queries; (3) negative externalities such as pollution; and (4) a public expenditure channel if resource taxes are collected or reallocated preferentially to the producing areas. In the remainder of this section, we discuss each of these aspects.

First of all, the production of resources may correspond to a specialization of the local economy in extractive activity to the detriment of other sectors (commercial, agricultural, and industrial). Another approach proposes to consider that the exploitation of resources corresponds to a shock on the local demand for goods and services.

Most empirical studies conclude that there are positive economic spillovers from industrial exploitation at the local level[6]. Work that positively correlates industrial mining with poverty reduction argues that mining generates significant revenues that contribute to increased national income. These revenues can also be reinvested in social sectors such as health and education and in the construction of large-scale infrastructure, which in turn creates jobs (see Weber-Fahr *et al.* (2001), Davis (2009), and Jensen *et al.* (2012) to name but a few). Several other studies come to the same conclusion. For example, using the multiplier decomposition approach based on a social accounting matrix, Ge and Lei (2013) revealed that mining development has had significant and positive impacts on relatively wealthy households in China and has also contributed to poverty reduction. In Peru, Aragon and Rud (2013) observed that gold mining at the Yanacocha mine increased local real incomes despite rising local prices for non-tradables. Extending the analysis to all districts in Peru, Loayza and Rigolini (2016) found that mining activity led to a 9% increase in household spending and a 2.6 percentage point decrease in poverty in the districts where

6 These studies measure mining activity in various ways, such as a binary variable indicating the existence of activity, or a continuous variable indicating the quantities of minerals extracted or their value.

mining takes place. However, this positive effect is mitigated by an increase in inequality. More recently, the Santos study (2018) indicated that industrial gold mining generated employment in Colombia and contributed to local development.

In Africa, Zabsonré *et al.* (2018) built a panel of Burkina Faso departments from household data to analyze the impact of gold mining on living conditions between 2003 and 2009. Exploiting the rapid increase in gold production due to industrial extraction by mining companies, the authors concluded that the poverty rate in the departments where extraction took place was reduced by eight percentage points and consumption increased by 12%. Bazillier and Girard (2020), on the other hand, concluded that there was no impact of the opening of industrial gold mines in Burkina Faso on household consumption, after extending the sample over time and distinguishing the impact of artisanal mines from industrial mines. Chuhan-Pole *et al.* (2017) examined the socioeconomic effects of industrial gold mining in Sub-Saharan Africa, particularly in Ghana, Mali, and Tanzania. It is one of the few studies based on microeconomic data involving different countries and which showed positive effects of industrial mining on employment, wage levels, expenditures, and economic activities in areas close to mining[7]. Furthermore, their results suggest that the structural transformation of mining localities is linked to the extraction activity. This is a strong argument in favor of mining. More recently, Mamo *et al.* (2019) established a positive impact of mining discoveries and operations on light emissions, a proxy for development, across Africa. The question is how these local light emissions actually translate into improved household living conditions.

In order to have positive local economic impacts, the extractive industries must go beyond what is one of their main characteristics: their functioning in enclaves. This term from Ferguson (2005) is used to characterize the fact that extractive industries do not have upstream or downstream linkages with local firms or other sectors of the host country economy that could provide production inputs or whose product they could consume. Mining investments are often made in secure enclosures. They require sophisticated imported equipment and are largely externally financed and owned[8]. This limits the impact on the rest of the national economy and does not contribute to efforts to reduce the impact of mining on poverty. Africa's mining industries are no exception to this rule. South Africa and

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7 Other exceptions with similar results are Stijns (2006) and Davis (2009). Based on data from 152 countries covering the period 1975–2000, Stijns (2006) found that mineral-rich countries had higher levels of human capital than other non-mining countries. Similarly, based on an analysis of 88 countries, Davis (2009) argued that the poor would have benefited more from growth in mineral-rich countries than other countries.

8 As mining is capital intensive, these investments not only employ few people, but also highly skilled people. The local labor force is mainly made up of blue-collar workers.

Botswana have been able to develop value-adding policies at the local level, establishing upstream and downstream economic linkages. However, most African mining countries are still characterized by centralized governance and fail to implement institutional reforms that would empower local communities over resources and broaden exploitation rights. What makes the two countries unique compared to others is the favorable context they enjoy, marked by good governance and high quality institutions. They have also put in place local regulatory measures through political action and negotiations with mining companies.

Local content initiatives can help overcome this functioning in enclaves. Aragon and Rud (2013) highlighted the positive impact of a local content initiative in Peru. Since 2000, the presence of the International Finance Corporation in the capital of Yanacocha has resulted in a policy of increasing the share of mine inputs purchased locally; Aragon and Rud cited construction equipment, chemicals, and cleaning products, or simple electronics, as examples. This requirement has had positive economic benefits for local communities.

However, the execution of these local content requests is not always possible. Thus, it is necessary to start by having a local productive sector that can respond to the demand of industries. To take the example of construction equipment or cleaning products cited by Aragon and Rud (2013), these are not “local” products existing in most of the villages in Africa where the mines are located. Another characteristic of extractive industries is the lifespan of the mines. A local industry may be created to try to meet the demand of extractive industries, but the creation of such enterprises is hampered by another central feature of industrial extraction: the exhaustion of mineral resources. Finally, the local productive sector may suffer from the presence of extractive activity. De Haas and Poelhekke (2016) thus showed that companies surrounding industrial extraction areas in eight countries reported more problems with access to transportation, corruption, and access to an educated workforce.

Extractive industries may also use (or be required to use) corporate social responsibility investments. In his analysis based on Peru, Hinojosa (2013) noted that the social responsibility of mining companies contributed to the development of the human capital of younger generations in the communities surrounding the mine. These initiatives also appear to reduce the risk of resource-related conflicts across the African continent (Berman *et al.* 2017). However, Pegg and Zabbey (2013) argued that local development was not a priority for mining companies, while Campbell and Laforce (2016) produced disappointing results.

In addition to its direct economic impact, a third channel through which extractive activity affects local communities is pollution. The substances used can destroy ecosystems; increase air, soil, and water pollution; and force people to migrate. Water and soil pollution can have a negative impact on the health of populations (Coast 2013). Reference can be made to Campbell's (2009) book on Ghana, Guinea, Madagascar, Mali, and other African countries, where the mining industry has failed to reduce poverty due to corruption, weak institutions, low royalty rates, relatively high expatriate staff, and negative social and environmental impacts. Aragón and Rud (2016) showed that pollution induced by increased gold production in Ghana has reduced farm productivity around the mines by 40%.

Finally, a fourth and last channel relates to the fact that resource production can also be a source of tax revenue at the local level, which could serve as a springboard for development through the financing of public goods. Achieving a positive local impact from extractive activities then comes up against the question of local institutions. The prospect of rents generated by natural resources can attract individuals interested in these rents to power and provide them with income to help them stay in power. For example, Asher and Novosad (forthcoming) showed that in India, candidates running for election in resource-rich localities are more likely to already have a criminal record. Moreover, once elected, these individuals are more likely to engage in criminal activities, and to become personally wealthy, when natural resource prices are high. Such rent-seeking activities may shed some light on why Caselli and Michels (2013) found that oil-rich Brazilian municipalities officially report spending more money on public services, even though these public services appear to be non-existent in reality (based on household survey responses). Thus, the institutional mechanism of the natural resource curse can be found also at the local level.

Industrial mines provide 90% of the minerals we consume (Buxton 2013), which explains the initial focus of the entire economic literature, and of this chapter, on the issue of industrial mining. However, more than 40 million people, representing the vast majority of workers in the extractive sector, are in artisanal mines (Delve 2019), to which we dedicate the rest of this chapter.

9.3. The case of artisanal mines

9.3.1. *Presentation of artisanal exploitation*

According to the most recent estimates, artisanal mining is central to the lives of 100 million people (World Bank 2009). Figure 9.2 reveals that these mines are a source of income for a significant portion of the rural population in many countries around the world.

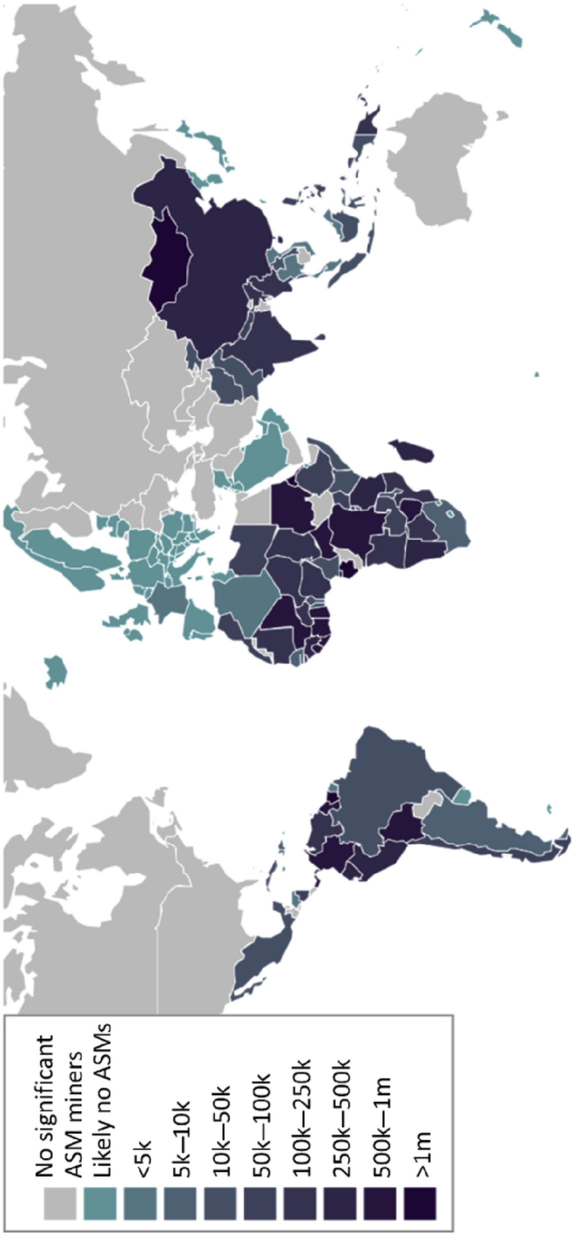


Figure 9.2. *Share of rural population working in artisanal mines (ASMs) (Yeomans 2019) (data source: mining.org). For a color version of this figure, see www.iste.co.uk/fizaine/mineral1.zip*

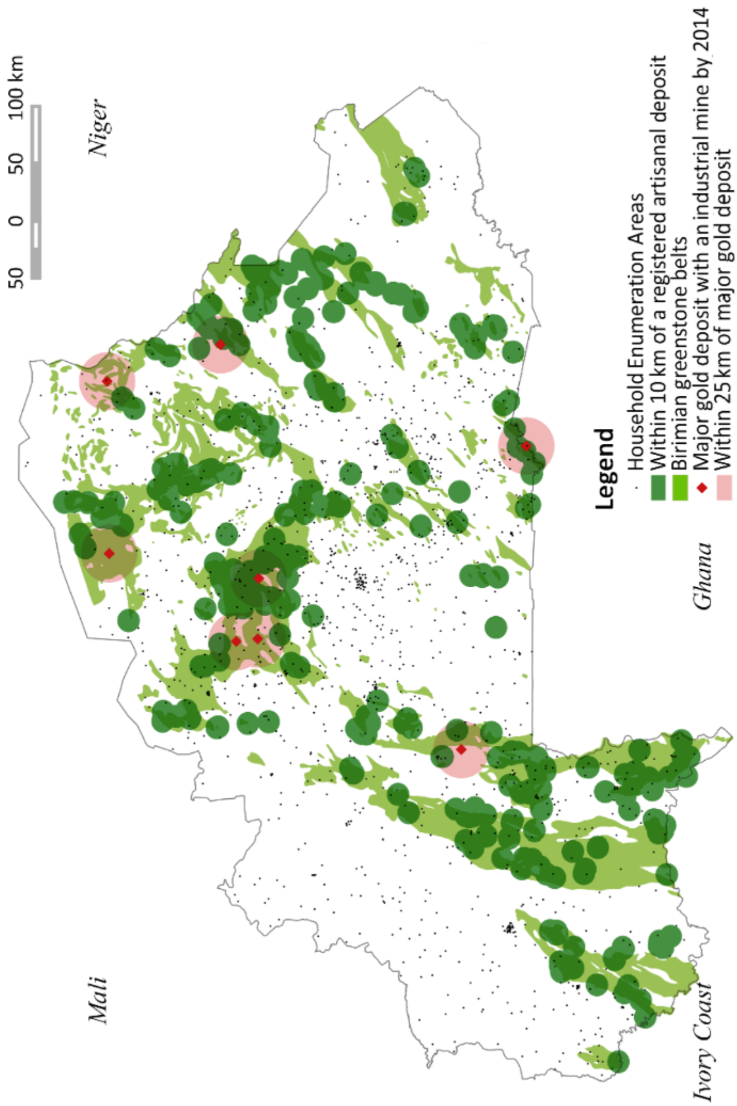


Figure 9.3. *Geology and gold mining in Burkina Faso (Bazillier and Girard 2020). For a color version of this figure, see www.iste.co.uk/fizaine/mineral1.zip*

COMMENT ON FIGURE 9.3. – *In terms of geological strata, gold in Africa is mainly located in the ancient basement domains represented here by the Birimian greenstone belt. Note that the location of artisanal mines registered with the Burkina Faso's Ministry of Mines closely follows this geological formation, as do the industrial gold mines that were producing in 2014 (or the map of industrial exploration permits, not included here).*

Artisanal and industrial mines differ in almost every respect. Artisanal activity is more labor-intensive than industrial activity. In addition, the workers in artisanal mines are more likely to be nationals or neighbors of the country of operation, who can learn mining techniques on the ground. Finally, the tools used in artisanal mines are traded or even produced locally. This is in contrast to industrial mining, which relies primarily on foreign capital for financing and a workforce made up of a larger proportion of expatriates (although local content initiatives, such as those studied by Aragon and Rud (2013) in Peru, are becoming more widespread). In addition, for the exploitation of minerals such as gold, coal, copper, and coltan, the final product is the same, regardless of the artisanal or industrial production method. For example, on average 20% of gold is produced artisanally (Buxton 2013), but it is almost impossible when buying a gold object to know what percentage of artisanal ore it contains[9]. Finally, it should be noted that where artisanal mines are present, artisanal and industrial mines may compete for land, seeking to exploit overlapping areas (World Bank 2009; Bazillier and Girard 2020; Figure 9.3).

The commonly accepted definition of artisanal mining to date is that of the OECD, which encompasses any "formal or informal mining operations with predominantly simplified forms of exploration, extraction, processing, and transportation" (OECD 2016). This broad definition covers a wide variety of practices, from an artisanal gold mine in Burkina Faso with dozens of deep, narrow tunnels (Balme and Lanzano 2013), to the giant pit of an artisanal coal mine in India (Deb *et al.* 2008). It can also cover mining at different times of the year, sometimes taking place primarily when households have nothing to do in the fields (Bazillier and Girard 2020) or sometimes only pausing when the rainy season makes the sites non-operational (Funoch 2014).

9.3.2. *Local impact of artisanal enterprises*

The collective imagination often associates artisanal mines with poverty, child labor, pollution, and even violence. The qualitative literature allows for a more

9 Most recently, a movement has emerged to promote fair trade gold, that is, gold produced manually in conditions that respect fair trade standards. However, this movement still results in very little production for the time being.

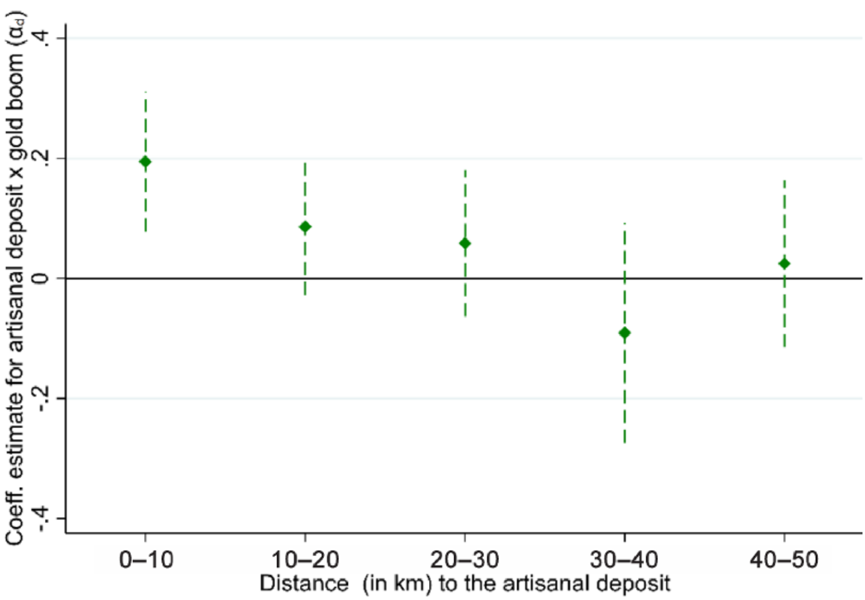
nuanced approach, emphasizing that artisanal mining is a source of income for households, and even that some children work there to finance their schooling (Hilson 2006, 2012; Potter and Lupilya 2016).

Recent empirical studies to date have highlighted three aspects of artisanal mining that we will present here in turn.

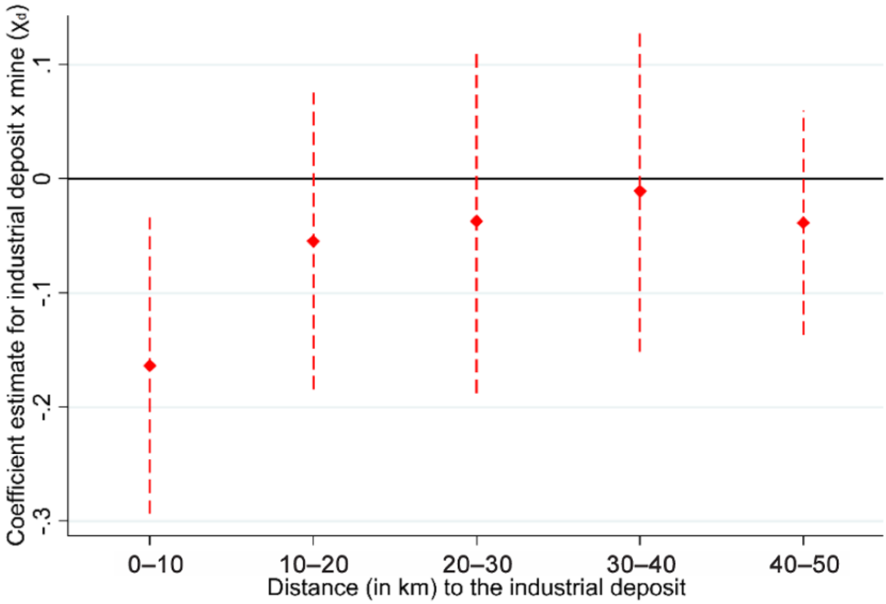
First, artisanal mining appears to have positive economic benefits. Artisanal activity increases the standard of living of households near these mines (Zabsonré *et al.* 2018; Bazillier and Girard 2020). Both studies focus on Burkina Faso, a country where artisanal mining activity has existed since the droughts of the 1980s and experienced a boom with a fourfold increase in the price of gold during the 2000s. Exploiting this quasi-natural experiment, Bazillier and Girard (2020) concluded that households living near artisanal mines saw their consumption levels increase faster than households in the rest of the country during the artisanal mining boom, with consumption 15% higher during the artisanal mining boom (consumption being the best way to approximate economic living standards in this context (Deaton and Zaidi 2002)). In addition, the economic effect of artisanal mining is significant; the additional household consumption attributable to the artisanal mining boom in 2014 is equivalent in size to the taxes that industrial mines remitted to the Burkinabe government in the same year. It should be noted that the same study highlights that the opening of industrial mines has not led to any local wealth effects in the country. Figure 9.3 provides a representation of the spatial distribution of the data used by Bazillier and Girard (2020) and Figure 9.4 provides an overview of the difference in the effects they document on the local wealth of artisanal mines (with a positive effect on consumption) and industrial mines (with no effect, or even a negative effect, on consumption). Thus, artisanal mining in Burkina Faso does not appear to suffer at the local level from the natural resource curse. However, this economic success is not guaranteed; the long-term effect of artisanal mining, its health costs, and its consequences on local political institutions and security need further research.

Second, when looking at changes in local health conditions, the negative health impacts of artisanal mining appear to be more than offset in the short term by their positive economic impacts (Parker *et al.* 2016; Bazillier and Girard 2020). We must emphasize here that artisanal mines undoubtedly expose their workers and neighbors to poor health conditions and are the primary source of human mercury pollution (EPA 2019). However, if we focus on the health consequences at the individual level, two effects compete. First, the income effect of artisanal mining makes it possible for people to eat better and take better care of themselves and thus improves their health. Second, the pollution effect negatively affects health. A positive income effect could be such that it cancels or even exceeds the negative pollution effect, which is consistent with the results of Bazillier and Girard (2020). Similarly, Parker *et al.* (2016) observed a deterioration in the health of neighbors of artisanal mines as they cease operations in the Democratic Republic of Congo. However, such results should be interpreted bearing in mind that the pollution effect does not have the same temporality as the income effect; once the price of an ore is low, the income effect melts away, while the pollution accumulated during past production remains. The question of the long-term health consequences of artisanal activity, therefore, requires further study.

Third, artisanal mining seems to be subject to the political curse of natural resources. The form taken by the political curse of natural resources is different between artisanal and industrial mines because the income generated by artisanal mining is lower; however, artisanal production is also easier to capture. Thus, there appears to be a clear link between the type of ore mined artisanally and the form of financing of armed rebel groups in the Democratic Republic of Congo (Sanchez de la Sierra 2020), as well as an increased likelihood of local conflict around artisanal mining, both in the DRC and across the African continent (Stoop *et al.* 2019; Rigterink 2020).



a)



b)

Figure 9.4. *Household consumption responses to gold mines*

COMMENT ON FIGURE 9.4. – *Panel (a) shows the results of a comparison, all other things being equal, of the differentiated evolution of household consumption levels, by physical distance from artisanal activity, between 1998–2003 (before the gold price boom) and 2009–2014 (after the price boom). The results indicate a positive wealth effect of artisanal mining at the local level, up to 30 km from the areas of mines registered with the Ministry of Mines. Panel (b) shows the results of a comparison, all other things being equal, of the differing evolution of household consumption levels, by physical distance from industrial activity, before and after the opening of industrial mines. The results indicate an absent or even negative wealth effect of industrial operations at the local level. The bars around each point represent the 90% confidence interval. Econometric estimates based on household surveys collected by the National Institute of Statistics and Demography of Burkina Faso in 1998, 2003, 2009, and 2014 (Bazillier and Girard 2020).*

9.4. Conclusion

Natural resources have the potential to reduce poverty. However, achieving this potential is not self-evident. Two points are of particular interest at the end of this chapter and require further research.

First, any virtuous use of natural resource rents requires quality institutions. Resource exploitation can pervert or destroy institutions through corruption or conflict. Recognizing this risk makes it possible for us to work towards its reduction. For example, corporate social responsibility initiatives, like those promoted within the International Council on Mining and Metals (ICMM) or membership in the Extractive Industries Transparency Initiative (EITI), appear to help to mitigate the link between resources and conflict (Berman *et al.* 2017).

Second, the role of artisanal mining requires more research. Artisanal mining is the second largest source of income in rural areas of Africa and a source of income diversification for farming households (Zabsonré *et al.* 2018; Bazillier and Girard 2020). As climate change will continue to increase the variability of climatic conditions, making agricultural activity increasingly risky, recognizing and understanding the consequences of artisanal activity as a poverty reduction strategy is more urgent than ever.

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Conclusion

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At the end of this first volume, several lessons can be drawn concerning the context and the issues of mineral resources economics.

C.1. Mineral resources issues, object of human representation

To begin with, the four introductory chapters on the context of mineral resources made it possible for us to realize that the world of mineral resources is above all governed by mental and social constructions, in the prism of specific models, rules, and language. *As we are not able to directly perceive the nature and extent of our connection with mineral resources, human societies deliberately use concepts and models to quantify mineral resources*.

These representations evolve with societies and do not appear to be independent of human conventions. Thus, as Jebrak illustrated very well, the notion of a country's resource endowment itself undergoes significant variations depending on whether one considers production, reserves, resources, or the subjective perception of a country's mining resources by individuals. To this multiplication of representations of the same object is often added a strong temporal, disciplinary, and geographical variability. The notion of reserve base, for example, is no longer provided directly by the USGS, which now prefers the more restrictive notion of reserves to represent a country's mineral endowment. In other circumstances, it is the very unity of a calculation that subtly changes the perception we have of the

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state of a resource. Thus, copper is often quantified, by convention, in tons of pure copper, while gold is often quantified in ounces (oz), lithium in lithium carbonate equivalent (Li_2CO_3), and uranium in pounds of triuranium octaoxide (U_3O_8), etc. Although correspondences can be established between these units and other uses, they do not facilitate a rapid and unbiased understanding of the concepts of mineral resources, not to mention the difficulty of comparisons when measuring the material footprint of these mineral resources is at stake. Similarly, assessing the abundance of this resource depends on the discipline of the reviewer. The geologist may be interested in the concept of abundance of an element in the earth's crust and the engineer may be interested in the concept of reserves, while the economist will probably use price as an indicator.

Another illustration of these shifting rules is that the very perception of the nature of a mineral resource varies over time and space, and can be pejorative or, on the contrary, positive. What can be said about the evolution of the perception of lead: initially worked as goldsmith's jewelry in prehistory (Smith *et al.* 2018) because of its malleability and usability in its native state (causing lead poisoning), it is now part of the "despised" class of heavy metals –metals that have no value, or even which, by their presence, reduce the value of other assets (housing prices come to mind). In the same way, the craze for radium at the beginning of the 19th century, which was then introduced in soft drinks, cosmetics, and medicines, ceased fairly quickly after Hermann J. Muller's discovery of the potential toxicity of rays at the end of the 1920s. Today, metals with high radioactive potential no longer have a good press and the excessive fear generated by radioactivity is perhaps just as irrational as the exaltation born with its discovery. *The reason is that we do not have a scale of values to give an absolute measure of mineral resources. In other words, most of these measurements depend on calculation rules and conventions set by humans.*

The difficulty in grasping the complexity of mineral resources also explains the motivation of researchers to use analyses that reconstruct concepts from scattered data to make them intelligible. The MFA undertaken by Raphaël Danino-Perraud, Maïté Legleuher, and Dominique Guyonnet does nothing more than try to reconstruct the path of cobalt from the mines of the Democratic Republic of Congo to its most diverse uses (batteries, electronics, superalloys, catalysts, etc.) and then its end-use, mostly in a landfill. This is with the aim of being able to provide orders of magnitude for the flows and stocks of cobalt circulating here and elsewhere. As they are based on assumptions that are not always verified and verifiable and because the data are imprecise, these models do not give the reality but simply a representation of what it could be. The end in itself is not to establish precisely the stock of cobalt at stake in the anthroposphere. Moreover, can we really speak of stocks when this material is geographically scattered in different sectors, in various chemical forms, and sometimes in very low concentrations? No, it is more precisely a question of obtaining a sufficiently credible representation of the mineral resource system to make another use of it. We then move from the positive to the normative; the model described and its results then support conclusions and recommendations to justify potential action. In the framework of this contribution, the objective was to evaluate the extent of the European Union's dependence on cobalt imports, but we could very well have wondered about the conflicts of use or complementarities that might exist between European industries that consume cobalt and thus make a completely different use of it.

The financialization of mineral resources does not escape the game of representation; the rush for rare metals (notably indium and bismuth) through the Fanya Metal Exchange – which was created in 2011 and which disappeared in 2015 – shows to what extent operators do not only obey rational logic and also remain guided by visions and constructions conveyed in a certain context. In fact, a review of the situation would have made it possible to understand that a physical market the size of indium (200 million dollars per year in 2019) is not a sufficiently large market to justify the creation of an exchange platform[1]. We should remember that cobalt and molybdenum were introduced in 2010 with a physical market of 4 and 11 billion dollars, while the financial markets for nickel and aluminum appeared in 1978 with markets of 12 and 68 billion dollars (constant 2010 dollars). The perception of the (occasional) scarcity of "rare" metals through their prices has probably greatly helped to convince investors to make this type of investment. Here again, the use of price or its variants (spot, futures, forward prices) must be analyzed carefully to avoid over-interpretation and unfounded conjectures. In this respect, while price captures the scarcity of a resource, it also captures a whole series of other effects, and therefore the desire to project past trends into the future at all costs also reflects a strong belief in our societies – that information about the future should be contained in that of the past.

Yet researchers have shown that the price of a resource follows a random walk (Krautkraemer 1998), which means that measuring trends and replicating them in the future remains a normative and potentially perilous exercise. While our positive models of the factors that guide commodity prices are still very incomplete, the transition to future projection is even more problematic. As Albert Einstein rightly reminds us, "No path leads from a knowledge of that which is to that which should be." Even very prominent researchers such as Simons or Erhlich ended up wanting

1 Without even looking at the needs of commercial operators in terms of hedging and the volatility affecting the price of indium.

to project their worldview and their model onto the reality of commodity markets, leaving the outcome and final decision to random price shocks[2]. The disconnection between reality and prediction can then occur in a sometimes brutal way, leading experts to deny reality and to maintain the conclusions of their model. Beyond the anecdotal, this example also echoes the shift in researchers' interest from issues related to raw materials to those related to the state of the environment, following the oil counter-shock and the fall in raw material prices (Fisher and Ward 2000; Simpson *et al.* 2005). Logically, the rise in prices at the end of the 2000s revived the interest in the issue of raw materials, as if a choice had to be made between resource or garbage problems (Giraud 2014), and the price signal was an appropriate indicator of the urgency and priority of the problem. Here again, there is confusion between what is positive and what is normative, and the idea that price would be a good measure of the magnitude of our problems is a challenge.

This confusion of genres also exists in geopolitics. The contribution of Didier Julienne shows it well. While science merely describes the facts, it says nothing about what should be (normative). Thus, if we can objectively describe a country's dependence on the import of a particular resource – there are no two different results – quantifying the sensitivity and risk associated with these imports requires moving from the positive to the normative point of view. We then enter the field of representations of the world, in which a large gap can appear between reality and its perceptions. Calling science to distinguish between several visions will not be of much help because here we are outside its field of application.

It is, therefore, necessary for researchers to clarify as much as possible what belongs to the scientific approach, which is limited to describing the facts, and what is intended to provide recommendations and which requires in one way or another the application of a representation or model. This distinction, moreover, in the social sciences and humanities, is often blurred and some use scientific discourse to carry a political project, which contributes to blurring the lines and feeding the growing mistrust toward "experts".

C.2. Some enlightenment regarding physico-socio-economic feedback

The contributions made throughout Volume 1 of this work have also highlighted the importance of constant feedback and backtracking between physico-technical

2 Having failed to provide sufficiently important factual evidence on the general evolution of the world and its future, the two researchers ended up betting on the evolution of raw material prices at ten years to decide the question of the relevance of their representations (Kiel *et al.* 2010; Lawn 2010).

representations on the one hand and socio-economic models of mineral resources on the other.

To begin with, physico-chemical realities exert a decisive influence on our socio-economic development models. As it depends on natural resources (matter and energy), the economy is governed by physico-chemical laws that frame the development of socioeconomic-cultural activities. Technical progress makes it possible to get closer to these laws but not to abstract from them. While platinum exceeds the market value of gold today, its technical and economic inaccessibility until the 16th century made it unsuitable for the development of a cult as it may have existed around the yellow metal, a “barbarous relic” according to the expression of John Maynard Keynes.

Similarly, the enhancement of steel’s energy efficiency, jointly with the emergence of abundant and inexpensive energy sources, has freed steel from previously frugal economic uses. Does this mean that technical progress can consistently reduce the cost of making steel to zero? Definitively not. The reality of this interaction between physical limits and economic needs is well described by Olivier Vidal as well as by Jacques Villeneuve (and his team) in their respective contributions. Knowledge makes it possible for us to get closer to the physical limits but not to exceed them. Thus, Olivier Vidal shows that the physical laws of resource depletion have a tangible economic reality (via the energy and monetary cost of metals) and that this physical reality will have to impose itself on us as soon as we continue on the same development trajectories and the energy efficiency of the mining sector will eventually exhaust the last deposits of productivity. To counter our potential defeat in the face of this physical wall, the author calls for greater support for the economics of recycling.

However, the physico-chemical laws are here again likely to impose themselves on us, at least for a large number of metals. This is, first of all, because the waste streams cannot be mobilized immediately (thanks to the product life times) and, therefore, cannot necessarily cover at any given time all the needs of a growing economy; and, secondly, contrary to what is often argued, because a very large share of the urban mine shows a poorer ore grade than the natural mine and its deposits, at least when minor metals are concerned (Fizaine 2018). This feedback from the physical world on the economy is also perceptible through the contribution of Jacques Villeneuve and his team. A certain number of developed economies now rely mainly on service[3] economies, which could lead us to believe that our lifestyle has gradually become

3 At least when based on the share of services in GDP or the share of total employment in services. This idea is, moreover, contested in particular by Baumol’s paradox.

less and less materialized. This could be observed in particular through the observation of indicators such as domestic extraction or, to a lesser extent, domestic consumption (production indicator). However, as the authors show quite well, the environmental impact is being relocated outside our national economies through the interplay of international trade in products and services. The input–output (IO) methodology used by the authors to calculate a material footprint enables us to bring our intuition back into line with reality. The physical reality of our growing material consumption has not disappeared, it has simply been moved to countries specializing in the production of material and energy-intensive goods and services. Thus, more than 80% of the metal production aimed at serving the final demand in France is carried out abroad. This material reality of our economies is also noted by other authors on global macroeconomic data (Charlier and Fizaine 2020; Lefèvre 2021).

The socio-economic "laws" and interactions, while they do not modify the immutable laws of physics, nevertheless affect the organization of our physical world and its evolution. A good example is the anthropogenic global warming that upsets the natural trajectory of the Earth System. However, the thermo-industrial system set up by modern societies would probably not have been so destructive if it had not combined taking technology further and socio-economic dynamics.

On this issue, Romain Debref's contribution shows that the improvement in eco-efficiency, through the "rebound effect", has always led in the long term to an increase in the quantities of resources consumed and not to a reduction in their use. There is a fundamental interaction between the technique (which reduces the need) and the socio-economic dynamics (which uses it as a leverage for growth). In this context, the technical response to environmental issues only accentuates the problem. However, this outcome has nothing to do with any kind of determinism. We have probably not reached the Anthropocene era in an inevitable way; it is a series of choices influenced in part by the socio-cultural context that has led to this result.

Our preference for technical progressivism and cultural conservatism has deliberately favored certain options. To illustrate this, we need only look at our inability to change our socio-economic model, which has led us, for example, to favor the electric car over bicycles or public transportation. The electric car is a technological response to transportation pollution, whereas the bicycle or public transportation (to a lesser extent) is a socio-economic response. In the first case, our values and our way of perceiving development from a rather quantitative standpoint are not questioned: still more urban sprawl through the generalization of the individual housing, the absence of physical effort, minimal discomfort, and the absence of travel restrictions. In the second case, we need to review our socio-economic model, the formation and development of cities and territories and the structure and location of jobs, to match the limited travel power of these alternative transport modes. Still, the choice of a slightly modified version of the original (all-electric) will introduce a profound modification of the dynamics of space, energy, and materials consumed. For the vehicle design itself, if we do not wish to change anything (very long range, rapid energy recharging) and switch to an electric version of our traditional thermal car, this will imply an inflation of the energy cost of the transport equipment via a new increase in the vehicles' weight. A thermal Clio weighs 1 ton; its equivalent, the electric Zoe, weighs 1.5 tons (that is 50% more raw materials). Not to mention that using electricity instead of gasoline or diesel fuels the illusion that an electric vehicle consumes less energy[4] and costs less; filling up a Zoe in France costs €7.5 compared to €65 for the Clio. Of course, the gap is narrowing per km, but appearances persist: about 2 ct per km for the electric vehicle compared to 7–10 ct per km for the thermal equivalent.

If the forces of capitalism, through technical progress and the exploitation of scale economies (which Tesla is trying to exploit with its gigafactories), succeed in drastically lowering the cost per kWh of electric battery capacity (which constitutes a significant fixed cost), we will surely move towards a generalization of the electric vehicle. However, even beyond the fact that the electric vehicle has a non-negligible environmental cost (local and global), it is above all likely to bring with it a non-negligible rebound effect: that of lightening the burden of our responsibility associated with the choice of traveling ever faster and further, and also an extension or even an accentuation of current trends connected to low-cost energy services. These are all things that are far from being limited to the sole problem of global warming (urban sprawl/diminishing natural spaces, fragmentation of spaces, increasing extraction of raw materials). However, this choice of eco-efficiency through technical response is the result of a socio-cultural-technical model and not a deterministic constant towards which humanity is inexorably tending. It is, therefore, time for the human sciences to regain control over these margins of action, not only by discussing the plausibility of the technical response and its best support to alleviate an apparent problem, but also through the possibility of proposing credible alternatives that are not solely technological. For the moment, our transition models (and especially our votes) favor "doing as much with less" rather than "consuming differently" and "consuming differently" rather than "consuming less". It is, therefore, necessary to study now how this hierarchy of values can be reversed so that societies can backpedal in terms of their environmental impact.

4 In reality, the energy yields over the entire energy production chain are only slightly favorable to the electric car.

The treatment of the natural resource curse probably also offers another illustration of this influence of socio-economic representations, which convey the idea that it would be a fatality from which no country should escape. In the first place, the work by Audrey Aknin, as well as that by Victoire Girard and Agnès Zabsonré, shows that the link between the exploitation of natural resources and weak growth is far from being mechanical or even inevitable and that it depends on the context (institutions, regulations, type of extractivist model, etc.). In other words, this means that some countries have managed to achieve high economic growth and poverty reduction even in the presence of a high natural resource endowment. Second, it shows that it is high time to shift the focus from the problem of growth in the strict sense (and its continuation) to that of development and well-being, through its relationship with proxies of capabilities such as health, life expectancy, education, and inequality, all areas where the impact of mining activities can be very different from one context to another.

In any case, these contributions must be considered as first steps towards research that will help clarify the conditions for escaping the resource curse. If, as this first volume has shown, the energy transition will maintain a strong pressure on mineral resources, which generate economic activities and rents, it is necessary to ensure that this is done for the good of all and first and foremost for the populations of the countries that host these extractive industries; an ambitious objective, but not unattainable. Volume 2 of this book will enable us to define the legal, geopolitical, and migratory issues at stake and to list the various levers of action available to us in this field.

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