The Mining of Minerals and the Limits to Growth

Simon P. Michaux

GEOLOGICAL SURVEY OF FINLAND   **DOCUMENTATION PAGE**

Date 01/03/2021

Authors	Type of report
Simon P. Michaux	Open File Work Report
	Commission by
	GTK

Title of report

The Mining of Minerals and the Limits to Growth

Abstract

Current industrialization has a foundation in the continuous supply of natural resources. The methods and processes associated with this foundation have significant momentum. This paradigm will not be undone easily. Human nature and human history make it so. Currently, our industrial systems are absolutely dependent on non-renewable natural resources for energy sources.

For the last 15 years, it has been apparent that the industrial business environment has been more challenging and volatile. This report will present the thesis that this persistent volatility is the forerunner temporal markers that show the industrial ecosystem is in the process of radically changing.

Current thinking is that European industrial businesses, will replace a complex industrial ecosystem that took more than a century to build. This system was built with the support of the highest calorifically dense source of energy the world has ever known (oil), in cheap abundant quantities, with easily available credit, and unlimited mineral resources. This task is hoped to be done at a time when there is comparatively very expensive energy, a fragile finance system saturated in debt, not enough minerals, and an unprecedented number of human populations, embedded in a deteriorating environment.

It is apparent that the goal of industrial scale transition away from fossil fuels into non-fossil fuel systems is a much larger task than current thinking allows for. To achieve this objective, among other things, an unprecedented demand for minerals will be required. Most minerals required for the renewable energy transition have not been mined in bulk quantities before. Many of the technology metals already have primary resource mining supply risks

At its foundation, the current industrial ecosystem was and still is based around the consumption of natural resources, which were considered to be infinite. The very idea that there might be system based limits to the global extraction of resources is considered foolish by the current economic market. The volume of manufacture was influenced by the consumption demand of products. Growth and expansion with no considered limits of any kind was the underlying paradigm.

The majority of infrastructure and technology units needed to phase out fossil fuels has yet to be manufactured. Recycling cannot be done on products that have yet to be manufactured. In the current system, demand for metals of all kinds have been increasing, just as the grade of ores processed has been decreasing.

Global reserves are not large enough to supply enough metals to build the renewable non-fossil fuels industrial system or satisfy long term demand in the current system. Mineral deposit discovery has been declining for many metals. The grade of processed ore for many of the industrial metals has been decreasing over time, resulting in declining mineral processing yield. This has the implication of the increase in mining energy consumption per unit of metal.

Mining of minerals is intimately dependent on fossil fuel based energy supply. Like all other industrial activities, without energy, mining does not happen. A case can be made that the window of viability for the fossil fuel energy supply ecosystem has been closing for 5 to 10 years.

GTK

It becomes highly relevant then to examine how mining ecosystem interacts with the energy ecosystem. The IMF Metals Index and the Crude Oil Price Index correlates strongly. This suggests that the mining industrial operations to meet metal demand for the future are unlikely to go as planned.

The implications are that the basic prediction of the original Limits to Growth systems study (Meadows *et al* 1972) was conceptually correct. Just so, it should be considered that the industrial ecosystem and the society it supports may soon contract in size. This implies that the current Linear Economy system is seriously unbalanced and is not remotely sustainable. The Limits to Growth conclusions suggest at some point, the global society and the global industrial ecosystem that support it will radically change form.

It is clear that society consumes more mineral resources each year. It is also clear that society does not really understand its dependency on minerals to function. Availability of minerals could be an issue in the future, where it becomes too expensive to extract metals due to decreasing grade.

This report proposes that the fundamental transformation of the global ecosystem predicted by the original Limits to Growth study, has been in progress since 2005, for the last 16 years. The industrial ecosystem is in the process of transitioning from growth based economics to contraction based economics. This will affect all sectors of the global ecosystem, all at the same time (in a 20 year window). We are there now and should respond accordingly.

If the Limits to Growth study is truly a good model for predicting the industrial ecosystem, then the current industrial practice is inappropriate. The continued development of the economic growth paradigm would become increasingly ineffective, and a waste of valuable resources. All such efforts would be pushing in the wrong direction with poor results.

The rules of industrialization and the sourcing of raw materials are changing into a new era of business model. Change is happening, whether we are ready for it or not.

A possible response to these structural changes is presented after conclusions on page 52, where it was recommended that a new resource management system should be developed after genuinely understanding the net position of long term minerals supply. Also, it was recomended that new mining frontiers be opened, but the minerals extracted should be used differently.

Contents

Documentation page

TABLE OF CONTENTS

1   INTRODUCTION

For the last 15 years, it has been apparent that the industrial business environment has been more challenging and volatile. This report will present the thesis that this persistent volatility is the forerunner temporal markers that show the industrial ecosystem is in the process of radically changing.

Current thinking is that European industrial businesses, will replace a complex industrial ecosystem that took more than a century to build. This system was built with the support of the highest calorifically dense source of energy the world has ever known (oil), in cheap abundant quantities, with easily available credit, and unlimited mineral resources. This task is hoped to be done at a time when there is comparatively very expensive energy, a fragile finance system saturated in debt, not enough minerals, and an unprecedented number of human populations, embedded in a deteriorating environment.

Most challenging of all, this is to be done in a few short decades, with a stated target of 100% of the vehicle fleet will be EV's by 2050 (European Commission 2019a). It is the authors opinion that this will not go to plan.

It is apparent that the goal of industrial scale transition away from fossil fuels into non-fossil fuel systems is a much larger task than current thinking allows for. To achieve this objective, among other things, an unprecedented demand for minerals will be required.

Most minerals required for the renewable energy transition have not been mined in bulk quantities before. Many of the technology metals already have primary resource mining supply risks (Figure 1).
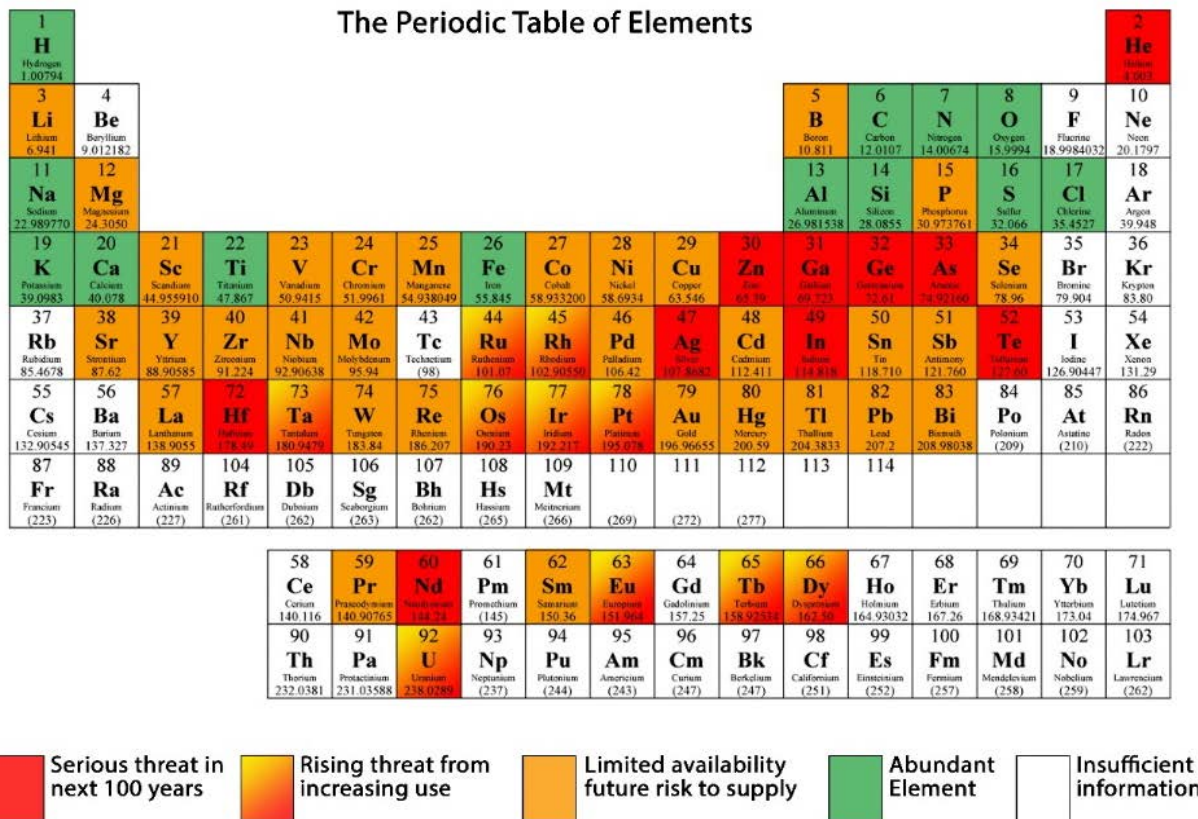

Figure 1. Some primary mining sources for a number of metals have clear supply risks (Source: Report On Critical Raw Materials For The EU May 2014) (Copyright License: https://creativecommons.org/licenses/by-nc-sa/4.0/)

In 2019, less than 0.5% of the global fleet of vehicles are EV based technology and in 2018, renewable energy (excluding hydroelectricity) accounted for less than 5% of primary energy demand (BP Statistical Review of World Energy 2019 & IEA 2019). The vast majority of the proposed Circular Economy support systems have yet to be manufactured. As it is not possible to recycle something that has yet to be manufactured, the source for this unprecedented quantity of metals will have to be sourced from mining.

Very preliminary calculations show that current production rates of metals like lithium, nickel and cobalt are much lower than what will soon be required. It is equally apparent that current global reserves are also not enough. This will require sharp increase in the required mines to be operating in a few short years. Just so, a very large number of feasibility studies and pilot scale studies will be needed.

2 THE LINEAR ECONOMY AND WHAT MINERALS DO FOR US

The Circular Economy was designed to replace the Linear Economy (Figure 2). This was the system that evolved out of the industrial revolution phases IR1, IR2 and IR3. The basic formula was the raw materials needed for manufacture was sourced by mining of minerals only, and growth that later has been shown to be exponential. Waste products were dumped into landfill, or simply abandoned at the point of being discarded. Recycling was a very limited activity. All energy sources were fossil fuel non-renewable finite natural resources (oil, gas, and coal).
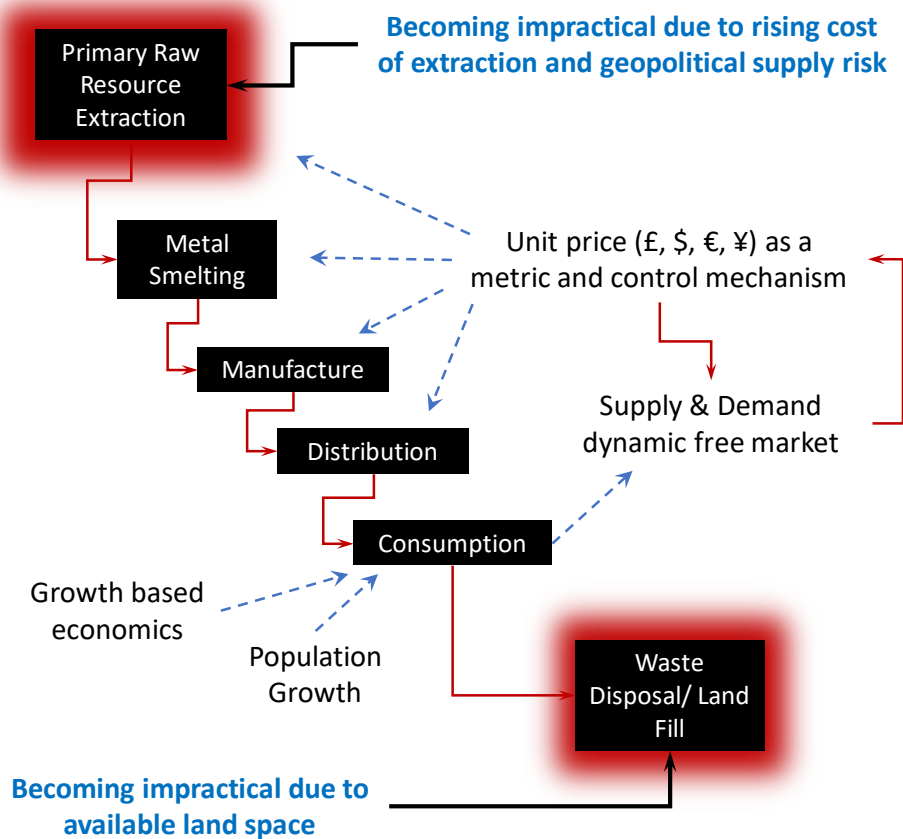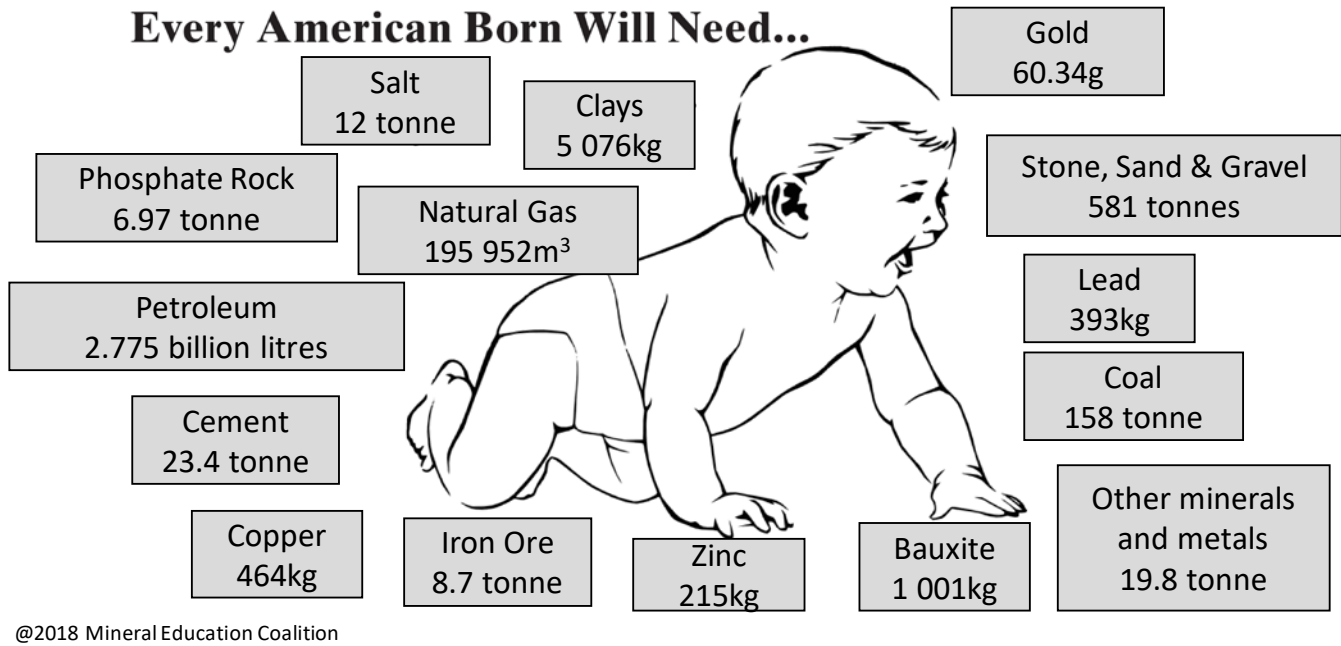

Figure 2. The Linear Economy (Image: Simon Michaux)

At its foundation, the Linear Economy was and still is based around the consumption of natural resources, which were considered to be infinite. The very idea that there might be system based limits to the global extraction of resources is considered foolish by the current economic market. Figure 2 should be put in context of Figure 3, that shows human population growth and energy consumption growth.

Every American Born Will Need...

Gold 60.34g	
Salt 12 tonne	Clays 5 076kg
Phosphate Rock 6.97 tonne	Natural Gas 195 952m³
Stone, Sand & Gravel 581 tonnes	
Petroleum 2.775 billion litres	Lead 393kg
Cement 23.4 tonne	Coal 158 tonne
Copper 464kg	Iron Ore 8.7 tonne	Zinc 215kg	Bauxite 1 001kg	Other minerals and metals 19.8 tonne

@2018 Mineral Education Coalition

**Total consumption over the lifetime:
1,37 million kilograms of minerals, metals and fuels**

*Figure 3. Estimated total resource consumption by each person in American society across their lifetime, 2018 data
(Source: U.S. Mineral Education Coalition)*

The volume of manufacture was influenced by the consumption demand of products. Growth and expansion with no considered limits of any kind was the underlying paradigm. The Linear Economy was made possible with the harnessing of fossil fuels, a cheap abundant energy source. Oil in particular was the most calorifically dense energy resource the World had ever known (Michaux 2019).

This system would have continued if certain limitations had not become apparent. In Europe, development of land use made it very difficult to justify landfill waste disposal. For a short time, some waste was shipped to the Southern Hemisphere for disposal. The catalyst for the development of a new more sustainable system was the realization that almost all of the Critical Raw Materials was sourced outside of Europe. So, both the primary raw material extraction and the waste disposal parts of the Linear Economy became a perceived difficulty for the future of Europe.

From a systems point of view, the Linear Economy is showing signs of stress and strain. The logical progression would be the transformation of the Linear Economy into something else, that was structured to manage the limits of resource consumption, and resource stewardship more effectively (Taylor 2008).

The genius of the Circular Economy was to merge these two bottleneck points in the linear value chain, where the output of one could be the input of the other. Just so, recycling became the strategic important technology to develop.

3   THE CIRCULAR ECONOMY IS NOT REALLY GEARED FOR CURRENT METRIC OF ECONOMIC GROWTH

In the current industrial ecosystem, the underlying metric for operational success is growth. Current economic ecosystems are geared to a growth of 2% per annum. Growth in all its forms is a metric of the current system (The Linear Economy). Just so, the consumption of natural resources has steadily increased. The Circular Economy is an attempt to be sustainable. So, a fundamentally different business model must be the foundation of whatever the Circular Economy might become. While the Circular Economy attempts to do this, at its foundation, it still is based on market growth and uses money made as the metric for success, where target objectives are to still deliver 2% p.a. growth while reducing resource consumption.

4   THE MINING OF PRIMARY RESOURCES

Figure 4 shows how resource consumption has increase on a global scale between the year 2000 and the year 2018. Consumption of most metals, minerals and energy raw materials from mining have increased in this time frame.
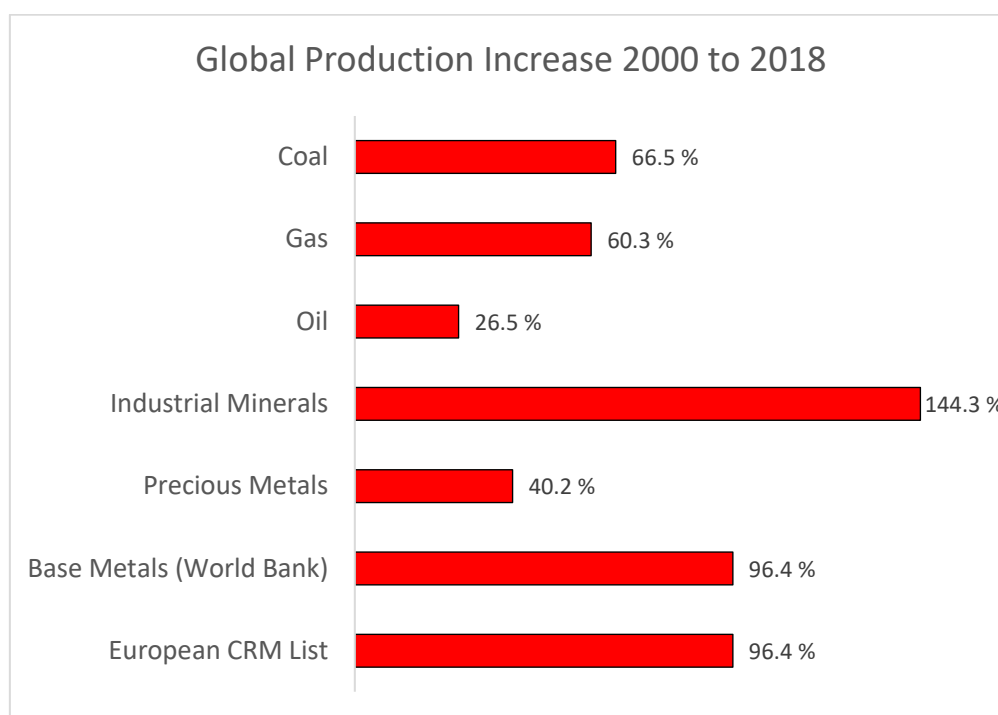

Figure 4. Global annual consumption of mineral resources between the year 2000 and 2018
(Source: USGS data, World Bank data, BP Statistics 2011, BP Statistics 2019)

There is a school of thought that economic growth can be sustained with "intangible value creation". Figure 4 shows that the industrial ecosystem and the economic growth it outputs, requires physical raw materials to function. The system is not getting more efficient in consuming physical raw materials. For intangible value creation to work, a fundamental restructuring of how the technology is delivered and applied would be required. Innovations like cryptocurrencies may be virtual in nature (exist as data on the internet), but they still have a real world physical footprint.

For example, on March 18, 2021, the annual power consumption of the Bitcoin cryptocurrency network was estimated to be 129 terawatt-hours (TWh) (Source: Cambridge Centre for Alternative Finance, Science Mag,

New York ISO, Forbes, Facebook, Reedy Creek Improvement District, Worldometer). To put this in context, the annual electric consumption of the nation Netherland's in 2019 was 121.0 TWh (BP Statistical Review of World Energy 2020).   All economic activity has a footprint in the physical world in some context, with a raw materials consumption profile.

The World Bank uses copper consumption as one of the proxies to model the global industrial ecosystem. Figure 5 shows global production of some metals, and Figure 6 shows global copper production over the last 112 years. Copper consumption between 1985 and 2008 (23 years) accounted for half of all copper ever mined globally in a historical context. Projected world consumption between 2009 and 2030 (21 years) is predicted to exceed all of the copper metal ever mined historical prior to 2009.

In 2019, global consumption of copper metal was 24.5 million tonnes and global copper reserves was reported at 870 million tonnes (USGS mineral statistics). Using a straight and crude calculation, this means that current reserves represent 35.5 years of supply at 2019 mining and recycling rates. Copper demand is projected to increase to approximately 100 million tonnes per annum by the year 2100. Just so, more copper deposits are required to be discovered and developed into producing mines. This may be more difficult than first understood (Figure 13).
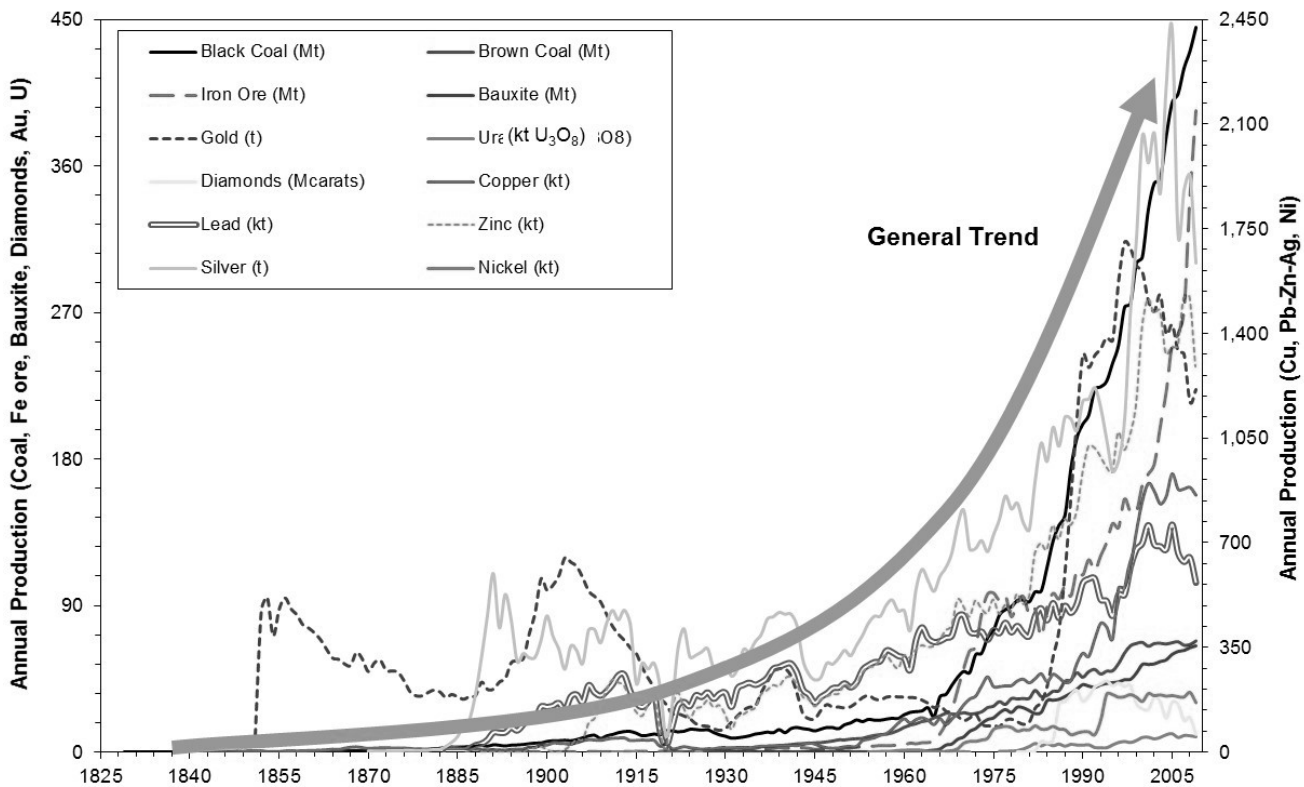
Figure 5. Mining production 1825 to 2008 (Source: Mudd 2009- updated 2012, Analyst- Gavin Mudd)

There is a current paradigm to phase out fossil fuels and all associated infrastructure. This will require an unprecedented volume of metals of all kinds. In particular, Technology metals. Technology metals are the building materials needed to manufacture much of current state-of-the-art technology. Technology metals could include: Be, B, Sc, V, Ga, Ge, Se, Sr, Y, Zr, In, Te, Cs, Ba, La, Hf, Ta, Os, Tl, Li, Ru, W, Cd, Hg, Sb, Ir, Mo and Mg. For Europe in particular, most global supply of these metals is sourced externally and is highly dependent on imports (Figure 7).

Figure 6. Global copper production 1800 – 2012 (Source: Mudd 2009 - updated 2012, Analyst - Gavin Mudd)
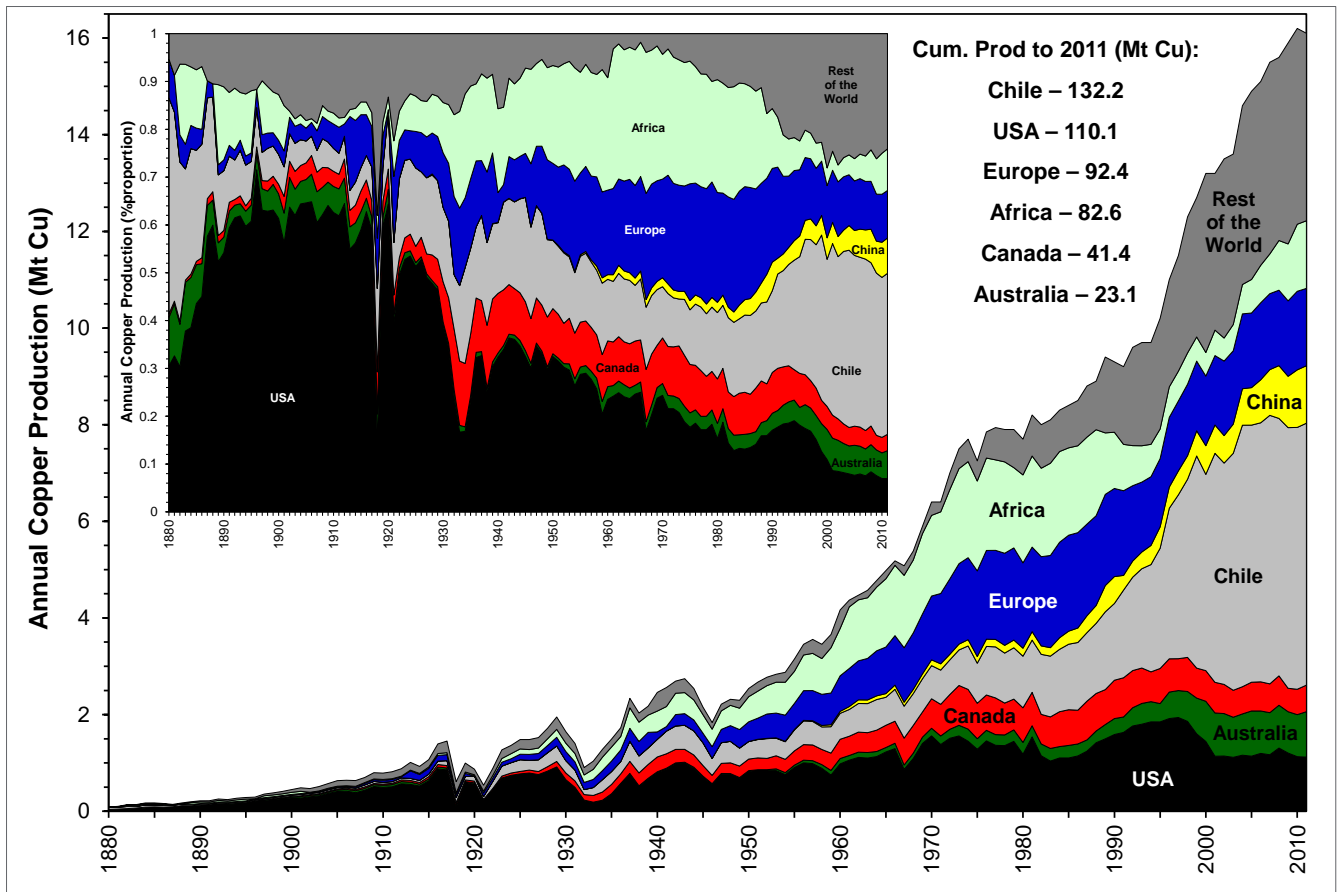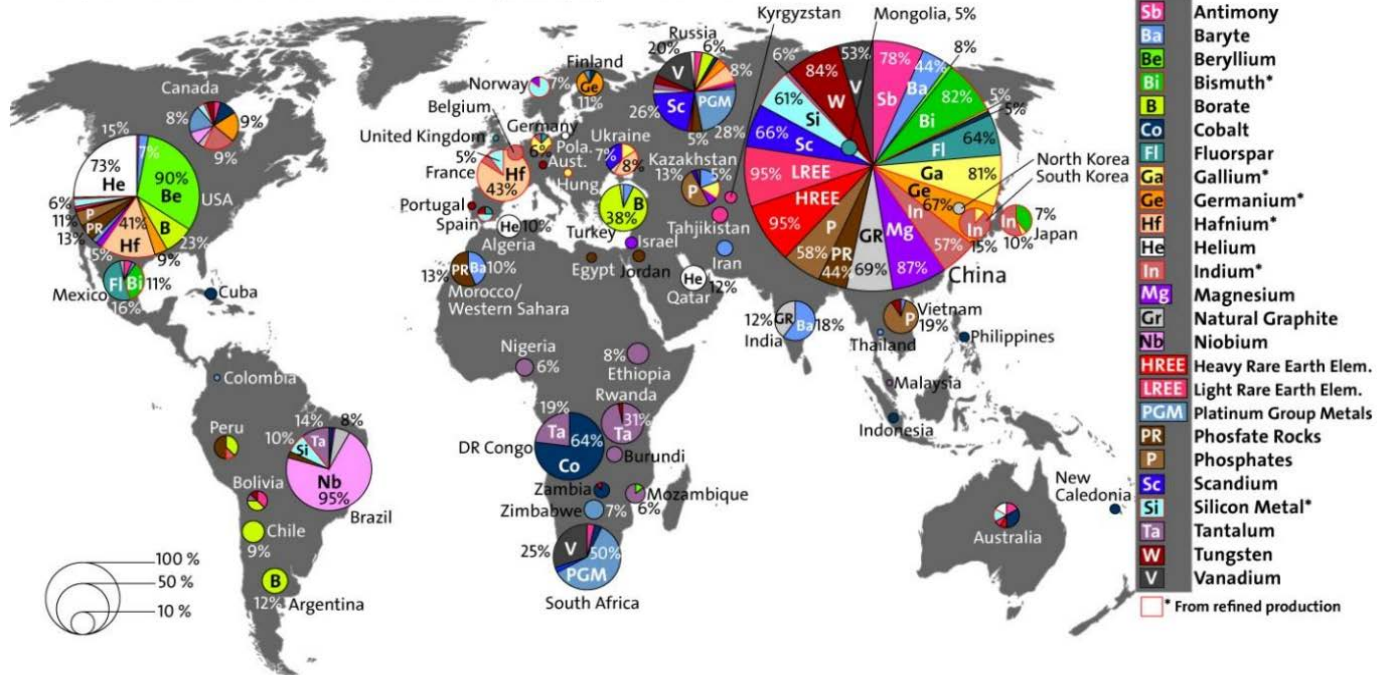

Figure 7. Global supply of EU Critical Minerals and Metals (Source: SGU)

5   RECYCLING

Base metals like Al, Cu, and Fe can be recycled with mature processes to a high degree of stream recovery. Precious metals like Au, Ag and PGE can also be recycled through more complex process methods. This has been developed due to the high value of the target metals. The recycling of technology metals is either not done very well, or not done at all.

Recycling also can only be done so many times before the feedstock becomes useless. Natural laws such as physics and thermodynamics determine the maximum achievable recycling rate as a function of the quality of the recycling (side stream intermediate) products (Reuter *et al* 2006). It can be concluded that the recyclability of a product is not only determined by the intrinsic property the different materials used, but by the quality of the recycling streams (Reuter *et al* 2006). This material stream quality is determined by the mineral classes (combination of materials due to design, shredding and separation), particle size distribution and degree of liberation (multi-material particles) and the efficiency of physical separation.

This implies that waste streams cannot be recycled indefinitely before they need to be valorized by some other form. This is something that is not included in current thinking. Figure 8 shows the recycling rates in 2011. Current recycling rates will resemble these extraction efficiencies.
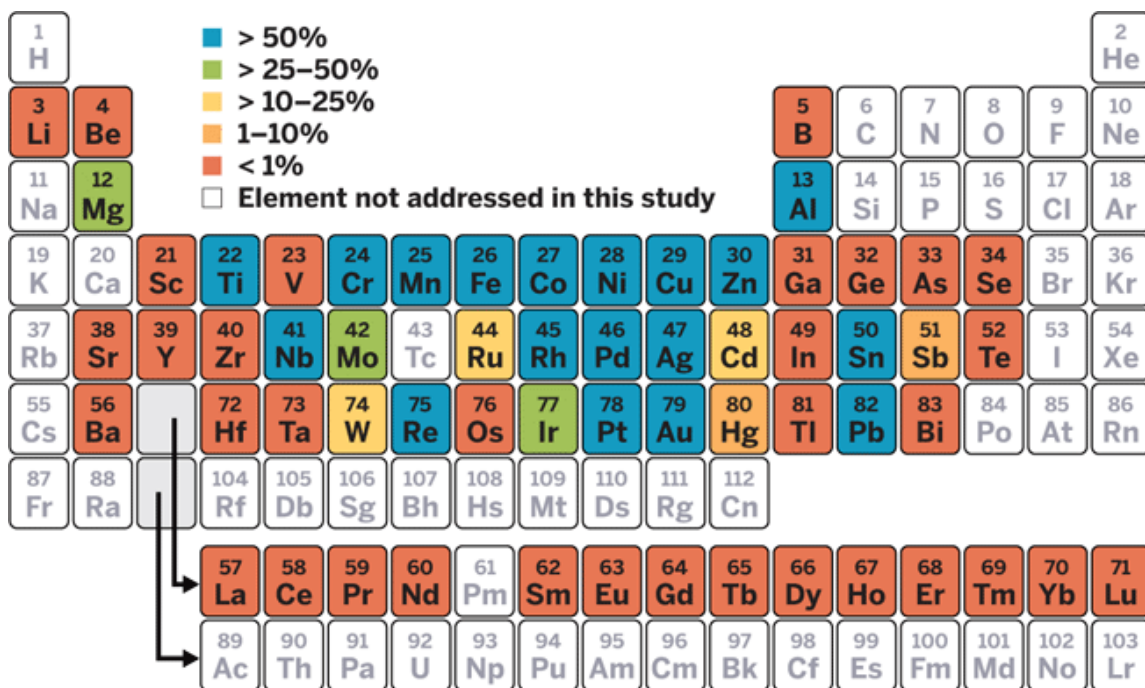
Figure 8. Recycling rates of metals (Source: United Nations Environment Programme, Recycling Rates of Metals (2011) / C&EN May 30, 2011) (Copyright License: https://creativecommons.org/licenses/by-nc-sa/4.0/)

In 2019, there was 7.2 million Electric Vehicles (IEA 2020). The global fleet of vehicles was estimated to be 1.416 billion vehicles (Michaux 2021).   This means that just 0.51% of the global fleet is currently EV technology, and that 99.49% of the global fleet has yet to be replaced.

In 2018, the global system was still 84.7% dependent on fossil fuels, where renewables (including solar, wind, geothermal and biofuels) accounted for 4.05% of global energy generation. At the very least, 84.7% of the primary energy supply is required to be replaced with non-fossil fuel systems.

The majority of infrastructure and technology units needed to phase out fossil fuels has yet to be manufactured. Recycling cannot be done on products that have yet to be manufactured. The current focus of the Circular Economy development is recycling, with the perception that mining of mineral resources is not relevant. However, the system to phase out fossil fuels (whatever that is) has yet to be constructed, and this will require a historically unprecedented volume of minerals/metals/materials of all kinds.

6   MINERAL RESERVES AND RESOURCES

A useful way to quantify resource materials like metals in context of energy consumption or embedded energy previously consumed, is exergy. In thermodynamics, the exergy (in older usage, available work and/or availability) of a system is the maximum useful work possible during a process that brings the system into equilibrium with a heat reservoir. After the system and surroundings reach equilibrium, the exergy is zero. Figure 9 and Figure 10 shows the known reserves of various metals, minerals, and energy resources, in terms of exergy.

Much like oil extraction, once you get to the peak of production the start of difficulties to deliver product become common place. These difficulties in production are more of an inefficiency rather than a genuine problem, resulting in stagnation in output. Then there is the downward slide of production on the back side of the peak. This same pattern will be observed in metal mining.
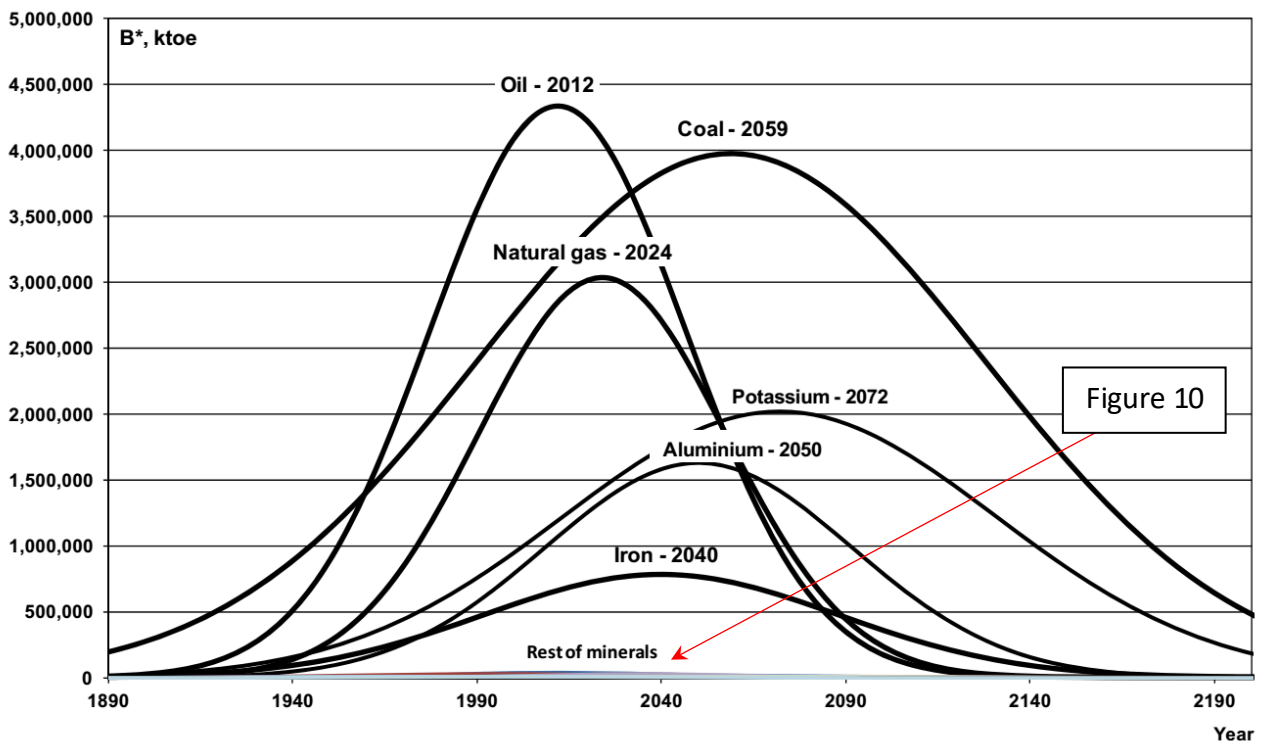
Figure 9. Metals and minerals raw material manufacturing landfill cycle – energy resources
(Source: Valero & Valero 2014 - A Thermodynamic Cradle-to-Cradle Assessment) (copyright granted)
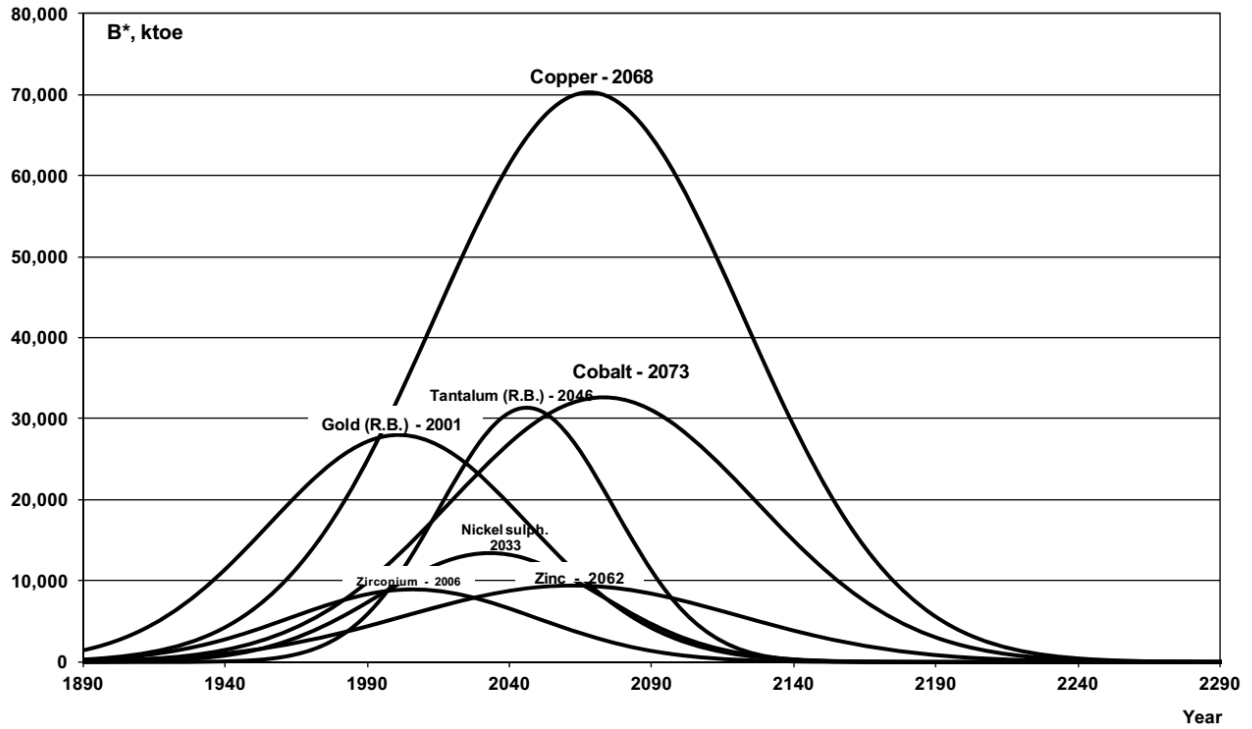
Figure 10. Metals and minerals raw material manufacturing landfill cycle – mineral resources
(Source: Valero & Valero 2014 - A Thermodynamic Cradle-to-Cradle Assessment) (copyright granted)

Figure 11 and Figure 12 shows the results of a study that examined existing reserves, deposit by deposit, in context of predicted future copper production. As can be observed, more copper deposits will be required to be discovered and a considerable size of copper content within a few decades.
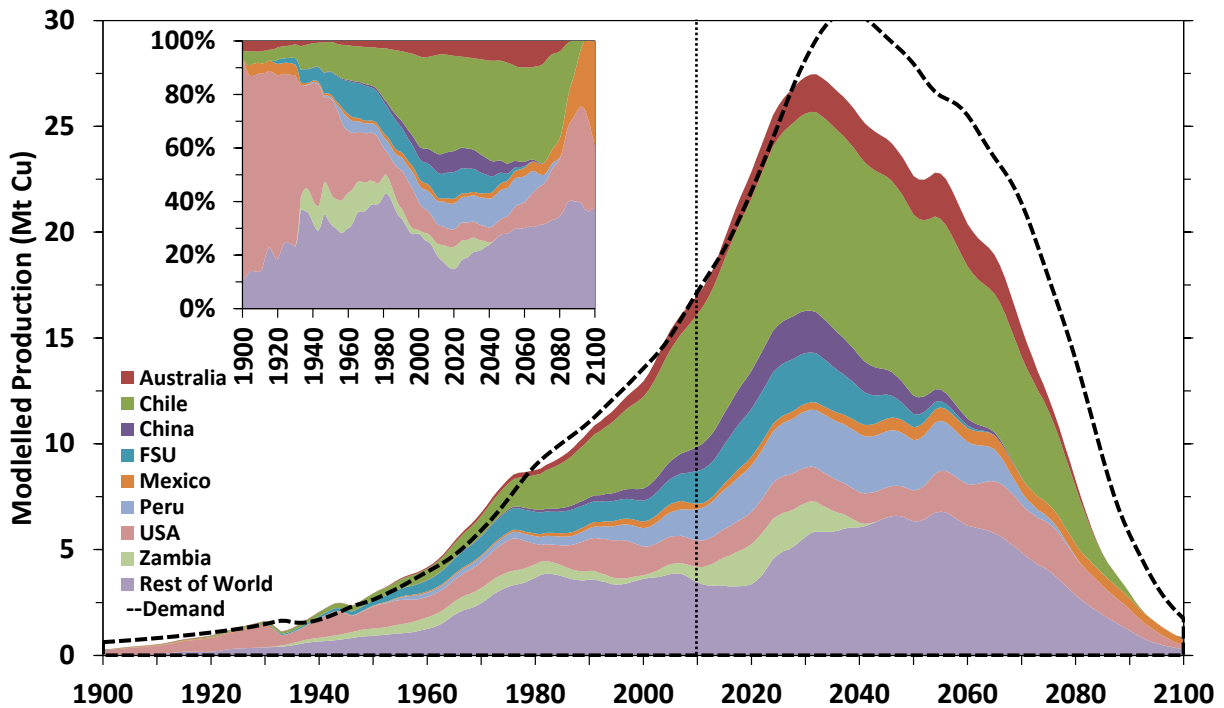
Figure 11. Peak copper production prediction Geologic Resources Supply-Demand Model (GeRS-DeMo) all producing countries summed
(Source: Northey et al 2013)
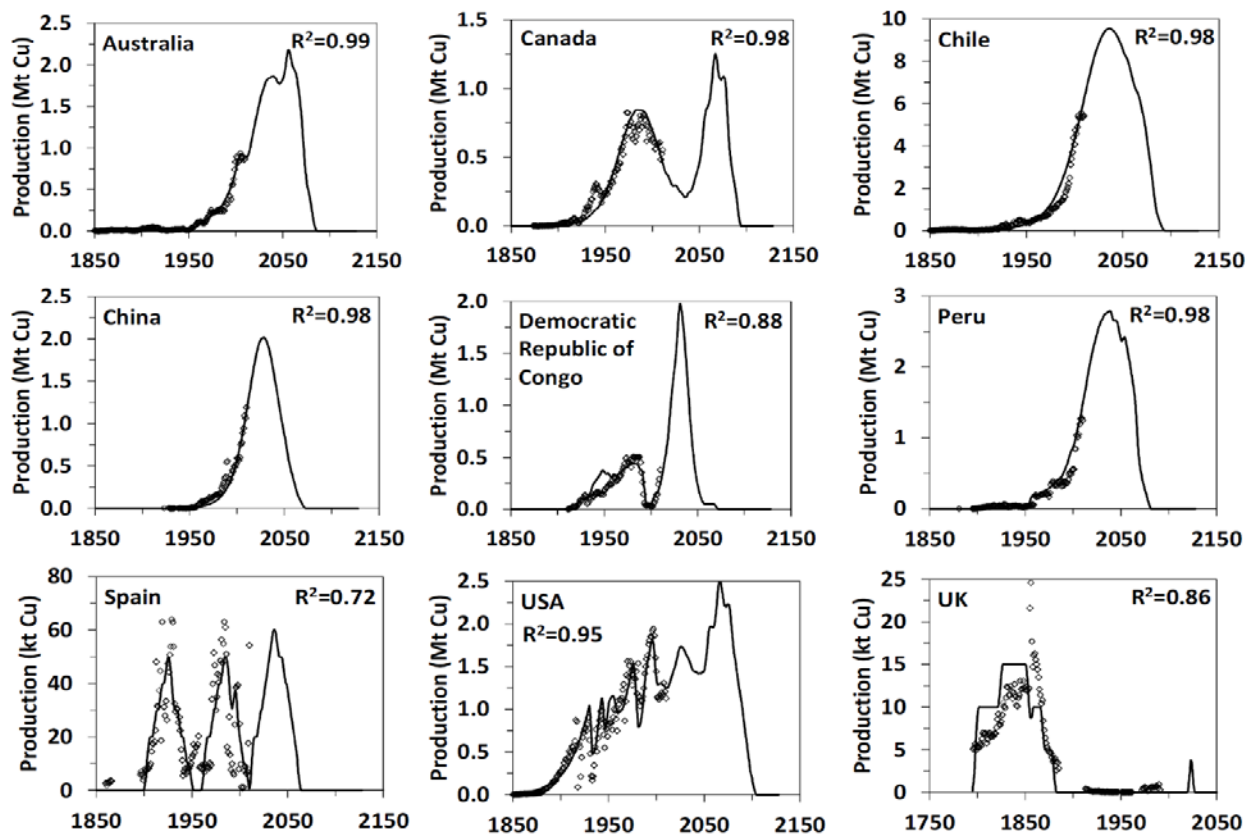
Figure 12. Peak copper production prediction Geologic Resources Supply-Demand Model (GeRS-DeMo) by country (Source: Northey et al 2013)

7   DECLINING MINERALS DISCOVERY

Mineral deposit discovery has been declining for many metals (Figure 13 to Figure 15). As demand has increased, all the large high grade, and easy to extract deposits have been found and mined out. It is getting harder to find new deposits to replace the ones being consumed. The full extent of this pattern across all industrial minerals is relatively unknown as the relevant data has not been complied into one dataset.
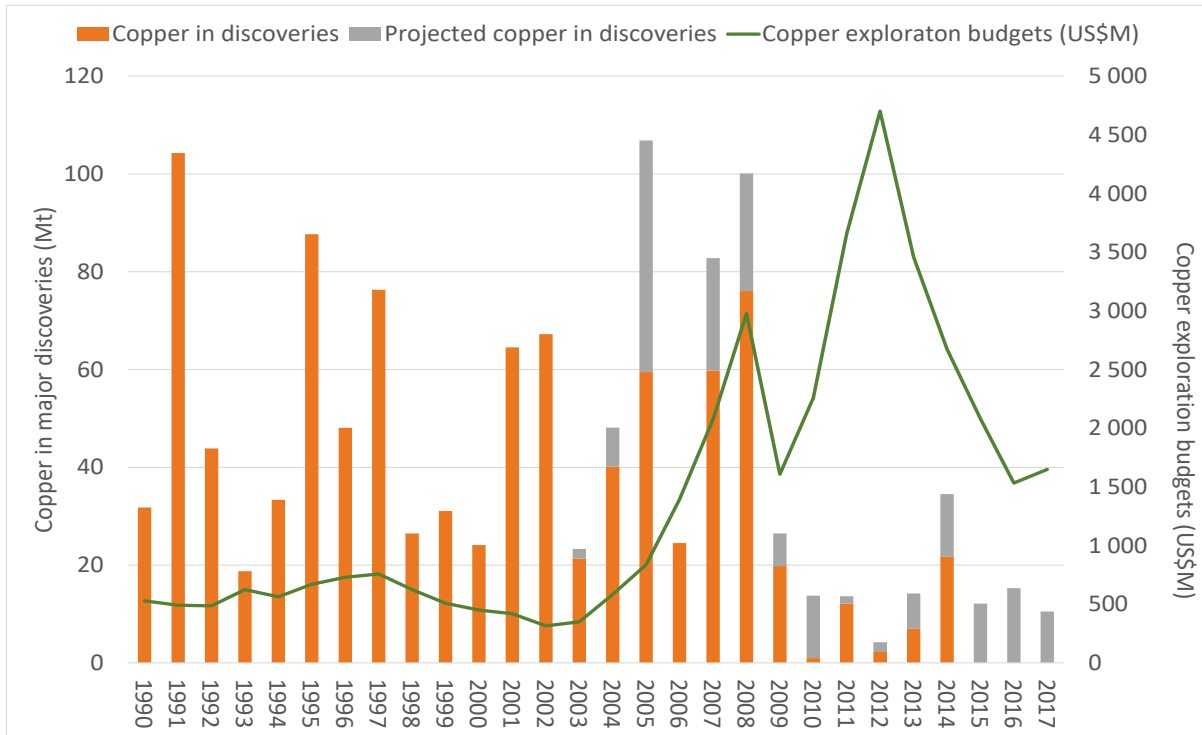
Figure 13. Copper in major discoveries by year, 1990-2017 (Data as of July 18, 2018)
(Source: S&P Global Market Intelligence)
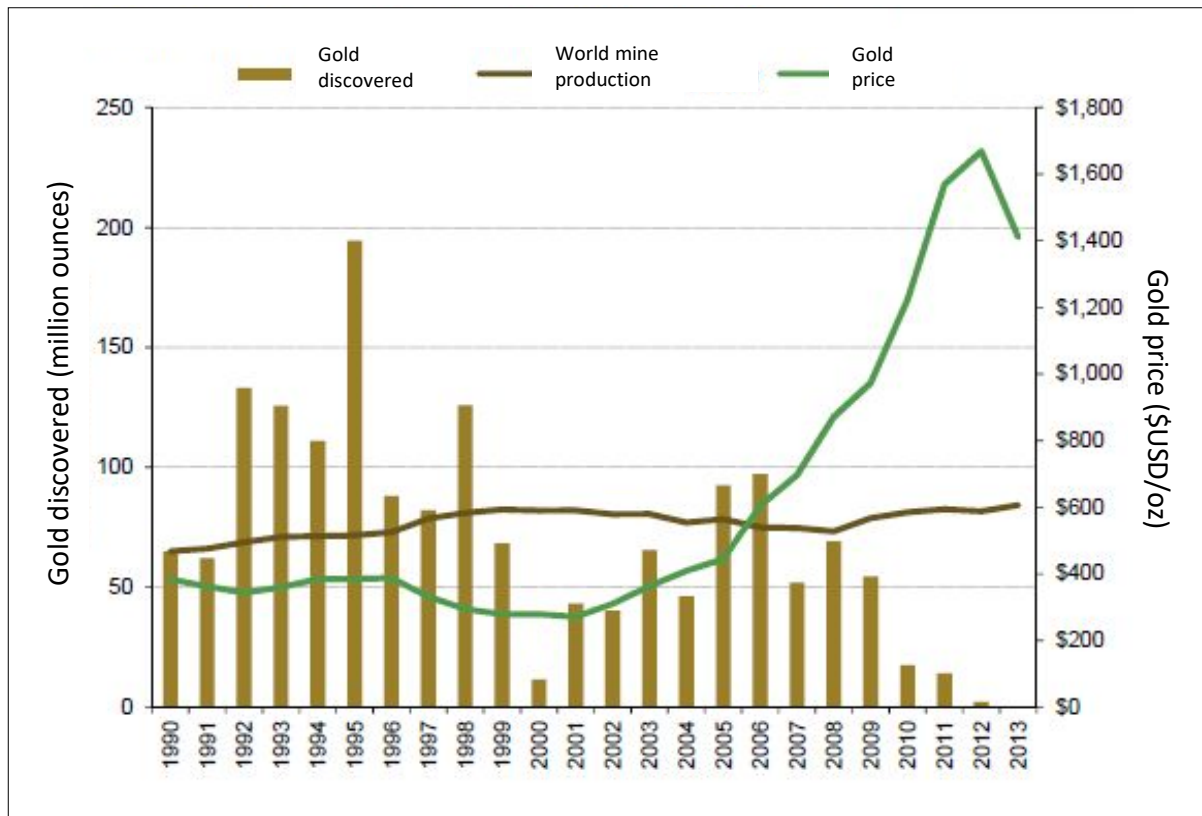
Figure 14. Gold discoveries, production and pricing 1990 to 2013 (Source: SNL Metals and Mining)
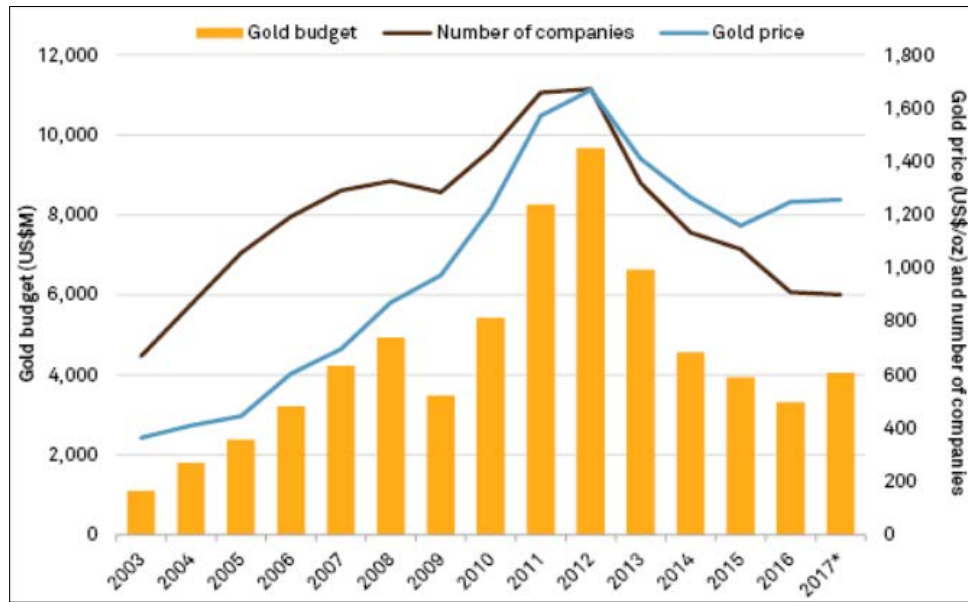
Figure 15. Gold exploration budgets 2003 to 2017 (Source: S&P Global market Intelligence)

Gold exploration budgets were at an all-time high in 2012, while discoveries were at an all-time low. The best gold discoveries are now years in the past.

8   DECREASING OF ORE GRADE

The grade of processed ore for many of the industrial metals has been decreasing over time (Figure 16 to Figure 18). This has the implication of the increase in mining energy consumption per unit of metal.
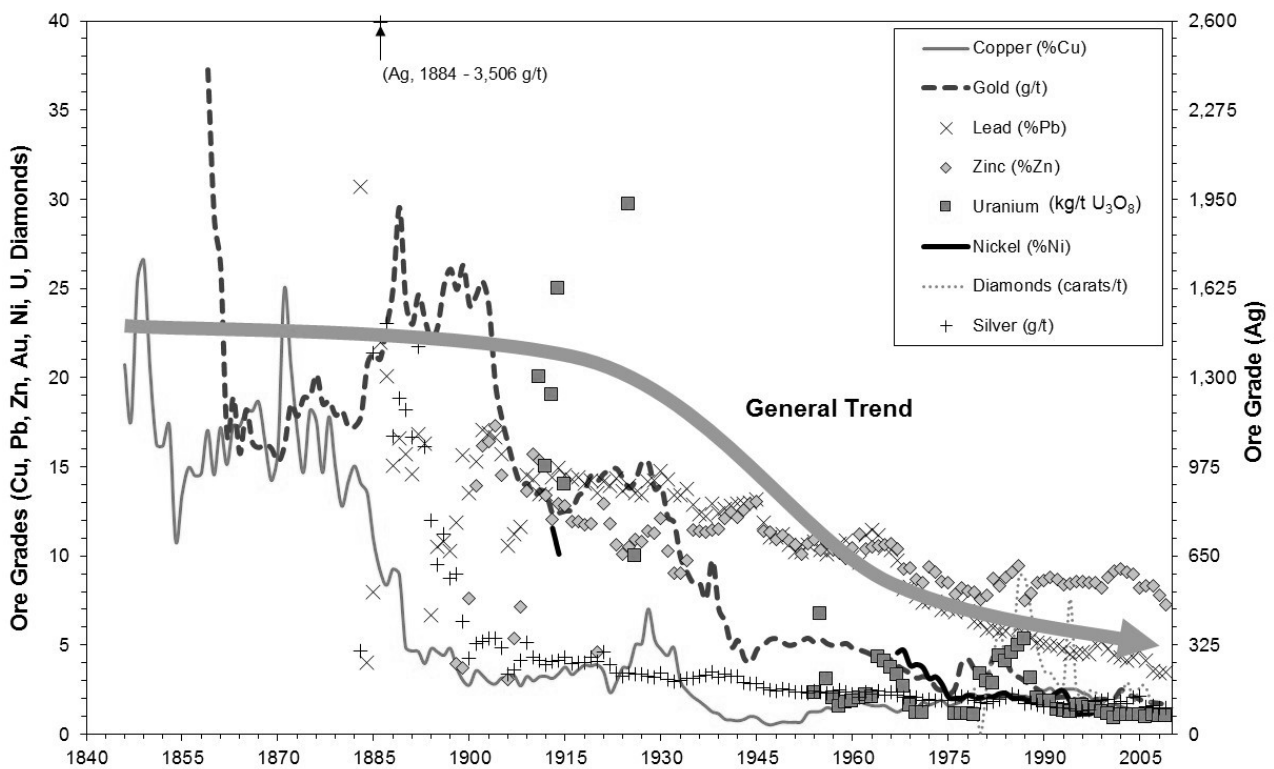
Figure 16. Grade of mined minerals has been decreasing (Source: Mudd 2009- updated 2012, Analyst- Gavin Mudd)

Gold-Barrick operations Nevada, Goldstrike & Cortez mines production & average gold yield
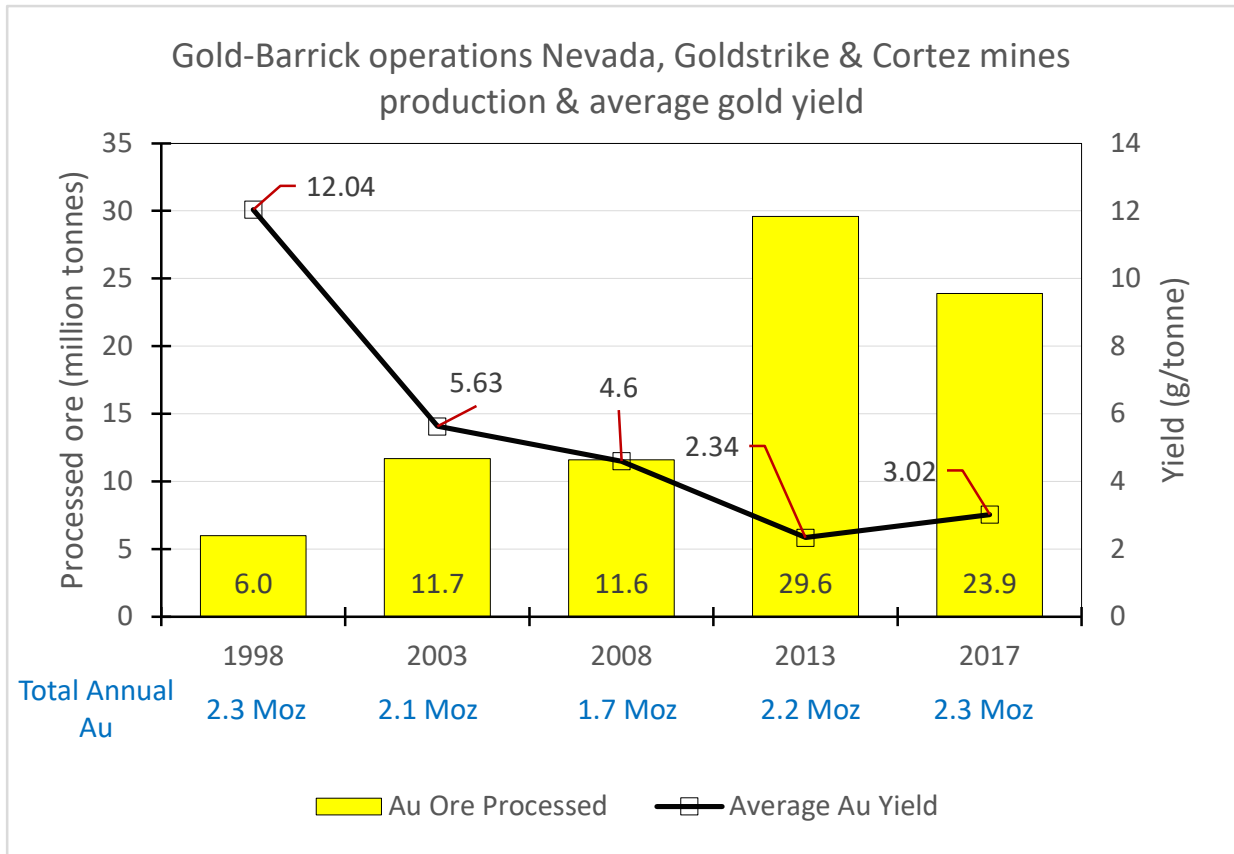
Figure 17. Gold-Barrick operations Nevada, Goldstrike & Cortez mines production & average gold yield (Source: SRSrocco Report)
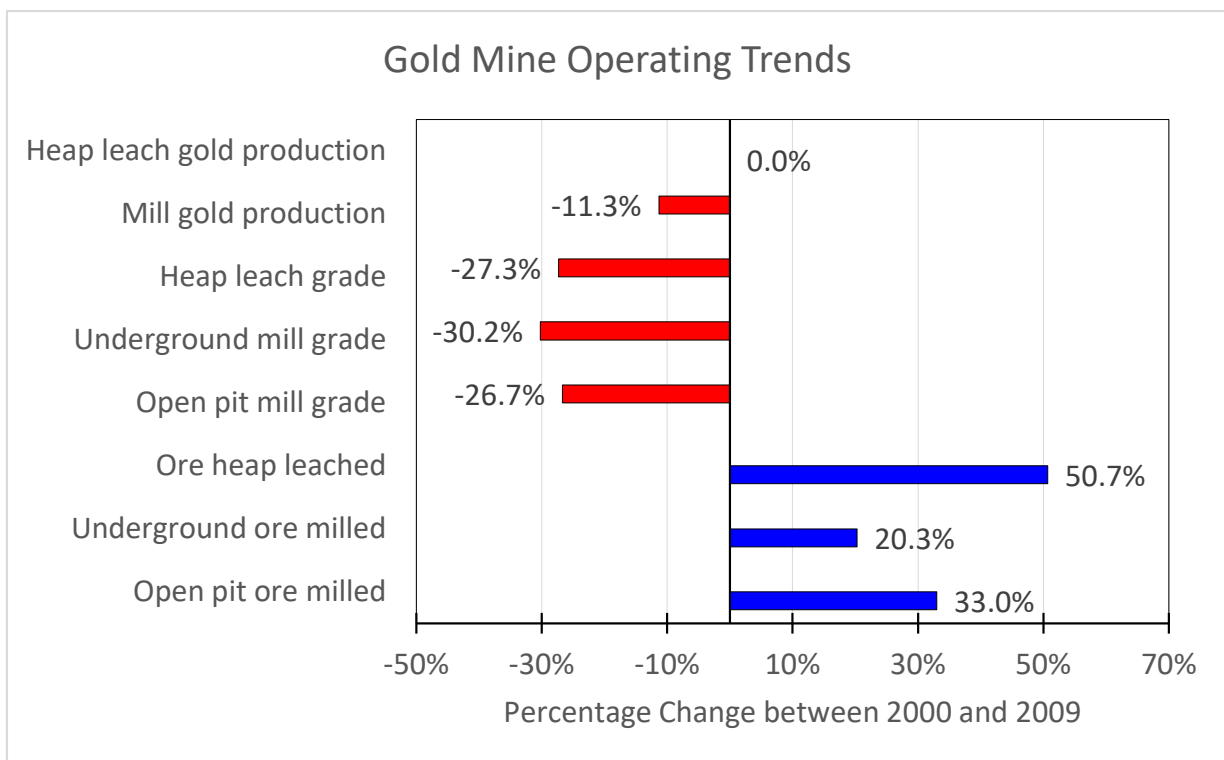
Figure 18. Gold mine operating trends (Source: redrawn from Brook Hunt Metals Cost Service Analysis 2011)

Figure 18 and Figure 19 show the problem of decreasing grade from an operational context. The volume of ore being processed increased between 20.3 to 50.7% between the years 2000 and 2009, gold production decreased -11.3% and 0.0%. Mill gold grade had decreased between -26.7 and -30.2%. During this operating period, an extra 12.1% of employee staff were employed. While productivity of volume of ore processed increased by 17.6%, actual gold metal productivity declined by 18.9%.
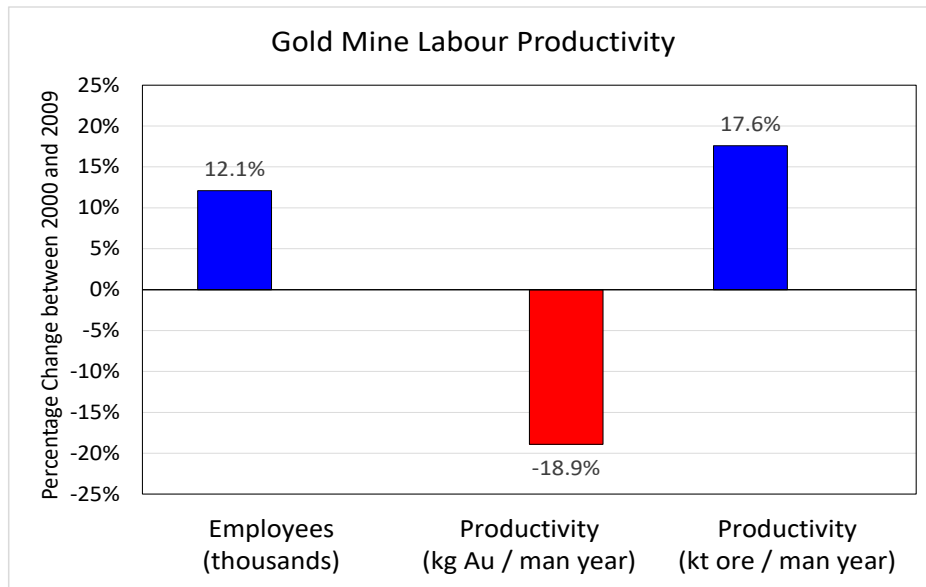
Figure 19. Gold mine labour productivity (Source: redrawn from Brook Hunt Metals Cost Service Analysis 2011)

The production metal yield of both gold (Figure 17) and silver (Figure 20) has been steadily declining.
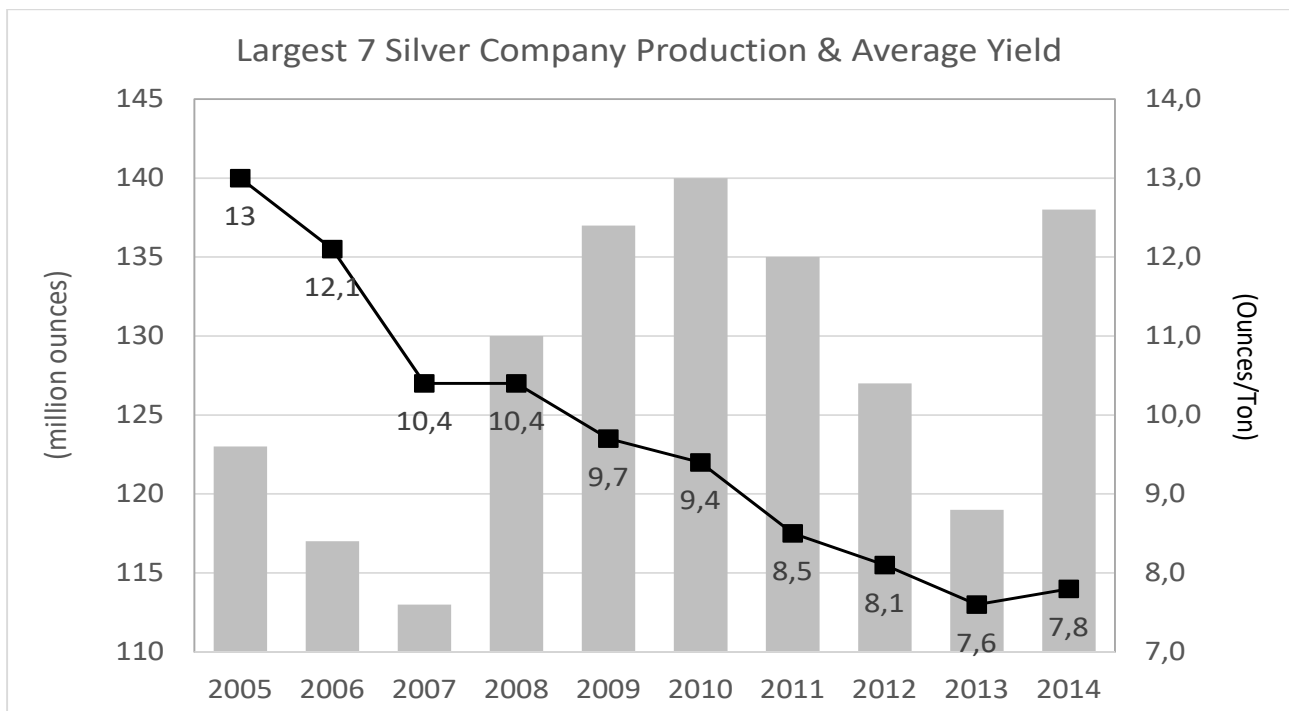
Figure 20. Decreasing efficiency of silver production (Source: SRSrocco Report)

Global peak silver production has already happened sometime between 1950 and the year 2000. 60% of all historical volume of silver has been mined since 1950 (Figure 21). The implications of the trend shown in Figure 16 to Figure 20 of decreasing grade is that more tonnes of ore needs to be mined for each unit of metal extracted. This drives the cost of mining up with each associated task, from drilling and blasting, excavation, haulage, crush and grinding and beneficiation (flotation or leaching).
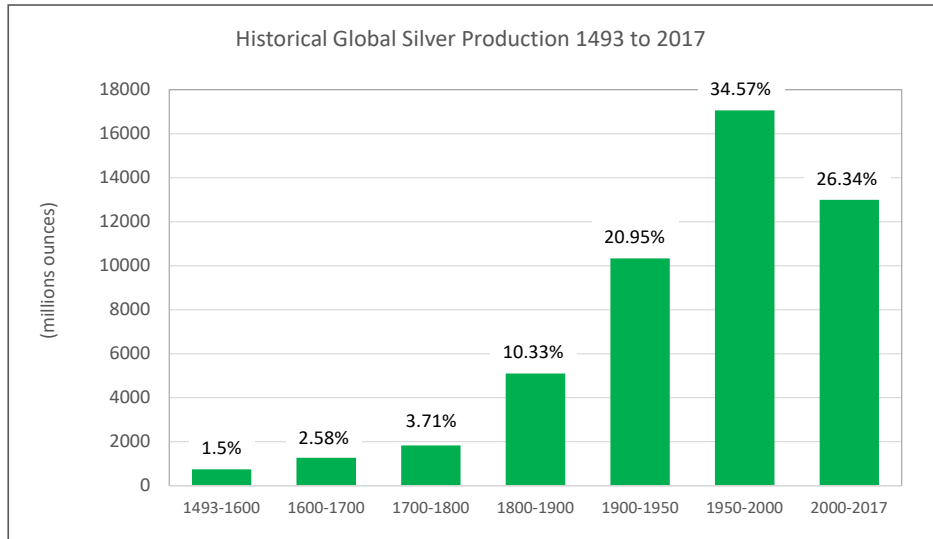
Figure 21. Historical global silver production 1493 to 2017 (Source: SRSrocco Report)
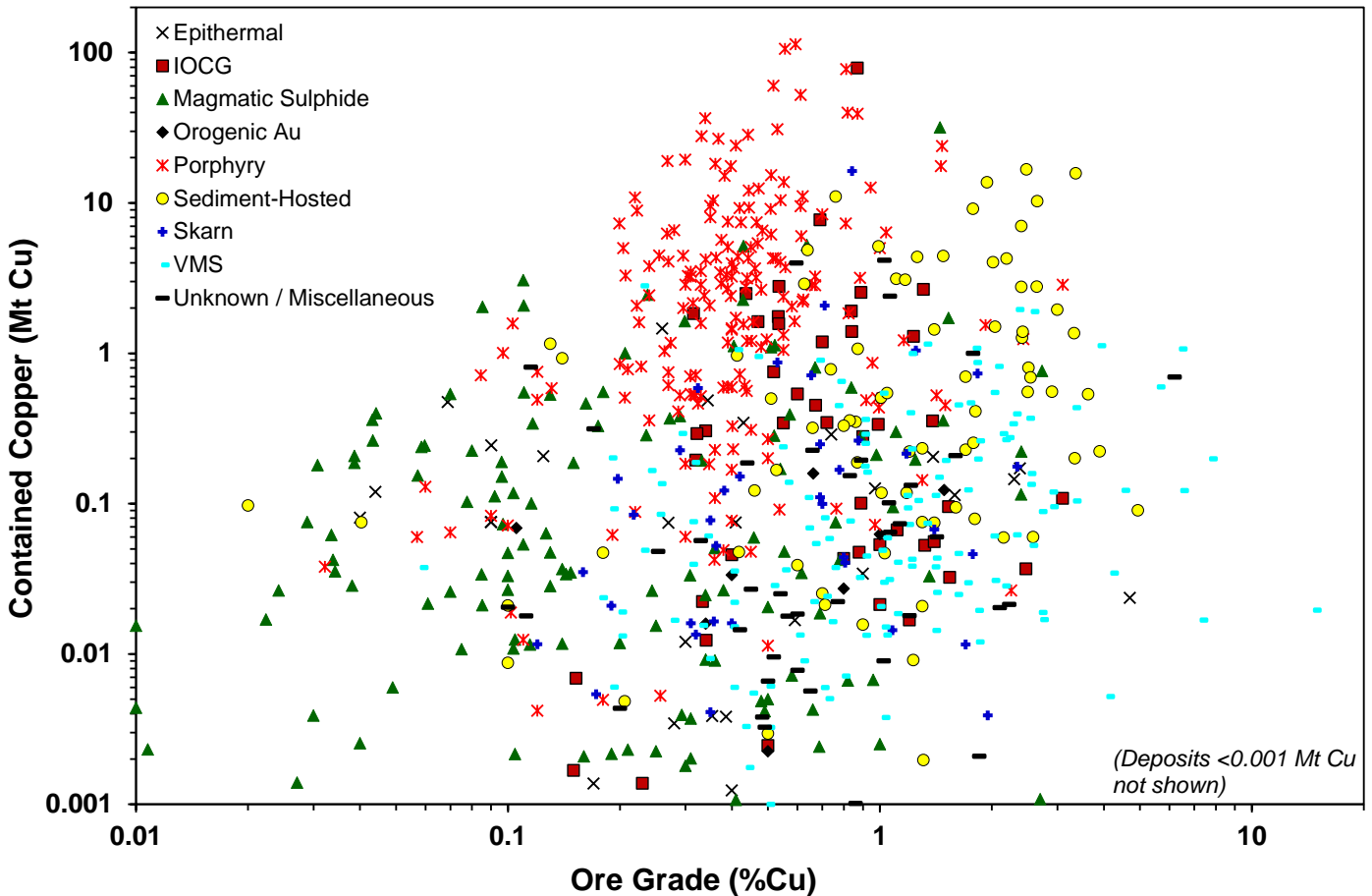
Figure 22. Global Copper Resources vs Grades (Source: Mudd et al 2013a)

Figure 22 shows a cross plot of how the different mineralogy's and lithologies present in context of copper grade vs. deposit size.

Figure 23 shows the current scientific thinking, how it is believed that the vast bulk of copper in mineralized form is in ore that is very low in grade, finely disseminated rock texture, with mineral grains that are very small (Source: Mudd et al 2013b). Far smaller than current grinding technology can liberate. This highlights the relationship between ore grade and mineral grain size.
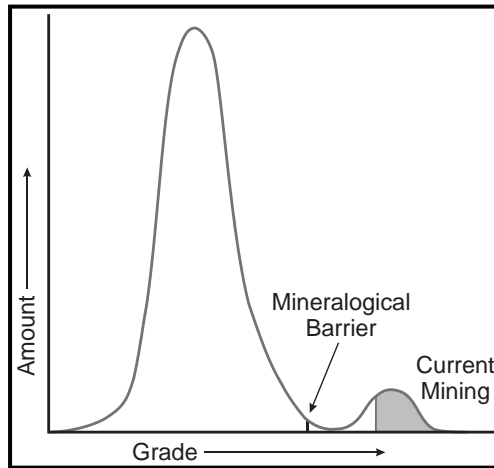
Figure 23. Most of copper ores are low grade finely disseminated textures (Source: Mudd et al 2013b)

There is an exponential relationship between ore grade and the tons of waste that needs to be excavated, per unit ton of metal produced (Figure 24). Again, this is driven by minerology.
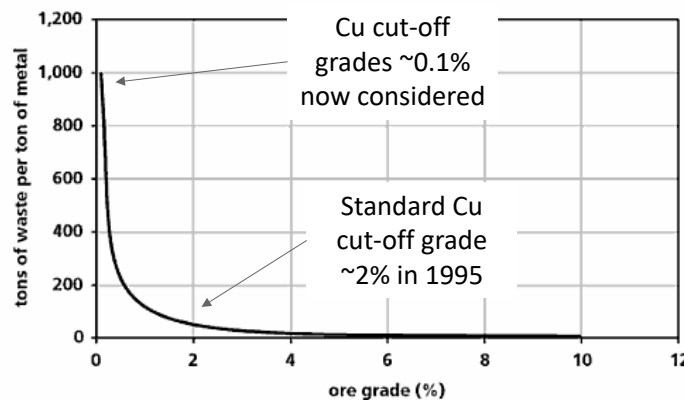
Figure 24. Ore grade vs. tons of waste per ton of metal, for copper ores in South America

What this means, is the cost of mining is being driven up, as each of the higher quality deposits are extracted and processed. In particular, the truck and shovel fleet in open pit mining is required to haul much more ore per unit of metal, resulting in an increase in diesel fuel consumption.

To put things in appropriate context, decreasing grade does not mean that the supply of copper in the ground is running out. It does mean that the supply of copper that is economical to extract is declining, forcing the production cost going up. It also makes mining very reliant on the energy (diesel fuel in particular).

What was considered ore in the year 2010 was considered overburden waste rock (due to grade being below cutoff) in the early 1900's. It could be argued that this was because it was not possible to extract the raw material under economic conditions. The long-term constant real copper prices reinforce this statement by showing that the industry have found a way to serve demand (using low grade ores) at reasonable prices. Therefore, the ore content alone is not suitable for making a statement about the availability of raw materials, but rather to show the enormous progress made by the technologies used (Rötzer & Schmidt 2018). That being stated, the next technological advance is required to become effective as soon as possible.

It could be shown that the exponential increase in the consumption of copper, for example, led to the mining of ever larger deposits, which often have lower ore grades (Rötzer & Schmidt 2018). New technologies have been developed to extract these deposits, and large shovel excavators and froth flotation, for example, have made it possible to use ores with a low concentration of metal. Technology has been used to apply economies of scale to meet increasing demand, while managing decreasing grades (Figure 25 to Figure 27).
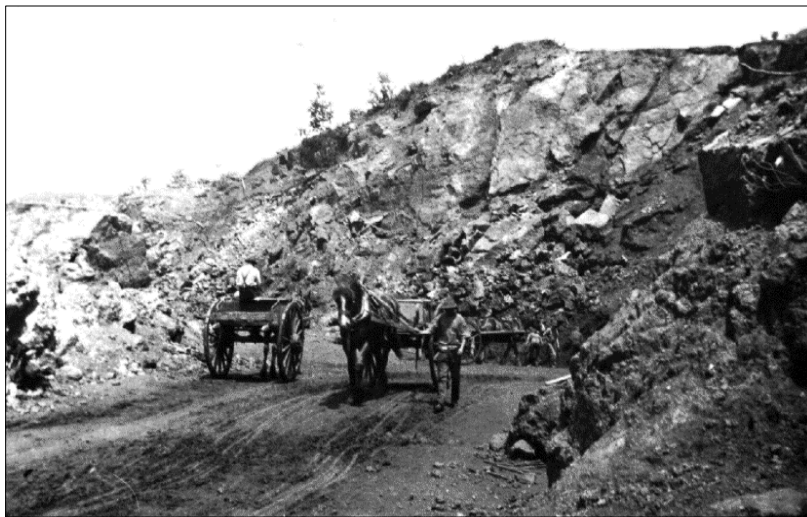
Figure 25. Excavated ore, was dug out with annual labor, and delivered by horse and cart to the process mill (Source: National Parks Survey 1972)

Figure 26. Open pit truck and shovel fleet (Image by DIEGO EFRAIN CADILLO TRUJILLO from Pixabay)

Figure 27. Mining haul truck (Source: Dee Bradshaw)

As can be seen, the scale of the whole enterprise has gotten larger and more expensive. In 2013, a large process plant had a capacity annual throughput of something like 50 million tonnes of ore, where a small one had only 10 million tonnes a year. In 2013, the typical installed grinding power was of the something like 28 MW. In 1940, the typical installed grinding power was of the something like ½ MW. The size of a standard haulage truck had the carrying capacity of 280 tonnes of ore per load. In 1940, the standard haulage truck was closer to 10 tonnes carrying capacity.

The industry is very far from running out of copper deposits. Large portions of the Andes mountain range in South America is one massive copper deposit of extremely low grade. Parts of this massive system is higher grade than others, which are economical to mine, where most of it is not. While copper market can sustain an increasing copper price as a consequence of the cost of production, and the consumable materials are still available (diesel fuel for example), then there will not be a shortage of copper. When the costs of mining become too high, or supply of a vital consumable becomes unreliable, then that all changes.

9   MINERAL PROCESSING PLANT GRIND SIZE IS DECREASING

Another pattern that has been observed over a period of decades has been a decreasing grind size (also called comminution plant closing size) in operating mines. This is related to the mineralogy of the ores being process. Most of the easy to process ore deposits have been mined out and now it is standard practice to process ores with more challenging rock textures.

Comminution is the process engineering term for rock breakage and is the reduction of mineralized ore from one average particle size to a smaller average particle size, by crushing, grinding, or other processes. The process of size reduction through comminution is important as it has economic significance. Curry *et al*. (2014) found that the mill (defined as crushing, grinding and separation) typically accounts for between 35 and 50 per cent of the total mine costs. This is the particle size (expressed as a P_{80}, or particle size that 80% of the sample is smaller than) to which all samples for process separation a milled down in size through grinding. The finer the required closing size, the more expensive and complex the comminution processing plant needs to be (Figure 28).

Figure 28. A mineral processing plant in the Southern Hemisphere (Source: Dee Bradshaw)

The comminution plant closing grind size is directly related to the mineral texture of the ore, and the average mineral grain size containing the valuable metal.   If the target minerals are very small in grain size or are embedded in complex rock texture, then the ore is required to subject to size reduction through grinding, until enough of the target valuable mineral is exposed on particle surfaces for separation process like flotation to work. Figure 29 shows the possible difference in rock texture at similar grades. Each example in Figure 29 would have a different recovery and would need to be reduced to different grind size for full liberation.

Figure 29. Different rock textures, each would have a different process recovery (Source and copyright: Cropp 2013)

The process of comminution is to subject the sample to size reduction. The particle size required for the effective liberation of the target mineral is defined by the mineralogy. For each mineral in the sample, there would be a range of mineral grain size distribution. For process separation to economically effective, enough of those particles have to be liberated or partially liberated (Figure 30).
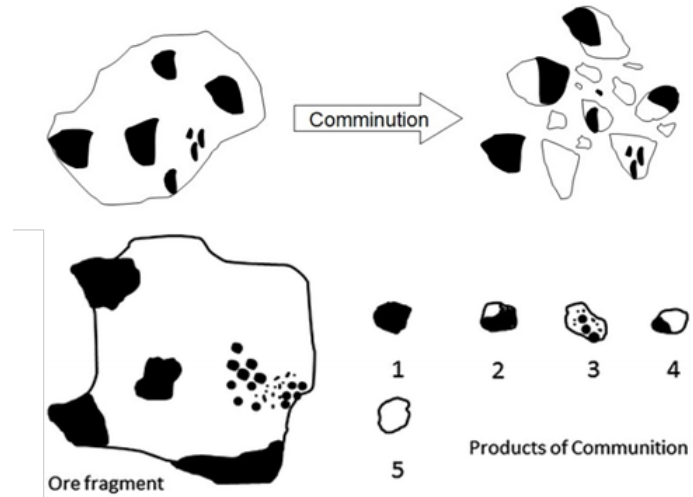
Figure 30. Particle size reduction through comminution and liberation of target minerals
(Image: Napier-Munn et al 1996, Copyright: JKMRC)

The size reduction to energy relationship is not linear though. The finer the grind size, the exponentially larger energy required to comminute the ore to that size (Ballantyne & Powell 2014 and Hukki 1961) (Figure 31).
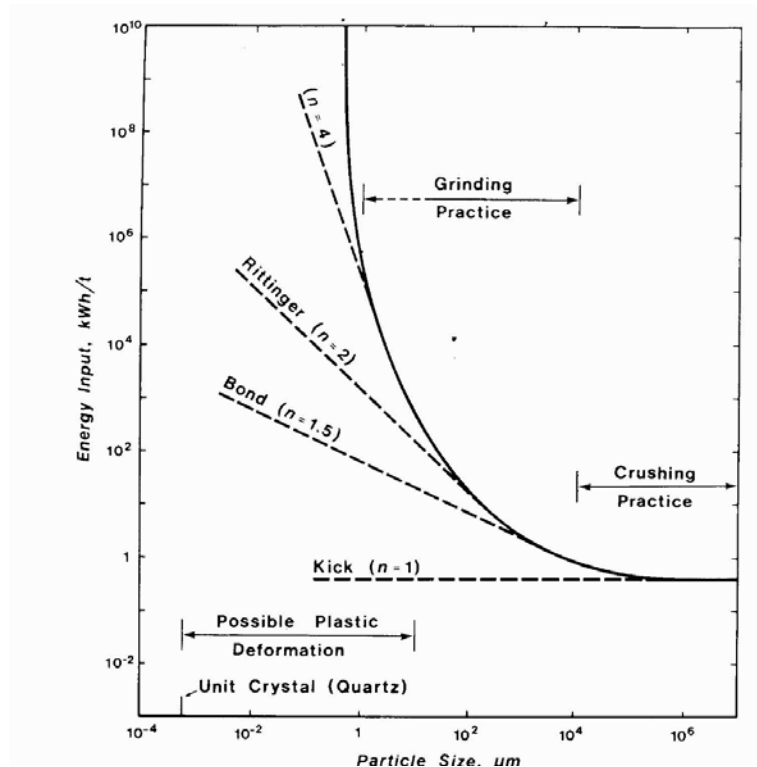
Figure 31. The Hukki energy size relationship shown as an imaginary example of the basic reduction characteristic plotted on logarithmic paper. (Source: Hukki 1961)

The implications of Figure 31 are that the finer the closing grind size, which is dictated by ore mineralogy and texture, the exponentially higher increase in energy requirements to grind that ore to that size. The tradeoff between the cost of comminution to the target grind size and the degree of liberation and texture of the valuable mineral particles has to be considered carefully.

A century ago, most ores being mined had mineral grains much larger than what is considered normal in 2021. In 1980, a sulfide mineral grain size requiring a plant grind closing size of 150 µm was considered typical. Currently, a plant grind closing size of 4 to 5 µm is now economically viable. This change has been driven by a change in ore texture regarding what has been considered economically viable (Figure 32).

Target ore P$_{80}$ = 150µm   Target ore P$_{80}$ = 4µm
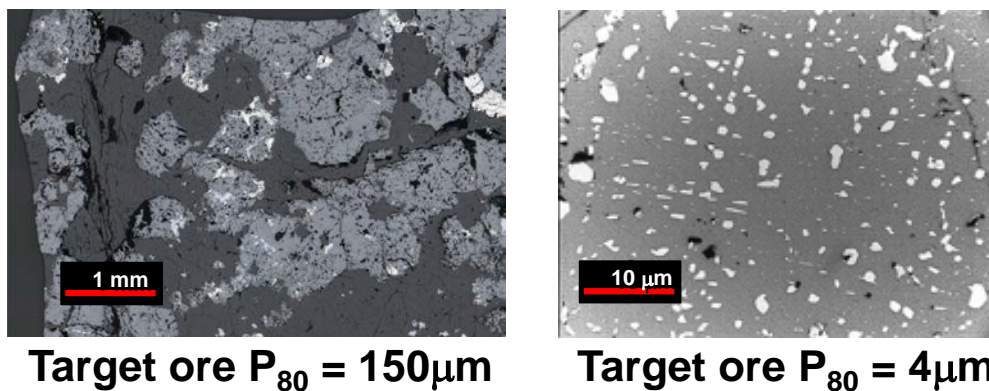
Figure 32. Two different Zn-Pb-Ag mineralogy's, resulting in two different plant grind sizes (Source: Dee Bradshaw)

As a broad pattern that can be seen over an extended period of decades, the ore's being processed have had increasingly smaller grind sizes to be economically viable. This has been one of the factors increasing energy consumption and the cost of mining.
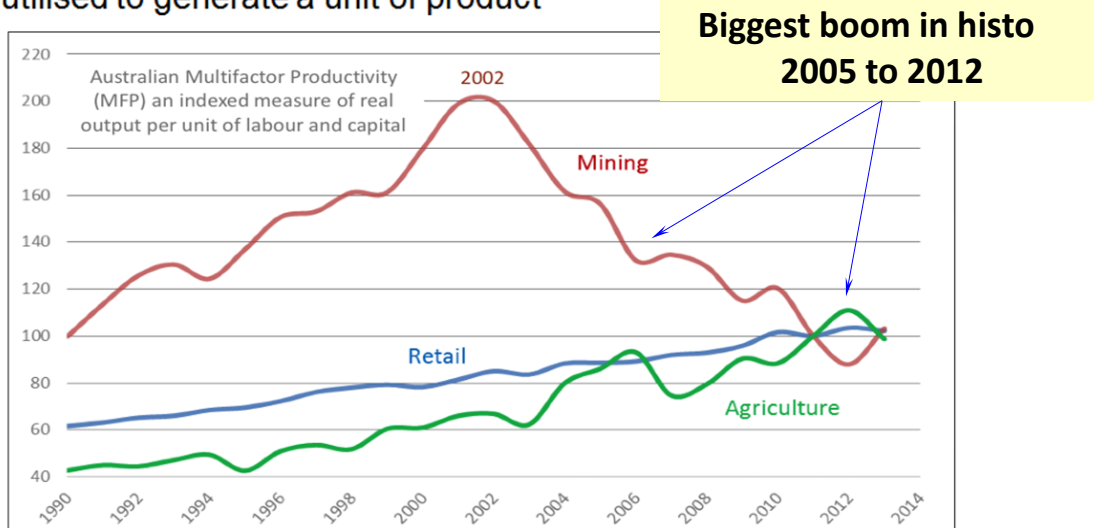
Figure 33. The Australian multifactor productivity index for the mining sector has been declining (Source: ABS 2015 Australian Bureau of Statistics)

Figure 33 shows a possible outcome of this at a regional scale. The Australian multifactor productivity index steadily declined from the year 2001, in spite of the Australian mining industry working to reverse this trend.

The Multifactor productivity index (MFP) is defined as output per unit of combined inputs. Combined inputs typically include labor and capital, but can be expanded to include energy, materials, and services. Figure 35 shows a 53% decrease in Multifactor Productivity between 2001 to 2012. This means that in 11 years, as steady increase in mining cost happened, where 53% more measurable work had to be done to produce the same unit mass of metal. What is interesting, is that the biggest mining boom in Australian mining history happened between the years 2005 and 2011, yet the MFP index continued to consistently decrease. The same pattern can be observed in South Africa and South America.

Something fundamental changed in the business model for the mining industry around the year 2001. What this was has not been clear. It could have been the technological advancement that made fine grinding economically viable. In 1999, there was a technological breakthrough. The IsaMill was released into the marketplace, which was a fine grinding mill that could reliably grind ore down to 10 mm (Gao *et al* 2002).

It then became economically viable to extract very fine grained ore types, which were much more commonplace. Starting in 1999, more and more mining operations procured and commissioned fine grinding mills and operated mines with very complex ore textures (Figure 34). Since then, other technologies have been developed. There was a short transitionary time period (late 1990's to the early 2000's), where conventional ball mills were tried to produce very fine closing sizes. Very quickly, it became apparent this was not very efficient and fine grinding took over.

The author hypothesizes, that from that point onwards, the business model behind mining changed, and the costs of mining started in increase. This would not be just energy consumption, but quantity of ore processed as well. This could be why the peak in the MPF was seen in 2001, and why it steadily declined from that point.
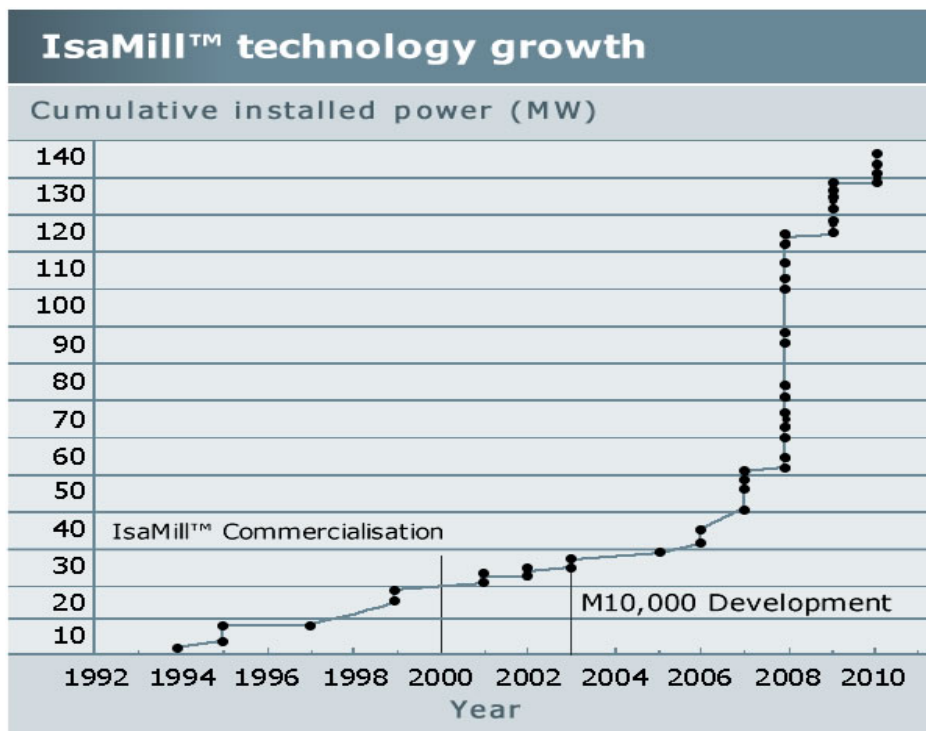
Figure 34. Cumulative installed power for commissioned IsaMill fine grinding units (Source: IsaMill)

10 ORE IS GETTING HARDER TO CRUSH AND GRIND

Ore has also been getting harder to break over the last few decades. This has a direct outcome of requiring more power draw (energy) to break the rock.

The mining's industry standard to measure rock hardness is a rock breakage test called the Drop Weight Test (or Drop Test). The Drop Test was developed by the JKMRC (Julius Kruttschnitt Mineral Research Centre) to model the rock breakage process in comminution machines (Figure 35). JKMRC comminution models are based on two sets of parameters (Napier-Munn *et al* 1996).

As the JKMRC methods aspired to model the ore characteristics separately from the processing machine characteristics, these parameters were to be measured independently. To be useful, these parameters needed to be experimentally measured in a way that the simulation models can exploit. The Drop Test has been the most successful way to characterize the high energy impact of mineralized ore this to date.
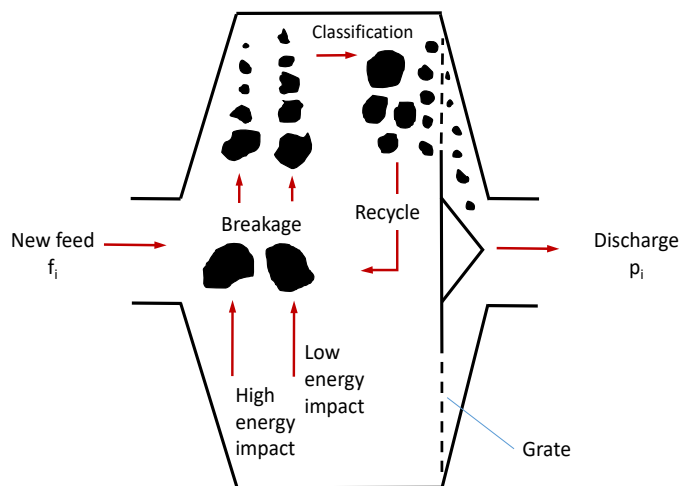
Figure 35. (LHS) SAG Mill at Ministro Hales, Chile
(Source: Codelco Flickr https://www.flickr.com/photos/codelco/36380894030/in/album-72157684452320742/)
(RHS) Schematic diagram of AG/SAG mill process mechanisms (Source: Napier-Munn et al 1996, copyright: JKMRC)

The objective of the Drop Test is to characterize the resistance to size reduction an ore has over a range of applied energies by measuring an energy breakage curve used for comminution engineering. Individual breakage events (points on the energy breakage curve) can be expressed as a specific comminution energy level, Ecs (kWh/t), or as breakage or appearance functions.
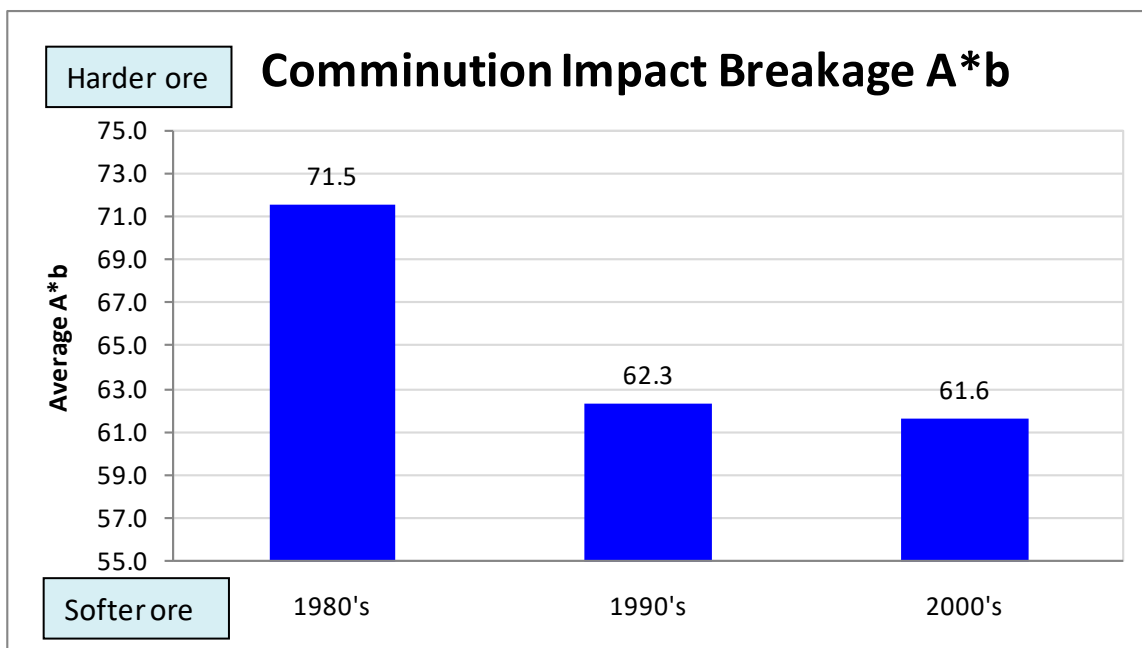
Figure 36. Comminution impact breakage summary of the JKTech database in 2012, of approximately 3 000 DWT tests (Source: Simon Michaux)

Figure 36 shows a summary of the measured A*b impact breakage parameter, from the JKTech data base of approximately 3000 Drop Weight Tests. These tests were measured between 1980 and 2010. Each column represents the average for the decade shown. The higher the number, the softer the rock that was measured. Conversely, the lower the number, the harder the rock. As can be seen in Figure 36, ore being processed in mines has been getting harder.

Over time, mines being opened have been processing different rock textures, which happen to be low grade ore with finely disseminated target minerals (very small mineral grain size). As it happens this kind of rock texture happens to be much harder to break. This has been one of the contributing factors increasing energy costs, and mining costs in general.

11   MINING WATER CONSUMPTION IS INCREASING

Potable water consumption in mining has also been increasing both in volume and per unit mass of metal produced. While mining is not the largest consumer of potable water, where industrial agriculture is the primary application (Figure 37). Mining consumption is included into the Industrial Use category. Nevertheless, an increase in water requirements at all will eventually become a sustainable development problem to resolve. Global water use in the year 2000 was divided as follow:

- 70% Agriculture
- 22% Industry
- 8% Domestic

World water use by economic sector (km³/year) (Shiklomanov 2000)
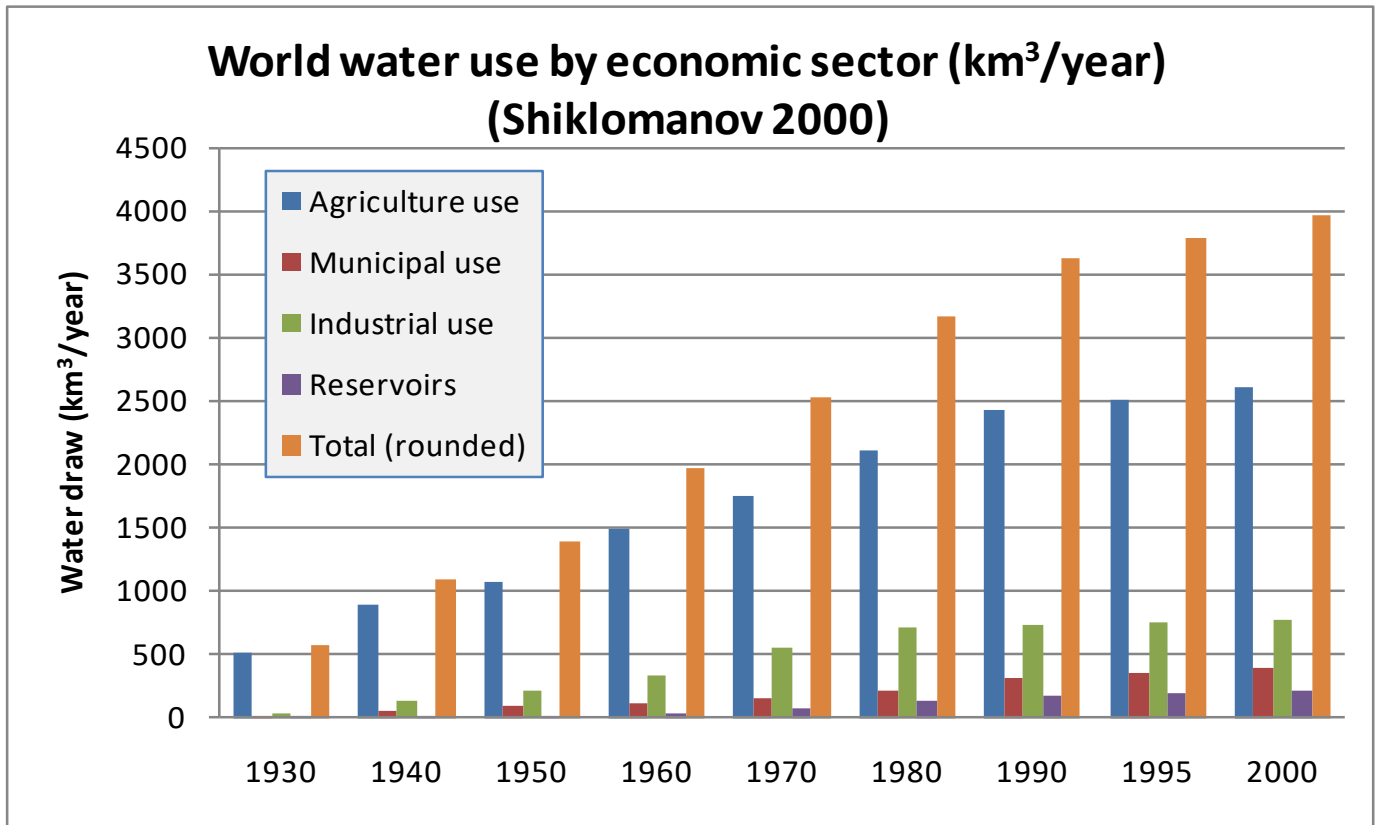
Figure 37. World water use by economic sector (Source: Shiklomanov 2000)

The issue with any increase in water consumption is related to the perceived water scarcity that exists already, let alone what may happen in the future with more human population and a deteriorating environment (Figure 38 and Guppy & Anderson 2017). Without altering current levels of water consumption and pollution, almost half of the world's population will suffer severe water stress by 2030, damaging the well-being of millions of people (UNEP 2016 and IRP 2016).   Under current trends, demand for water will exceed supply by 40 per cent in 2030, which will force governments to spend $200 billion per year on upstream water supply as demand outstrips cheaper forms of supply.

Global water consumption is approximately 500,000 liters of freshwater per person every year (IRP 2016). In 2016, one billion people lacked access to safe drinking water, and 2.4 billion people did not have access to adequate sanitation (Guppy & Anderson 2017).

Of the World's total water supply, 97% is seawater and of the remaining, less than 0.5% is usable unpolluted clean water. The amount of fresh water supply provided by the hydrological cycle does not increase. Water everywhere on the planet is an integral part of the hydrologic cycle.

Many major rivers: Colorado, Ganges, Indus, Rio Grande and Yellow are so over-tapped that they now run dry for part of the year (IRP 2016). Freshwater wetland has shrunk by about half worldwide between 1930 and 2000 (Shiklomanov 2000).

In the Western Society, we take water for granted. Most people don't actually think about the supply of water. Water access is easy to ignore provided you can still turn on a tap and water comes out. We still have the same amount of water in our ecosystem, but the supply of freshwater faces a three-pronged attack from population growth, climate change and industrialization. As it currently stands, there's not enough water to go around (Figure 39).

There has been a **55%** drop in globally available fresh water per capita since 1960[11]

By 2030, global demand for water is expected to grow by **50%**[12]

Water scarcity currently affects more than **40%** of the global population[13]

By 2050, an additional **2.3 billion** people can be expected to be living in areas with severe waterstress, especially in North and South Africa and South and Central Asia[14]

Agriculture accounts for **70%** of all water withdrawals globally and for over **90%** in the majority of Least Developed Countries (LDCs)...[15] and **70%** more food will be needed by 2050[16]

Water scarcity, exacerbated by climate change, could cost some regions up to **6% of their GDP**[17]

The 5th assessment of the Intergovernmental Panel on Climate Change (IPCC) projects that for each degree of global warming, approximately **7%** of the global population will be exposed to a decrease of renewable water resources of at least **20%**[18]

Worldwide, the total cost of water insecurity to the global economy is estimated at **US$500 billion** annually. Including environmental impacts, this figure may rise to **1%** of global gross domestic product (GDP)[19]

Figure 38. Global water consumption increase (Guppy & Anderson 2017)
(Copyright: https://www.unep-wcmc.org/terms-and-conditions)

Little or no water scarcity
Physical water scarcity
Approaching physical water scarcity
Economic water scarcity
Not estimated
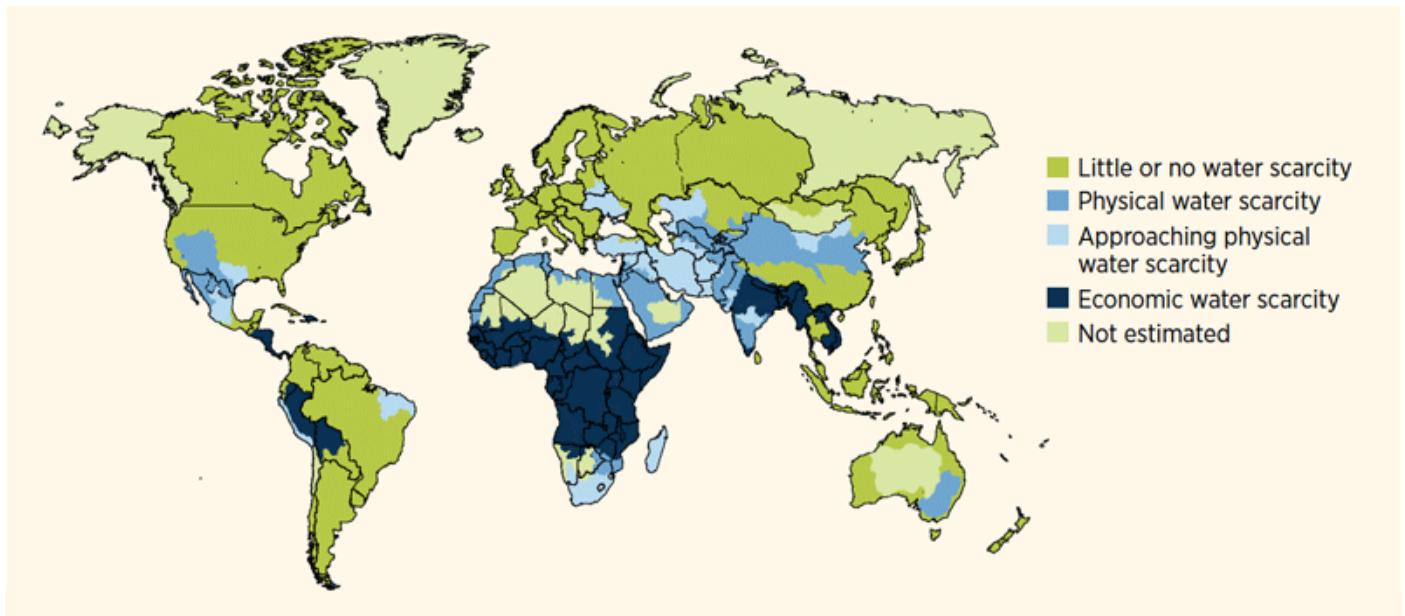
Figure 39. Global physical and economic water scarcity
(Source: World Water Development Report 4. World Water Assessment Programme (WWAP), March 2012)

The same paradigm of unawareness of potable water supply is within many parts industrial culture and is reflected in development in the industrial ecosystem. Development of industrial sites with high potable water volume requirements will increasingly conflict with the needs of the growing population.

Figure 40 shows a project developed to predict mining water use in Australia until the year 2050. As can be observed potable water consumption is predicted to increase, with bulk commodities accounted for most of the demand. The other metal ores (copper, gold, etc.) is a small proportion but will still increase.
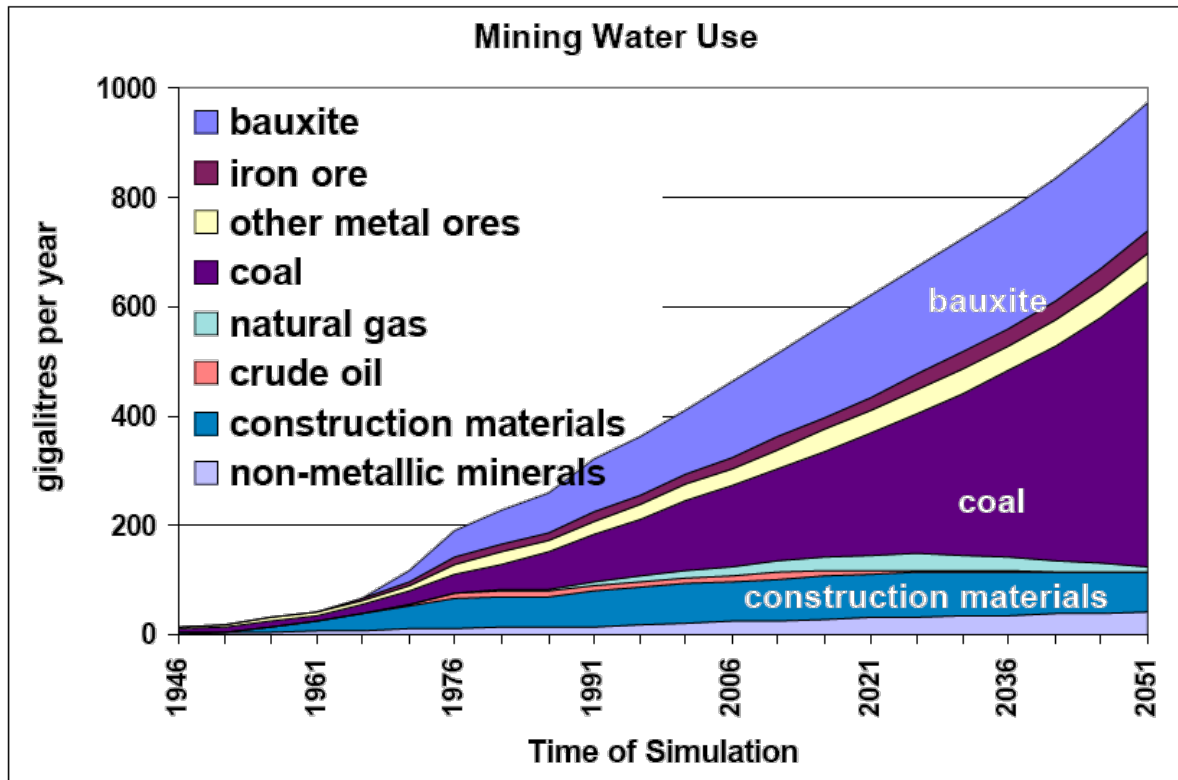
Figure 40. Total water required in gigalitres (10^9 liter) per year, in the base case scenario to 2050 for requirements of mining (Source: Foran & Poldy 2002)
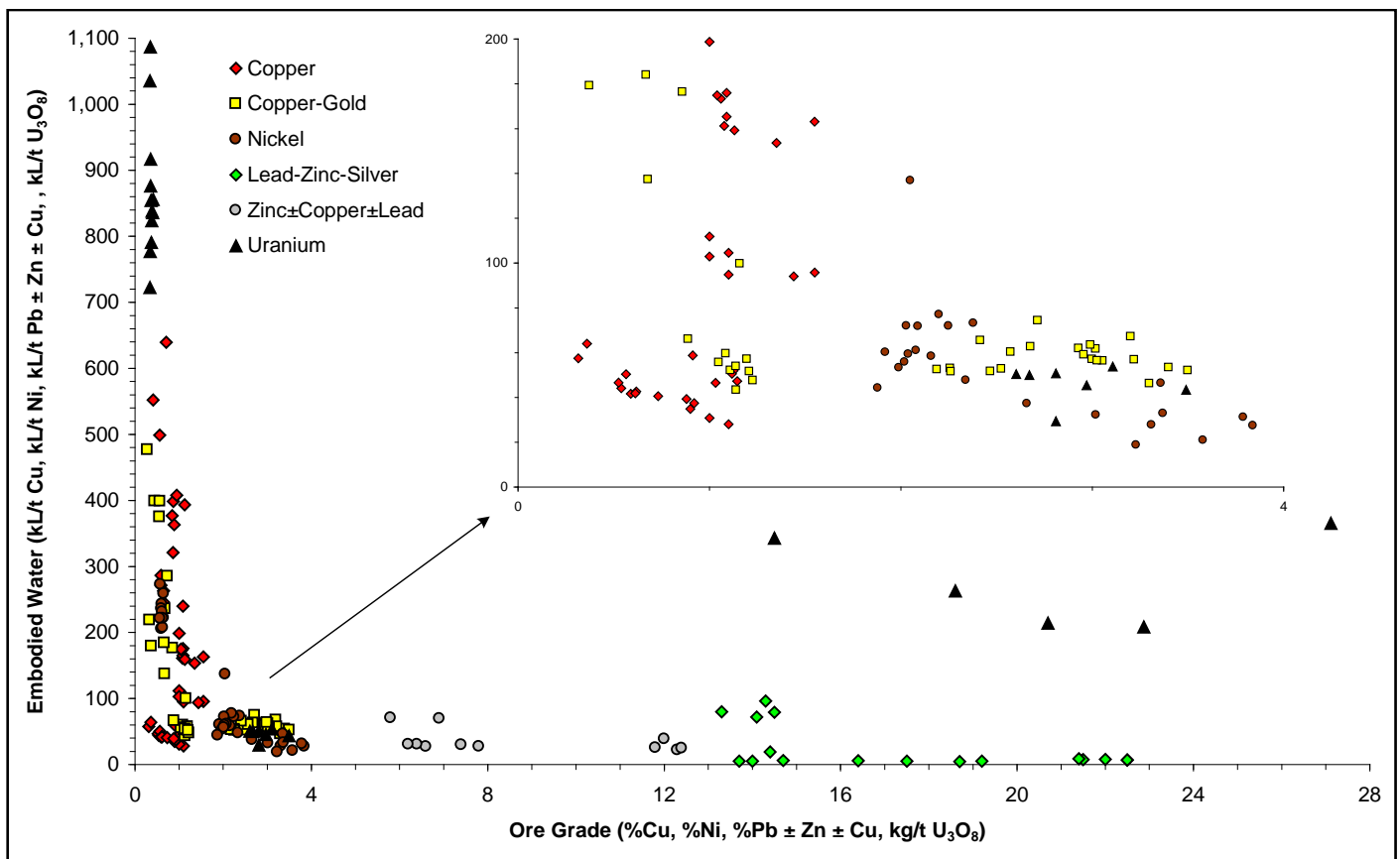
Figure 41. Water required by ore processing vs. ore grade in Australian mining industry (Source: Mudd 2011)

Figure 41 shows how the required volume of potable water to produce a tonne of metal, compared to ore grade. There is an inverse exponential relationship with water consumption and ore grade. What is driving this is low grade ore is usually also disseminated very fine mineral grains. This means that the ore has to be ground very fine (See Section 8). Grinding is a wet process and some of that water can be recycled. When the ore has been ground to a fine size, it is much more difficult to recycle the water as the slurry particles takes a long time to settle out in a thickener tank. This results in more water being consumed per unit of metal produced.

Currently potable water consumption is a design cost for process plant design. In areas like Canada, or on the Nordic Frontier (Finland, Sweden, Norway, Greenland, Denmark, and Iceland), potable water availability is not an issue. Conversely, in parts of Africa, South America, Central Asia and Australia, potable water supply is expensive and is managed carefully. These regions are where much of global mining is conducted. Any increase in water demand in these regions could make mining operations unviable.

12   PRODUCTION OF MINING WASTE IS INCREASING

Demand for metals of all kinds have been increasing, just as the grade of ores processed has been decreasing. The outcome of the combination of these two trends, is the massive increase in the generation of mining waste, both process tailings and overburden waste rock. There will come a point when this cannot happen in the way it has for the last 50 to 100 years. Figure 42 shows how the volume of waste rock has increased in Australia between 1898 and 2012.
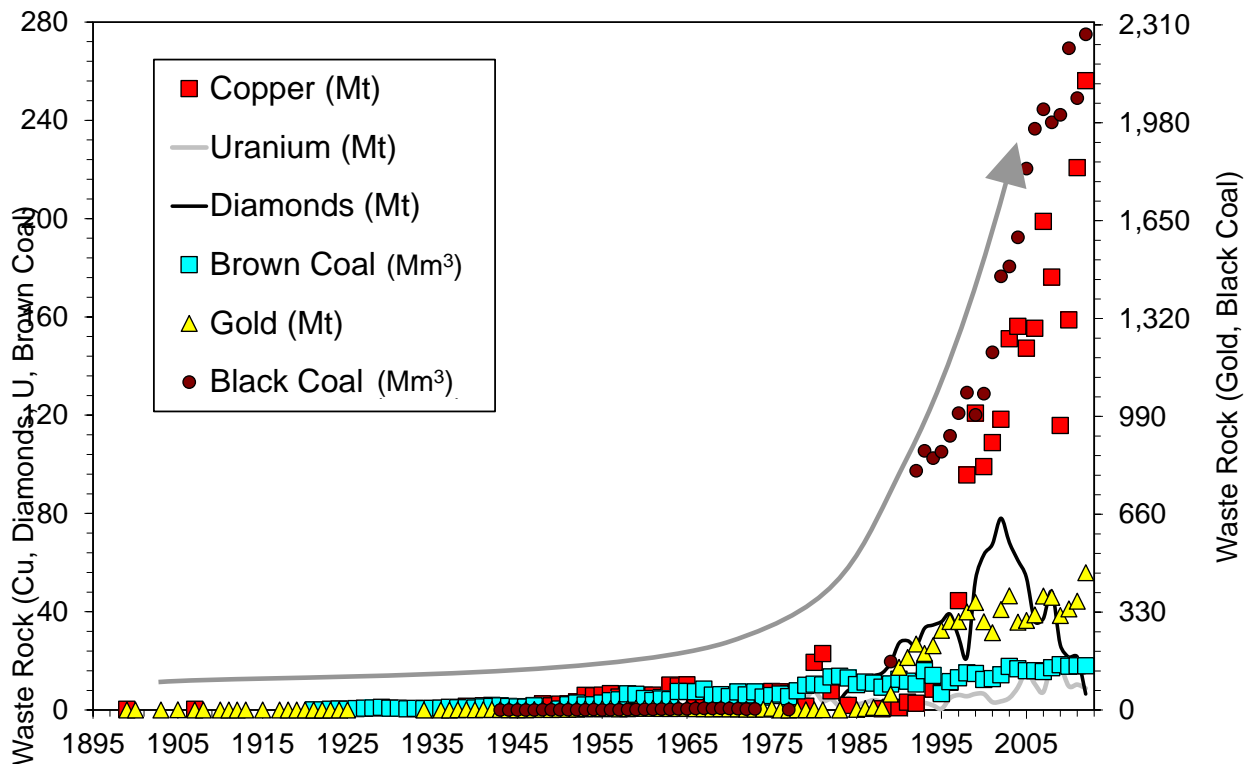
Figure 42. Volume of waste rock produced from Australian historical mining
(Source: Mudd 2009- updated 2012, Analyst- Gavin Mudd)

In 1920, global average copper grade was 1.6%. In 2019, the average copper grade was approximately 0.5%. Global demand for copper in 2019 was 24.5 million tonnes, which was extracted and refined, producing 4.9

billion tonnes of waste rock. The author has participated in feasibility studies for copper mines that had a cutoff grade of 0.1%. If this became the global average by the year 2100, where copper annual demand is projected to reach 100 million tonnes (ICSG), then 20 billion tonnes of waste rock would be generated each year. There will come a point where this will become logistically impractical, not economically viable, or environmentally irresponsible.

Figure 43 shows the waste plume from the Grasberg copper gold mine in Indonesia, as seen from satellite imagery. While in operation, this mine had an annual waste plume of 80 million tonnes of process tailings into the nearby river, and also annually produced 300 million tonnes of waste rock, placed in mullock heaps. Total mine waste production up until the year 2011, was 1330 Mt of process tailings into the river, and 3820 Mt of waste rock.

Figure 43. Grasberg (Cu-Au) mine in Indonesia waste plume (Source: Gavin Mudd 2011 personal communication)

13 ENERGY IN MINING

Mining of minerals is an industrial activity that is highly dependent on energy (Figure 42). From diesel fuel consumption to power the truck and shovel haulage fleet, to electricity power draw for the processing plant to function (where the electricity is often generated with gas or coal). Like all other industrial activities, without energy, mining does not happen. It becomes highly relevant then to examine how mining ecosystem interacts with the energy ecosystem.

Energy is the master resource. It allows and facilitates all physical work done, the development of technology and allows human population to live in such high density settlements like modern cities. The modern world is heavily interdependent. Many of the structures and institutions we now depend upon function in a global context. Energy as a fundamental resource underpins the global industrial ecosystem (Fizaine & Court 2016,

Meadow et al. 1972, Hall *et al.* 2009, Heinberg 2011, Martenson 2011, Morse 2001, Ruppert 2004 and Tverberg 2014).
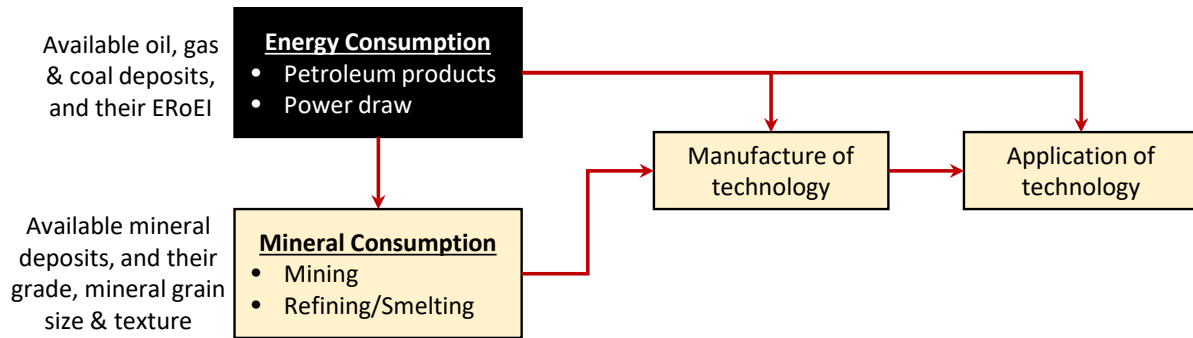
Figure 44. Energy is the master resource that facilitates all industrial activities (Image: Simon Michaux)

Figure 45 shows the Metals Index and the Crude Oil Price Index (both developed and used by the International Monetary Fund) plotted on the same chart. As can be observed, the metal's price correlates strongly with the oil price. Note the increase of both indexes around the year2001/2002. This correlates with the peak shown in Figure 33. Both indexes crashed around 2008, which correlates with the Global Financial Crisis.
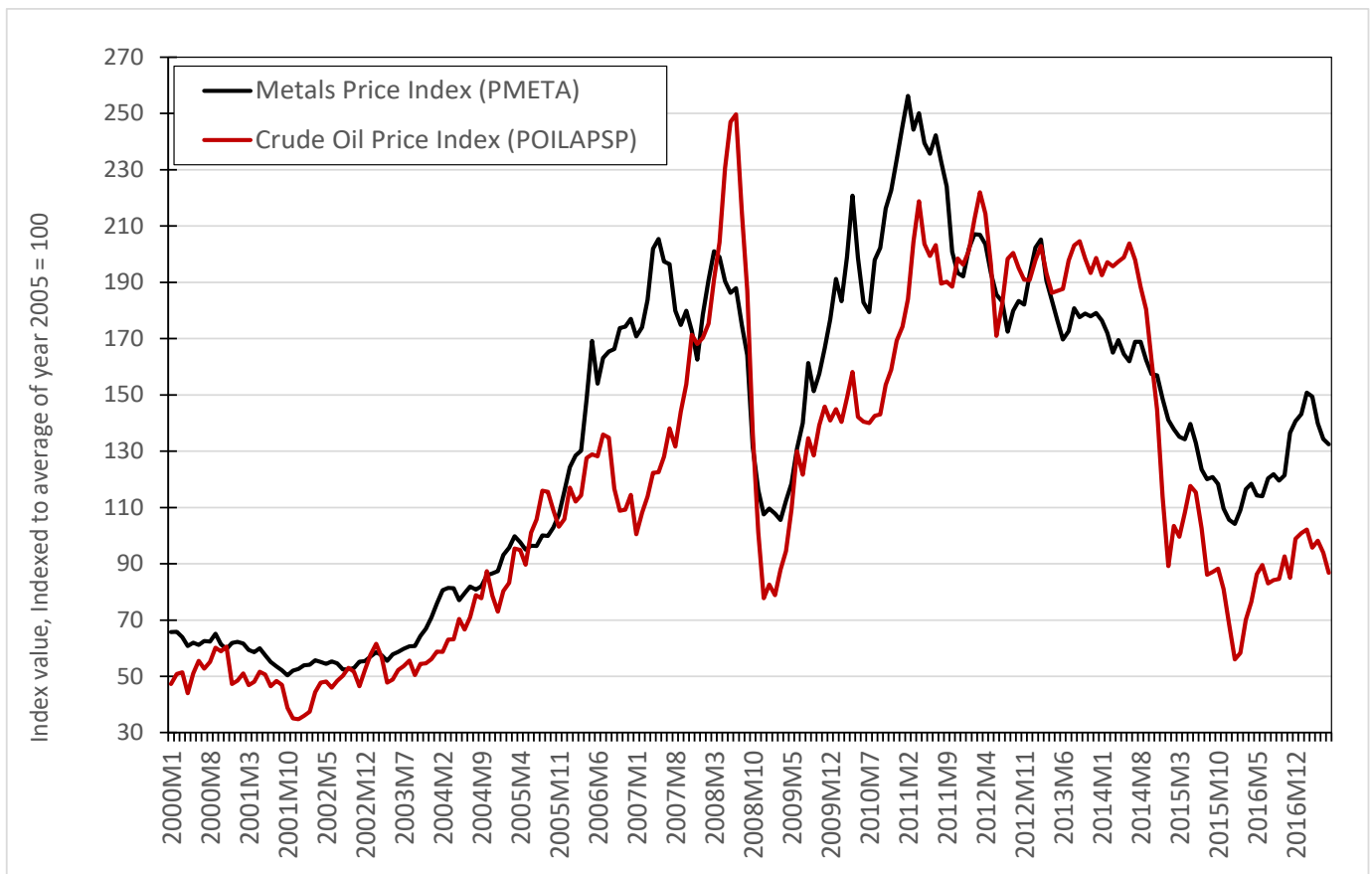
Figure 45. Correlation between global metal price and crude oil
(Source: IMF Primary Commodity Price System, http://www.imf.org/external/np/res/commod/External_Data.xls)

As has been shown, the energy requirements to produce a unit metal through the mining of minerals has been increasing for the last few decades for a number of fundamental reasons. Figure 46 shows how energy consumption in the Australian mining industry increased approximately 450% between the years 1973 and 2008.
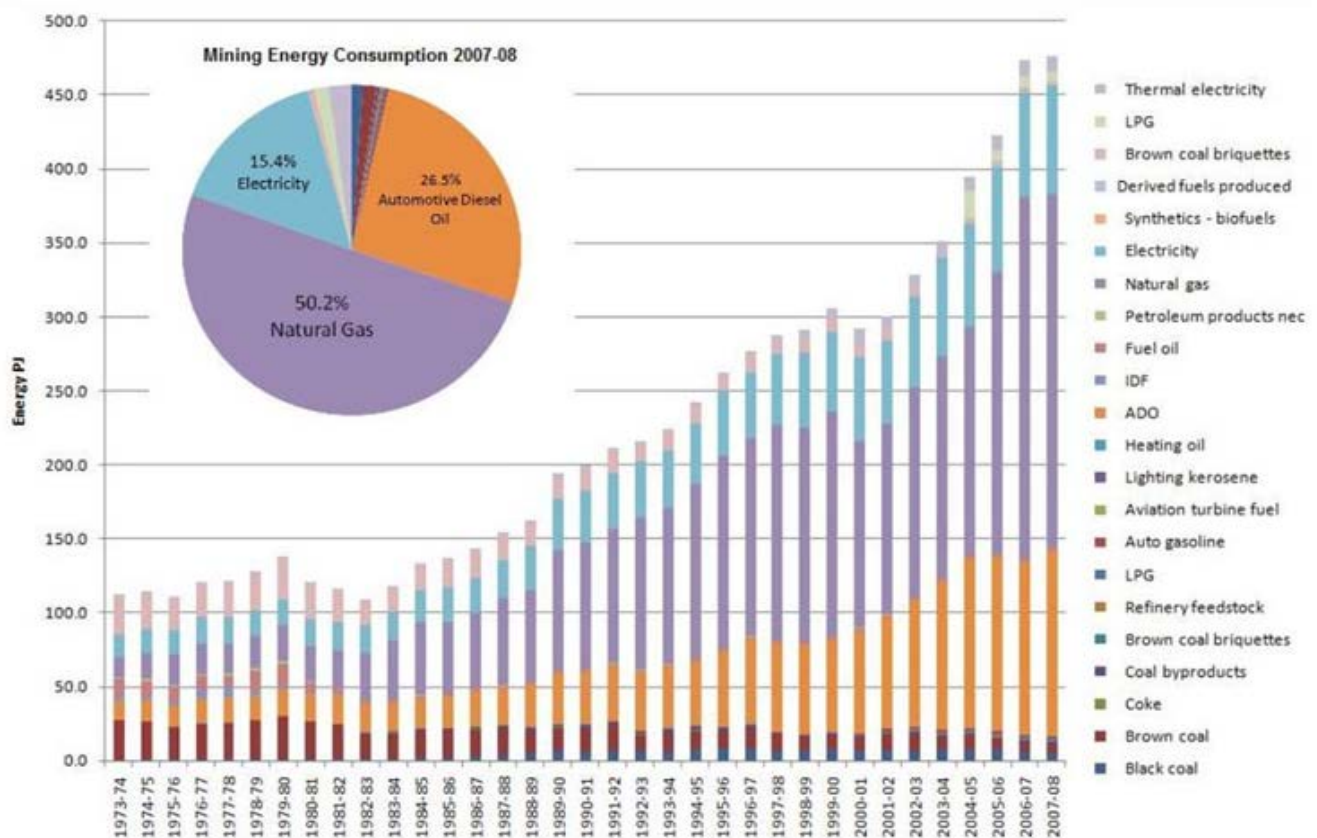
Figure 46. Mining energy consumption 1973 - 2007
(Source: Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES) 2008 Australian Mineral Statistics)

Figure 46 shows that gas and diesel fuel (oil) provide the majority of current energy supply for mining. Future development may be required to be operated using renewable energy supply in some form.

A challenge for the opening of new mines is their location, which is often in very remote undeveloped geographical regions. These regions other require all necessary infrastructure (roads, rail, power supply, etc.) to be constructed for the purpose of supporting the mine operation being proposed. For this reason, many new mines could be very remote from many of the proposed renewable electrical power generation network. Moreover, these mines could be in geographical areas that will be some of the last regions to be connected to the renewable power network. The challenge then becomes, to get a new mine opened, a renewable power generation source would be required to be constructed at the same time, close enough to the mine to be useful.

Future energy consumption in mining may become an increasingly sensitive design parameter and engineering sources of energy consumption may well be optimized at a greater priority.

Figure 47 shows how different mining and processing methods consume energy. This is a very different concept to recovery efficiency. Different mineralogy's require different process paths. Understanding where these process paths will change with lower grades and/or lower grind sizes is required.
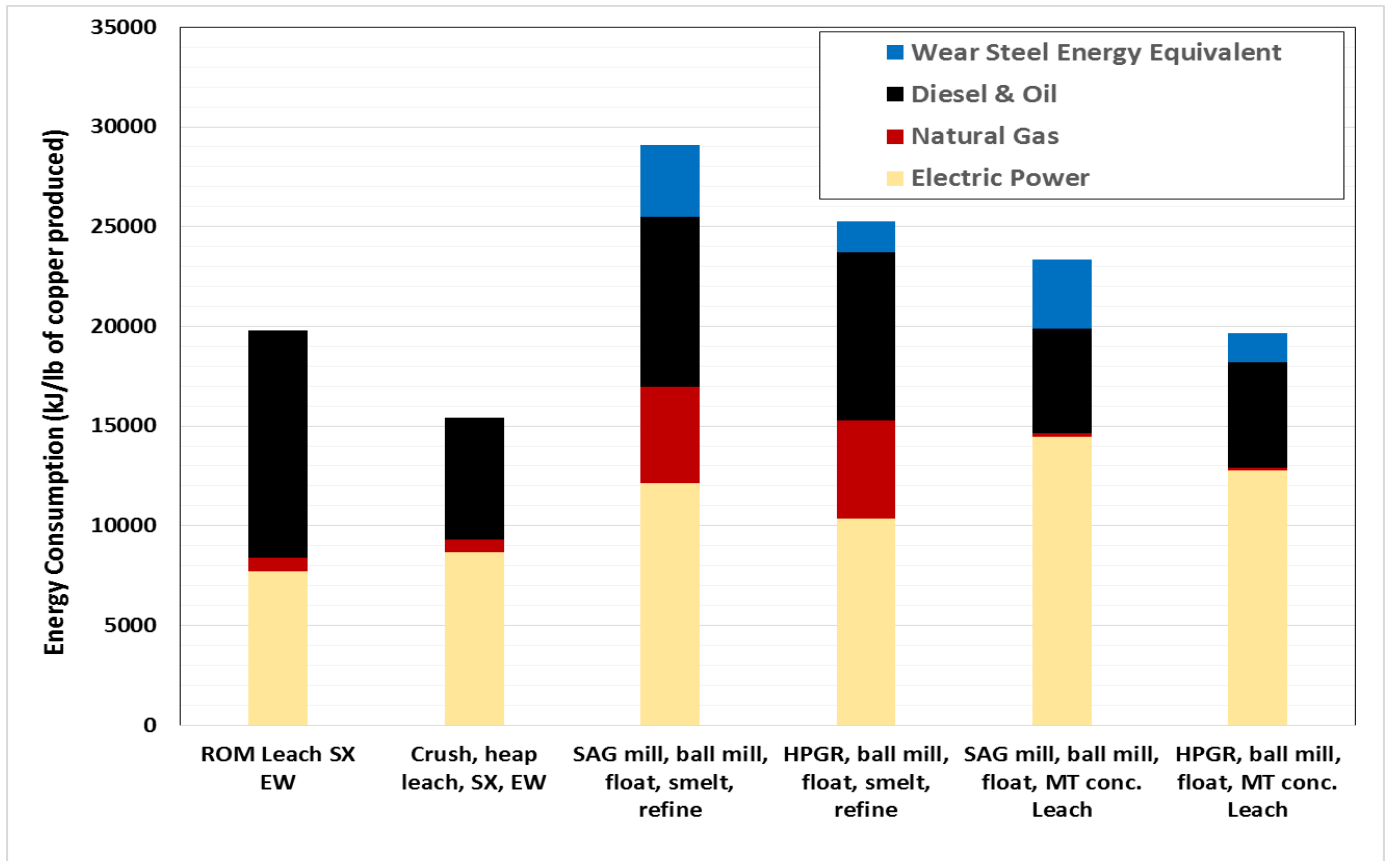
Figure 47. Total energy consumption by process path (Source: Marsden 2008)

Figure 48 shows the energy intensity of various different process paths as a function grade, where flotation (concentration – smelting) and leaching can be compared. The future availability of copper will also be determined by the energy costs of its production. If there is no technological progress, geological factors will be the main drivers of these costs. But in addition, the future development of geological parameters is not known. However, if, for example, the ore grade falls to 0.5%, the CED will rise nearly 30% to 89 GJ-eq/t Cu cathode in the absence of technological improvements. Figure 49 shows how different technological events could interact the shape of the curve shown in Figure 49.
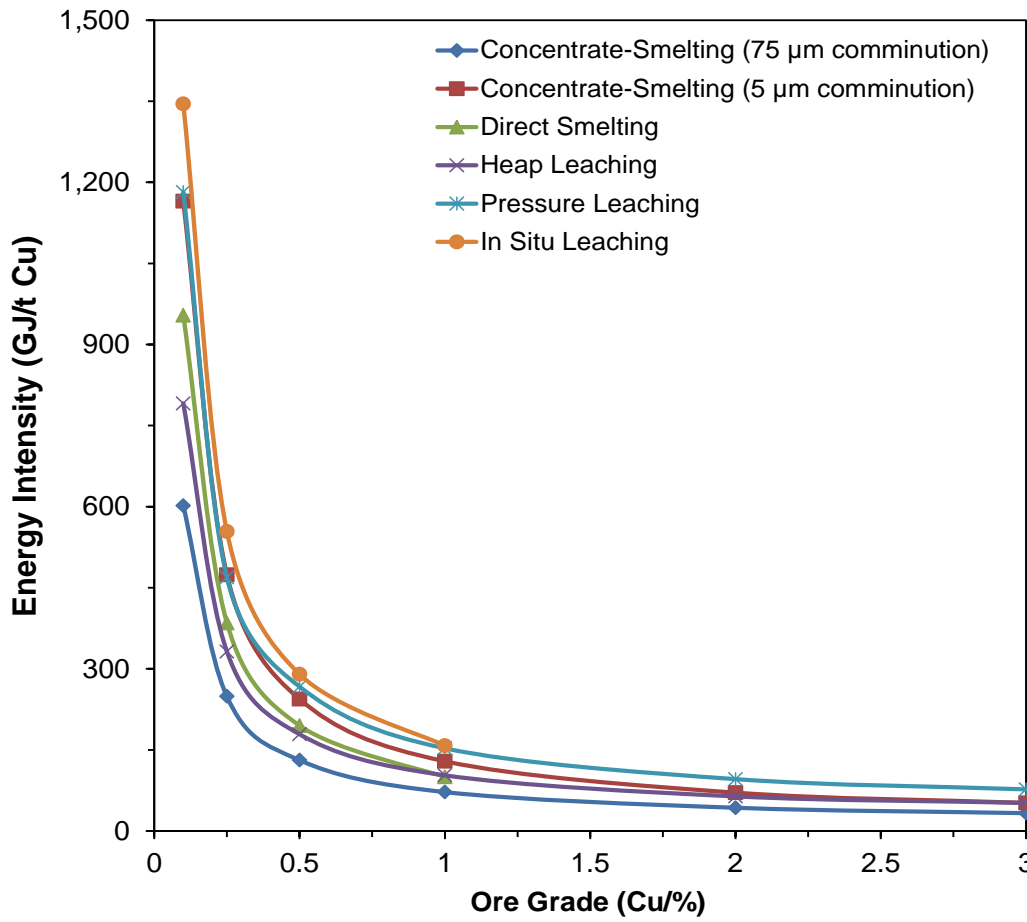
Figure 48. Relationship between energy intensity of processing a tonne of copper vs. ore grade of copper (Source: Norgate-Jahanshahi, 2010)
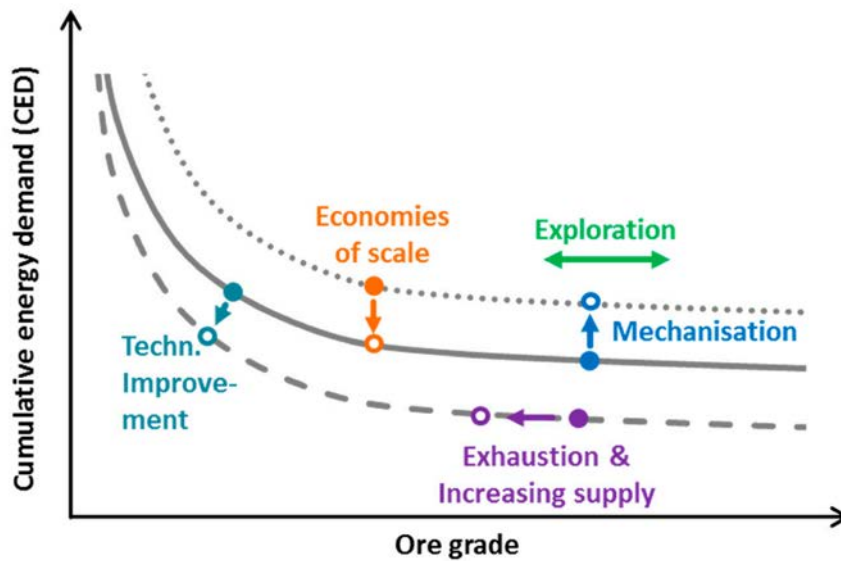
Figure 49. Schematic representation of the relationship between ore grade and cumulative energy demand (CED) and the influence of different market events (Source: Rötzer & Schmidt 2020)

Figure 50 to Figure 52 shows how energy is partitioned up in different parts of the process flowsheet, with some examples from Figure 47.
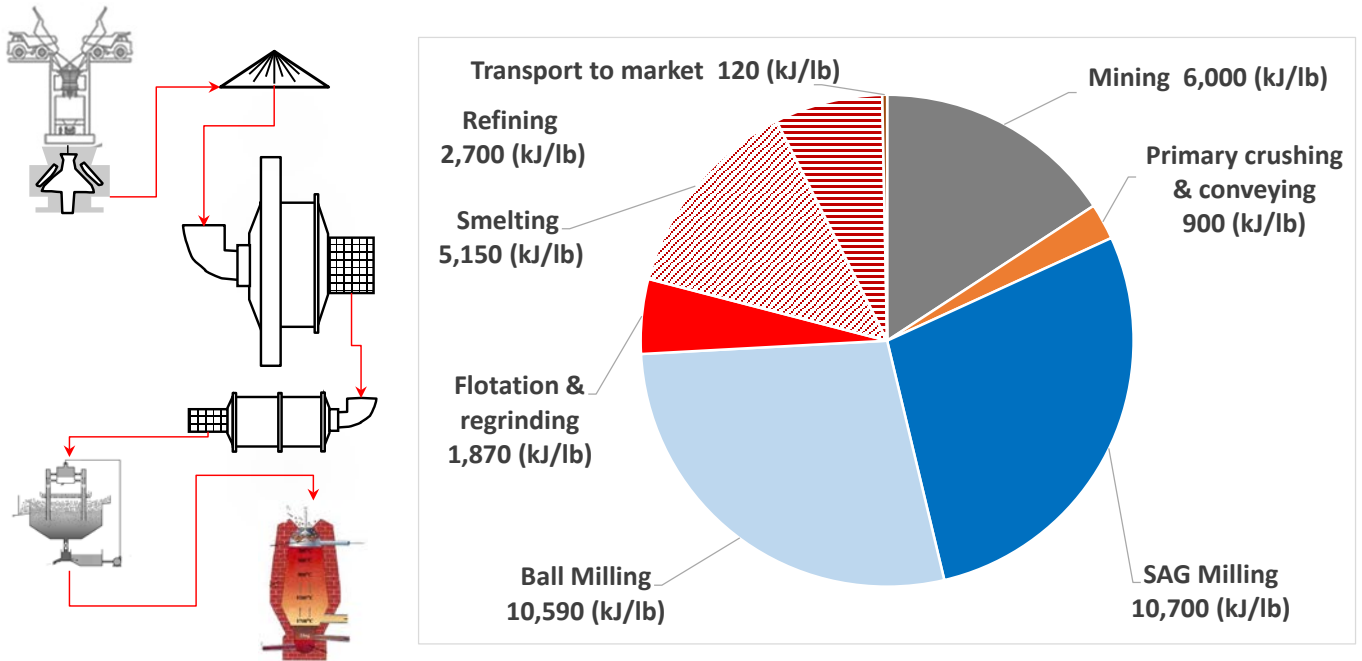
Figure 50. Energy consumed kJ per lb of copper produced, process path primary crush, SAG mill, ball mill, flotation, smelt, refine (Image: Simon Michaux) (Source: Marsden 2008)
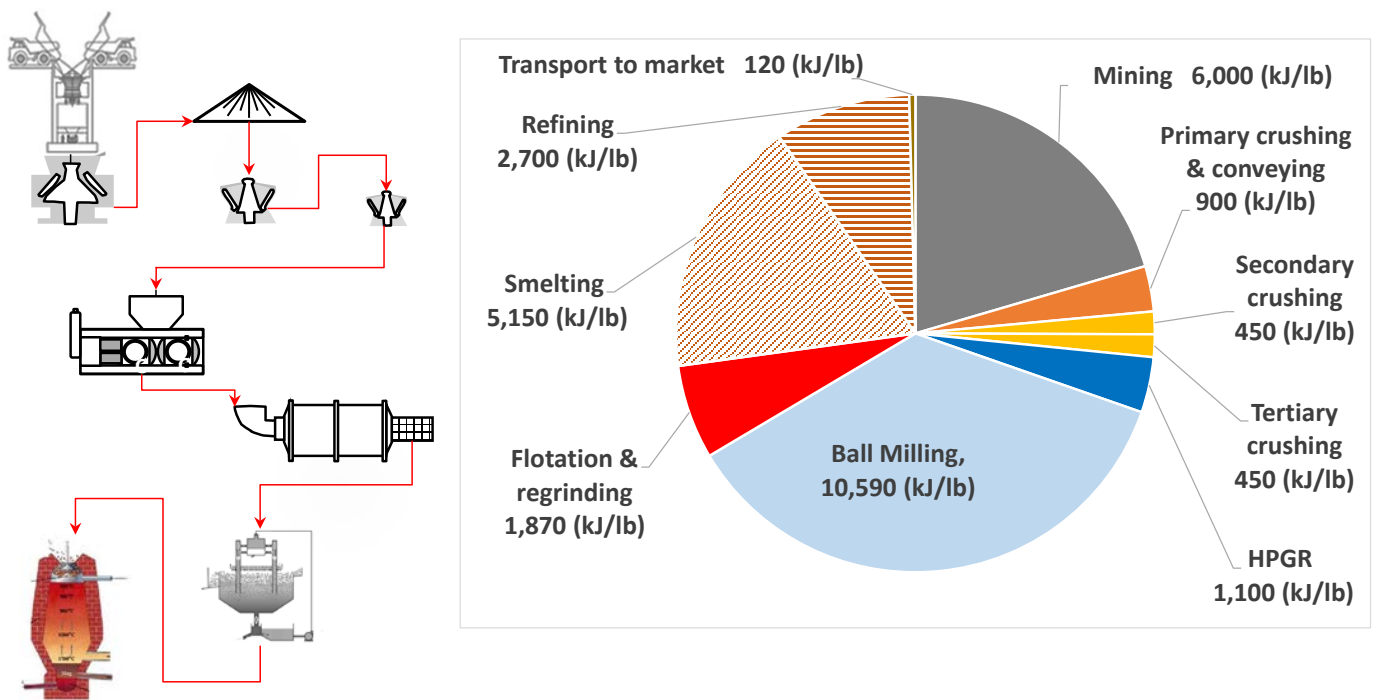
Figure 51. Energy consumed kJ per lb of copper produced, process path primary crush, secondary crush, tertiary crush, HPGR, ball mill, flotation, smelt, refine (Image: Simon Michaux) (Source: Marsden 2008)
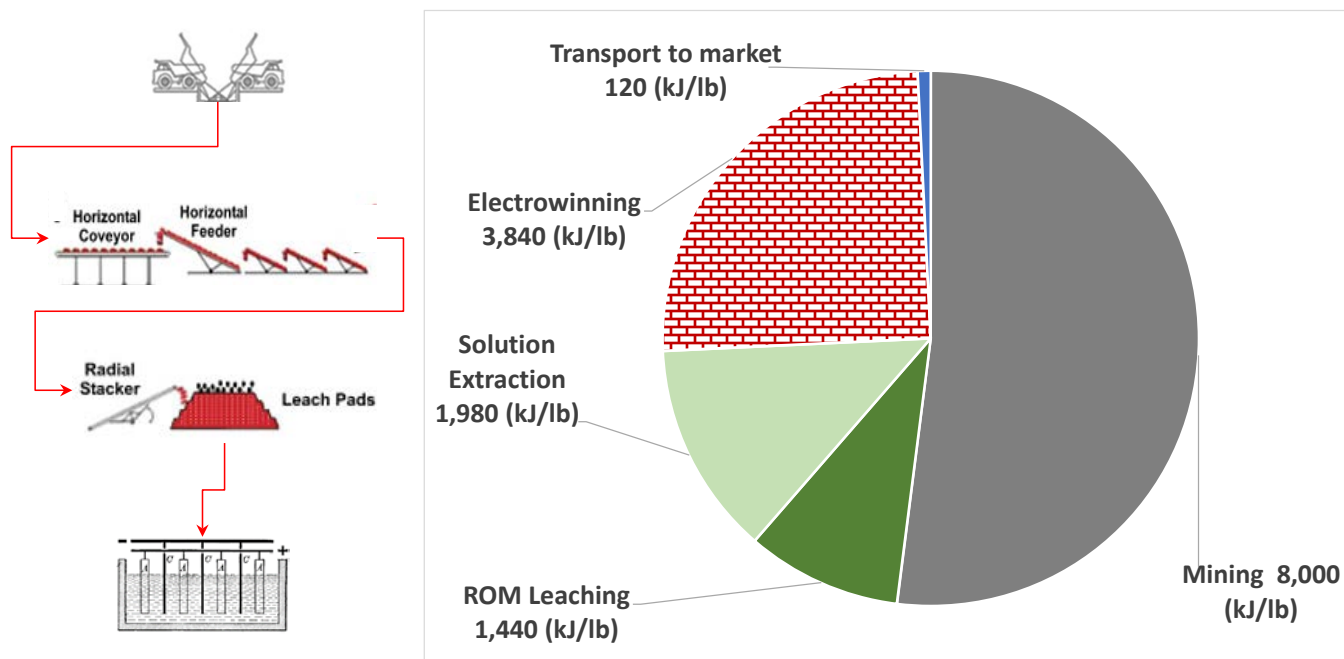
Figure 52. Energy consumed kJ per lb of copper produced, process path Run of Mine (ROM) leach, electrowinning (Image: Simon Michaux) (Source: Marsden 2008)

Figure 50 to Figure 52 show a desktop study calculation where operational energy consumptions have been added together. The author worked on the comminution part of the process flow sheet that show how the comminution parts in Figure 50 to Figure 52 need to be adjusted.

Comminution (rock breakage and grinding) accounts for up to half the cost of mining (Ballantyne & Powell 2014). Just so, it is appropriate to examine the energy efficiency of comminution. Figure 53 and Figure 54 shows some of the results of a study the author led in 2012, where the comminution efficiency of 5 different sulfide mineral process paths (various combination of crushing, grinding and HPGR) were compared at the same closing size (Michaux *et al* 2012). The cumulative energy consumed to process a sample to a target P_{80} is very similar across all conventional process paths examined.

This confirmed the theory that any efficiency gains from High Pressure Grinding Rolls (HPGR) over crushing and SAG mill scale grinding were lost when accounting for grinding. To state this colloquially, 'there was no free lunch'. The only way to save energy in mining was to put less ore in the mill without losing metal content.

This is particularly pertinent, as the resulting outcome of a decrease in grade is an exponential increase in the amount of ore that has to be processed (Figure 24). Figure 53 and Figure 54 shows that it is very difficult for conventional process technology to achieve energy efficiency gains. In addition to this, lower grade ore is often also very disseminated with the target minerals grains being very small. This requires a correspondingly smaller process plant grind closing size. The smaller the grind size, an exponential increase in required energy for comminution results (Figure 31).

This has a direct relationship in the quantity of energy required to grind the ore to a set closing size, and could explain why energy consumption has been increasing (Figure 46).

The energy consumption of the mining industry is quite small compared to other consumption requirements (like ICE passenger car consumption for example). It is unlikely that mining energy consumption will be the cause of an energy shortage elsewhere in the ecosystem. That being stated, it has been shown that the critical service mining provides to the industrial ecosystem is highly dependent on fossil fuel energy in

particular. To date, renewable energy generation systems like wind or solar have not been able to completely support a mining operation, let alone a large operation requiring lots of energy at the 28 MW capacity scale. It becomes appropriate to examine existing energy systems.
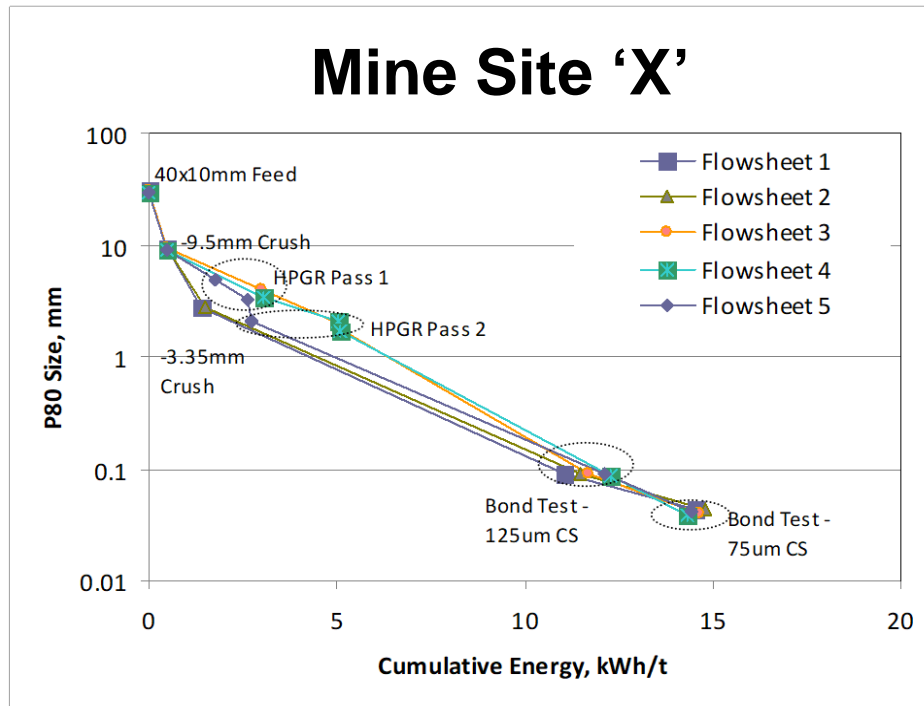
Figure 53. Comminution energy efficiency comparison between several conventional process paths – Mine Site X
(Source: Michaux *et al* 2012)
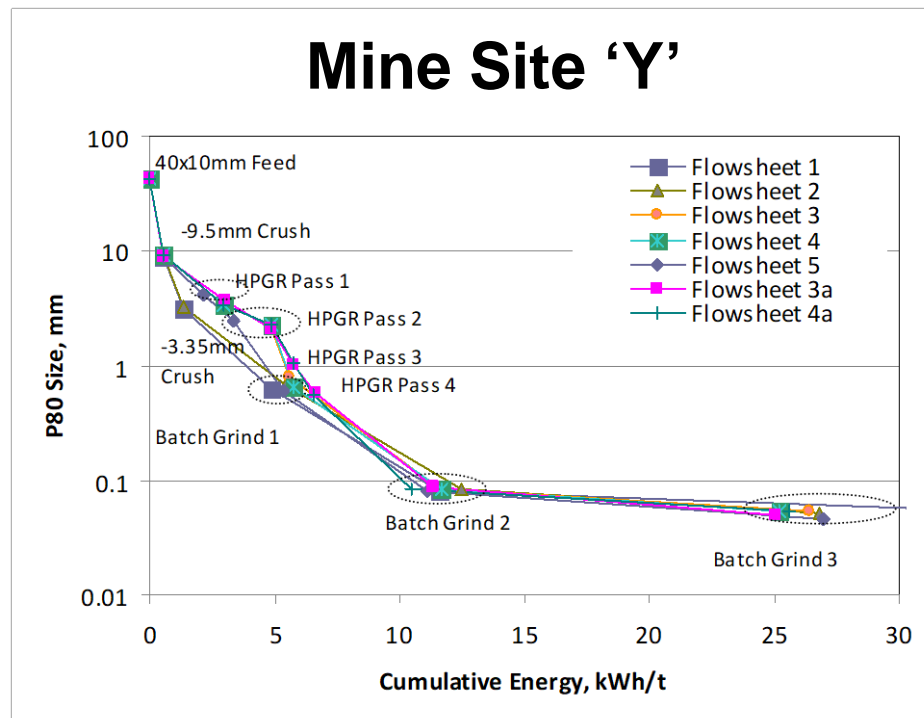
Figure 54. Comminution energy efficiency comparison between several conventional process paths – Mine Site Y
(Source: Michaux *et al* 2012)

14 THE CURRENT INDUSTRIAL ECOSYSTEM IS HEAVILY DEPENDENT ON FOSSIL FUELS

Current industrialization has a foundation in the continuous supply of natural resources. The methods and processes associated with this foundation have significant momentum. This paradigm will not be undone easily. Human nature and human history make it so. Currently, our industrial systems are absolutely dependent on non-renewable natural resources for energy sources. Oil, gas, and coal, and will continue to do so for some time. A group of economists (Covert 2016) explored whether market forces alone would cause a reduction in fossil fuel supply or demand. By studying the history of fossil fuel exploration and technological progress for both 'clean' (solar, hydro, geothermal and wind) and 'dirty' technologies (oil, gas and coal), they concluded that it is unlikely that the world will stop primarily relying on fossil fuels any time soon. While energy is the master resource, for which all other industrial activities are dependent on, oil seems to be an excellent proxy for economic activity (Michaux 2019). At this time a change in global GDP correlates with a change in oil consumption (Figure 55).
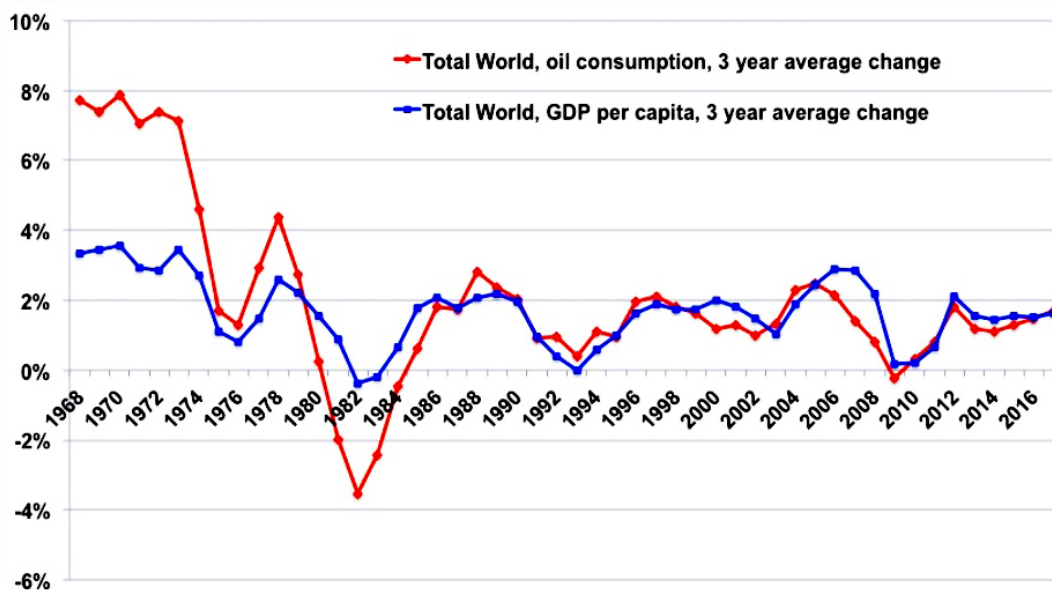
Figure 55. The annual relative change in world oil consumption and GDP per capita averaged over three years (Source: Data from BP Statistical Review 2019, World Bank)

So, if the oil industry is a sensitive proxy to model the industrial ecosystem and the economic ecosystem, the long term stability of the oil industry is considered important. Oil price has also been useful in modelling the metals markets (Figure 45).

A case can be made that the oil industry (in its current form) will at some point become unreliable in the supply of oil and gas. Figure 56 shows that discovery of oil deposits peaked in the mid 1960's and have been steadily declining. Figure 57 shows the same data but in a cumulative plot. The midpoint for net oil inventory gain (discovery minus production) was in 1981. The oil production midpoint was in 1994, where half of all oil ever consumed has been produced since 1994.

The implications for the mining industry are that the available energy required to mine minerals could become expensive and logistically unreliable. That energy would be needed elsewhere, and mining may have to reduce production capacity.
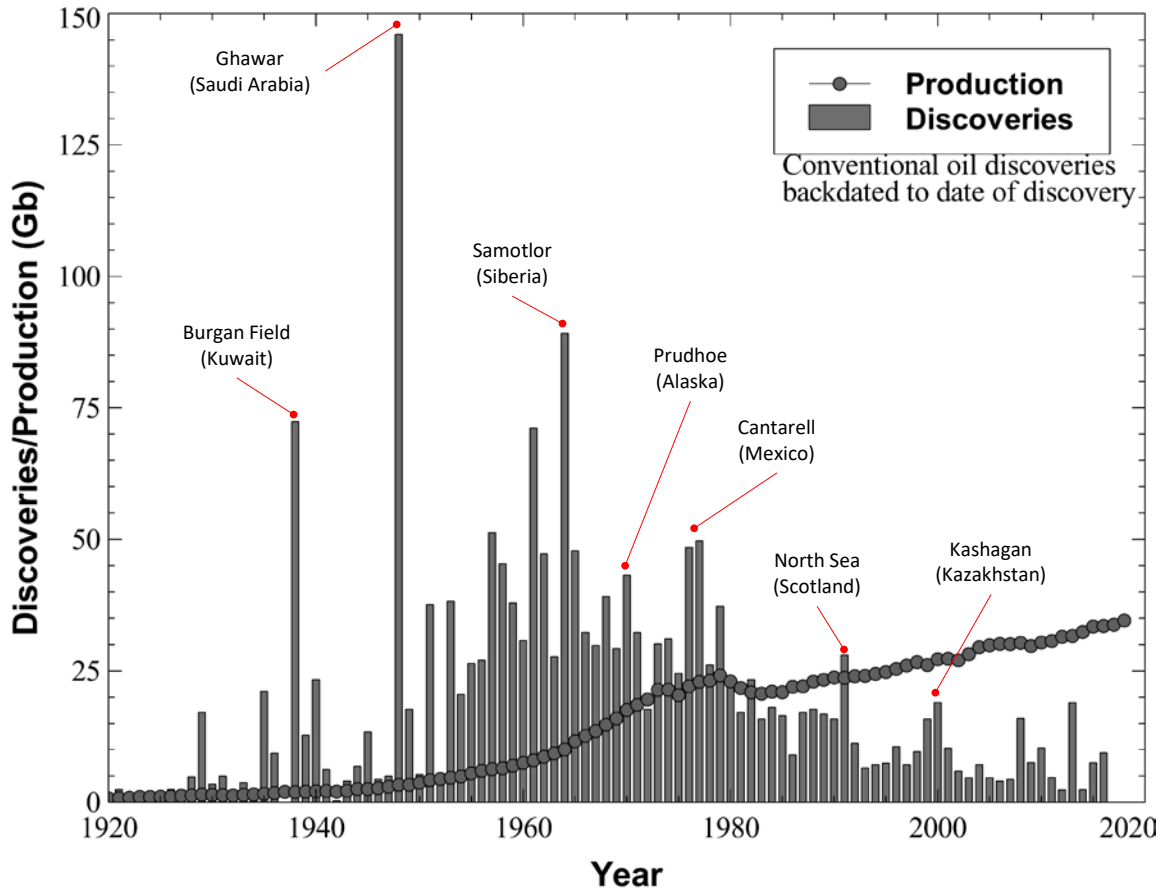
Figure 56. Oil resource discovery 1920-2018 (Source: Analyst – John Peach, data from ASPO 2019, Wood and Mackenzie, Oil Price 2017, Rsytad Energy 2018, Our World in Data 2019, BP Energy Statistics 2019 CNBC 2017)
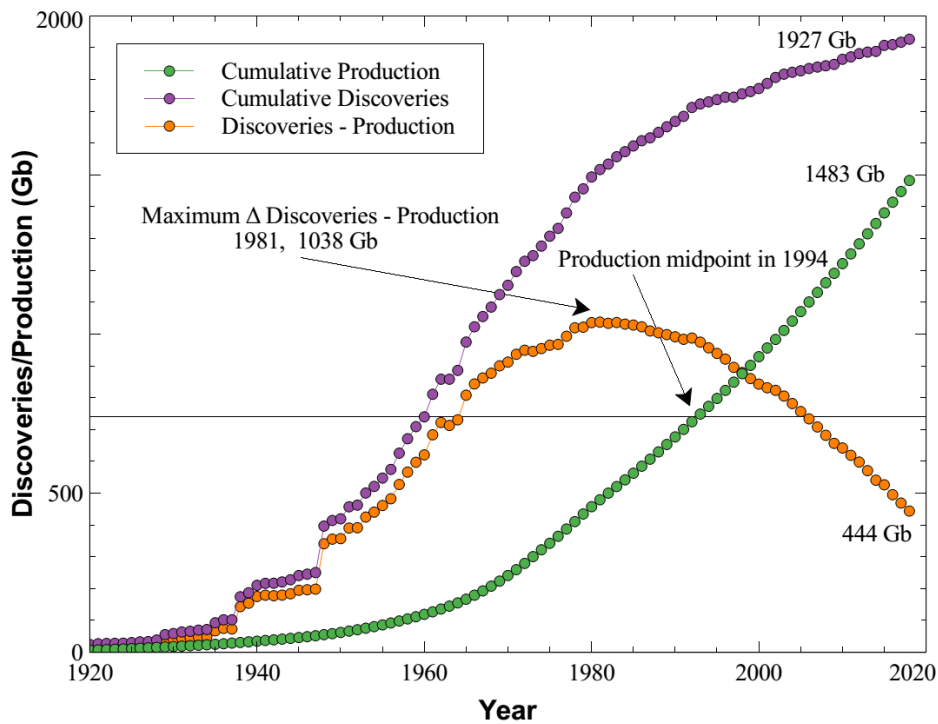
Figure 57. Cumulative global oil resource discoveries and global oil production, and net difference (Source: Analyst – John Peach, data from ASPO 2019, Wood and Mackenzie, Oil Price 2017, Rsytad Energy 2018, Our World in Data 2019, BP Energy Statistics 2019 CNBC

The question of when this happens becomes important. A Michaux (2019) put forward a model that suggested the oil industry is going to contract in a closing window of viability, modelled by the oil price (Figure 58). Due to market conditions related to debt saturation, and the rising cost of oil production, the upper limit of oil price is defined by consumers being unable to support the price, and the lower limit being defined by an oil price that can support the cost of oil production. These ideas were first developed by Gail Tverberg of OurFiniteWorld.com).

Figure 58. West Texas Intermediate (WTI or NYMEX) crude oil prices per barrel October 1999 to October 2019, Inflation adjusted (Source: MacroTrends) (Copyright: https://www.macrotrends.net/terms)

Figure 58 suggests that the oil industry has been in that closing window for the last 15 years. This suggests that among other sectors, the mining industry is required to understand the implications of Figure 56 to Figure 58 and develop a planned evolution of practice.

The logistical circumstance the primary mining industry, compared to 1900 to 2013, now has is as follows. In the year 1900, copper mine ore grade was often quoted in the 20-25% range (the concept of a cutoff grade was not really relevant), with deposits being very small in volumetric scope (small rock outcrop 20m wide to a few hundred meters depth underground shaft), yet the available energy ERoEI ratio of approximately 100:1. Energy resource deposits were huge in size and very easy to convert into useable energy. Copper resources were easy to extract and required comparatively little energy, capital or industrialization.

In the year 2014, a feasibility study copper mine cutoff grade for future projects was 0.1%, with the deposit size requiring an open pit 1km deep and 4km in rim to rim length, yet available energy ERoEI is now approximately 20:1. Energy resources are now comparatively quite small, very poor quality and expensive to extract. Copper resources alternatively are massive in size, very poor quality, requiring vast amounts of energy to process. This can be described with the resource pyramid conundrum (Figure 59).

Figure 59 shows the conundrum of the minerals resource pyramid, whereas time has gone on, more energy was required to deliver the demanded metal, while at the same time, the energy resource pyramid is showing a decrease in available net energy. When these two trends meet, mining of minerals will be required to transform into something else. As that something else is as yet unknown, thus not built yet, a global limit to growth will have been reached. Rates of mining will peak and decline, as a function of available energy, not as a function of available mineral resources.
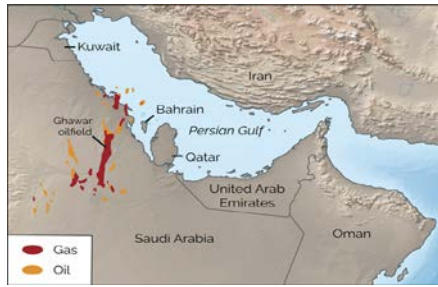
Geographical location of the Ghawar oil field
(Source: Earth Magazine)

Three-ton copper nugget found in Nugget Creek, 1903.
(Anchorage Historical & Fine Arts Museum)

Resource Pyramid
(for energy)

The largest 1% of oil fields provide 50% of world production
Giant field crude

Higher
EROEI

Increasing
ENERGY cost
of extraction

Canadian
tar sands

EROEI = 1
(NO NET ENERGY PROFIT)

Resource Pyramid
(for minerals)

Highly concentrated
Easy extraction/access

Better quality
resource

Increasing cost
of extraction
(including
MORE
ENERGY)

Low concentration
Difficult extraction/access

Truck and shovel in Oil Sands open pit mining
(Image: Suncor media release)

Image by Steven Harolds from Pixabay

High Quality ERoEI

Decreasing net energy
returned per unit of input

- Onshore, easy to refine liquid oil
- Shallow water easy to refine liquid oil
- Onshore, difficult to refine heavy liquid
- Ultra deep water oil
- Polar oil (Arctic reservoirs)
- Oil Shale (Fracking Tight Oil)
- Tar/Oil Sands

- Large pure Cu nuggets found in streams
- Cut off Cu grade 20%, 300μm grain size
- Cut off Cu grade 5%, 150μm grain size
- Cut off Cu grade 1%, 150μm grain size
- Cut off Cu grade 0.5%, 20μm grain size
- Cut off Cu grade 0.1%, 20μm grain size

(Mineralized ore)

Increasing energy requirement
per unit of metal

Low Quality ERoEI

Figure 59. The resource pyramid conundrum (Image: Simon Michaux)

15 LIMITS TO GROWTH

In 1968 the Club of Rome was formed to study the direction human society was developing. One of the technical outcomes was a sophisticated system dynamic based analysis of human society and its supporting resources, published as 'The Limits to Growth' (Meadows *et al.* 1972). The objective was to stabilize all inputs and outputs to human society. The base case scenario where the existing direction of human society development in the early 1970's was maintained with no change, then projected forward in time to the year 2100 (Figure 60). The underpinning paradigm of this study was to look at the resource limitations in context of growing human population. During the course of this study, 13 scenarios were considered, where strategic changes in human society were made. This study highlighted the global systems dependence on non-renewable finite natural resources. Without a steady supply of those resources, the system crashed.
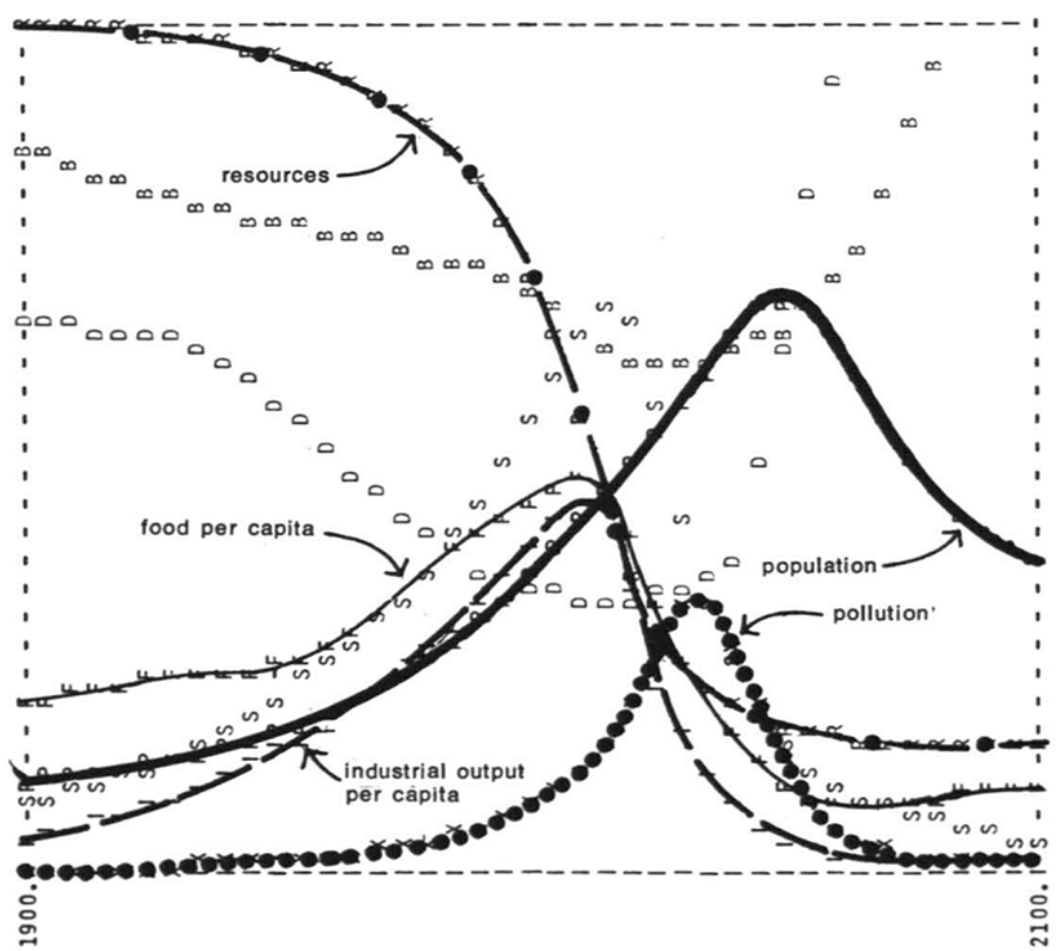
The "standard" world model run assumes no major change in the physical, economic, or social relationships that have historically governed the development of the world system. All variables plotted here follow historical values from 1900 to 1970. Food, industrial output, and population grow exponentially until the rapidly diminishing resource base forces a slowdown in industrial growth. Because of natural delays in the system, both population and pollution continue to increase for some time after the peak of industrialization. Population growth is finally halted by a rise in the death rate due to decreased food and medical services.

Figure 60. The standard run base case projected outcome of 1972 systems analysis modelling of global industrial society (Source: Meadows et al. 1972, copyright granted)

This remarkable study was one of the first of its kind in that it was conducted on one of the first computers available to civilians. Using a well thought out network of systems in an elegant experimental simulation design, the rates of consumption, population growth and associated pollution were each predicted. While this study was done in the early 1970's, an update that compare historical data mapped against the model predictions, show that the base case scenario model was conceptually correct (Turner 2008).

Figure 60 shows the 1972 study human population growth scenarios (with a model future prediction between 1970 and the year 2000), overlaid with historical data from 1970 to the year 2000 as measured (Turner 2008). The historical data shows that human population is following the Standard Run model from the 1972 Limits to Growth study. This is most pertinent as human population is one of the fundamental underpinning parameters in mapping resource consumption.
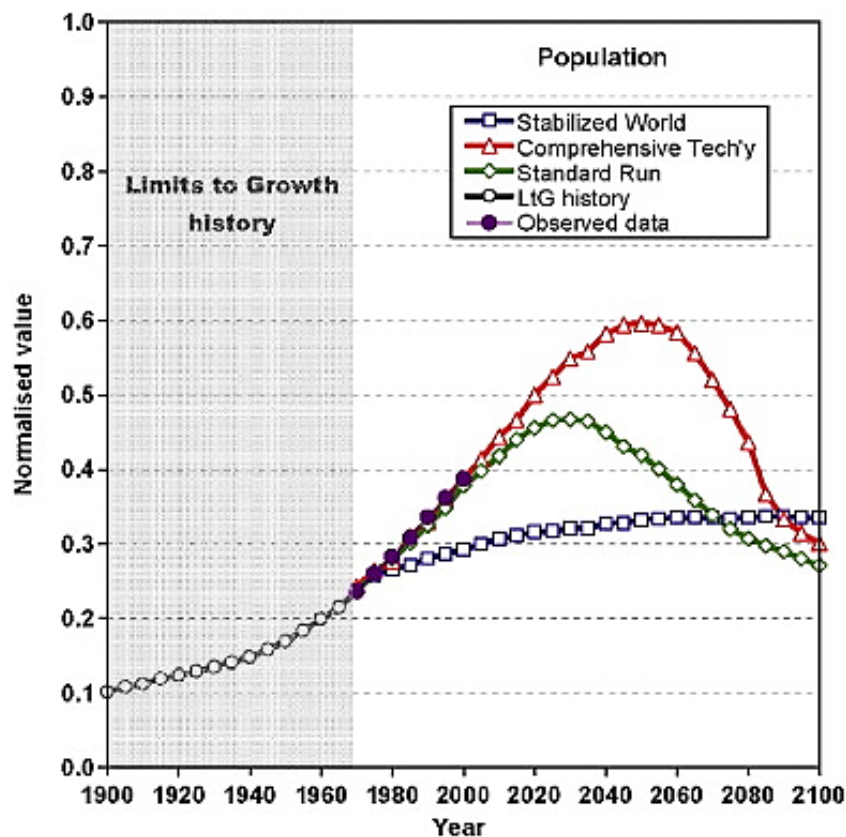
*Figure 61. Comparing 'Limits to Growth' scenarios to observed global data – human population
(Source: Turner 2008, Copyright granted)*

The implications of Figure 61 to Figure 63 are that the basic prediction of the original Limits to Growth systems study was conceptually correct. Just so, it should be considered that the industrial ecosystem and the society it supports may soon contract in size. This implies that the current Linear Economy system is seriously unbalanced and is not remotely sustainable.

The Limits to Growth conclusions suggest at some point, the global society and the global industrial ecosystem that support it will radically change form. When this might happen is a matter of debate. In the orginal Stand Run, the window of change was projected to be between the years 2015 to 2025. In 2017, food production per population capita was predicted to peak and decline. In 2019 the industrial output per population capita was predicted to peak and decline.

*Figure 62. Comparing 'Limits to Growth' scenarios to observed global data – industrial output
(Source: Turner 2008, Copyright granted)*

*Figure 63. Comparing 'Limits to Growth' scenarios to observed global data – Non-renewable resources
(Source: Turner 2008, Copyright granted)*

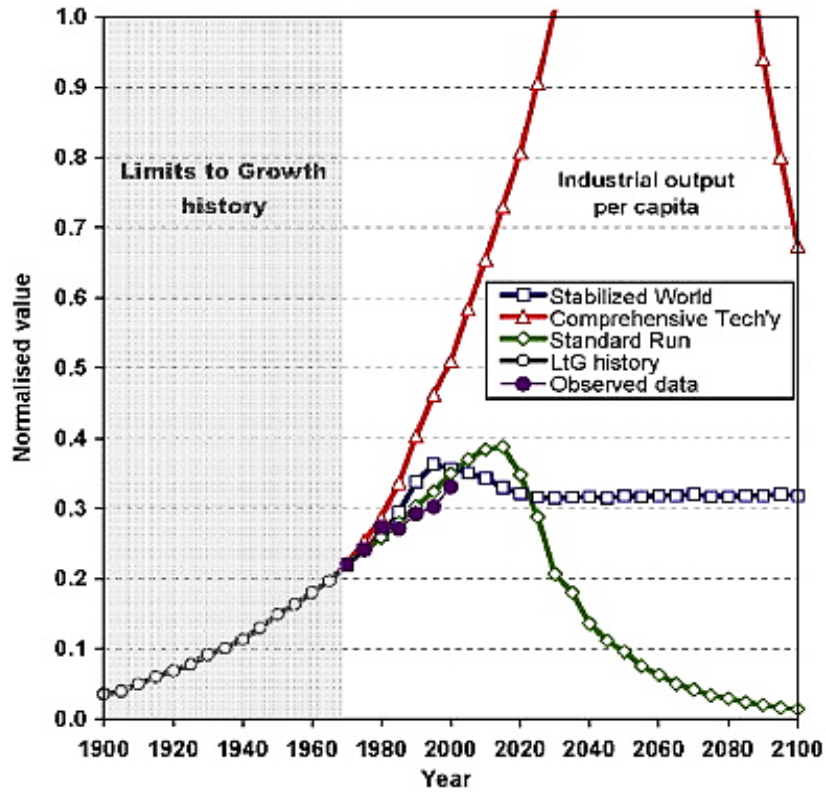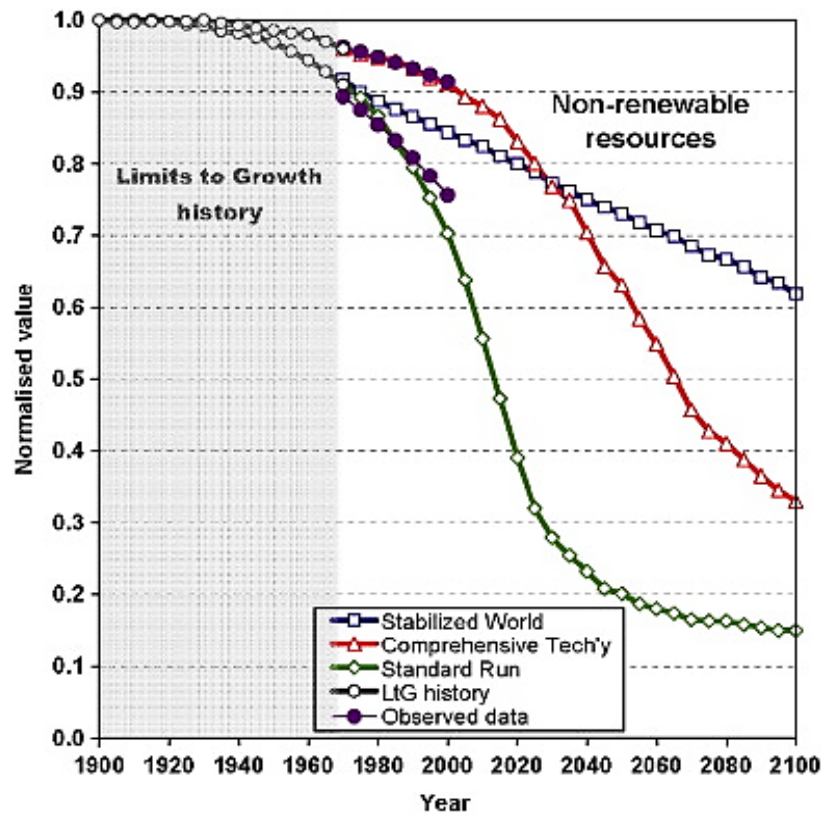As the Standard Run simulation in the Limits to Growth model has shown to be useful, the question becomes, are we seeing structural change in the industrial markets to support the idea that the change is in fact happening now. The simple answer to this is yes.

Figure 64 shows that the industrial ecosystem structurally changed in early 2005, where metal prices blew out, which may be caused by a chain relation of an outcome in the oil markets (Michaux 2019). Mining of metal market price is the transfer point between metal mining, heavy industry, and manufacturing industry. Conventionally, the industrial society sources its raw materials from mining. How this happens is an underlying foundation of the industrial society. Figure 64 show the metal price for 13 commonly traded commodities that the World Bank uses to track the performance of the global economy and the global industrial ecosystem.

The data trend lines were overlaid by indexing the real price to the date of December 2001 to the number 100. This is the price of metals market (the purpose of indexing the price data is to overlay the price curves, which shows time periods of relative stability and time periods of volatility).

Note that the price blowout in early 2005 was a few years before the sharp increase in M1 $USD monetary supply in mid-2008. This suggests that the industrial ecosystem and the over laying financial market has had a structural blowout that is still in progress. It has been hypothesized that the change in early 2005 was a chain reaction that had its genesis in a change in the oil industry, which happened in January 2005 (Michaux 2019). The whole industrial ecosystem was placed under unprecedented pressure, and the price of everything industrial spiked. Three years later, the weakest link in the economic system, the U.S. housing market, broke and the Global Financial Crisis (GFC) was initiated. The temporal marker for the start of the GFC was not in the housing industry, however. The starting point was marked by the peak and crashing of the oil price. The GFC was resolved by the application of unprecedented Quantitative Easing (QE) (Michaux 2019). Since then, most Central banks around the world have been using QE to keep economic growth constant. It is hypothesized that without QE, global economic growth and industrial activity in general would crash to unprecedented lows.

Figure 65 shows some pertinent data. Since the Global Financial Crisis (GFC) of 2008, M1 supply grew 79.3%, from 1 394 billion $USD to 6 741.8 billion $USD, through Quantitative Easing money creation. That is, 4 out of 5 US dollars in circulation was created without any hard asset backing in the previous 10 years.

Since the 30th of December 2019 to January 2021, 41.2% of the global M1 supply of US dollars was created without any hard asset backing. This means that during the Covid-19 pandemic lockdowns, when the vast majority of the global economy halted production, the M1 supply increased by 41.2%, at a time of global economic contraction.

Between June 1st, 1975 (a few years after the $USD was decoupled from the gold standard) to January 2021, the global currency $USD M1 supply grew by 24.7 times in size, without the backing of any hard asset.

This suggests a very real risk of hyperinflation and a currency default in the US dollar. A compelling case can be made that the global ecosystem is about to undergo an economic correction of historical proportions. The Great Reset as proposed by the International Monetary Fund (Georgieva 2020), is a possible reboot of the system of capitalism. Exactly what this entails beyond the briefings from the World Economic Forum and the International Monetary Fund is still not clear. What is implied is a fundamental reordering of the debt global society is carrying, which in turn suggests an evolution of the global financial system.

The combination of Figure 64 and Figure 65 shows that something structural happened in 2005, 3 years later, the system crashed with the GFC in 2008. To keep the markets growing, since 2008, the whole system has been propped up with quantitative easing, which is a stop gap measure at best. This supports the concept that the change shown in the Limits to Growth has been underway for the last 16 years.
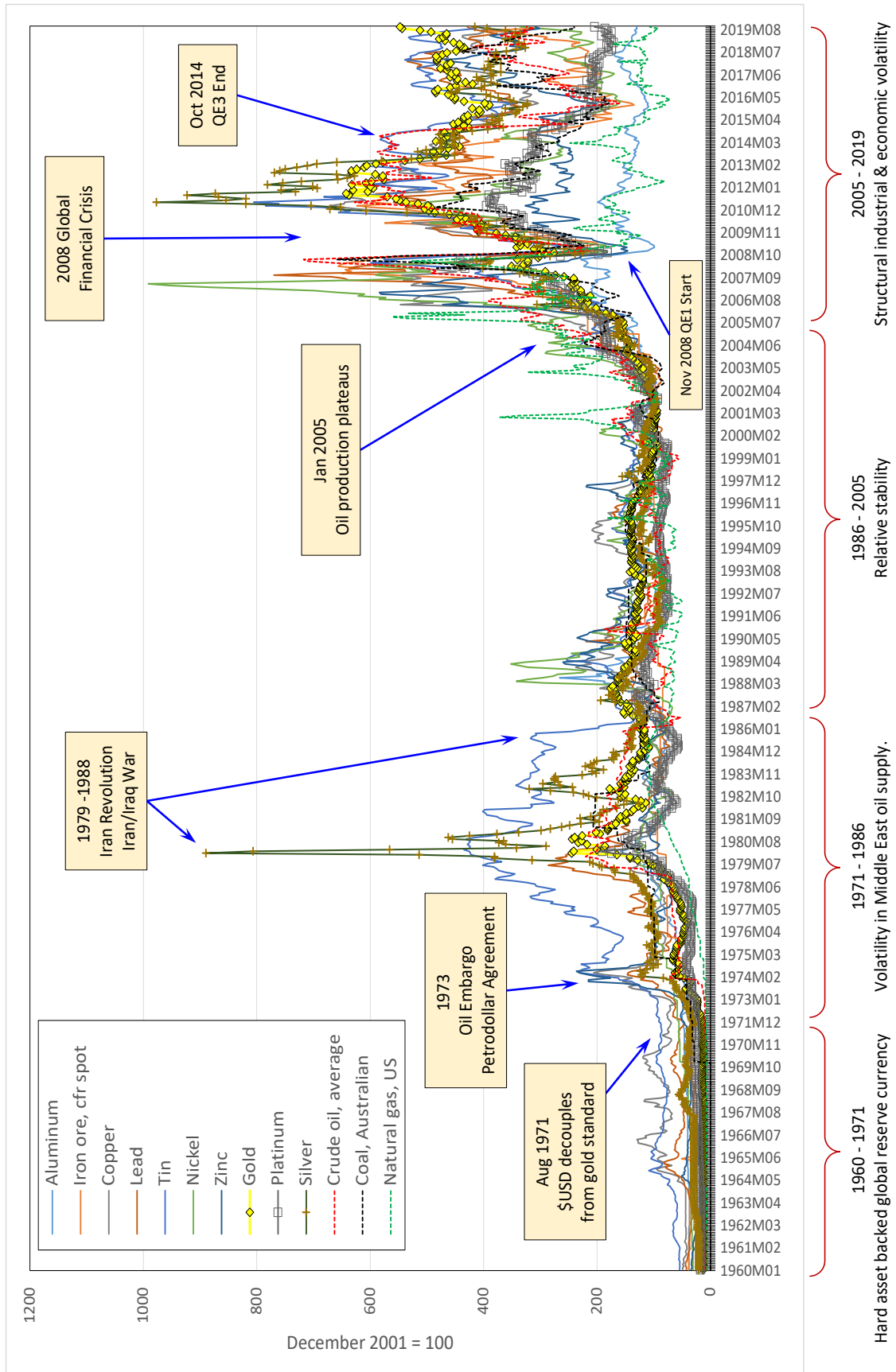
Figure 64. The price of industrial metals, precious metals and energy resources, January 1960 to September 2019, The price of metals Indexed to the year December 2001 = number 100
(Source: World Bank Commodity Price Data used to calculate Indices; monthly data updated Oct 2019)
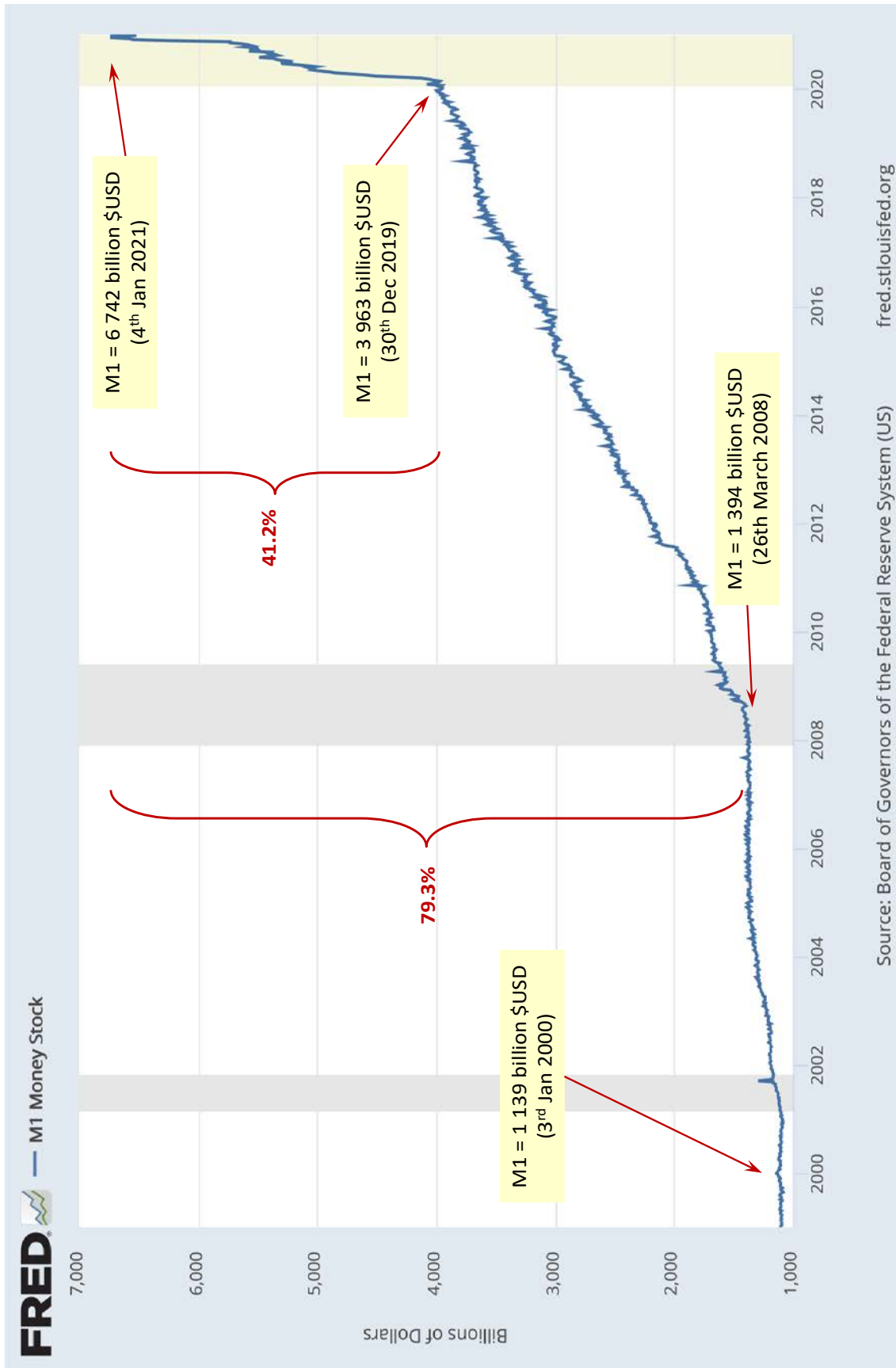
Figure 65. Monetary supply of U.S. dollars, M1, 1975 to 2021, (extracted Jan 2021)
(Source: Board of Governors of the Federal Reserve System (US), M1 Money Stock [M1], retrieved from FRED, Federal Reserve Bank of St. Louis; https://fred.stlouisfed.org/series/M1)

16   INTERNATIONAL FREE TRADE AND GLOBALIZATION IS UNDER STRAIN

Since 2008, global industrial production has been difficult to maintain. The Global Financial Crisis of 2008 was disastrous for the finance sector (Lund 2018). As oil is a vital part of our industrial society (Michaux 2019), *a sustained rise in oil price over a few years (2004-2008) will put pressure on the entire system*. As such, there will come a point where that system will be under such strain that something would blow out. The oil price spike in 2004 to 2008 preceded the largest global economic correction seen since the 1929 Great Depression. This has been labeled the Global Financial Crisis of 2008 (GFC). Just one of the outcomes was a large correction in the U.S. housing market. The stock exchange crashed, and trading was stopped on several occasions. The whole finance system was with a few hours from complete paralysis (Mathiason 2008).

As a direct consequence of the GFC, quantitative easing (QE1, QE2 and QE3 programs) were deployed by the U.S. Federal Reserve Bank (Yellen 2017). Since then central banks around the world have been engaging in Quantitative Easing (colloquially referred to as the printing of money). This is dangerous as it deteriorates the integrity of the monetary system. The volumes of money being created through QE is historically unprecedented.

It was only Chinese demand for metals that kept the mining industry still in growth between 2008 and 2012, while all other sectors were contracting. That global demand for metals peaked and declined in the year 2009 (Wee Chan & Baffes 2020). China was the only industrial economy that had net positive metals demand in 2009 (Wee Chan & Baffes 2020). After 2008, only the Chinese economy (and in some years Non-OECD economies) had net positive change in metals demand (Wee Chan & Baffes 2020). From Jan 2020, China accounted for almost all of the increase in metals demand in the global markets (Wee Chan & Baffes 2020). From 2009, Chinese industrial output (%YOY) declined and stabilized in 2016 at a much lower rate (National Bureau of Statistics of China). On August 11, 2015, the People's Bank of China (PBOC) conducted three consecutive devaluations of the yuan renminbi or yuan (CNY), removing over 3% off its value. Between 2005 and 2015, China's currency had appreciated 33% against the U.S. dollar, and the first devaluation marked the most significant single drop in 20 years (Investopedia 2019). Global industrial demand in 2020 was heavily supported by Chinese manufacture requirements (Stall 2020).

In 2016, the mining industry started to recover after a difficult period (Depreter 2021). In November 2018 the oil industry peaked production (Michaux 2019). In early 2020, the Covid-19 pandemic was declared, and whole regions of the world industrial eco-system went dormant under quarantine and travel lockdowns (Source: Accenture). Due to the impact of the Covid-19 pandemic on the industrial markets, at the time of writing this report, oil price and production volume has yet to recover to surpass the November 2018 peak.

Debt saturation is now an issue in all economies around the world. The International Monetary Fund (IMF) is now openly discussing some form of financial markets reset, in the form of The Great Reset (Georgieva 2020).

It is clear that for the last 10 to 15 years, the existing economic ecosystem and its supporting industrial ecosystem has been struggling to maintain targets of economic growth without intervention like Quantitative Easing (Bivens 2016, Keightley *et al* 2016, Stall 2020 and Yellen 2017).

Geopolitically, things have also been getting difficult, where economic sanctions have been applied by more than one large economic block against others. The two largest economies (the United States and China) have been engaging in a multifaceted trade war (Dezan Shira & Associates 2020). The difficulty for this is that China controls most of the raw materials supply chain and downstream industrialization in the global market (Wübbeke *et al* 2016 and Appendix A).

At the time of writing this report, China dominates the industrial ecosystem (The Economist 2019). In 2018, China controlled 69% of the battery market (Melin 2019). A relevant aspect to consider is what China (the largest and dominant industrial economy) is doing and is planning to do further in the minerals industry. Just as Europe has the Circular Economy plan for its future long-term security (European 2019b), the Chinese PRC government also has a plan (Malkin 2018 and Wübbeke *et al* 2016). This plan is fundamentally different to what Europe and the United States has been developing for their own resource security (Lee & Reimer 2018 and Lee 2019). In 2019, China directly controlled approximately 80% (an approximate estimation based on Chinese capital flow) of the raw materials value chain (mining, refining, smelting, manufacture, and recycling) (See Appendix A). This does not account for Chinese held corporate foreign investment in industrial assets on a global scale. The Made in China 2025 plan is designed to secure the remaining 20% for Chinese interests in the name of long-term security. If this Chinese plan is even partially successful, then Europe will struggle to maintain market share in industrial sectors and will lose market leader status in some cases (Malkin 2018). One of the implications (considering the United States strategic responses to this) could even be a serious malfunction of the smooth flow of global free trade.

There have been a number of global scale data based industrial signatures (see Figures 64 and 65) that suggest in a structural form, the industrial ecosystem is transforming and the concept of globalization could be evolving into a form of economic tribalism, but on a scale never seen before (Dezan Shira & Associates 2020, Reuters 2019 Jan 10th, Guardian 2019 Feb 21st, Young 2018, Government of Canada 2021, Wroughton *et al* 2021, European Union Newsroom, and Zalan 2018).

17   CONCLUSIONS

It is clear that society consumes more mineral resources each year. It is also clear that society does not really understand its dependency on minerals to function. The recycling industry is still in its infancy and is only just gaining momentum. Even when fully developed, industrial recycling cannot facilitate the transformation of the industrial ecosystem as a single solution. The mining of minerals is not only necessary in parallel to a fully developed recycling network but will be needed at an unprecedented volume to supply the construction of the post fossil fuel industrial system. Availability of minerals could be an issue in the future, where it becomes too expensive to extract metals due to decreasing grade. Discovery of new deposits is also decreasing.

To meet metal demand, future planning for the mining industry is based around another increase in economies of scale (Chitombo 2013). Future undergound block cave mines would have a similar size to current open pits. Future open pits are planned to be an unprecedented size, theoretically 1-2 km deep and as much as 4-5 km in diameter. The concept of a possible energy shortage or a potable water shortage was not considered.

Mining of minerals is intimately dependent on fossil fuel based energy supply. A case can be made that the window of viability for the fossil fuel energy supply ecosystem has been closing for 5 to 10 years. This suggests that the mining industrial operations to meet metal demand for the future are unlikely to go as planned.

Figure 64 suggests that the fundamental transformation of the global ecosystem predicted by the Limits to Growth study, has been in progress since 2005, for the last 16 years. The industrial ecosystem is in the process of transitioning from unlimited growth based economics to economics with limits/boundary conditions. Until a new industrial-technological-economical system is developed to new requirements, that

transition period could be defined with contraction based economics. This will affect all sectors of the global ecosystem, all at the same time (in a 20 year window). We are there now and should respond accordingly.

It has become clear that the evolution of the industrial ecosystem over the last few decades has been influenced by three basic trends that were conflicting with each other (Figure 66). The current industrial business model is one of technological development, based on the belief that there are no raw material supply limits. This meant that an ever increasing quantity of minerals of all kinds was required (Trend 1).
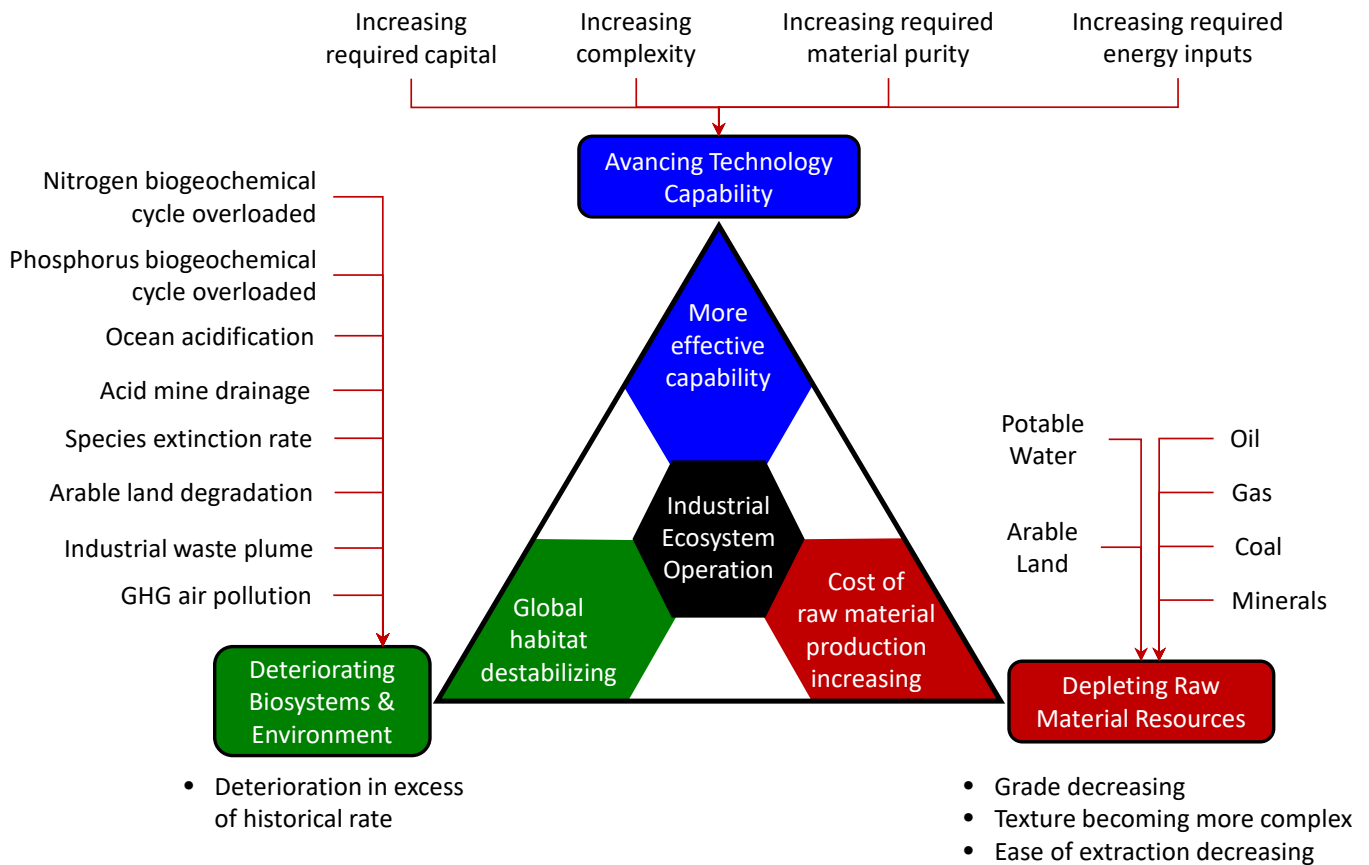
Figure 66. Industrial ecosystem is subject to three basic conflicting trends

As technology has developed, the material purity requirements have also increased, which has driven the cost up of production. The grade of most of the raw materials being extracted has been decreasing which has also been driving the cost of production up (Trend 2). Market forces and economics have been used to maintain production to meet demand. This would have continued if energy raw materials (oil, gas, and coal) were not decreasing in ERoEI quality and deposit size. Now that energy resources are much more expensive compared to 50 years ago, this decreasing grade is now more problematic. The trend of decreasing grade is something that has not been seen as an issue, as the economics can be forced to manage market forces of supply and demand. The true role of energy has been misunderstood in this context (Michaux 2019).

The third influencing trend is the deteriorating environment and the flora and fauna biosystems that inhabit it. Industrial pollution of all kinds has been observed in all sub-systems: the hydrosphere (rivers & oceans), the biosphere (flora & fauna), the atmosphere and the geosphere. The size and complexity of natural living systems has been vastly reduced on a global scale, being terraformed with industrial agriculture, cities, and

industrial activities (United Nations 2005). Global human society have changed ecosystems more rapidly and extensively than in any comparable period of time in human history, largely to meet rapidly growing demands for food, fresh water, timber, fiber, and fuel. This has resulted in a substantial and largely irreversible loss in the diversity of life on Earth (United Nations 2005).

Many of the natural biogeochemical cycles are now overloaded (Cameron & Osborne 2015), nitrogen and phosphorus in particular (related to industrial agriculture production) (Steffen *et al* 2015) (Figure 67). To date, the global environment has been required to absorb these impacts, with no real understanding of the implications being reflected in development of the global industrial ecosystem. The flash point for this trend will be around the production of food for the global population.
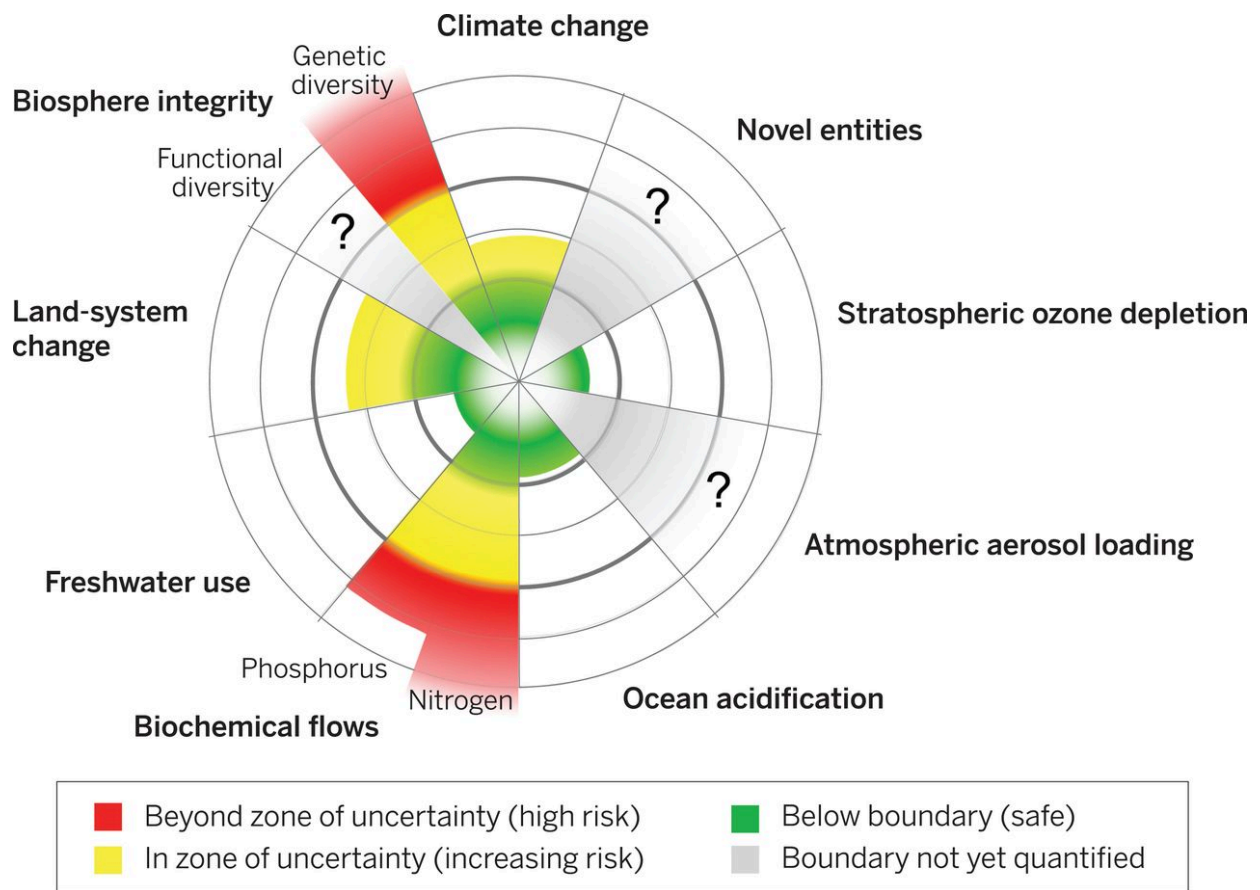
Figure 67. Status of variables controlling planetary boundaries (Steffen et al 2015)

If the Limits to Growth study is truly a good model for predicting the industrial ecosystem, then the current industrial practice is inappropriate. The continued development of the economic growth paradigm would become increasingly ineffective, and a waste of valuable resources. All such efforts would be pushing in the wrong direction with poor results (Figure 68).

*Figure 68. Perhaps our efforts are pushing in the wrong direction and are not producing the desired results
(Image: Simon Michaux - Bronze statue, South Bank Parklands, Brisbane, Australia)*

We are seeing the initial reactions to the shift in fundamentals that support our society. It could be argued that what we are seeing is merely another cycle. A case can be made to show that the supporting raw materials that make the modern world possible are now depleting and will soon not be able to meet the required demand. This has serious implications for the continued method of operation of our civilization at a fundamental level (Diamond 2005).

The rules of industrialization and the sourcing of raw materials are changing into a new era of business model. Change is happening, whether we are ready for it or not.

18   POSSIBLE RESPONSE TO THE CHALLENGE

To transition away from fossil fuels, unprecedented volumes of minerals (battery minerals in particular) will be needed. Demand for such minerals will spike all over the world, making them much more valuable. The existing approach to do this, which has served us well over the previous 200 years, is going to become increasingly ineffective. At a fundamental level, without a cheap abundant energy source, extracting mineral resources will become increasingly expensive and as time passes, will become harder to prevent decreased production rates. For the industrial ecosystem to return to how it operated when the Internal Combustion Engine technology supported infrastructure was constructed, a method to develop the production of refined petroleum at a sale price of less than $20 USD a barrel (Michaux 2019). As the quality of oil reserves have been declining for some time, this is highly unlikely to happen.

Just so, it is now entirely possible that the predicted challenges presented by the Limits to Growth report (Meadows *et al* 1972) are now in progress, which will require a fundamentally different approach to the consumption of natural resources of all kinds.

18.1 Develop a new resource management system

It is recomended to give some thought to the development of a new system of how to extract and use minerals, fundamentally different to what is used now. Currently, the free market is considered the best mechanism to manage the consumption of natural resources. Now that the global market is saturated with QE derived currency, and it is possible that peak oil production has just passed in November 2018, or could be observed in the next few years (Michaux 2019), this will no longer serve the best interests of all humanity. The Resource Balanced Economy (Michaux 2021) is presented as a start of this development.

The logistics associated with the net Energy Returned on Energy Invested for each physical action is not considered in the Circular Economy in its current form. The true energy cost of the extraction (be it mining or recycling) of resources needs to be embedded into decision making. Due to energy becoming more expensive (ERoEI), extracting, refining metals and the manufacture of products will become more difficult. As the sourcing of metals and plastics become more expensive, some form of the accounting of what resources are used, where and why is required. Conventional economics market forces will not be of use because the true cost of the whole value chain is generally not included.

There is a clear need for a methodology and a system to manage the handling of resources and their consumption that allows for the true accounting of the energy required in a balanced form.

This report proposes a solution that is an evolution of the Circular Economy, that accounts for the embedded energy requirements of resource management. This is a form of a Resource Balanced Economy (RBE), where the flow and management of resources is optimized against technological applications and the demand requirements of society. The paradigm for the proposed Resource Balanced Economy is the convergence towards long term resource sustainability, through the maximum effective use of each resource, with logistical energy constraints applied.

18.2 Open up new mining frontiers and use them differently

As it is possible global free trade may not be as easy as it is now, an unprecedented minerals and metals will be needed to transition away from fossil fuels, it is recommended that a European mining frontier be opened for exploration and mining operations commissioned.

Current thinking is that European industrial businesses, will replace a complex industrial ecosystem that took more than a century to build. The majority of infrastructure and technology units needed to phase out fossil fuels has yet to be manufactured. Recycling cannot be done on products that have yet to be manufactured. The current focus of the Circular Economy development is recycling, with the perception that mining of mineral resources is not relevant. However, the system to phase out fossil fuels (whatever that is) has yet to be constructed, and this will require a historically unprecedented volume of minerals/metals/materials of all kinds.

Very preliminary calculations show that current production rates of metals like lithium, nickel and cobalt are much lower than what will soon be required. It is equally apparent that current global reserves are also not enough. This will require sharp increase in the required mines to be operating in a few short years. A case can be made that not only is current mineral production not high enough to supply the projected quantity demand for metals, but current global reserves are not large enough to meet long term consumption targets.

Due to the predicted fierce international competition from large economic blocs like the United States and China, it is proposed that Europe will have to source its own raw materials from mining. A European mining frontier will be required to be developed, complete with the capability for refining, smelting and component manufacture. This will require all of the geological surveys of Europe to step up to the challenge, to explore

Europe for mineral deposits (most of Europe currently not surveyed below 100m). This has a number of implications, all of which are relevant in the management of resource extraction.

1. Technology (like batteries for example) should be designed using different mineral resources (primary and secondary). Find ways to make a viable battery using raw materials different to lithium, cobalt, and nickel.

2. Instead of selecting just one technology resource stream, all alternatives should be developed in parallel. Projected demand is much larger than current thinking allows for.

3. Long term consumption targets for all raw materials need to be understood. Full system replacement, followed by projected consumption for the following 100 years after, for all minerals needs to be mapped.

4. Exploration potential and capability needs to be refenced against global reserves and projected consumption requirements.

5. Any raw material that might have a supply risk should be assessed for substitution options.

6. Those substitution options should then in turn be refenced against global reserves and projected consumption requirements.

The list above shows that exploration of minerals, feasibility and mining of minerals is required, not just support the construction of the new ecosystem, but to be part of the design of that ecosystem. This should be done from the very beginning of the process. The following tasks should be considered for European Geological Survey's in particular:

- Minerals Intelligence is a highly relevant capability to navigate this fast-evolving minerals industry. This discipline should be developed in sophistication and scope.

- Development of a holistic integration of exploration methods to a depth of 3km is now required. This would have to be developed for a European exploration frontier. Exploration would have to be done in a fashion, where development on the surface would not be disturbed. To allow this to happen, a change in paradigm in the communities in Europe would be required to allow this to happen. More exploration campaigns will be required all over the world. The Nordic frontier in particular. This would have to be done by European geological surveys.

- More feasibility studies will be required to be conducted (quickly). Geometallurgy could be seen as a support action for next generation feasibility studies. This would have to be done by European operators.

- More pilot runs will be required once the Captains of industry and senior civil servants understand there is a serious incoming mineral supply shortage. Interaction with mining companies and corporate investment houses will increase and evolve.

- Any mining operation planned in Europe will be required to address each and every Social License to Operate (SLO) issue seen so far, funded with legal budgets larger than most current mining

corporations. Mineral processing will be required to be more efficient than ever before, leaving behind mine tailings of reduced environmental impact compared to current practice. The next generation of mineral processing problem solving, and tailings management is required to be developed.

19 REFERENCES

1. ABARES (March 2011): Australian Mineral Statistics ABS 1350.0 Financial Markets - Long term, http://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/1350.0Jul%202012?OpenDocument

2. Accenture: COVID-19- The industry impact of Coronavirus, Accenture, https://www.accenture.com/fi-en/services/consulting/coronavirus-industry-impact

3. Ballantyne, G.R., Powell, M.S., (2014): Benchmarking comminution energy consumption for the processing of copper and gold ores. Minerals Engineering 65, 109-114.

4. Bivens, J. (2016): Why is recovery taking so long—and who's to blame?, Economic Policy Institute, https://www.epi.org/publication/why-is-recovery-taking-so-long-and-who-is-to-blame/

5. BP Statistical Review of World Energy 2019: https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2019-full-report.pdf

6. BP Statistical Review of World Energy 2020: https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-full-report.pdf

7. Cameron, D., and Osborne, C. (2015): Soil loss: an unfolding global disaster, University of Sheffield's Grantham Centre for Sustainable Futures, presented at COP 21: UN climate change conference in Paris, published in News, Research, Policy by Grantham Centre for Sustainable Futures.

8. Chitombo, G. (2013): Personal communication

9. Covert, T. (2016): Will We Ever Stop Using Fossil Fuels?, Journal of Economic Perspectives . DOI: 10.1257/jep.30.1.117

10. Court, V., and Fizaine, F., (2017): Long-term estimates of the energy-return-on-investment (EROI) of coal, oil, and gas global productions, Ecological Economics Volume 138, August 2017, Pages 145-159

11. Depreter, M. (2021 Jan 29th): MINING SECTOR: IRON ORE AND COPPER PRICES SOARED ON THE BACK OF INCREASED CHINESE DEMAND, Credendo, https://www.credendo.com/country-news/mining-sector-iron-ore-and-copper-prices-soared-back-increased-chinese-demand

12. Dezan Shira & Associates (2020 Aug 25th): The US-China Trade War: A Timeline, China Briefing, Dezan Shira & Associates, https://www.china-briefing.com/news/the-us-china-trade-war-a-timeline/

13. Diamond, J. M. (2005): Collapse - How Societies Choose to Fail or Succeed. New York : Viking.

14. Economist, The (2019 Apr 29th): China's reboot of the Belt and Road Initiative, The Economist, https://country.eiu.com/article.aspx?articleid=597952843&Country=China&topic=Politics

15. European Commission (2017): *Study on the review of the list of Critical Raw Materials: Criticality Assessments.* Deloitte, BGS, BRGM, TNO. Luxembourg.

16. European Commission (2019a): *Going climate-neutral by 2050 A strategic long-term vision for a prosperous, modern, competitive and climate-neutral EU economy*, Directorate-General for Climate Action (European Commission), ISBN:978-92-76-02079-0, Catalog Number ML-04-19-339-EN-C

17. European Commission (2019b March 4th): REPORT FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS - on the implementation of the Circular Economy Action Plan, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52019DC0190&from=EN

18. European Union Newsroom: EU sanctions against Russia over Ukraine crisis, https://europa.eu/newsroom/highlights/special-coverage/eu-sanctions-against-russia-over-ukraine-crisis_en

19. Foran, B., and Poldy, F. (2002): Future Dilemmas: Options to 2050 for Australia's Population, Technology, CSIRO, Resources and Environment, https://www.researchgate.net/publication/242465235_Future_Dilemmas_Options_to_2050_for_Australia's_Population_Technology_Resources_and_Environment

20. Gao, M., Young, M. and Allum, P. (2002): IsaMill fine grinding technology and its industrial applications at Mount Isa Mines," in: Proceedings of the 35th Canadian Mineral Processors Conference, Vancouver, 28 April – 1 May 2002 (Canadian Institute of Mining, Metallurgy and Petroleum: Ottawa, 2002), 171–188.

21. Georgieva, K. (2020, June 3rd): *The Great Reset - Remarks to World Economic Forum*, Kristalina Georgieva, Managing Director, International Monetary Fund IMF, https://www.imf.org/en/News/Articles/2020/06/03/sp060320-remarks-to-world-economic-forum-the-great-reset

22. Government of Canada (2021): Canadian Sanctions Related to Iran, https://www.international.gc.ca/world-monde/international_relations-relations_internationales/sanctions/iran.aspx?lang=eng

23. Guardian, The (2019 Feb 21st): Chinese port bans imports of Australian coal, sending dollar tumbling
24. https://www.theguardian.com/business/2019/feb/21/chinese-port-bans-imports-of-australian-coal-sending-dollar-tumbling

25. Guppy, L., Anderson, K., (2017): Water Crisis Report. United Nations University Institute for Water, Environment and Health, Hamilton, Canada. https://inweh.unu.edu/wp-content/uploads/2017/11/Global-Water-Crisis-The-Facts.pdf

26. Hall, C., Balogh, S., Murphy, D., (2009): What is the minimum EROI that a sustainable society must have? Energies 2, 25–47.

27. Heinberg, R. (2011): The End of Growth – Adapting to Our New Economic Reality. Published by New Society Publishers, Canada, ISBN: 978-0-86571-695-7

28. Hukki, R.T., (1962): Proposal for a solomonic settlement between the theories of von Rittinger, Kick and Bond. AIME Trans. (mining), 1961, 220, 403-408.

29. ICSG, International Copper Study Group, https://www.icsg.org/

30. IEA (2019): Global EV Outlook- Scaling up the transition to electric mobility, International Energy Agency report

31. IEA (2020): Global EV Outlook- Entering the decade of electric drive?, International Energy Agency report

32. Investopedia (2019, Aug 23rd): The Impact of China Devaluing the Yuan, https://www.investopedia.com/trading/chinese-devaluation-yuan/

33. IRP (2016): Policy Options for Decoupling Economic Growth from Water Use and Water Pollution, International Resource Panel, United Nations Environmental Programme, https://www.researchgate.net/publication/304782064_UNEP_IRP_-_Policy_Options_for_Decoupling_Economic_Growth_from_Water_Use_and_Water_Pollution_-_Exec_Summary

34. JK Tech Pty. Ltd, https://jktech.com.au/

35. Keightley, M, Labonte, M. and Stupak, J. (2016): Slow Growth in the Current U.S. Economic Expansion, Congressional Research Service, Report 7-5700, R44543, https://fas.org/sgp/crs/misc/R44543.pdf

36. Lee, M. C., and Reimer, W. (2018): Challenge beyond the Horizon Made in China 2025, FAME Project presentation, GKZ Freiberg

37. Lee, M. C. (2019): Mining, SLO and China, MIREU Mining and Metallurgy Regions of EU Conference

38. Lund, S. (2018 Sept 13th): How secure is the global financial system a decade after the crisis?, McKinsey Global Institute, https://www.mckinsey.com/industries/financial-services/our-insights/how-secure-is-the-global-financial-system-a-decade-after-the-crisis#

39. Malkin, A. (2018): Made in China 2025 as a Challenge in Global Trade Governance: Analysis and Recommendations), Centre for International Governance Innovation, CIGI Papers No. 183, https://www.cigionline.org/sites/default/files/documents/Paper%20no.183_0.pdf

40. Marsden, J. (2008): Energy efficiency and copper hydrometallurgy, Freeport McMoran Copper & Gold

41. Martenson, C. (2011): The Crash Course: The Unsustainable Future Of Our Economy, Energy, And Environment, Wiley and Sons, New Jersey, ISBN 978-0-470-92764-9

42. Mathiason, N., (2008 Dec 28th): Three weeks that changed the world Business, The Guardian Newspaper https://www.theguardian.com/business/2008/dec/28/markets-credit-crunch-banking-2008

43. Meadows, D., Meadows, G., Randers, J., and Behrens III, W. (1972): *The Limits to Growth*. New York, Universe Books. ISBN 0-87663-165-0.

44. Melin, H. E. (2019): State of the art in reuse and recycling of lithium-ion batteries – a research review, Circular Energy Storage, Commissioned by The Swedish Energy Agency

45. Michaux, S., O'Neill, T., and Wilkes, F. (2012): Quantification of Energy Efficiency in Comminution - Rock type energy saturation breakage characterization, CRC Ore research report

46. Michaux, S. (2019): Oil from a Critical Raw Material Perspective, GTK Open File Work Report, Serial Number 70/2019, ISBN 978-952-217-404-8 (pdf) http://tupa.gtk.fi/raportti/arkisto/70_2019.pdf

47. Michaux, S. P. (2021): Restructuring the Circular Economy into the Resource Balanced Economy, GTK internal report, Report serial 3/2021, ISBN 978-952-217-412-3, https://tupa.gtk.fi/raportti/arkisto/3_2021.pdf

48. Morse, E (Chair), Jaffe, A (Project Director) (2001): Strategic Energy Policy - Challenges for the 21st Century, A report of an independent task force cosponsored by the James A Baker III Institute and The COUNCIL OF FOREIGN RELATIONS

49. Mudd, G. (2007, Revised April 2012): *The Sustainability of Mining in Australia - Key Production Trends and Their Environmental Implications for the Future*, Department of Civil Engineering, Monash University and the Mineral Policy Institute

50. Mudd, G. (2011): Best Practice & Sustainable Mining (?) some key issues, Darwin Environmental Policy Seminar, Monash University presentation

51. Mudd, G. M., Weng, Z., & Jowitt, S. M. (2013a). A detailed assessment of global Cu resource trends and endowments. Economic Geology, 108(5), 1163 - 1183. https://doi.org/10.2113/econgeo.108.5.1163

52. Mudd, G. M., Weng, Z., Jowitt, S. M., Turnbull, ID., & Graedel, TE. (2013b). Quantifying the recoverable resources of by-product metals: the case of cobalt. Ore Geology Reviews, 55, 87 - 98. https://doi.org/10.1016/j.oregeorev.2013.04.010

53. Napier-Munn, T., Morrell, S., Morrison R. and Kojovic T. (1996) JKMRC Monograph Mineral Comminution Circuits, Their Operation and Optimization. The University of Queensland, Julius Kruttschnitt Mineral Research Centre JKMRC Brisbane Australia.

54. National Bureau of Statistics of China, Industrial Production https://www.investing.com/economic-calendar/chinese-industrial-production-462

GTK

55. National Parks Survey (1972): American Labor History, A national historic landmark theme study, Draft 2003, National Park Service, U.S. Department of the Interior, NPS Form 10-900-b, OMB No. 1024-0018

56. Norgate, T. and Jahanshahi, S. (2010): Low grade ores – Smelt, leach or concentrate? Minerals Engineering - MINER ENG. 23. 65-73. 10.1016/j.mineng.2009.10.002.

57. Northey, S., Mohr, S., Mudd, G., Weng, Z. and Giurco, D. (2013): Modelling Future Copper Ore Grade Decline Based on a Detailed Assessment of Copper Resources and Mining. Resources, Conservation and Recycling. 83. 10.1016/j.resconrec.2013.10.005.

58. Peach, J., (2019): Personal communication

59. Reuters (2019 Jan 10th): U.S. sanctions against Nord Stream 2 wrong solution: Germany's Maas https://www.reuters.com/article/us-germany-russia-pipeline/us-sanctions-against-nord-stream-2-wrong-solution-germanys-maas-idUSKCN1P42IH

60. Rötzer, N. and Schmidt, M. (2018): Decreasing Metal Ore Grades—Is the Fear of Resource Depletion Justified?, Resources 2018, 7, 88; doi:10.3390/resources7040088

61. Rötzer, N. and Schmidt, M. (2020): Historical, Current, and Future Energy Demand from Global Copper Production and Its Impact on Climate Change, Resources 2020, 9, 44; doi:10.3390/resources9040044, file:///C:/Users/smichaux/Downloads/resources-09-00044.pdf

62. Reuter, M., van Schaik, A., Ignatenko, O., and de Haan, G.J. (2006): Fundamental limits for the recycling of end-of-life vehicles, Minerals Engineering 19 (2006) 433–449

63. Reuter, Markus. (2011): REVIEW PAPER: Limits of Design for Recycling and "Sustainability": A Review. Waste and Biomass Valorization. 2. 183.

64. Ruppert, M. (2004): Crossing the Rubicon - the decline of the American empire at the end of the age of oil, New Society Publications, Canada, ISBN 0-86571-540-8.

65. Shiklomanov, I. (2000): Appraisal and Assessment of World Water Resources, Water International, 25:1, 11-32, DOI: 10.1080/02508060008686794

66. Stall, R. (2020 Jan 16th): Disruption in the global steel sector: Peak steel demand and increasing environmental concerns, https://www.linkedin.com/pulse/disruption-global-steel-sector-peak-demand-increasing-robert-stall/

67. Taylor, G., (2008): Evolution's Edge: The Coming Collapse and Transformation of Our World, New Society Publishers, Canada, ISBN: 978-0-86571-608-7

68. Turner, G. (2008): *A comparison of The Limits to Growth with 30 years of reality, Global Environmental Change*, Volume 18, Issue 3, Pages 397-411, ISSN 0959-3780, https://doi.org/10.1016/j.gloenvcha.2008.05.001. (http://www.sciencedirect.com/science/article/pii/S0959378008000435)

69. Tverberg, G. (2014a Jan 2nd): Why a Finite World is a Problem, Our Finite World Blog
https://ourfiniteworld.com/2014/01/02/why-a-finite-world-is-a-problem/

70. Tverberg, G. (2014b Jan 29th): A Forecast of Our Energy Future; Why Common Solutions Don't Work, Our Finite World Blog, https://ourfiniteworld.com/2014/01/29/a-forecast-of-our-energy-future-why-common-solutions-dont-work/

71. UNEP (2016 March 21st): Half the world to face severe water stress by 2030 unless water use is "decoupled" from economic growth, says International Resource Panel". United Nations Environmental Programme (UNEP) Press release, https://www.unep.org/news-and-stories/press-release/half-world-face-severe-water-stress-2030-unless-water-use-decoupled

72. United Nations (2005): Millennium Assessment Reports, https://www.millenniumassessment.org/en/index.html

73. USGS, United States Geological Survey Mineral Statistics, https://www.usgs.gov/centers/nmic/international-minerals-statistics-and-information

74. Valero Capilla, A., and Valero Delgado, A., (2014): *Thanatia- The Destiny of the Earth's Mineral Resources: A Thermodynamic Cradle-to-Cradle Assessment*, Hackensack, NJ, USA: World Scientific Publishing Company, 2014, 672 pp., ISBN 978-981-4273-93-0

75. Wee Chan, K. and Baffes, J. (2020 Dec 8th): The outlook for metals: resilience and cautious optimism, World Bank Blogs, https://blogs.worldbank.org/opendata/outlook-metals-resilience-and-cautious-optimism

76. World Bank (2018): World Bank Open Data, https://data.worldbank.org/

77. World Copper Fact book 2017, International Copper Study Group, Lisbon, Portugal

78. Wroughton, L., Cohen, L., and Parraga, M. (2019 March 10th): U.S. presses India to stop buying oil from Venezuela's Maduro: envoy, Reuters News, Commodities, https://www.reuters.com/article/us-venezuela-politics-india-envoy/u-s-presses-india-to-stop-buying-oil-from-venezuelas-maduro-envoy-idUSKBN1QR0DC

79. Wübbeke, J., Meissner, M., Zenglein, M., Ives, J., and Conrad, B., (2016): MADE IN CHINA 2025 - The making of a high-tech superpower and consequences for industrial countries, Mercator Institute for China Studies

80. Yellen, J., (2017 June) 103rd Annual Report 2016 Federal Reserve. Board of Governors of the Federal Reserve System. https://www.federalreserve.gov/publications/files/2016-annual-report.pdf

81. Young, J (2018, Nov 13th): Sanctions Remove Iran from SWIFT, Will it Switch to Crypto as Planned?, CNN news network, Capital & Crypto, https://www.ccn.com/sanctions-remove-iran-from-swift-will-it-switch-to-crypto-as-planned

82. Zalan, E. (2018, Feb 6th): EU plans sanctions if UK violates Brexit transition deal, The EU Observer,

https://euobserver.com/brexit/140881

20 APPENDIX A – CHINESE CORPORATE INVESTMENT & MINERAL SUPPLY GLOBAL MARKET SHARE

This appendix is a compilation of data for the Chinese market share in the industrial ecosystem. Clearly it is not a comprehensive survey but only presents some of the parts of the industrial ecosystem. Some of the charts in this report were developed by Meng-Chun Lee in the FAME Project (Lee & Reimer 2018 and Lee 2019)
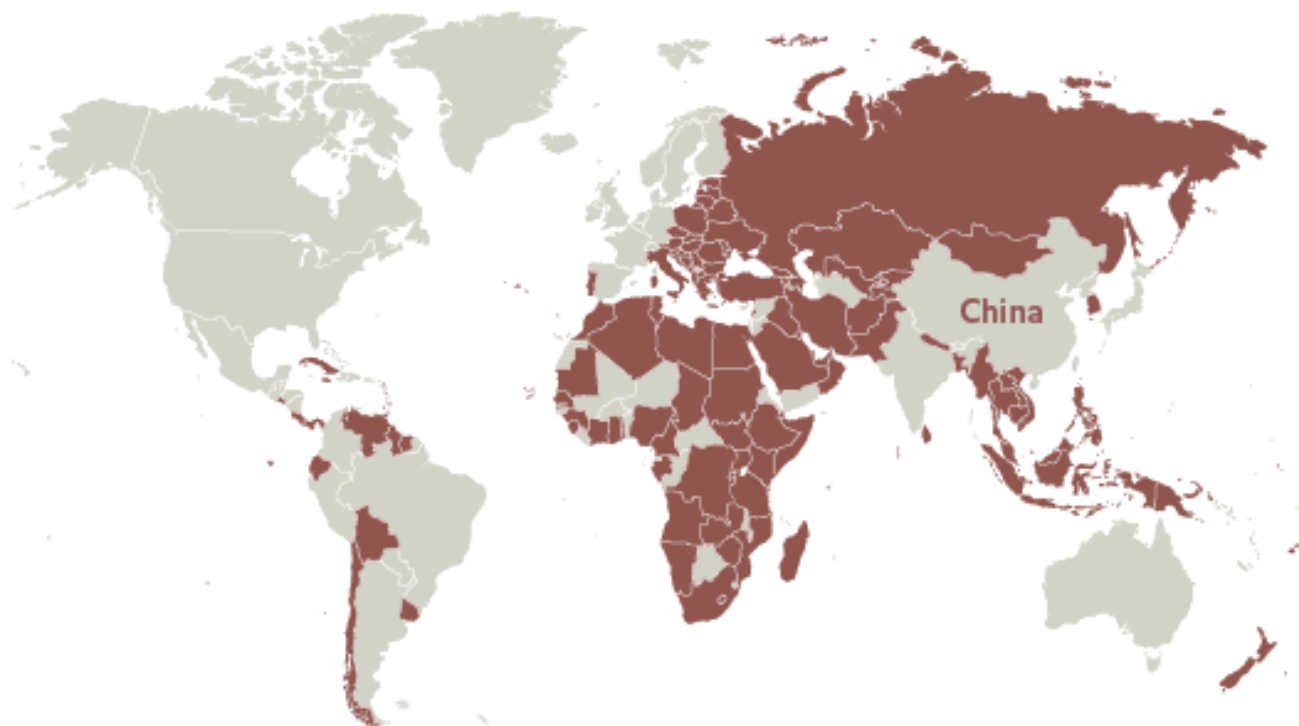
Note: Up to April 2019.
Source: http://www.yidaiyilu.gov.cn/

Figure A1. China Going Global 131 countries have signed China Belt and Road Initiative by 04/2019
(Source: Economist 2019, and CCP Belt and Road Portal, , https://www.yidaiyilu.gov.cn/xwzx/bwdt/13764.htm)
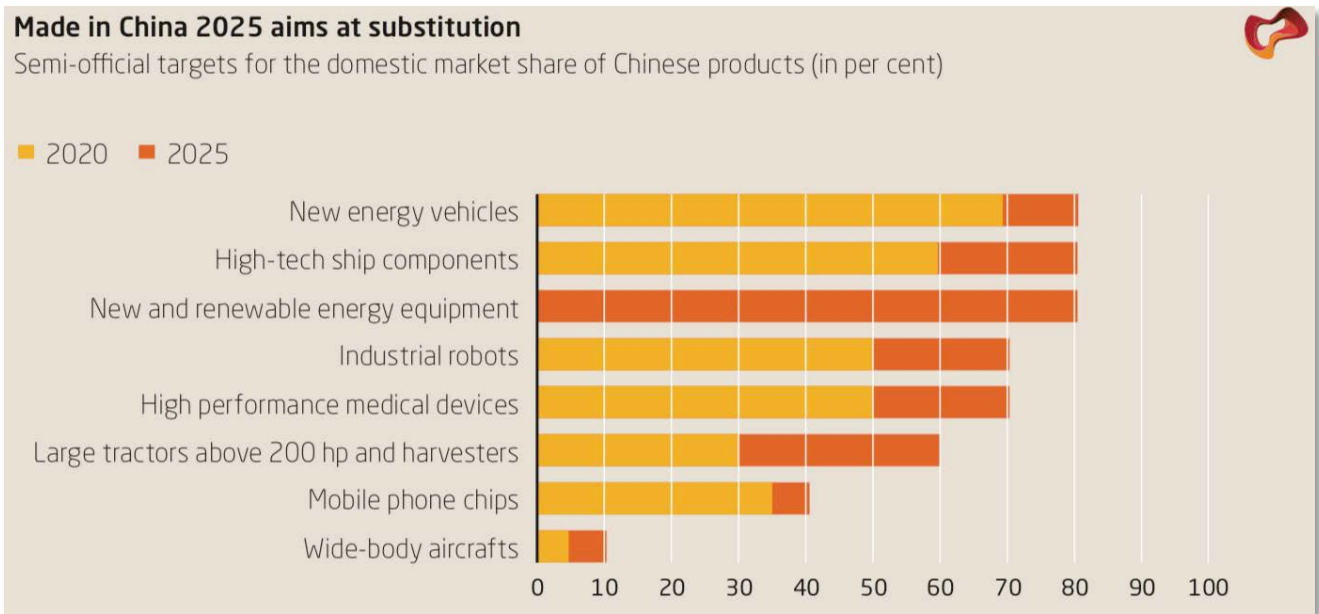
Figure A2. Semi-official targets for the domestic market share of Chinese products
(Source: MIC 2025 Green paper 2015 and MERICS 2016)
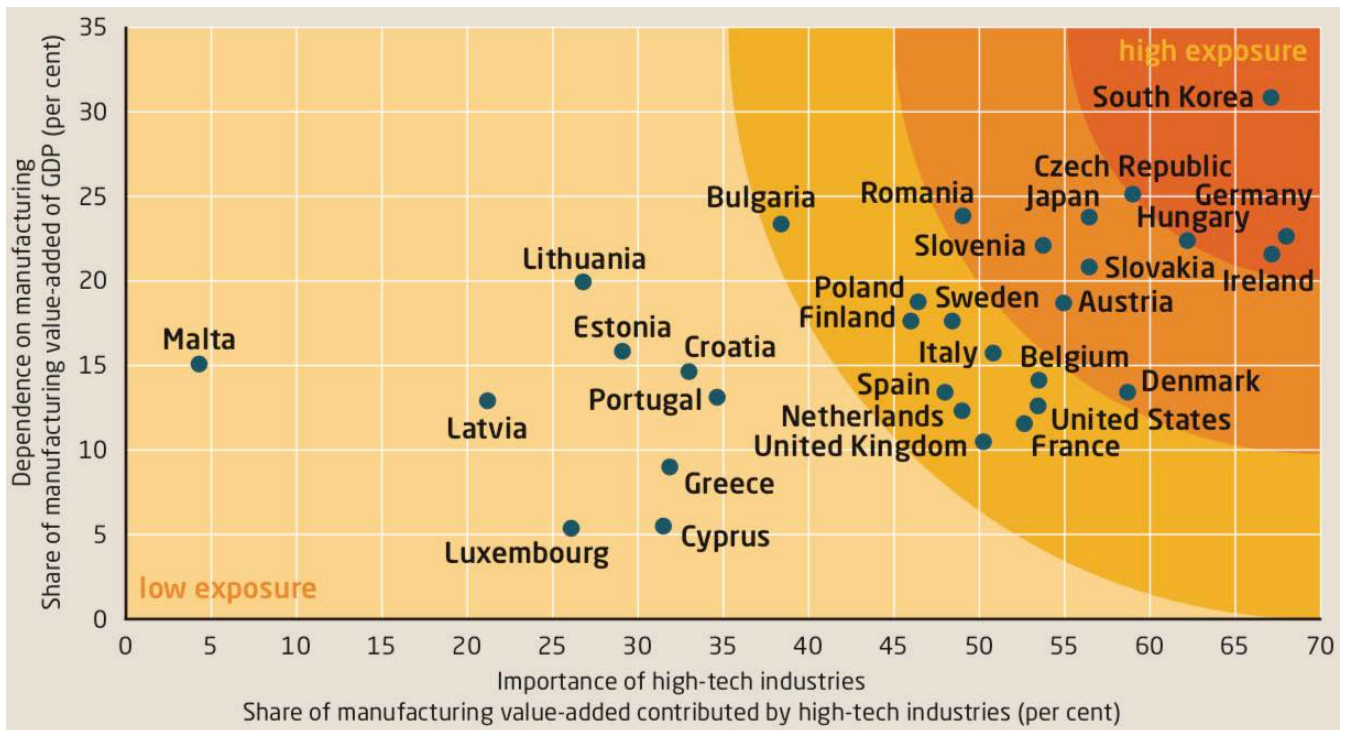
Figure A3. Level of risk exposure to Chinese corporate investment
(Source: Malkin 2018)

The European Union (EU) continues to be a desired destination for Chinese investors, with more than EUR 35 billion of completed OFDI transactions in 2016, an increase of 77 per cent from 2015.

Chinese FDI in the EU-28 2000–2016
in EUR million

Legend:
- 0–1,000
- 1,000–3,000
- 3,000–7,000
- 7,000–13,000
- >13,000

Sweden 1,592
Finland 6,854
Estonia 23
Latvia 3
Lithuania 33
Denmark 209
Ireland 2,723
U.K. 23,633
Netherlands 5,598
Belgium 1,808
Germany 18,817
Poland 936
Czech Republic 569
Slovakia 49
Luxembourg 499
France 11,458
Austria 551
Hungary 2,051
Slovenia 8
Romania 889
Croatia 4
Portugal 5,726
Spain 3,015
Italy 12,839
Bulgaria 337
Greece 840
Malta 70
Cyprus 45

Figure A4. Chinese FDI in the EU-28 2000 to 2016
(Source: MERICS & Rhodium Group 2017)

The growing imbalance in two-way FDI lows, persisting asymmetries in market access, and growing Chinese acquisitions of advanced technology and infrastructure assets have spurred heated debates in Germany and other nations about related risks.

Chinese Investors Target High-Tech, Services and Infrastructure Assets
Distribution of Chinese OFDI in the EU-28 by industry 2016
Bubble size represents total investment 2000–2016
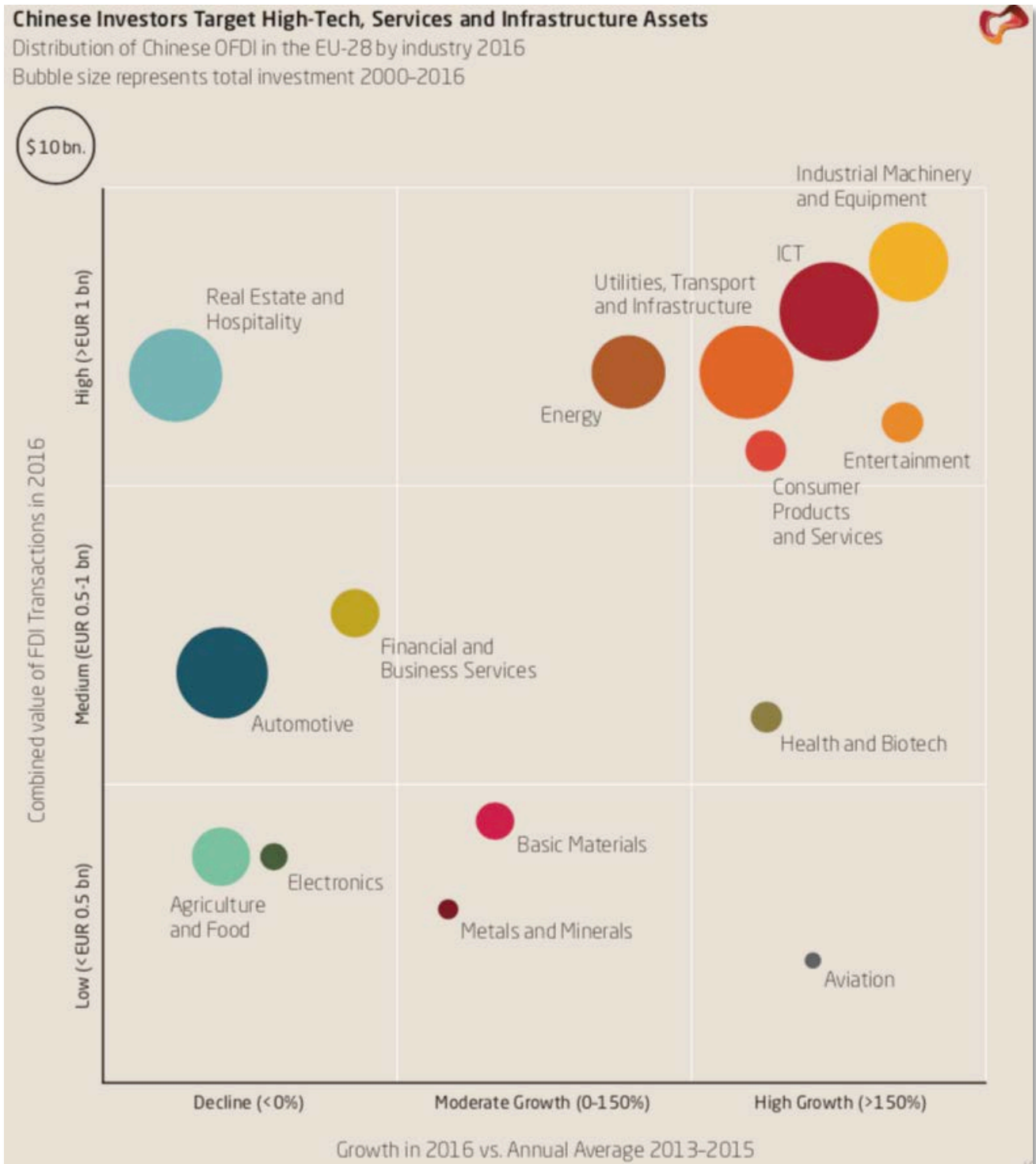
Figure A5. Chinese Investors Target high-technology, services and infrastructure assets
(Source: MERICS & Rhodium Group 2017)

In contrast to this sustained rise in Chinese investment in the EU, European companies have become more hesitant to invest in China. The value of EU FDI transactions in China continued to decrease for the fourth consecutive year to only EUR 8 billion in 2016, which is less than one third of the combined value of all Chinese investments in Europe
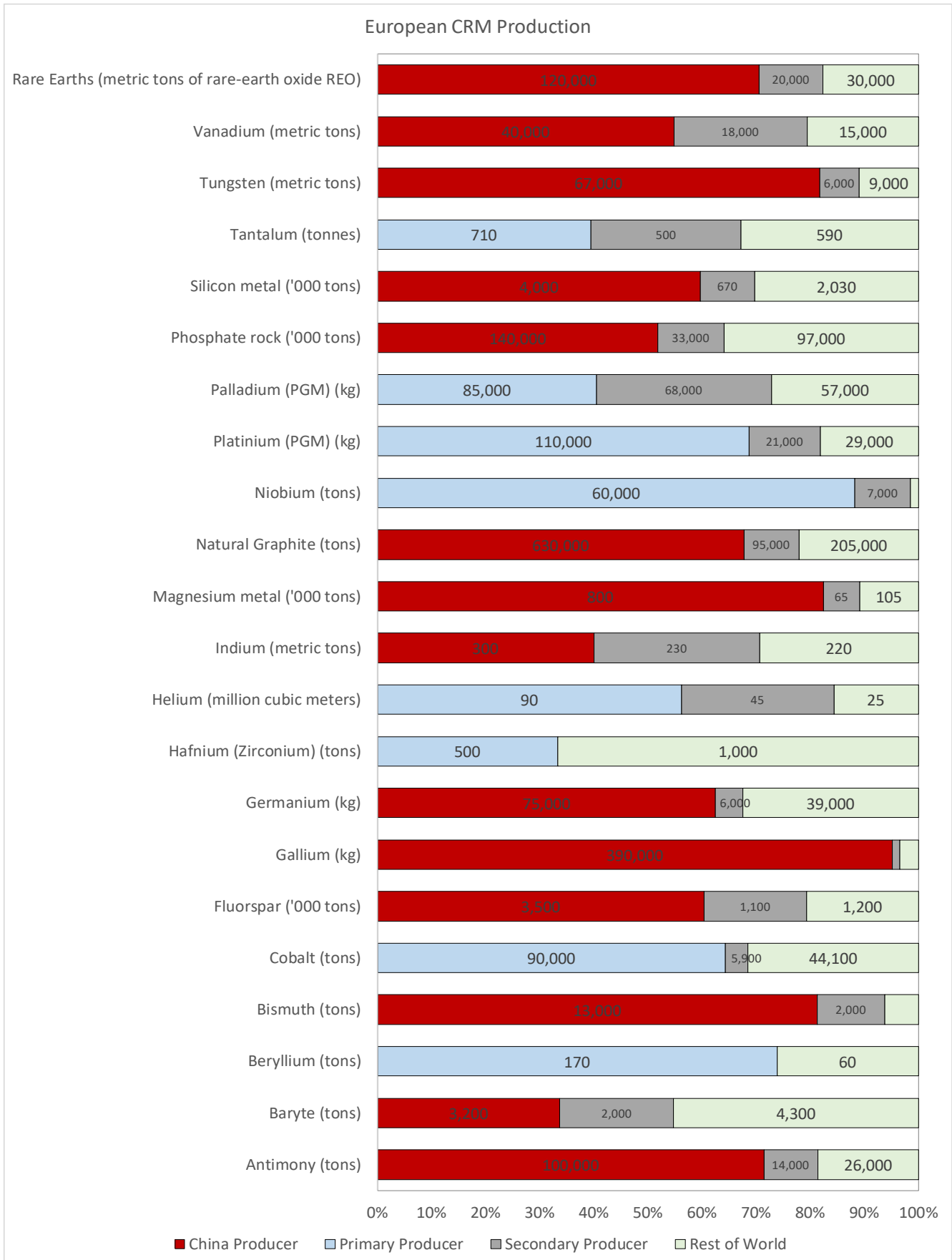
Figure A6. Chinese global market footprint of CRM raw material supply
(Source: USGS data)
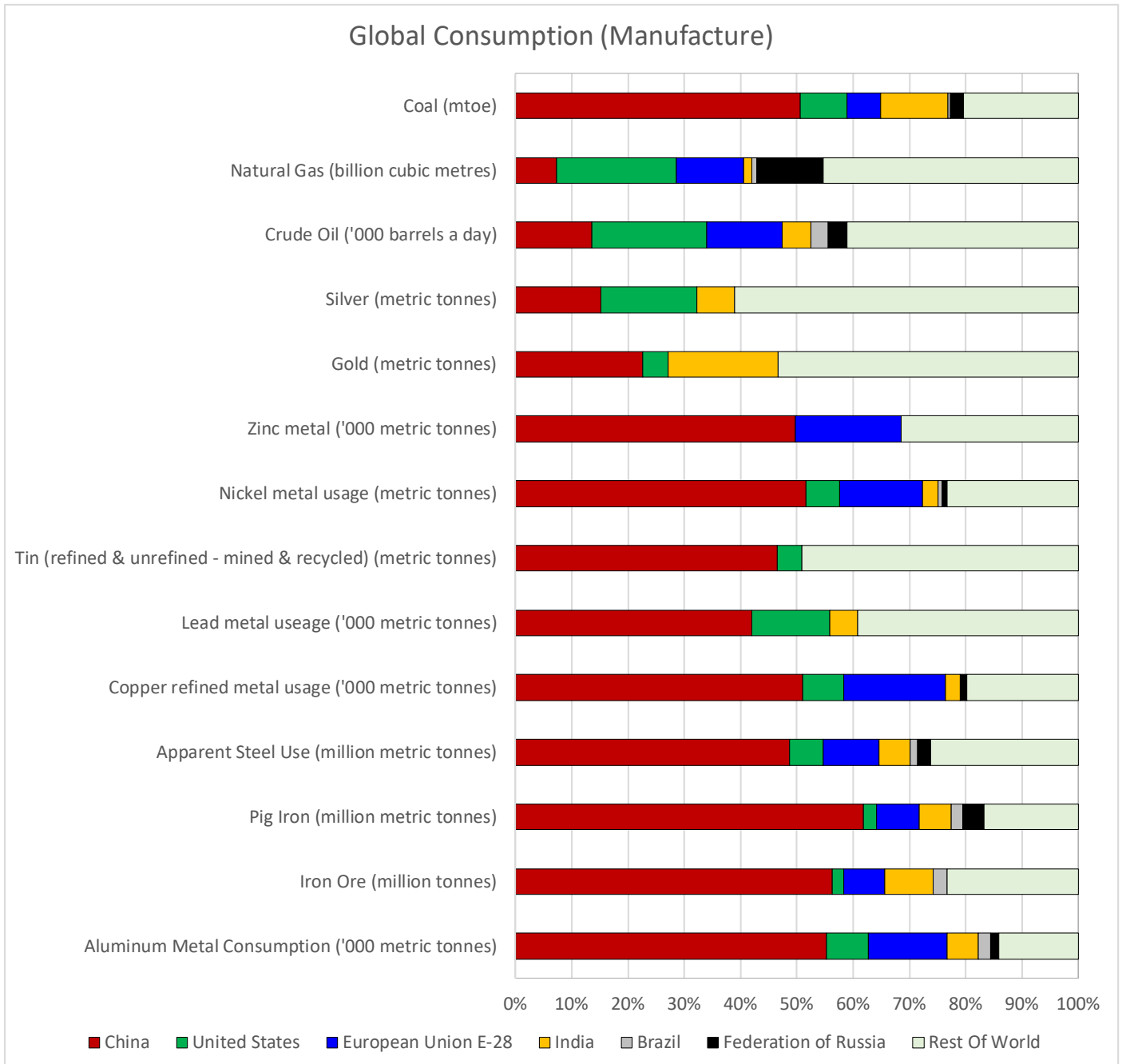
Figure A7. Chinese global market footprint of metal consumption
(Source: Data taken from World Coal association, World Gold Council, World Silver Council, BP Statistical Review of World Energy 2019, International Zinc Association, The Nickel Institute, International Tin Association,
International Lead Association, International Wrought Copper Council, World Steel Association, Australian Aluminium Council, USGS)

Metals Tracked by the World Bank

Metal	China Producer	Primary Producer	Secondary Producer	Rest of World
Silver (metric tons)	6,100	9,900		17,300
Gold (metric tons)	400		310	2,550
Zinc Refined metal production ('000 tonnes)	6,666			7,510
Zinc ('000 metric tons)	4,300		2,300	6,400
Nickel metal production (metric tons)	885,200			1,498,200
Nickel mine production (metric tons)		606,000	340,000	1,382,700
Tin (metric tons)	90,000		83,000	137,000
Lead metal Production ('000 tonnes)	4,954			6,842
Lead ('000 metric tons)	2,100			2,578
Copper refined metal ('000 metric tons)	8,356			15,742
Copper Smelter production ('000 tons)	8,600			11,500
Copper Mine production ('000 metric tons)		5,800	2,400	12,375
Finished Steel Products (million tonnes)	895		100	777
Raw Steel (million metric tons)	928		107	774
Pig Iron (million metric tons)	721		77	448
Iron Ore (million tons)		883	436	848
Aluminum Smelter Capacity ('000 metric tons)	47,890		4,060	28,440
Aluminum Metal Production ('000 metric tons)	33,000		3,700	27,600
Aluminum (Alumina) ('000 metric dry tons)	73,000		19,000	39,000
Aluminum (Bauxite) ('000 metric dry tons)		75,000	76,000	155,000

■ China Producer   ■ Primary Producer   ■ Secondary Producer   ■ Rest of World

Figure A8. Global consumption of metals tracked by the World Bank
(Source: same data sources as Figure A7)

Geologian tutkimuskeskus | Geologiska forskningscentralen | Geological Survey of Finland

Industrial Minerals & Refined Products

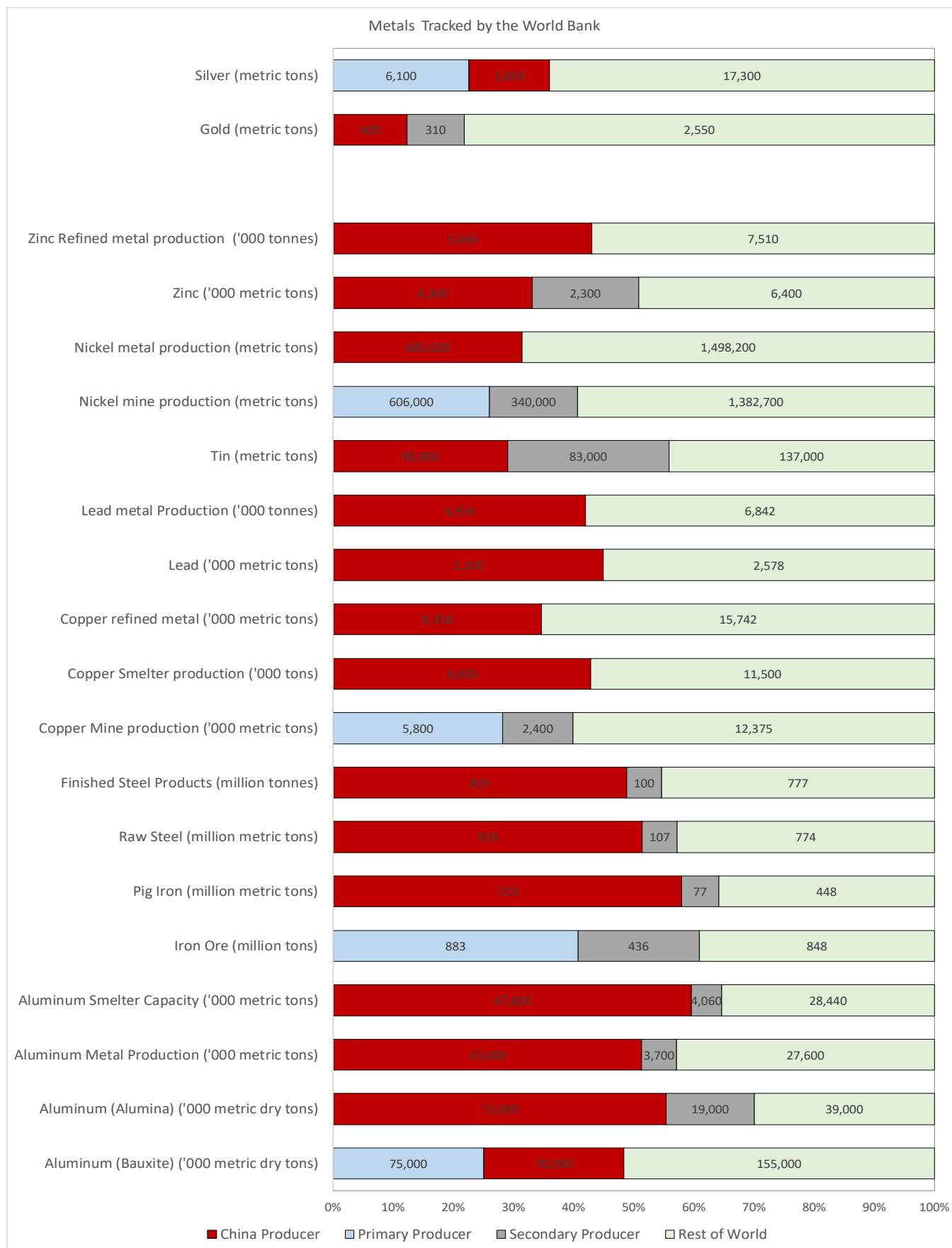| Product	China Producer	Primary Producer	Secondary Producer	Rest of World
Titanium & Titanium Dioxide Pigment Capacity (metric tons)	3200000		1370000	3,040,000
Titanium & Titanium Dioxide Sponge Capacity (metric tons)	110000		68800	114,200
Titanium & Titanium Dioxide Sponge Production (metric tons)	70000		52000	58,000
Sulfur ('000 metric tons)	17000		9700	53,300
Silicon Carbide Abrasives (Manufactured) (tons)	455000		80000	465,000
Phosphoric Acid ('000 tons)	35000			48,000
Nitrogen (fixed) Ammonia ('000 metric tons)	44000			96,000
Corundum Fused Alumiunium Oxide Abrasives (Manufactured) (tons)	800000		80000	420,000
Purified Spherical Graphite (SPG) (tons)	100000			
Clinker Capacity ('000 tons)	2000000		280000	1,520,000
Cement production ('000 tons)	2370000		290000	1,440,000
Mica (Natural) Sheet (metric tons)		1,000		200
Mica (Natural) Scrap & Flake (metric tons)	80000		55,000	205,000
Lime ('000 metric tons)	300000			101,000
Salt ('000 metric tons)	68000		42,000	190,000
Talc & Pyrophyllite ('000 metric tons)	3,800		900	4,800
Potash ('000 metric tons of K20 equivalent)	12,000		7,500	22,500
Arsenic Trioxide (metric tons)	24,000		6,000	5,000
Tellurium (metric tons)	300		36	104
Wollastonite (metric tons)	580,000		150,000	120,000
Molybdenum (metric tons)	130,000		42,000	128,000
Mercury (tons)	3,400	3,000		
Lithium (tons)		51,000	16,000	18,000
Cadmium (metric tons)	8,200		5,600	12,200
Chromium ('000 metric tons)		16,000	6,500	13,500

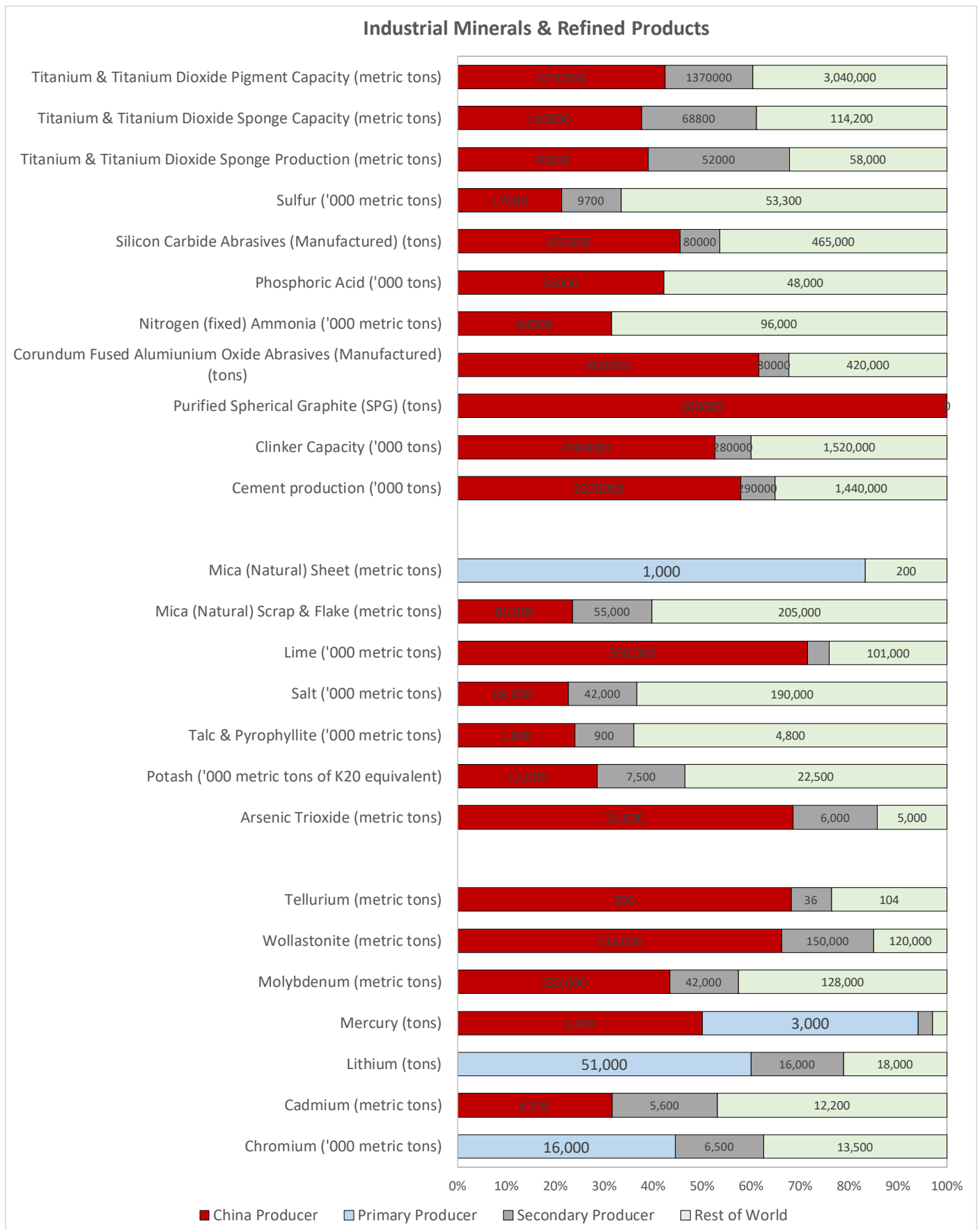■ China Producer   □ Primary Producer   ▨ Secondary Producer   □ Rest of World

Figure A9. Chinese global footprint in industrial mineral supply
(Source: USGS data)

GTK