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Restructuring the Circular Economy into the Resource Balanced Economy

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Executive Summary

The Linear Economy (LE) is showing signatures of stress and strain, where the paradigm of exponential growth and the perception of unlimited natural resources is now facing resistance to further economic growth. In 1972, the Club of Rome released their Limits to Growth report. An update study in 2004 projected historical data (1970 to 2000) onto the Limits to Growth study outcomes, which showed the industrial ecosystem is tracking the Base Case Scenario. This implies that the global industrial ecosystem will soon peak in production per capita, then contract in size from that peak. It is appropriate to transform this current system into something else. This transformation process has already started, but not necessarily in a way to help society in context of long terms sustainability.

Circular Economy (CE) as a proposed solution is a good start but ultimately not a viable replacement in its current form. This is due to the CE not being able allow for economic growth or human population growth, yet still develop a system based around recycling only. The mining of minerals is considered not relevant as it is to be phased out.

Usually, the CE is presented in very vague terms without much structural detail, or context to map details onto. It could be that the CE has not been thought through in this manner, and policy makers have been waiting for a more structured counter proposal like what is presented in this report.

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. An example of this is waste disposal in a local area. Currently large volumes of waste are exported to other countries for disposal where costs are lower and environmental restrictions are more lenient. If an economy was truly circular, all waste would be disposed of within that economy, not exported.

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 proposed Resource Balanced Economy is an evolution of the Resource Based Economy, with the integration of exergy as a limit derived decision tool. The original concept of the Resource Based Economy is the development of a system over time, where all resources, technology and services are available to everyone in the human population. This is deployed without the use of money, credit, barter, or servitude of any kind, while maintaining basic human rights like privacy and free speech. For this to be attained, all resources must be declared as the heritage of all humans in a global context. All resources are defined as existing valuable commodities subject to mining, and the waste side stream secondary resources. The proposed Resource Balanced Economy is an evolution of this, which includes a thermodynamical exergy term as a limiting metric to produce a practical system.

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. The architecture of this RBE is developed with six dominant considerations that could be developed as structural parts of the economic system.

1. Resource accounting
2. Management of dynamic equilibrium
3. Strategic design
4. Statistical entropy coupled with material flow analysis of each resource
5. Biophysical signatures
6. Technology application evolution/devolution over time

Industrial ecology concepts like thermodynamics, exergy and biomimicry are proposed, using systems network theory. At a foundation level, uncertainty could be allowed for, with the use of fuzzy logic and/or neural networks.

An evolution of how raw materials are characterized is recommended. A unified characterization protocol, capable of mapping samples from all parts of the value chain (from mineralized ore to recycled waste) for each mineral, metal, or material is proposed. Related minerals, metals, or materials characterized in this fashion would become what is proposed to be the Materials Atlas.

A series of system maps are proposed to be developed, tracking the industrial steps in transforming a natural raw material (for example mineralized ore) into a refined chemical or pure metal. Another series of system maps are proposed to track the industrial steps in the use of refined chemicals and pure metals in the manufacture of a technological unit (like a computer or wind turbine). A further series of system maps are proposed to optimize how society would use technology units together to perform a useful task (like the supply of electrical power to consumers).

In the Circular Economy, generally systems architecture of only one material life cycle loop is considered, based around recycling of waste. The proposed RBE has three Raw Material Loop Cycles. RM Loop Cycle A is the mining and refining of minerals to manufacture to waste handling. RM Loop Cycle B is the valorisation or the remining of industrial waste streams, to manufacture, to waste handling. RM Loop Cycle C is the recycling of waste streams to manufacture, to waste handling. All three RM Loop Cycles are merged into a single system that dynamically interacts.

The controlling paradigm that guides the use of the system maps and characterization protocols is to be thought through carefully. This involves a subtle redirection of the 4th Industrial Revolution paradigm. A series of control systems are proposed, where the controlling paradigm would administer an Artificial Intelligence guided Machine Learning network (or similar tools) to manage complex data streams. Block Chain technology (or similar tools) is recommended to be used to track and trace the flow of materials through the value chain and through the whole industrial ecosystem.

If it comes to pass that the global energy sector does transition into a low energy future, the proposed RBE could be a way of managing the inevitable reduction in complexity of the industrial ecosystem, in a way that allows an equitable outcome for society. This report proposes the starting point for the development of a form of Resource Based Economy. This system has the potential to manage more effectively technology and its supporting resources in a low energy future. It is hoped that this system could address some of the wealth inequalities in current society.

This proposed RBE involves a change for several existing paradigms.

- The relationship between the industrial ecosystem and fossil fuels and the mining of minerals is to be quantified into a more realistic posture.
- It is now recognized that to construct a substitution system for the current fossil fuels powered infrastructure will require a historically unprecedented supply of metals and raw materials.
- It is recognized that as this new replacement system (CE or RBE) is not yet constructed, recycling cannot supply those metals and raw materials.
- It is recognized that the mining of minerals is the most practical way of supplying the needed resources due to required volumes of demand, and also could have a lower ERoEI than recycling.
- Current production rates are not enough. Existing mineral reserves need to be transformed into producing mines.
- The long term consumption requirements of minerals may exceed global reserves in their current form.
- More exploration will be required. As all nation states in the world are in a similar predicament, access to mineral deposits could become more difficult. It may become necessary for Europe to be explored for mineral deposits.
- It is possible that a European mining frontier will have to be developed, complete with a self-sufficient refining and smelting capacity

It is recommended that a simple and small version of this system be developed, which could later be nurtured into a more complex system with a wider catchment scope. To start this process, it is proposed to bring together technical professionals in the data intelligence parts of these technology sectors (those that understand the concepts in this report). Host a 'Seven Sisters of Industrial Data Intelligence' conference, where a response to this report is presented from each sector. From this conference, assemble a development team of people and start the process of creating this conceptual data management system. Once developed to a state of stability, the developed RBE industrial ecosystem could be merged with other networks to include communications, food supply, potable water, sewerage sanitation and monetary financial systems.

These ideas have implications and opportunities for GTK, which is well positioned to contribute to the development of the RBE and assist our stakeholders as society navigates these challenges.

Keywords Circular Economy, Resource Balanced Economy, Resource Based Economy, Mining, Recycling, Waste, Exploration, Energy, Exergy, Entropy, 4th Industrial Revolution, Artificial Intelligence, Machine Learning, Block Chain, China			
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Contents

Both of these quotes are pertinent to the task before us

What are immutable foundations of human health and prosperity, and how do we construct a system which meet those needs for the entire human population, understanding we live on a finite planet, while ensuring the sustainability of this habitat for future generations?

- *Peter Joseph, The Zeitgeist Movement 2010*

The inevitable energy transition away from high quality fossil fuels to lower quality, more expensive energy forms—which will be completed well before the close of this century, and quite possibly much earlier—will force a paradigm shift in the organization of civilization.

- *Nafeez M. Ahmed 2017*

1 INTRODUCTION

The Circular Economy (CE) dominates any European sustainability discussion. Any application of any given raw material is examined in this context. This is true for any mined mineral primary resource or any recycled secondary resource.

The current system, Linear Economy (LE), is based on economic growth, with monetary value as the metric, is in a state of stress in multiple sectors. There is a very real need to develop a replacement system to a practical level of operation while the current system is still productive.

It is also apparent that the Circular economy is structurally flawed. The visible flaws have serious implications and mean our best and brightest scientists and engineers are working on the wrong projects. This report will attempt to discuss these flaws. A replacement for the existing system is also needed. The current system, that the Circular Economy was designed to replace, is seriously unbalanced and unsustainable. So, the flaws of the Circular Economy need to be understood, then in a new system is proposed that would attempt to address those flaws.

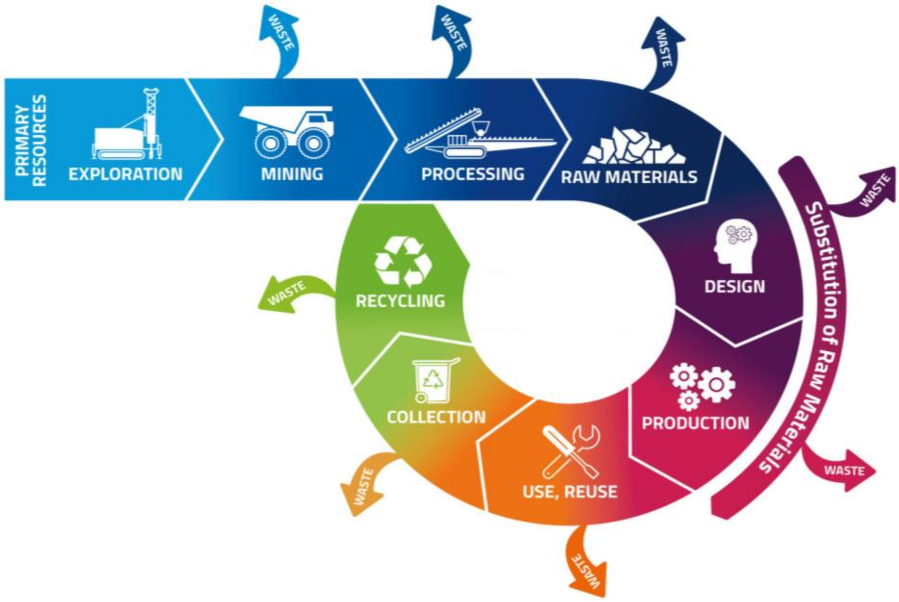


Figure 1. The Circular Economy to develop the future European industrial ecosystem
(Source: EIT Raw Materials)

The creation of a truly sustainable system is the creation of optimal industrial ecological systems with optimally linked best available techniques and methodologies. This must maximize the recovery of materials from mineralized ores and industrial waste residue recyclates within the boundaries of consumer behavior, product design/functionality, thermodynamics, legislation, technology, and economics.

This report presents an evolution of the Circular Economy in the form of a Resource Balanced Economy (RBE).

2 THE CIRCULAR ECONOMY

The Circular Economy was proposed in 2010 (European Commission 2010) to address the perceived flaws of the existing raw materials supply system in context of sustainability and environmental impact. It was proposed that the CE would alleviate the impact of human activity on the environment as a result of an ever-increasing demand of raw materials. The majority of developments of the CE since 2008, has been a variation of Figure 2.

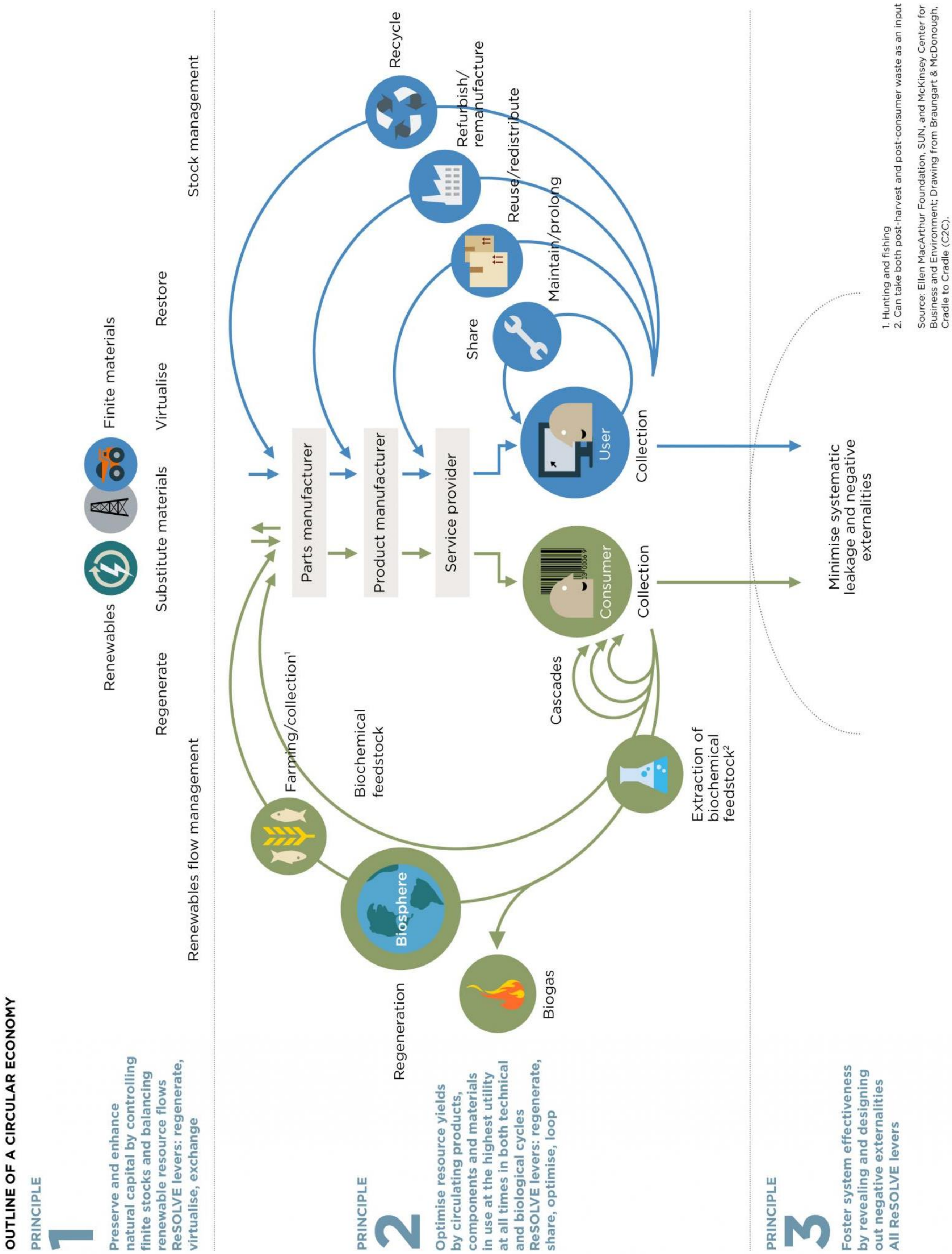


Figure 2. The Circular Economy
(Source: European Commission 2019 March 4th, Ellen McArthur Foundation)

The author spoke to someone who was at the very first Circular Economy meeting in 2008. This man told him the thinking at the time was quite clear. The European Commission was concerned about raw materials supply for certain European businesses (he would not elaborate which ones but suggested they were all positioned for technology leadership market share in their respective fields).

The concern was not being faced with a minerals/metal's shortage in a global context so much as Europe no longer controlled any of these raw materials sources. The unspoken (but very clear) primary underlying issue was that one nation (China) dominated supply of most of these raw materials. Figure 3 below captures the true concern that motivated the formation of the Circular Economy, the CRM list and the H2020 project. See Appendix A – Chinese Corporate Investment & Mineral Supply Global Market Share Footprint.

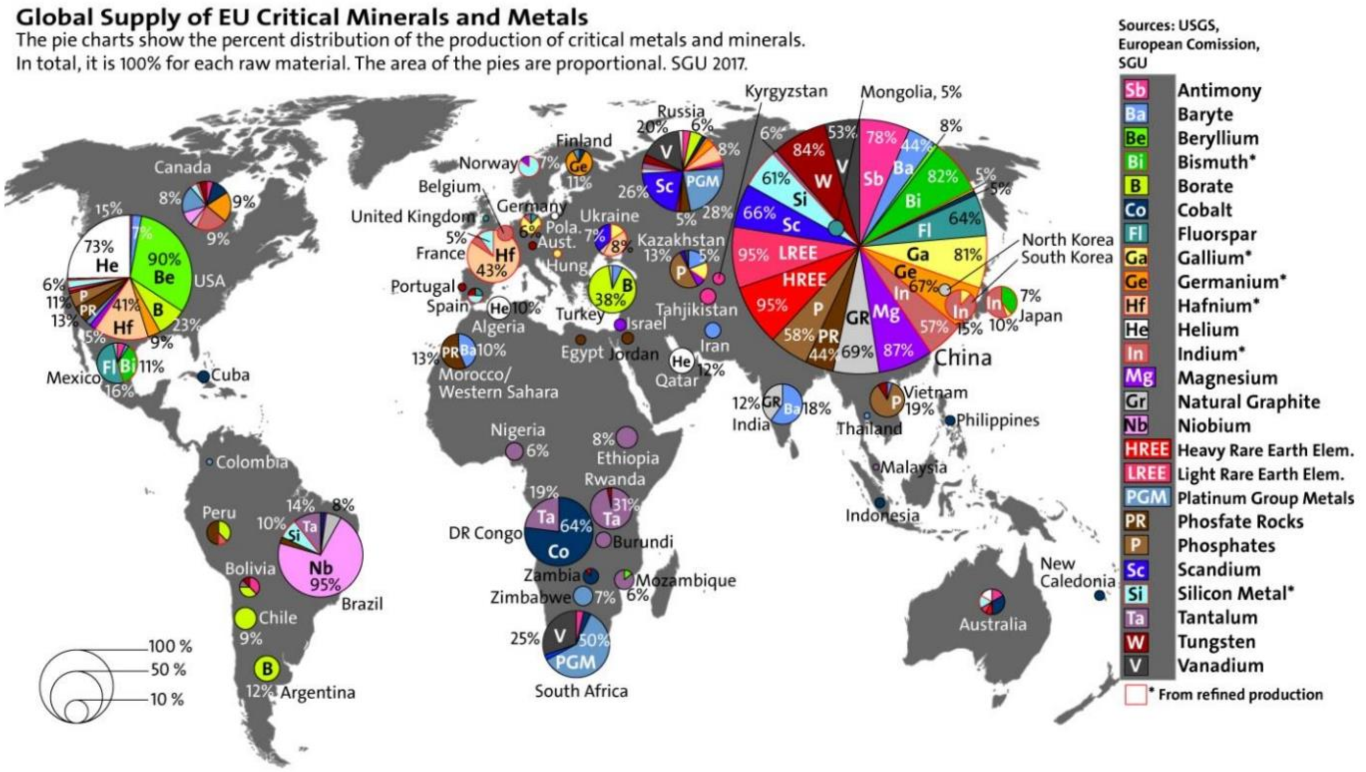


Figure 3. Global supply of EU Critical Minerals and Metals
(Source: SGU)

This is also shown in Figure 4 with the example of natural graphite and Figure 5 for magnesium metal.

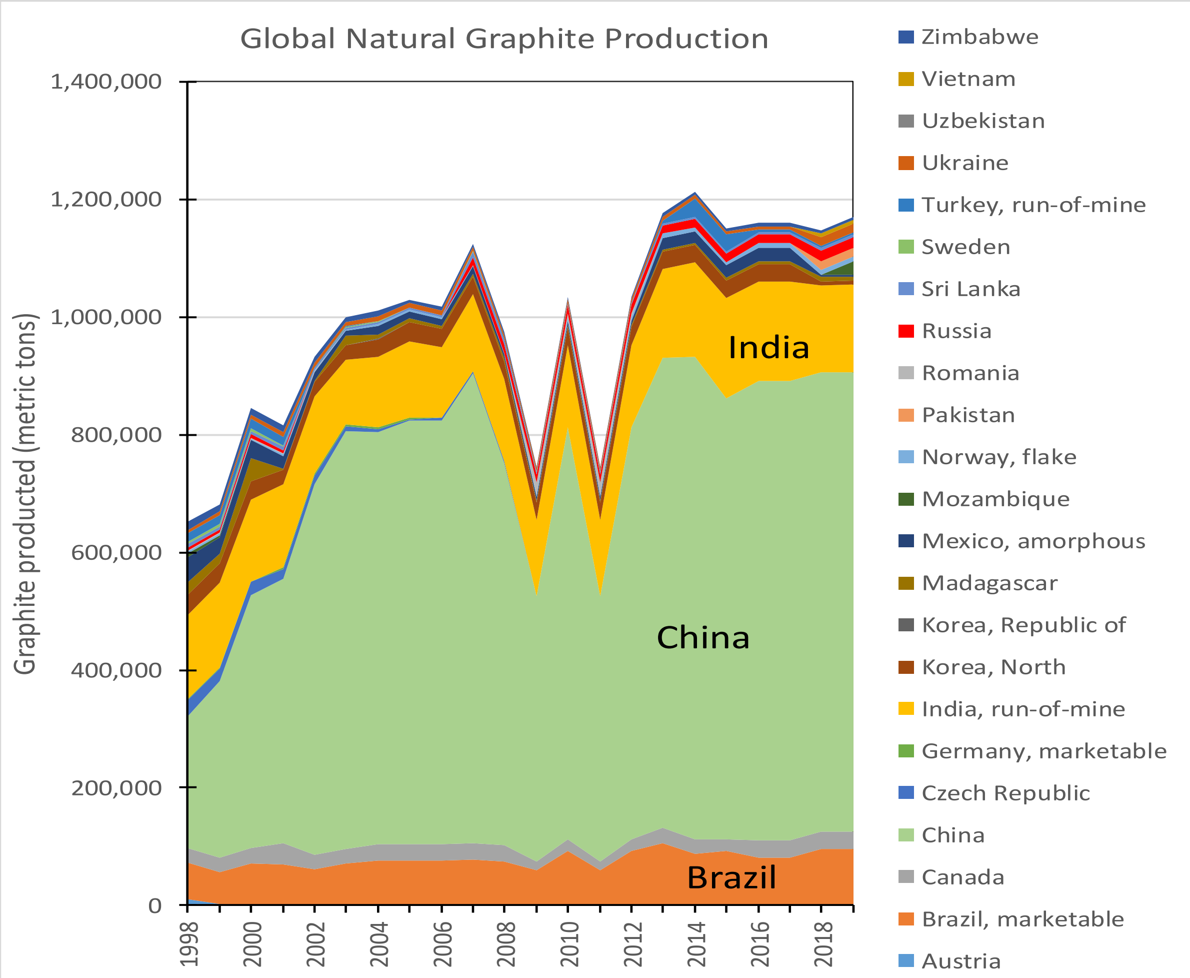


Figure 4. Annual Natural Graphite Production 1998 to 2017
(Source: Michaux 2018a, USGS)

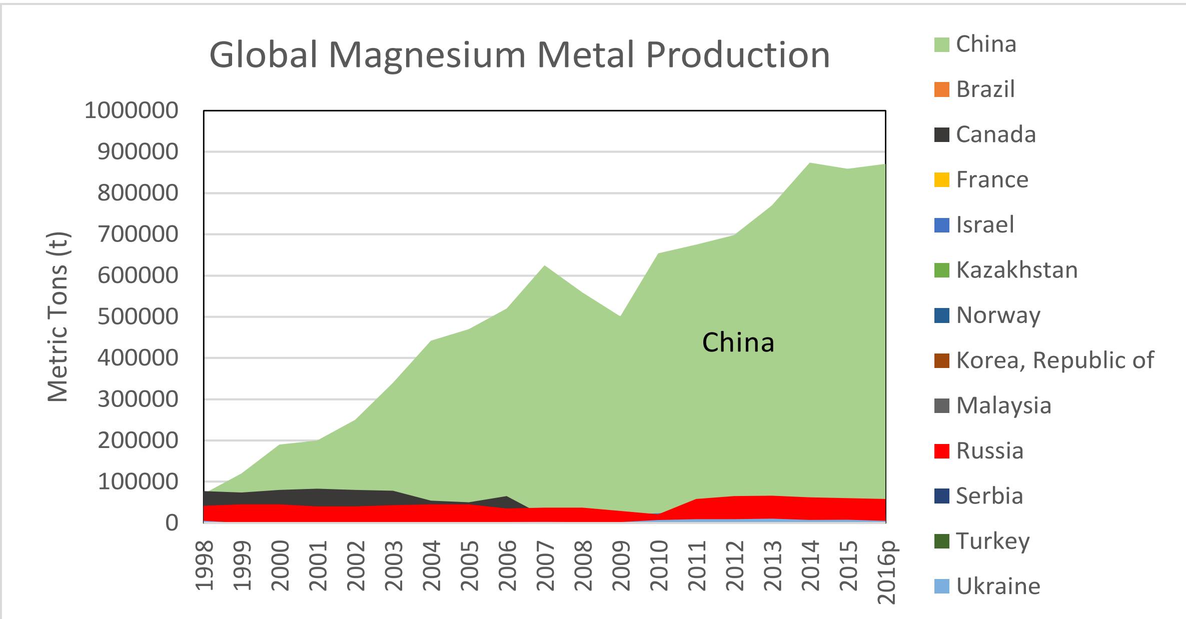


Figure 5: Global production of magnesium metal. This figure excludes the United States as data has been withheld since 1998
(Source: Michaux 2018b, USGS)

Figure 6 shows a graphical description of the Circular Economy, where it was recognized that the raw materials value chain started with mineral exploration, and there is waste generated at each stage. As can be observed, it is not actually circular.

Currently, the European mindset still does not allow for exploration or mining to be considered as a sensible activity, favouring recycling instead.

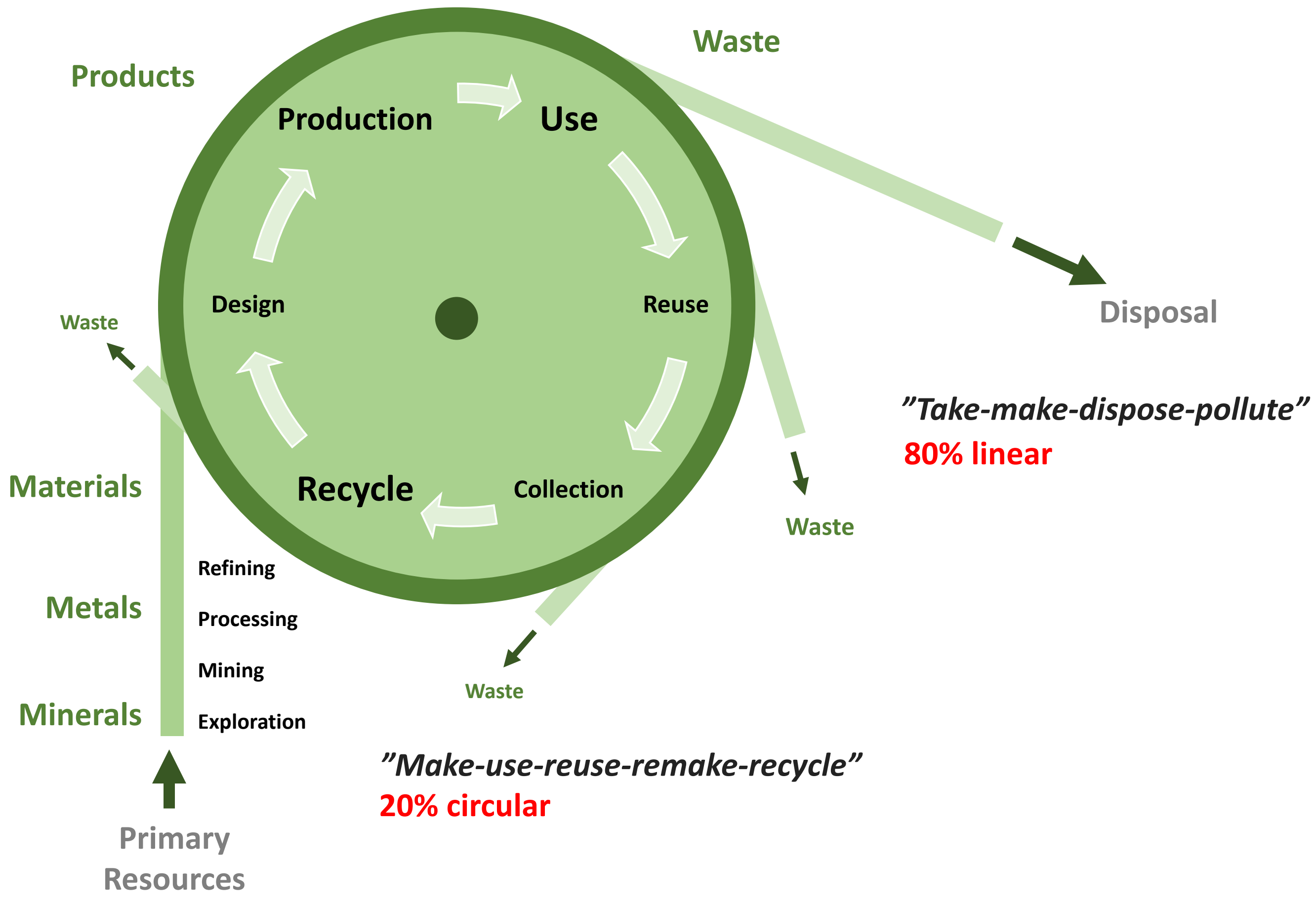


Figure 6. The Circular Economy accounting for primary resource extraction
(Image: Alan R Butcher)

2.1 The Critical Raw Materials list

As part of the development of the Circular Economy, a list of metals, materials and minerals was developed (Deloitte et al 2017) called the CRM list. The purpose of the CRM list (Table 1) was to track the production challenges faced by European industry.

At the time of the establishment of the first CRM list, a policy decision was made not to examine energy resources (oil, gas, coal, and uranium). The logic behind this decision was the European Commission could advise what nation states could do with data for mineral supplies consumption, but energy resources consumption was to be the affair of each nation member state only. This decision was enforced by the Commission from the beginning. This paradigm was still in force in 2018/2019 when the author was working for the SCRREEN project, where even discussing energy resource consumption was discouraged. There was the belief that others were attending to this task and it was of no concern. This was the motivation to write the report Oil from a CRM perspective (Michaux 2019), to the purpose of examining exactly what was the status the Electric Vehicle Revolution was to replace.

This meant that not only was the CRM list mapping the previous four years of production data (not future demand) but it had excluded energy resources. This is a problem as energy is the master resource, that without which, no physical activity of industrial production is possible. This highlighted a very clear blind spot that professional analysts developing European long term sustainability all had as a self-reinforcing work culture.

Table 1. The 2017 list of Critical Raw Materials (Source: Deloitte et al 2017)

2017 Critical Raw Materials (26)			
Antimony	Gallium	Magnesium	Scandium
Baryte	Germanium	Natural graphite	Silicon metal
Beryllium	Hafnium	Natural Rubber	Tantalum
Bismuth	Helium	Niobium	Tungsten
Borate	HREEs	PGMs	Vanadium
Cobalt	Indium	Phosphate rock	
Fluorspar	LREEs	Phosphorus	

Figure 7 below shows the Critical Raw Materials list (from Table 1) shown in context of economic importance and supply risk. These estimates for each CRM material are done on the previous four years of production data. They do not look to future demand.

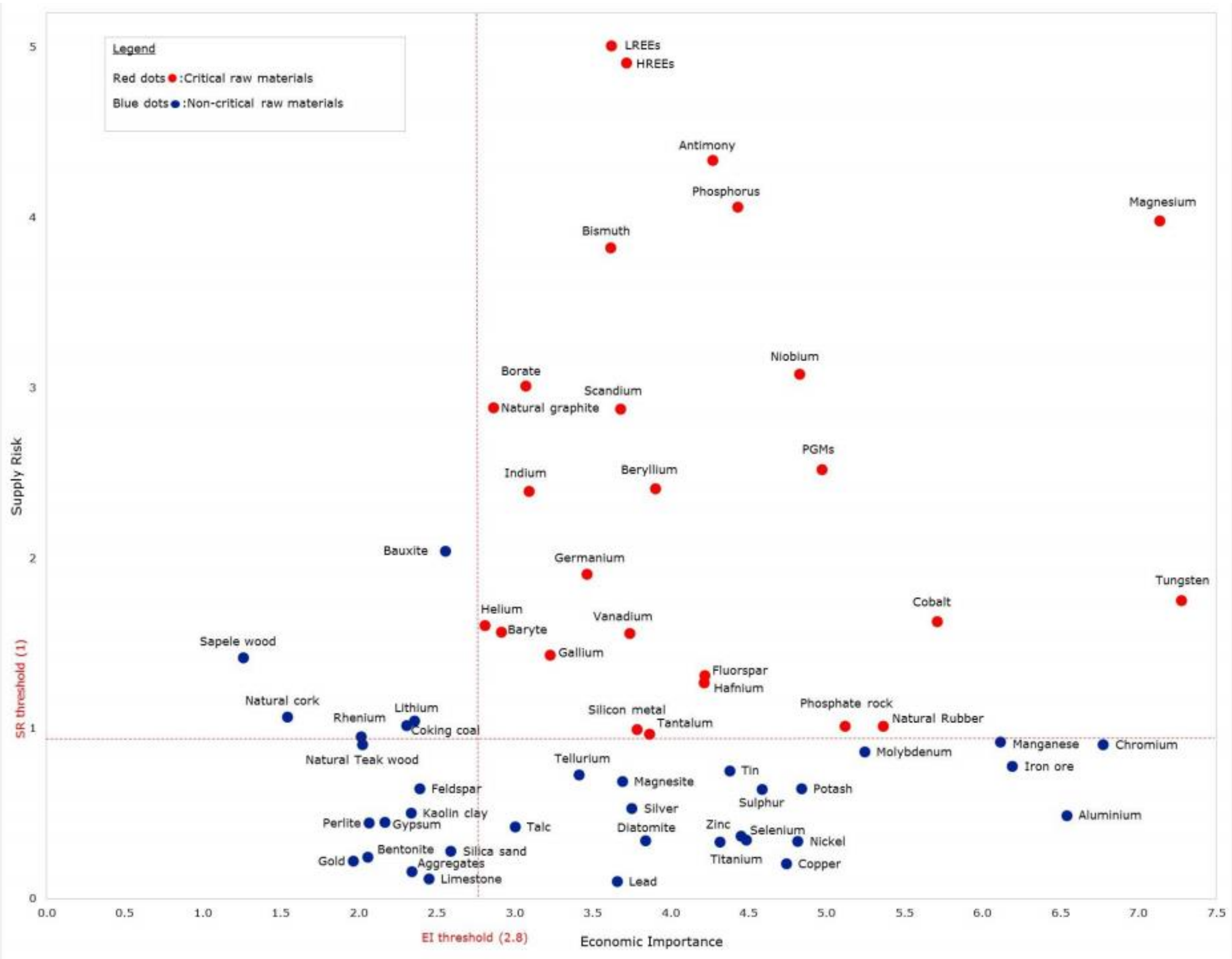


Figure 7. Economic importance and supply risk results of 2017 criticality assessment
(Source: Deloitte et al 2017)

An alternative perspective is the CRM list developed and maintained by the DERA group (A department of BGR) in Germany. The DERA mission is to contribute to a secure, affordable, and sustainable mineral raw material supply for Germany. Considering the energy transition (batteries) and further key and future technology developments, they evaluate commodity markets and international mineral supply sources.

Each Critical Raw Material (CRM) that is relevant to supply the German industrial eco-system is examined both upstream and downstream from any given point in its market presence. An effort is made to map the past, present and future of each individual mineral. The stages looked at in varying degrees of depth are:

- Deposit resources and reserves
- Mining of deposits
- Refining of metal
- Rates of recycling
- Market price and volumes

This however is down in a purely market reporting context. The desired level of precision is a market macro trend and pattern diagnosis only. The collect numbers from investment reports only. The CRM map of economic importance vs. possible supply risk is updated each year with DERA data, from an industry needs context (Figure 8). This looks a little different to the conventional map that is often used in H2020 publications. What is curious is the position of gold (Au) in risk group 1. This highlights the focus of this work. Gold is not that necessary for industry needs but is of great geopolitical importance.

Figure 8. The DERA map for CRM's
(Source: DERA 2016)

While Figure 7 was based around the paradigm of securing European businesses, Figure 8 is based on the paradigm of what German industry requires.

3. THE LINEAR ECONOMY

The Circular Economy was designed to replace the Linear Economy (Figure 9). 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).

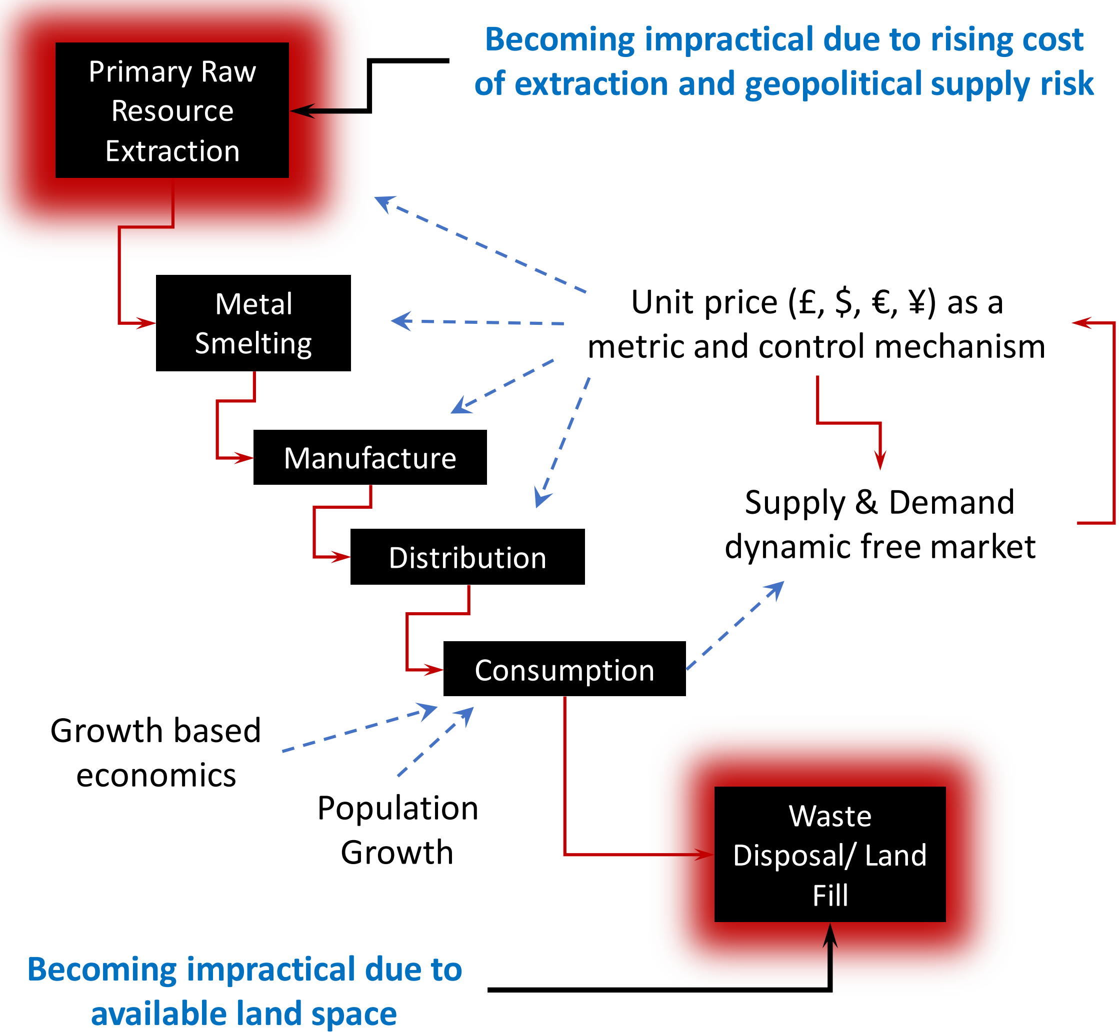


Figure 9. The Linear Economy
(Image: Simon Michaux)

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 9 should be put in context of Figure 10, that shows human population growth and energy consumption growth.

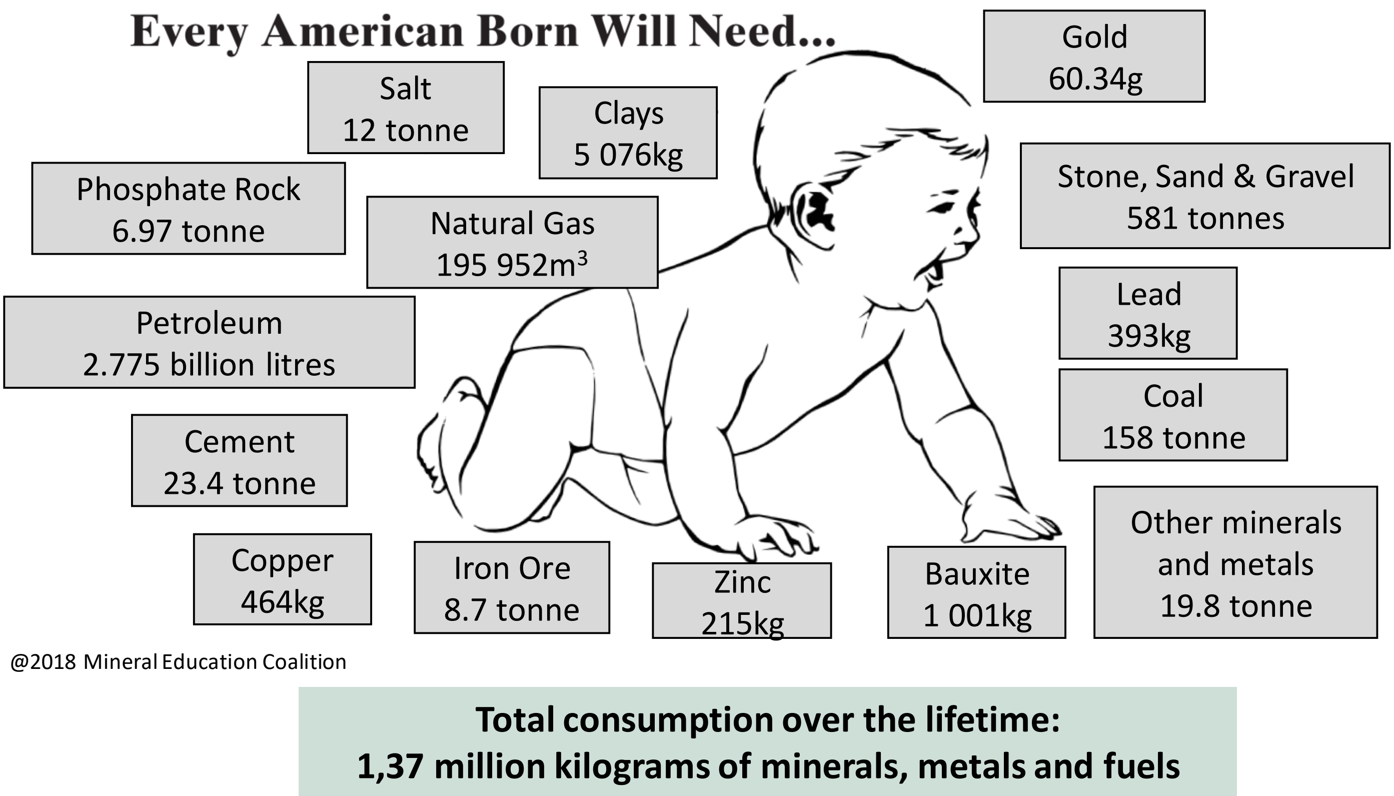


Figure 10. Estimated total resource consumption by each person in American society across their lifetime, 2018 data (Source: U.S. Mineral Education Coalition)

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.

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.

3.1 The current Linear Economy 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 soon. At this time a change in global GDP correlates with a change in oil consumption (Figure 11).

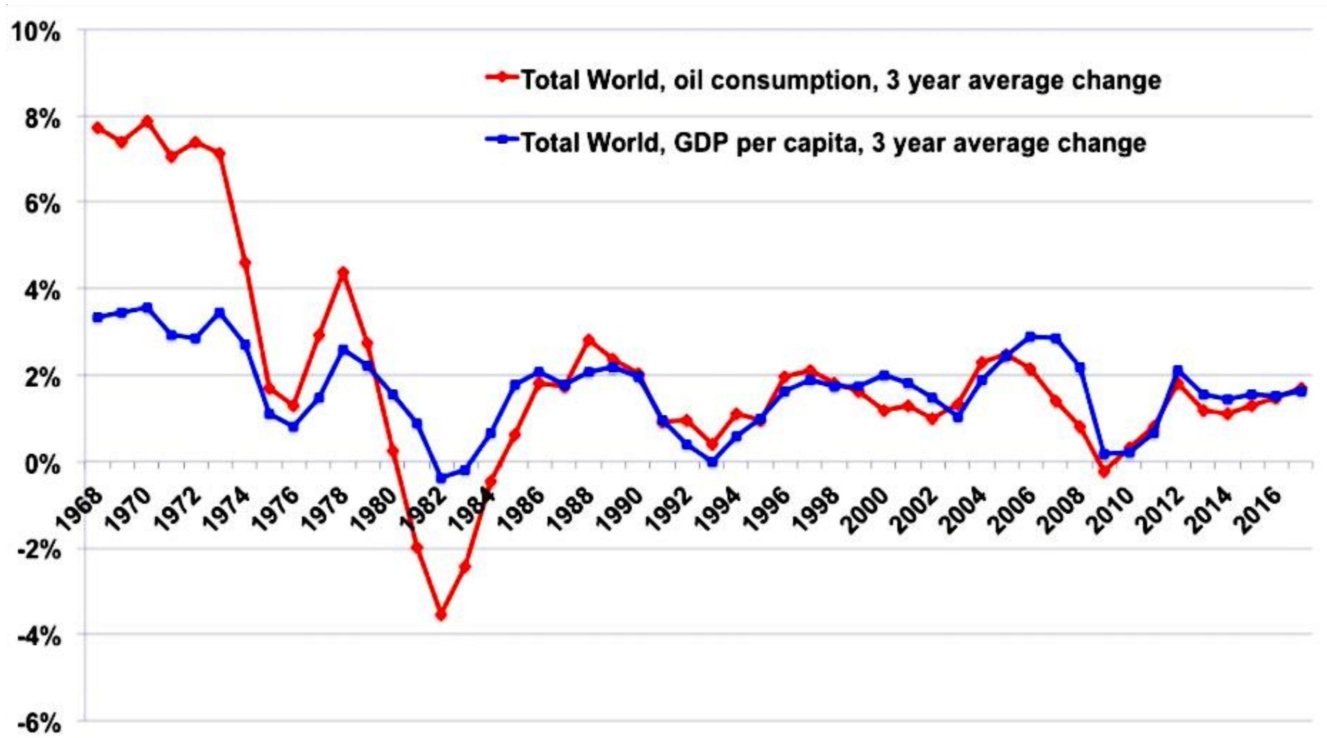


Figure 11. The annual relative change in world oil consumption and GDP per capita averaged over three years (Source: Data from BP Statistical Review 2019, World Bank)

Over the last 100 years western society has evolved into a petroleum driven economy. Economic activity correlates strongly with the transport of goods. All industrial activity, energy use in general and economic indicators like GDP all correlate strongly with energy consumption (Heinberg 2011 and Martenson 2011), oil in particular. Figure 12 shows the global energy consumption by source between 1820 and 2018. 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.

This fossil fuel dependency is what the Circular Economy was initiated to phase out. It can be argued that how the CE approaches this does not account for the role of energy in an industrial ecosystem.

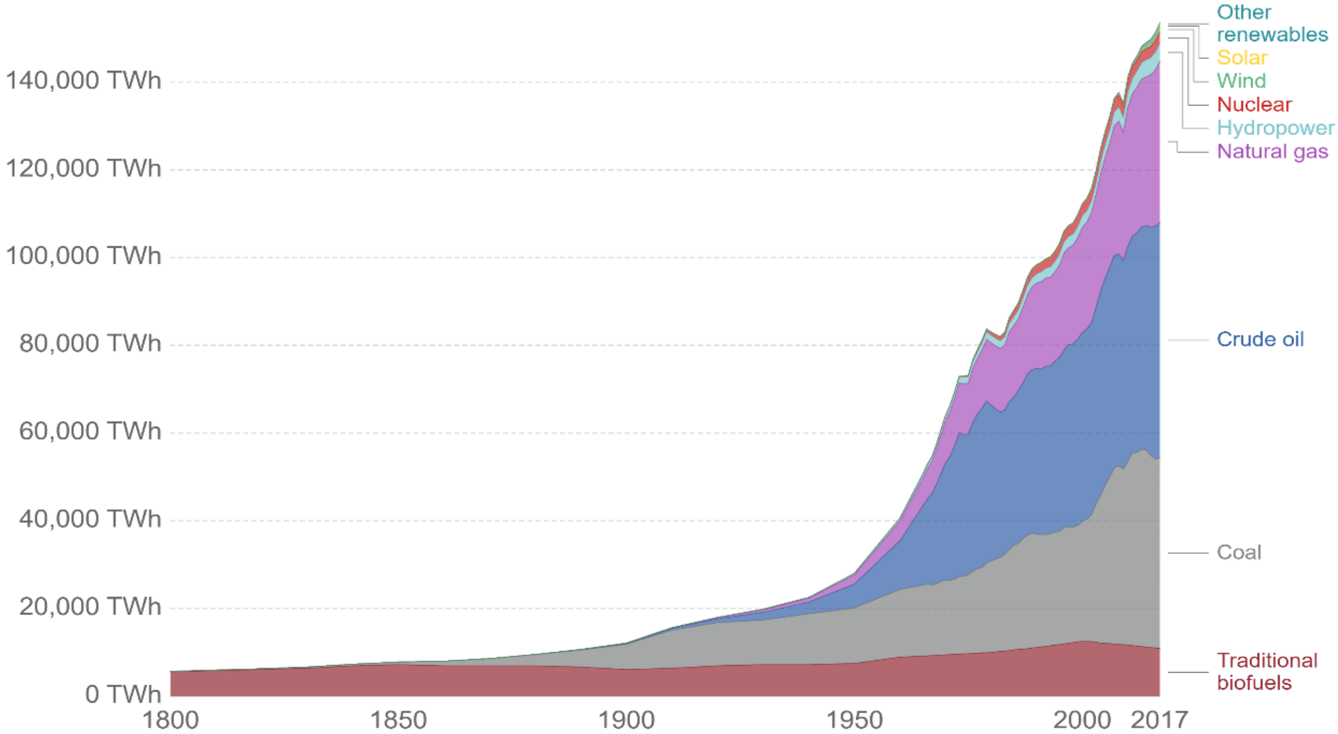


Figure 12. Global Primary energy consumption. Units measured in terawatt-hours (TWh) per year. Classification 'other renewables' are renewable technologies not including solar, wind, hydropower and traditional biofuels. (Source: Our World in Data, BP Statistical review of World Energy 2018) (Copyright License: https://creativecommons.org/licenses/by-nc-sa/4.0/)

4 THE STRUCTURAL FLAWS OF THE CIRCULAR ECONOMY

The CE was started to protect European businesses, nothing to do with resources themselves. The CRM list is more about supply bottlenecks controlled by political adversaries rather than concern over resource capacity. It is an excellent first step but is needs to evolve into something else.

This section presents a number flaws in the CE in context of practical limitations in applying the CE system. Most of these flaws could be due to how the CE has been presented. Usually, the CE is presented in very vague terms without much structural detail, or context to map details onto. It could be that the CE has not been thought through in this manner, and policy makers have been waiting for a more structured counter proposal like what is presented in this report.

4.1 The Circular Economy does not account for energy requirements of industrialization

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. Any new system to be developed has to have what energy is used for and how it is sourced at its very foundation. The Circular Economy does not do this.

Energy consumption correlates directly with the real economy (Bradley and Fulmer 2008). The real economy is the part of the economy that is concerned with actually producing goods and services, as opposed to the part of the economy that is concerned with buying and selling on the financial markets.

Future projections of global energy demand are usually developed on past behavior, with no understanding of finite limits or depleting resources. Generally, reserves have been projected on by past production and demand has been defined by population growth and economic GDP.

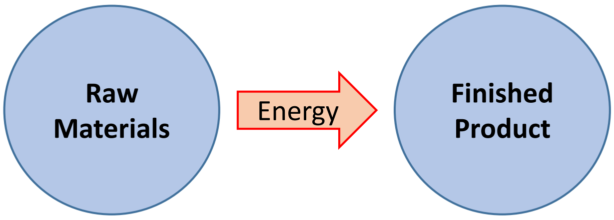


Figure. 13 Relationship between raw materials and finished manufactured goods

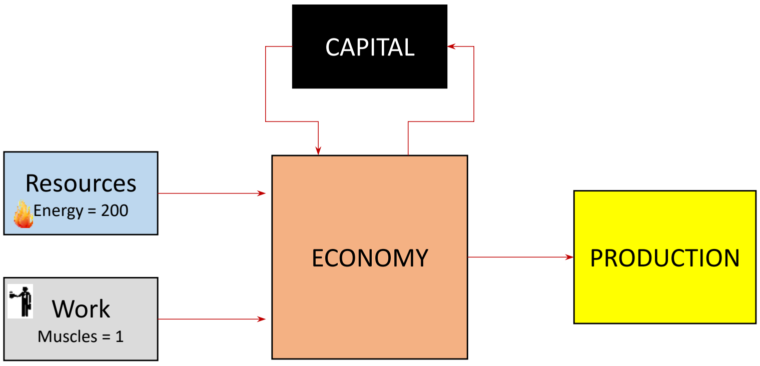


Figure 14. A simplified flow physical flows that sustain our productive system
(Source: Jancovici 2011)

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 system (Fizaine & Court 2016, Meadow *et al*. 1972, Hall *et al*. 2009, Heinberg 2011, Martenson 2011, Morse 2001, and Tverberg 2014a).

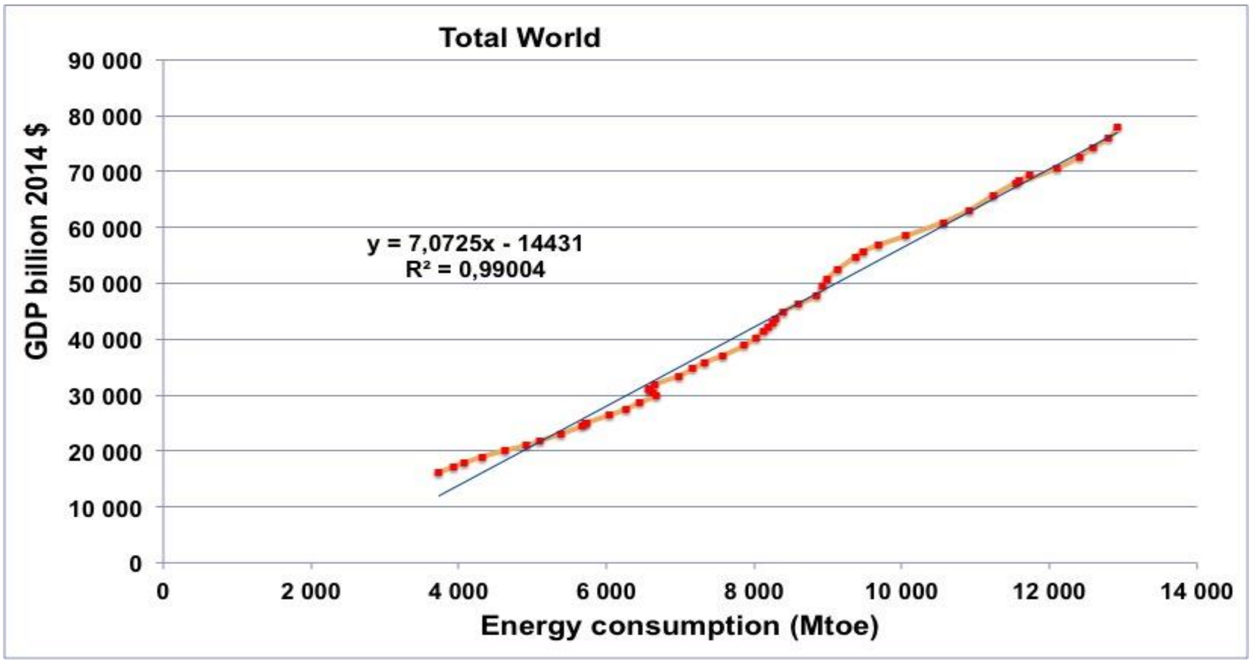


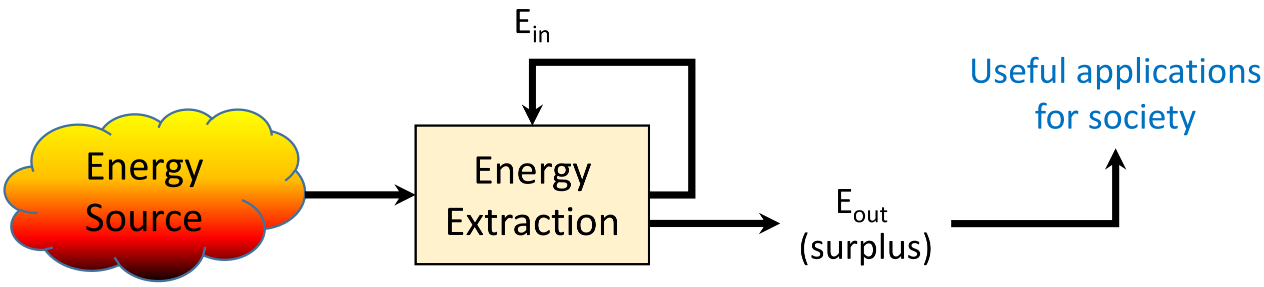
Figure 15. World GDP in constant dollars (vertical axis) plotted against the world energy consumption in million tonnes oil equivalent (horizontal axis), from 1965 to 2014.
(Source: BP Statistical Review, 2015, and World Bank 2015 (GDP), Jancovici 2011)

The Circular Economy as it stands is to develop then implement non-fossil fuel renewable energy systems like solar, wind and hydro. Current dependency of fossil fuels energy resources is not considered. All CE developments do not acknowledge their current dependence on finite non-renewable natural resources like oil, gas, coal, and uranium. All systems developed are currently dependent on fossil fuels in some form. Most of the new initiatives do focus of renewable energy substitution systems like solar, hydro or wind, but do not consider their current dependency on fossil fuels (or metal sources to manufacture – see Section 3.1).

The majority of the CE development is organizing and optimizing of renewable power systems, <u>after they have been manufactured and commissioned</u>. What is not accounted for is the consumption of fossil fuel energy resources and the mineral resources to construct the planned Circular Economy. The scope of this proposed work is much larger than current thinking allows for.

4.2 EROEI needs to be accounted for

The Energy Returned on Energy Invested (ERoEI) ratios of each of these proposed systems is much lower than all of the fossil fuel systems (Hall *et al* 2009, Hall, Klitgaard 2012, Hall *et al* 2014). The implications of this have not been discussed, and as such not been accounted for in development.



$$\text{Energy Return on Investment (ERoEI)} = \frac{E_{out}}{E_{in}}$$

Figure 16. Energy Return on Energy Invested ratio basic form
(Image: Simon Michaux)

All currently proposed non-fossil fuel systems have an ERoEI ratio <u>lower</u> than all of the fossil fuel systems that were used to develop the current industrial ecosystem. When oil extraction first started and 'oil gushers' were observed, ERoEI for oil was an extraordinary 500:1. In the 1900-1930 era, ERoEI for oil was still 100:1. In 1970, ERoEI for oil was approximately 30:1 (Michaux 2019).

What a decline in ERoEI means in context of an oil resource is a decline in quality. The deposit is harder to get to (deeper in drilling depth) or under the ocean floor (more expensive in terms of CAPEX and OPEX). Once the oil has been extracted, the quality of the oil itself is heavier and sourer in sulfur content. This requires more refining steps, which decreases the net value of the oil (Michaux 2019).

Currently, the industrial ecosystem is not in a position to phase out fossil fuels in the desired time frame (full ICE vehicle substitution with EV by 2050) and is also largely unaware that fossil fuel systems are about to become unreliable (Michaux 2019). In 2018, 84.5% of primary energy consumption was fossil fuel sourced, and renewable power systems accounted for 4.6% (the remainder was nuclear) (BP Statistical Review of World Energy 2019).

An excellent example of what a change in ERoEI over time looks like has been the conventional oil industry. ERoEI is a method to compare the required physical work done between different extraction methods for the same final product (per unit/quantity and quality).

When oil was discovered in the Pennsylvania oil rush from 1859 to the early 1870s, the first oil boom in the United States began. In this early period of oil exploration and extraction, oil was comparatively easy to gain energy from. Crude oil would often bubble to the surface in small springs, which still occur in small examples today.

Most of the oil found in the 1860 to 1920 time period would today be classified light sweet crude, containing small amounts of hydrogen sulfide and carbon dioxide (less than 0.42%). This kind of oil requires very little (and in some case none at all) processing steps before use as a saleable commodity (Burrough 2010)

Drilling depths were very shallow by current standards. During this time period, a drill depth of 1,300ft (400m) was considered standard (Burrough 2010), with some producing wells as shallow as 200ft (60m). Also, some of these early reserves had extraordinary oil pressure. There are many examples where oil would blowout and fountain high into the air (Figure 17).

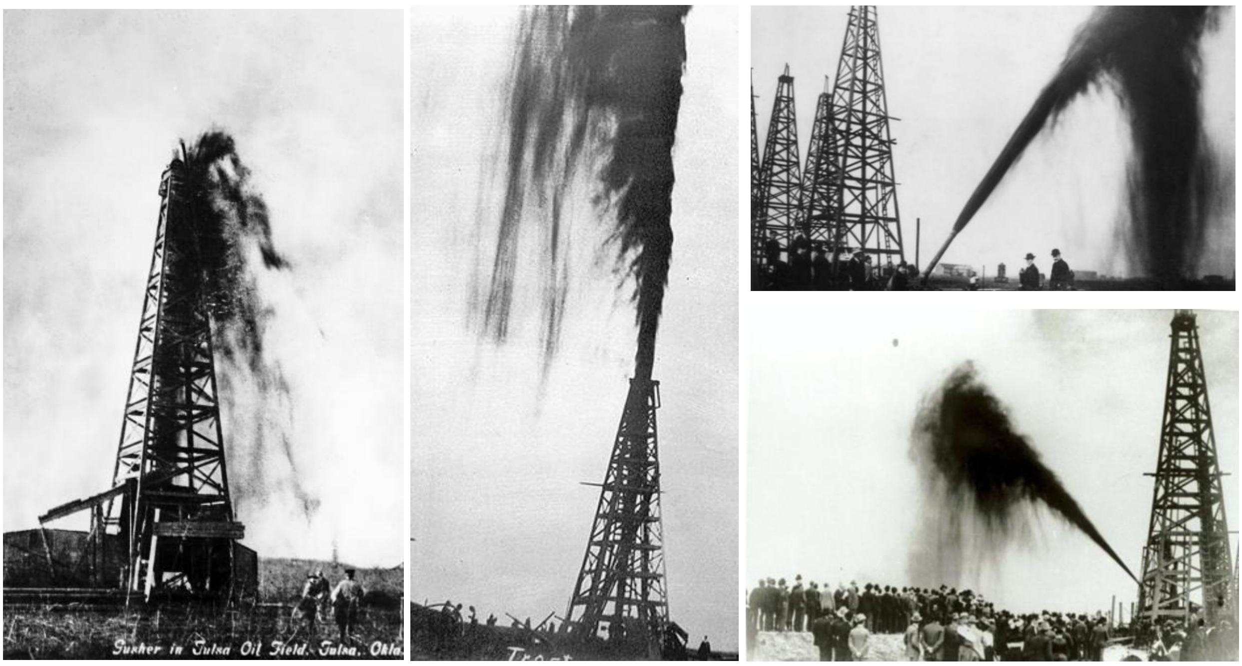


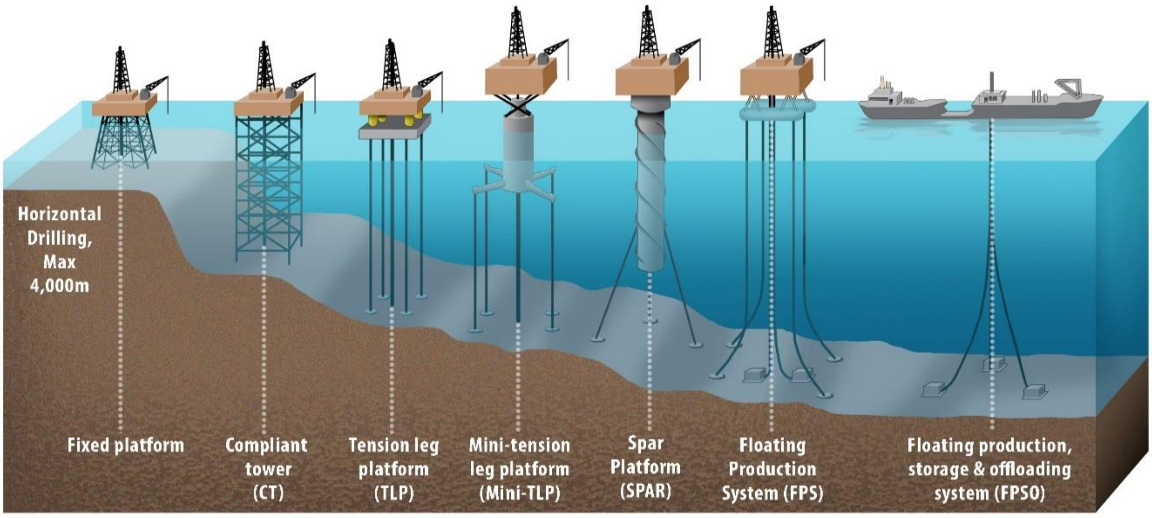
Figure 17. The Pennsylvania oil rush in northwestern Pennsylvania from 1859 to the early 1870s
(LHS) The Tulsa gusher at Oaklahoma and (Middle) The Lucas gusher at Spindletop and (RHS) Gusher in Port Arthur, Texas Oil Well in 1901 (Source: American Oil & Gas Historical Society, Petroleum History Almanac, https://www.aoghs.org/)

In 2019 however, much more effort was required to get the same unit of oil compared to 1900 in Texas. Processing and refining steps are now much more complex. The startup CAPEX capital expenditure costs of commissioning an oil extraction well have been steadily increasing. Both CAPEX and OPEX are many times the size of what they were for oil extraction in 1900.

In terms of oil extraction infrastructure, offshore drill platforms are now accounting for 1/3 of global oil production. These engineering structures are quite large in size and scale (Figure 18 LHS).

Also, as most oil extracted now is classified as sour crude, the stages of oil refining have become more complex. The size and scope of an oil refinery have become much more complex than oil refining in 1900 (Figure 18 RHS). In addition to this, these large scale industrial structures are required to operate in increasingly deep areas of ocean and drill to increasingly deep drill depths starting from the ocean floor (Figure 19).

Figure 18. LHS Deep water oil & gas drilling platform (Image by PublicDomainPictures from Pixabay)
RHS. Oil refinery in Indiana USA (Image by David Mark from Pixabay)



	Fixed platform	Compliant tower (CT)	Tension leg platform (TLP)	Mini-TLP	SPAR	FPS	FPSO
Water depth (m)	600m	450-900m	450-1,800m			450-2,100m	1,000-3,000m
Total drilling depth (m)	9,000+m	9,000+m	10,000+m			10,000+m	12,000+m

Figure 19. Types and depth capabilities of different offshore drilling platforms
(Image: Tania Michaux)

The energy cost of refining is also getting more difficult. More energy has been invested than ever before for the same return. Thus, the ERoEI and EROI for oil in has degraded and reduced.

Any new system for an industrial ecosystem needs to understand this and account for this. Both in the degrading ERoEI ratio for the existing fossil fuel the existing system is currently dependent on, and the true ERoEI ratio of the proposed replacement systems.

Table 2. Energy Returned on Energy Invested for fossil fuel sources (References taken from several sources, as quoted)

Energy Source	Year	Country	ERoEI	Reference
Conventional Oil & Gas production	1999	Global	35:1	Gagnon 2009
Conventional Oil & Gas production	2006	Global	18:1	Gagnon 2009
Conventional Oil & Gas (Domestic)	1970	United States	30:1	Cleveland et al 1984, Hall et al 1986
Discoveries	1970	United States	8:1	Cleveland et al 1984, Hall et al 1986
Production	1970	United States	20:1	Cleveland et al 1984, Hall et al 1986
Conventional Oil & Gas (Domestic)	2007	United States	11:1	Guilford et al 2011
Conventional Oil & Gas (Imported)	2007	United States	12:1	Guilford et al 2011
Conventional Oil & Gas production	1970	Canada	65:1	Freise 2011
Oil & Gas production	2010	Canada	15:1	Freise 2011
Conventional Oil & Gas production	2008	Norway	40:1	Grandell 2011
Conventional Oil production	2008	Norway	21:1	Grandell 2011
Conventional Oil & Gas production	2009	Mexico	45:1	Ramirez 2013
Conventional Oil & Gas production	2010	China	10:1	Hu et al 2011
Hydraulic Fracking oil	2015	United States	29:1	Brandt et al 2015
Oil tar sands	2010	Canada	11:1	Poisson & Hall 2013
Hydraulic Fracking Natural Gas	2005	United States	67:1	Sell et al 2011
Natural Gas	1993	Canada	38:1	Freise 2011
Natural Gas	2000	Canada	26:1	Freise 2011
Natural Gas	2009	Canada	20:1	Freise 2011
Coal (Run of Mine)	1950	United States	80:1	Cleveland et al 1984
Coal (Run of Mine)	2000	United States	80:1	Hall et al 2011
Coal (Run of Mine)	2007	United States	60:1	Hall et al 2014 and Balogh et al 2012
Coal (Run of Mine)	1995	China	35:1	Hu et al 2013
Coal (Run of Mine)	2010	China	27:1	Hu et al 2013

Table 2 shows a summary of the ERoEI calculations for the non-fossil fuel energy systems. These systems are used to generate electricity. In comparison, Table 3 shows a summary of the ERoEI calculations of the non-fossil fuel systems and their relative efficiencies in electrical power generation.

Figure 20 shows how the long term ERoEI for fossil fuel have been in decline since 1955. Note the trough at around the early 1970's correlate with the 1973 oil crisis.

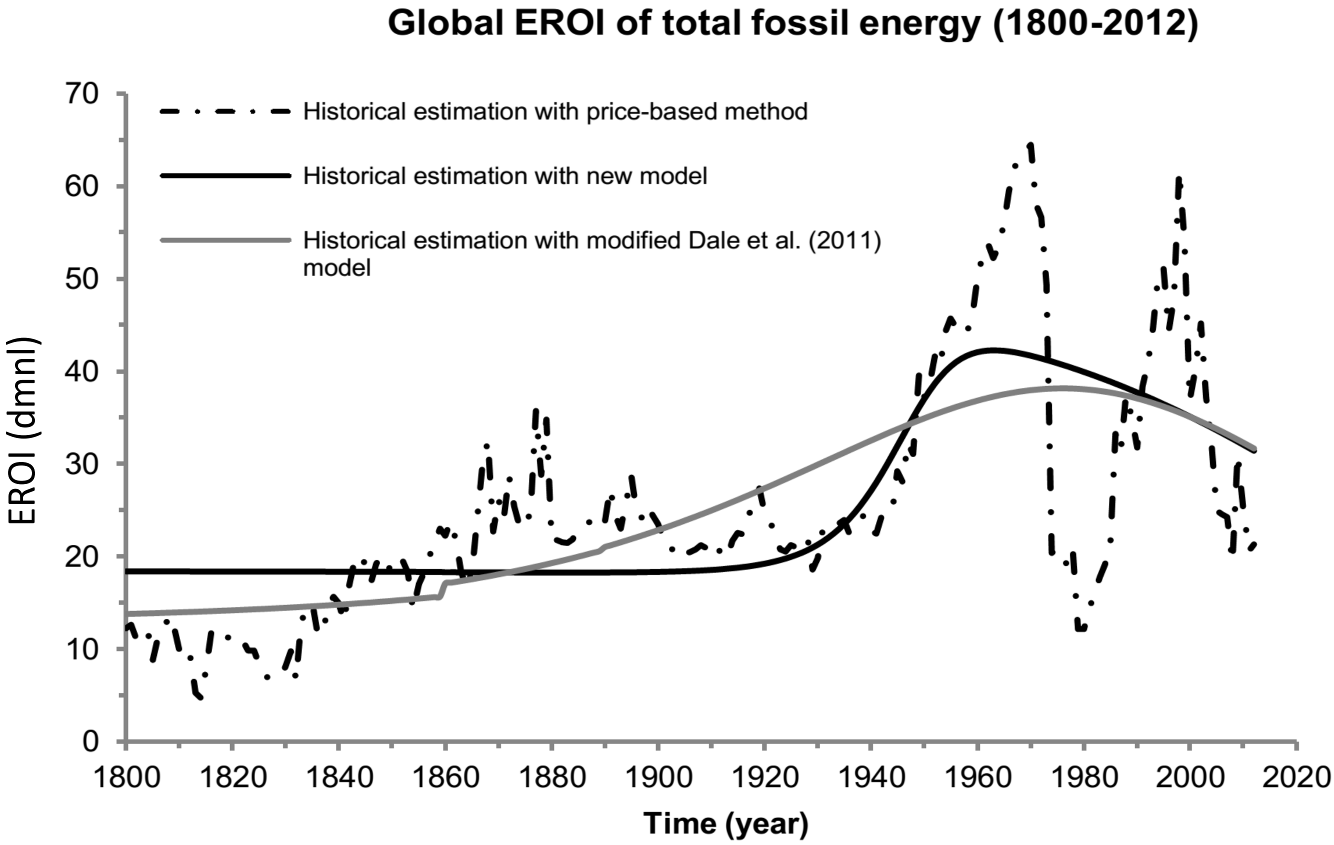


Figure 20. Global EROI of total fossil energy 1800 to 2012
(Source: Court & Fizaine 2017)

Table 3. Energy Returned on Energy Invested for non-fossil fuel sources

Energy Source	ERoEI	Reference
Nuclear	15:1	Hall et al 2011
Nuclear (incuding U mining & enrichment)	5:1	Lenzen 2008
Hydroelectricity	50:1	Capellán-Pérez et al 2019
Geothermal	7:1	Capellán-Pérez et al 2017
Oceanic wave	3.25:1	Capellán-Pérez et al 2017
Wind Turbine	18:1	Kubiszewski et al 2010
Solar Thermal	2.4:1	de Castro & Capellán-Pérez 2018
Solar PV (conventional EROEI analysis)	9 to 10:1	Raugei et al 2017
Solar PV (dynamic EROEI analysis)	7 to 8:1	Raugei et al 2017
Ethanol (sugarcane)	0.8 to 10:1	Yuan et al 2008 and Pimental et al 2005
Corn based ethanol	0.8 to 1.6:1	Pimental et al 2005 and Farrell et al 2006
Biodiesel	1.3 to 1.5:1	Capellán-Pérez et al 2017, and Pimental et al 2005

Figure 21 shows an approximate graphical comparison of the ERoEI of fossil fuel energy sources, nuclear and some of the renewable energy systems.

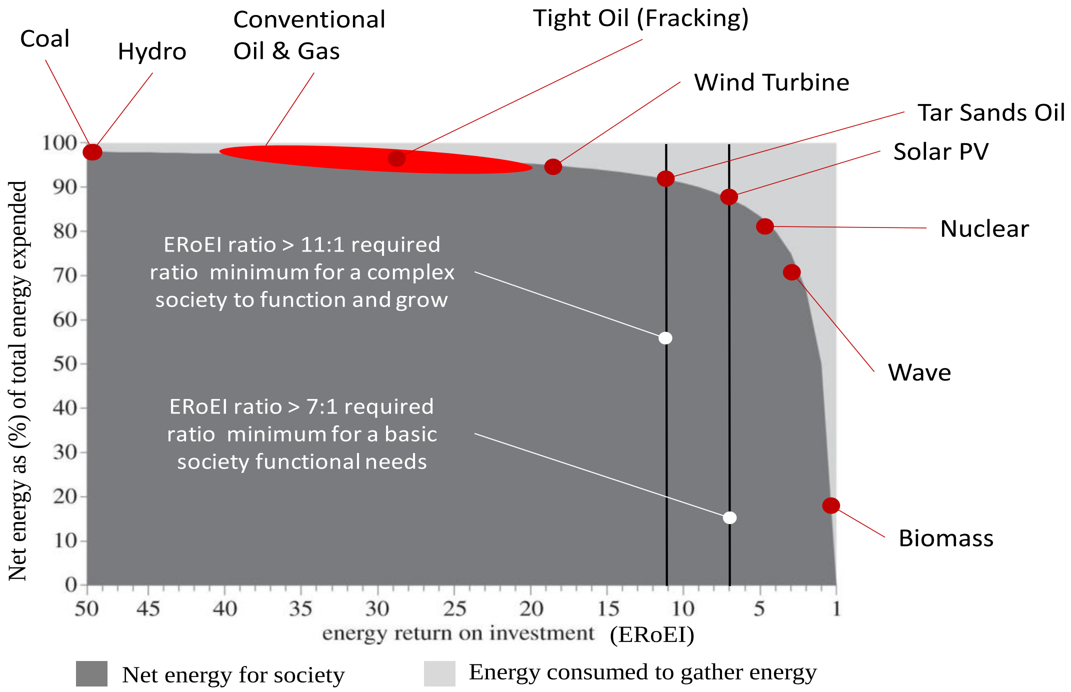


Figure 21. The net energy cliff with published numbers of ERoEI
(Source: Michaux 2019)
(Source: Court and Fizaine 2017) (Copyright granted)

A more targeted example of this could be of metal production from mining (primary resource). The logistical circumstance the primary mining industry 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 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.

In the year 2014, feasibility study copper mine cutoff grade for future projects is now 0.1%, with deposit size requiring an open pit 1km deep and 4km in lateral length, yet available 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 22). Decreasing grade is one of the causes of this pattern (Figure 23).

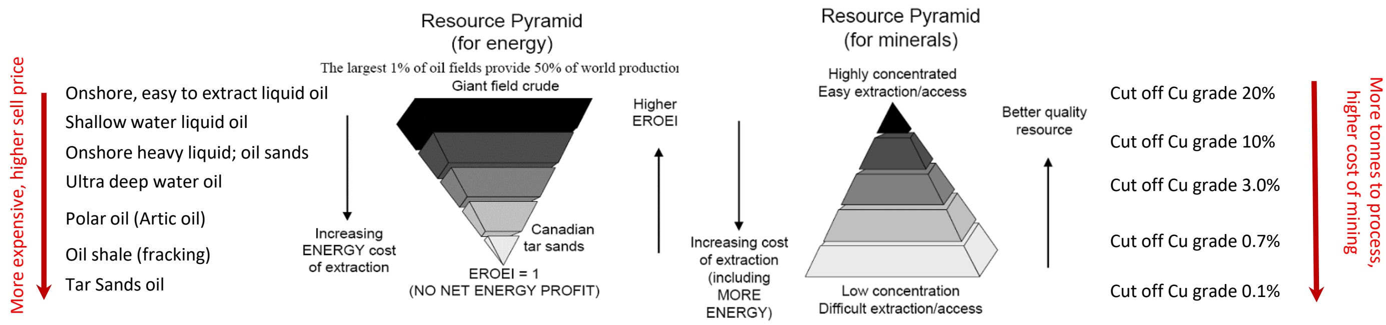


Figure 22. The resource pyramid conundrum
(Image: Simon Michaux)

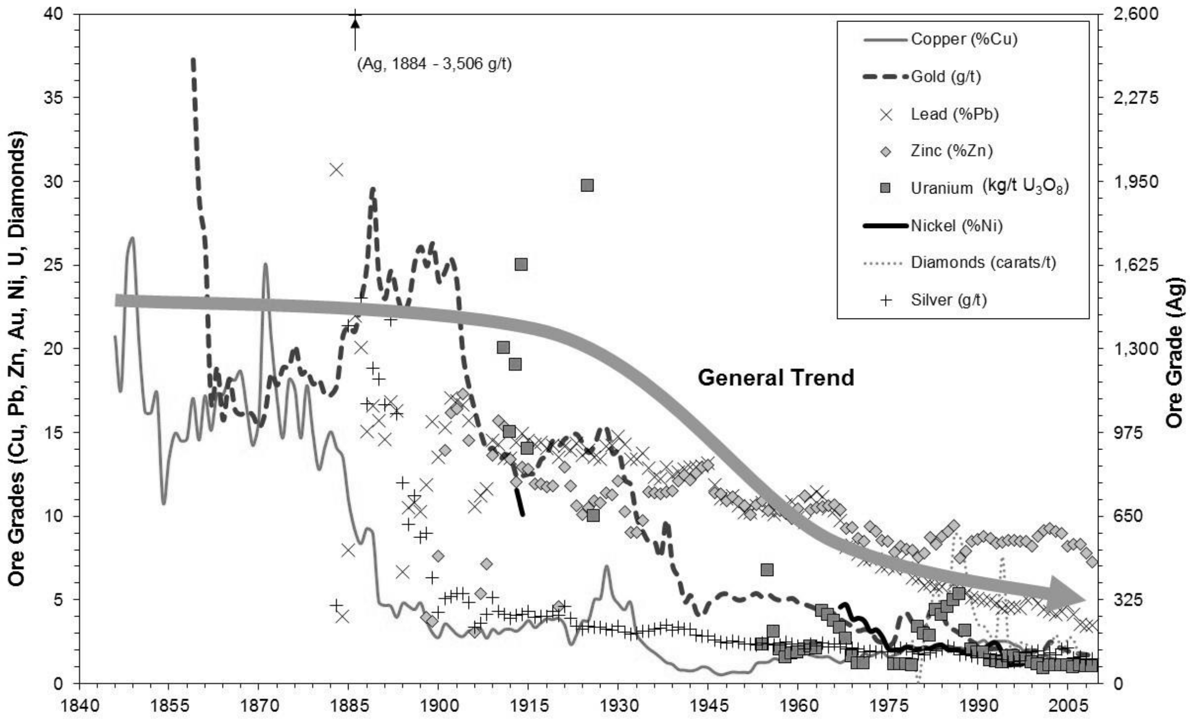


Figure 23. Grade of mined minerals has been decreasing
(Source: Mudd 2009, Analyst- Gavin Mudd)

4.3 The link between energy consumption and technology complexity needs to be accounted for

An example of society capability and energy consumptions related to technology complexity is the oil energy source. Oil when it was first discovered was the most concentrated source of energy the world had ever seen. It did not require much in the way of processing. It could be stored easily and transported easily. It is now understood is that as time has progressed, the quality of energy has deteriorated in in practical terms. The ERoEI ratio for energy sources (sometimes termed EROI) in general but in particular for oil have all sharply reduced since their first discovery (Hall 2014).

Oil based technology developed over approximately the same time has developed in capability and complexity. Compare for example the 1921 Hudson Super Six Speedster (Figure 24) to the 2013 Lamborghini Aventador (Figure 25).

In 1921, the Hudson Super Six Speedster was powered by a 289 cubic-inch six-cylinder engine rated at 76 horsepower (57 kW). The Hudson Model Six-54 Advertisements claimed a maximum speed of 65 mph for the car and the ability to reach 58 mph (93.3 km/hr) from rest in half a minute. A total of eight Detroit businessmen formed the company on February 20, 1909, to produce an automobile which would sell for less than US$1,000 (equivalent to approximately $27,885 in 2018 funds). This was considered to be the fastest automobile of its day.

Figure 24. The 1921 Hudson Super Six Speedster Phaeton was powered by a 289 cubic-inch six-cylinder engine rated at 76 horsepower (57 kW). (Source: Image by David Mark from Pixabay)

In 2013, the Lamborghini Aventador LP 700–4 had a top speed of approximately 354km/hr, delivered a power of 510 kW and cost US$4,500,000 (in 2018). The manufacturer claims that it can accelerate from 0–97 km/h (0–60 mph) in 2.9 seconds and will achieve a top speed of 217 mph (349 km/h) (https://www.lamborghini.com/en-en/).

Not only had the effort to extract oil based energy gotten more complex and expensive, but the applications in its use also became more technologically complex and expensive. More effort, capital cost, infrastructure support, raw materials of a greater purity is now required to get the best fast ICE car of the day. Yes, the resulting vehicle is much more capable, but so much more was required for the production of each vehicle (technology unit).

This example can be extended to every part of our industrial society. The link between energy source and technology complexity needs to be better understood.

Figure 25. The Lamborghini Aventador LP 700–4 uses Lamborghini's new 700 PS (510 kW; 690 bhp) 6.5 litre 60° V12 engine weighing 235 kg. (Source: Image by Ola Wirdenius from Pixabay)

4.4 The Circular Economy does not account for materials that cannot be recycled, or are lost to the environment

There are many mineral-based materials which can never be fully, or even partially, recycled and some are even lost to the environment. A common example would be clay minerals. Certain clays are highly prized because of their special properties that are useful in the production of ceramics or bricks. However, there is currently no known process that can reverse the changes that occur to clay within a kiln. We cannot, for example, make clay again from a re-cycled brick, or a ceramic dish. Figure 26 shows this graphically, where clay is heated in a kiln to high temperatures (firing) and transformed into ceramic pottery. This process cannot be reversed. This means that clay is a finite natural non-renewable resource. Whatever system replaces the Linear Economy should have a waste stream system map with the capability to map this and manage global clay resources appropriately.

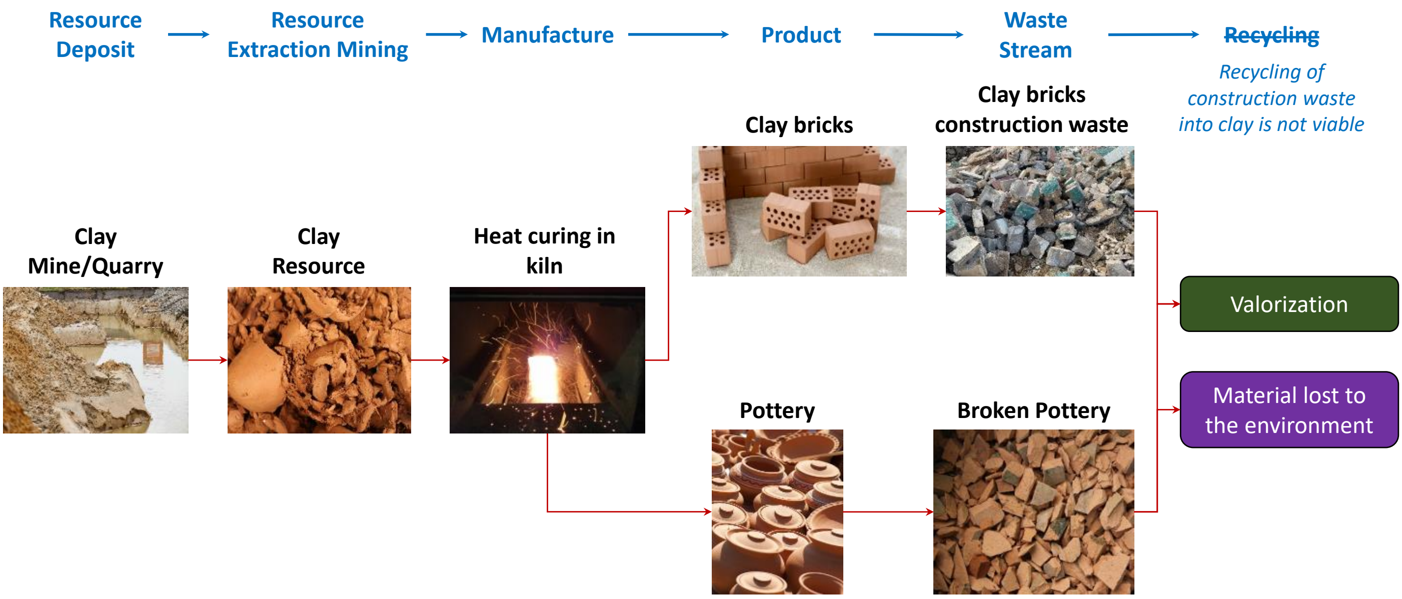


Figure 26. Products made from clay cannot be recycled back into clay, after they have been fired in a kiln (Image: Alan R. Butcher, one image by anabel2160 from Pixabay, one image by SatyaPrem from Pixabay, one image by Samuel Faber from Pixabay, one image by bluebudgie from Pixabay, one image by Aviavlad from Pixabay)

Due to the business model that assumes all resources are infinite and relatively inexpensive, products are often designed purely for high performance over a short time period. It makes more economic sense to design a product that wears out and has to be replaced, thus gaining more sales. Some products are designed to function where parts them wear out during operation and the worn parts are not able to be recovered for recycling.

Speciality metals (e.g., gallium, indium, and thallium) and some heavy rare earth elements are representative of modern technology. Their loss due to a lack of viable recycling process path provides a measure of the degree of unsustainability in the contemporary use of materials and products (Ciacci *et al.*, 2015). An example of this is the Apple iPhone 7, which due to the high dergee of component integration and micronization, there is no real recycling solution. Thus all those exotic technology metals are lost to furnace slag waste dumps in such low concentrations that is not viable to consider recycling. In other common uses, metals are incorporated into products in ways for which no viable recycling approaches exist, examples include selenium in colored glass and vanadium in pigments. Even where uses are currently compatible with recycling technologies and approaches, end of life recycling rates are in most cases well below those that are potentially achievable.

Figure 27. Brake pads by design are made to wear and metals are lost to the environment.
(Image LHS: by Gerald Oswald from Pixabay , Image RHS: by Patrick Grüterich from Pixabay)

Examples are copper in brake pads, zinc in tires, and germanium in retained catalyst applications being examples (Ciacci *et al.*, 2015). Brake linings can be classified as consumable surfaces, and they wear-by-design. Thus, metals that make up the brake pads are lost to the environment during wear and can therefore never to be recovered. A study carried in Stockholm (Westerlund & Johansson, 2002) calculated that in this one city alone, 3,300 kg of brake linings are used by buses per year.

An example of semi-circularity is to be found in the re-use of railway tracks. Originally made from iron - that was milled to form pellets, that were then sintered to form steel - some tracks are now finding a new life as re-forged steel balls, which in turn are being used again in ball mills to grind even more ore. However, once the steel ball has worn out, due to attrition within the mill, the resulting worn “scats” are typically small and are never recycled, but simply disposed of. So, after one cycle of re-use, this material is likely lost (Figure 28).

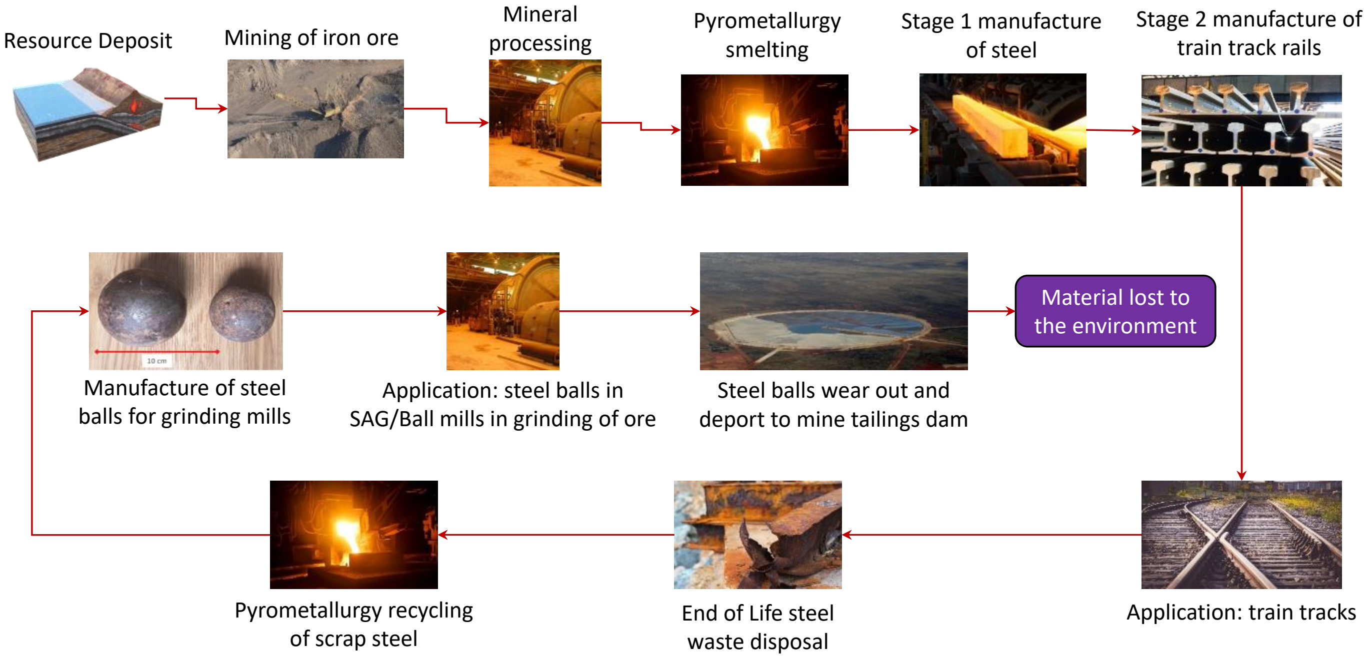


Figure 28. Steel recycling, by manufacturing steel balls used in ore grinding mills, cannot be further recycled.
(Image: Alan R. Butcher, one image by Simon Michaux, one image by Dee Bradshaw, one image by Malcolm Powell, one image by by Martinelle from Pixabay, one image by zephylwer0 from Pixabay, one image by keesstes from Pixabay, one image by Peter H from Pixabay, Andreas Glöckner from Pixabay, Martinelle from Pixabay)

To determine quantitatively the scope of these losses to RM Loop Cycle C and losses to the environment, the uses of major metals and metalloids need to be assessed and subject to resource accounting. The outcomes of this could provide guidance in identifying product design approaches for reducing material losses so as to increase element recovery at end-of-life.

4.5 The current focus of the Circular Economy is based around the development of 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. 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.

Figure 29 shows the recycling rates in 2011. Current recycling rates will resemble these extraction efficiencies.

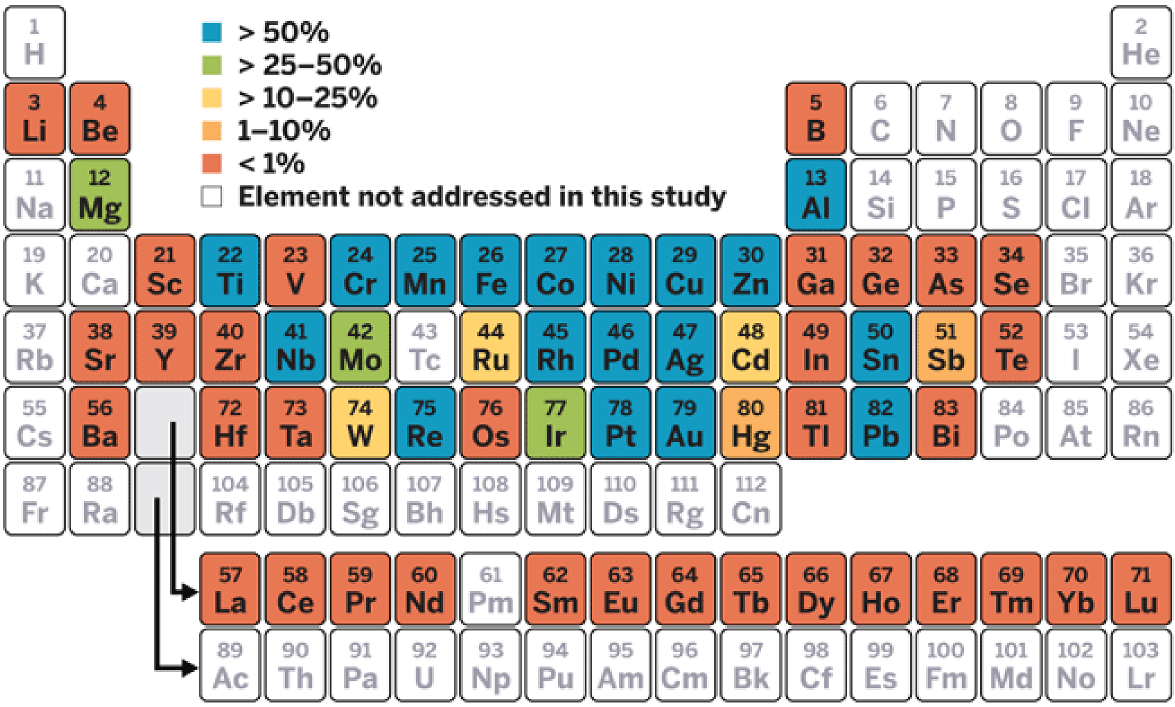


Figure 29. Recycling rates of metals
(Source: United Nations Environment Programme, Recycling Rates of Metals (2011) / C&EN May 30, 2011)

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.

4.6 The Circular Economy does not account for the role of mining of primary resources

Current thinking is that European industrial businesses will replace a complex industrial ecosystem that took more than a century to build in a few short decades (current targets are 100% substitution of ICE technology with Electric Vehicles by 2050). The current fossil fuel supported ICE system was created 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 renewable energy transition plan is 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 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 have primary resource mining supply risks (Figure 30).

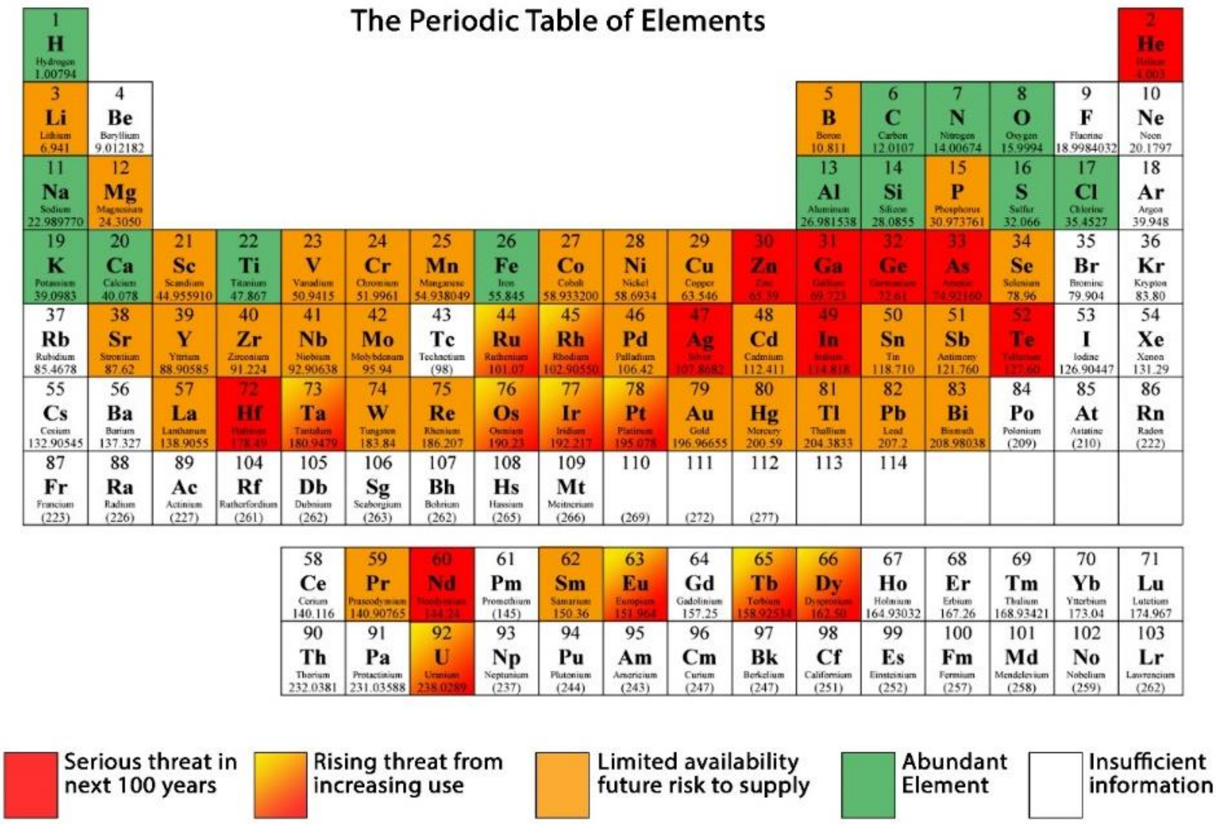


Figure 30. Some primary mining sources for a number of metals have clear supply risks
(Source: Report On Critical Raw Materials For The EU May 2014)

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. GTK - KTR is well placed to meet this demand. Mineral exploration all over the world will also be required to increase. GTK-MTR and GTK-GFR are well placed to assist in meeting this demand.

4.7 The Circular Economy is not structured to meet international competition

The CE was started to secure the long term sustainability of Europe, when currently the raw materials value chain is international in form. A true and genuine analysis of the raw materials value chain has to be done in context of geopolitical sensitivities. It is relevant to understand the following:

- Where raw materials come from internationally
- Which corporate entity controls the bottleneck assets
- United States strategic plans post World War II
- Chinese strategic plans post year 2000

A relevant aspect to understand is what China 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, the Chinese also have a plan. This plan is fundamentally different.

In 2001 there was a change in policy from the Peoples Republic of China Government, with the release of the Going Out Policy (10th Five-year Plan) and the 1st National Mineral Resource Plan. These policy documents have gone through several stages of evolution. In 2016, the policy plans had developed and released as the One Belt One Road, Made in China 2025 (13th Five-year Plan) and the 3st National Mineral Resource Plan. These policy documents make a series of recommendations which Chinese capital investment groups have been following for some time now. This plan is of significance for the rest of the industrial world. See Appendix A – Chinese Corporate Investment & Mineral Supply Global Market Share Footprint.

In 2019, China directly controlled approximately 80% of the raw materials value chain (mining, refining, smelting, manufacture and recycling). 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 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): Made in China 2025 as a Challenge in Global Trade Governance: Analysis and Recommendations). One of the implications (considering the United States strategic responses to this) could be a break down in global free trade.

As the future will require an unprecedented volume of minerals, there is current supply risks at low levels of consumption and international free trade of minerals could become difficult, Europe will be required 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).

4.8 The Circular Economy does not allow for human population growth

The Circular Economy is designed to develop a society that is stable in a long term sustainable fashion. It is based around the idea that the only resources that are used are what that society discards as waste. This does not allow for population growth.

Population growth is another fundamental driver to this current set of circumstances. Consumption is a function of the number of people who consume. An increase in production or an achieved efficiency has to be put in context of the population growth across that time frame. Population has grown in a manner that strongly correlates with the increase in energy consumption once all sources have been summed together (Bartlett 1994 and Bartlett 1996). Since the start of the industrial revolution, population has been empowered by technology coupled with increased energy density (coal vs biomass wood, followed by the introduction of oil).

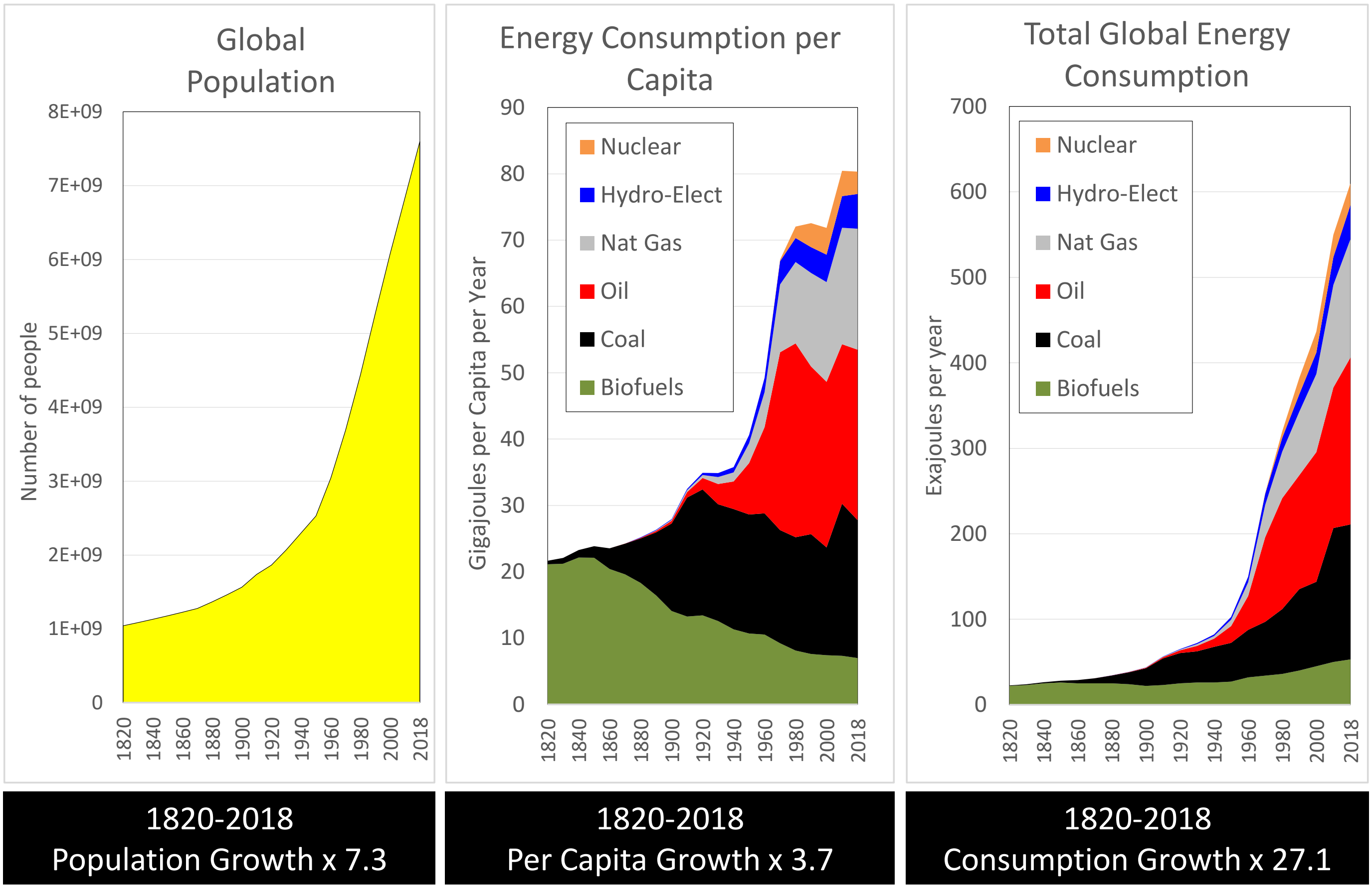


Figure 31. World population, per capita-, and total energy consumption, 1820-2018
(Source: Data from Tverberg, G. https://ourfiniteworld.com/, and BP Statistical Review of the World Energy 2019, US Census Bureau)

Figure 31 shows an example of a Jevons Paradox. Fossil fuels (coal first, then oil, then gas) provided society with a very calorifically dense energy source. Energy was a technology enabler. As more energy became available, more complex technology was developed (see Figure 24 and 25 as an example), and the faster that energy was being consumed. The middle chart in Figure 31 show a steep increase in the consumption energy per capita as time went on. So, as it became easier to access, more energy was consumed by each member of society.

A Jevons paradox is an economic concept. The paradox occurs when technological development or government policy increases the efficiency with which a resource is used. The amount of needed resourced necessary for any one use is reduced, but the rate of consumption of that resource rises due to increasing demand (Bauer & Papp). The paradox is where the end result being the resource is consumed to depletion much faster as a consequence of an increase in efficiency.

In 1865, the English economist William Stanley Jevons observed that technological improvements that increased the efficiency of coal-use led to the increased consumption of coal in a wide range of industries. He argued that, contrary to common intuition, technological progress could not be relied upon to reduce fuel consumption (Alcott 2005).

If the Linear economy was truly sustainable, then the charts in Figure 31 would be flat lines or in a cycle between set upper and lower limits. They are not. the Linear Economy has been growing in size and complexity, consuming ever more resources. This is by design as economic growth at an exponential rate is at the very heart of its paradigm (a corporation must show 8-10% annual profit if they to be considered useful).

4.9 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. Figure 32 shows how resource consumption has increase on a global scale between the year 2000 and the year 2018.

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.

In the current industrial ecosystem, money language and making more money is the decision making system. To make the most sustainable choice often means accepting a less economically cost effective outcome. Currently most industrial activities happen outside Europe (often in China), because the cost of operation is much lower, and actions taken are often no legal in in Europe (environmental compliance legislation). This implies that a new set of choices, and a new system of decision making needs to be developed.

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. 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.

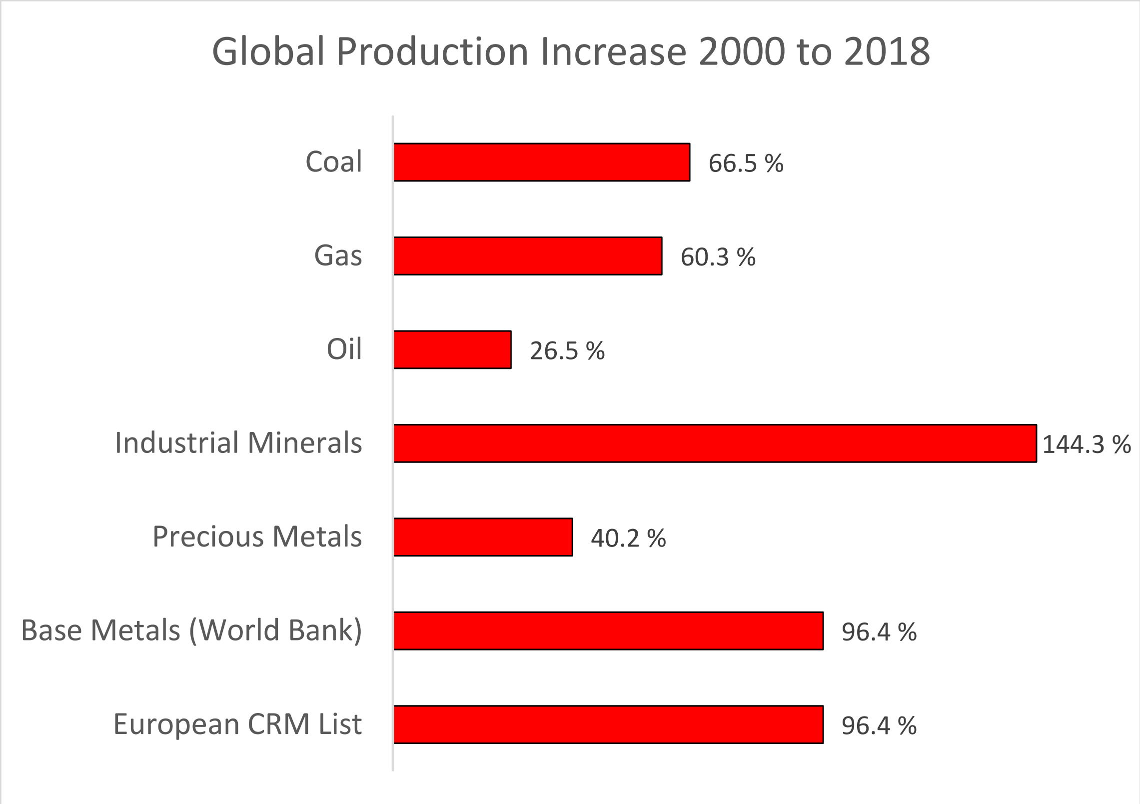
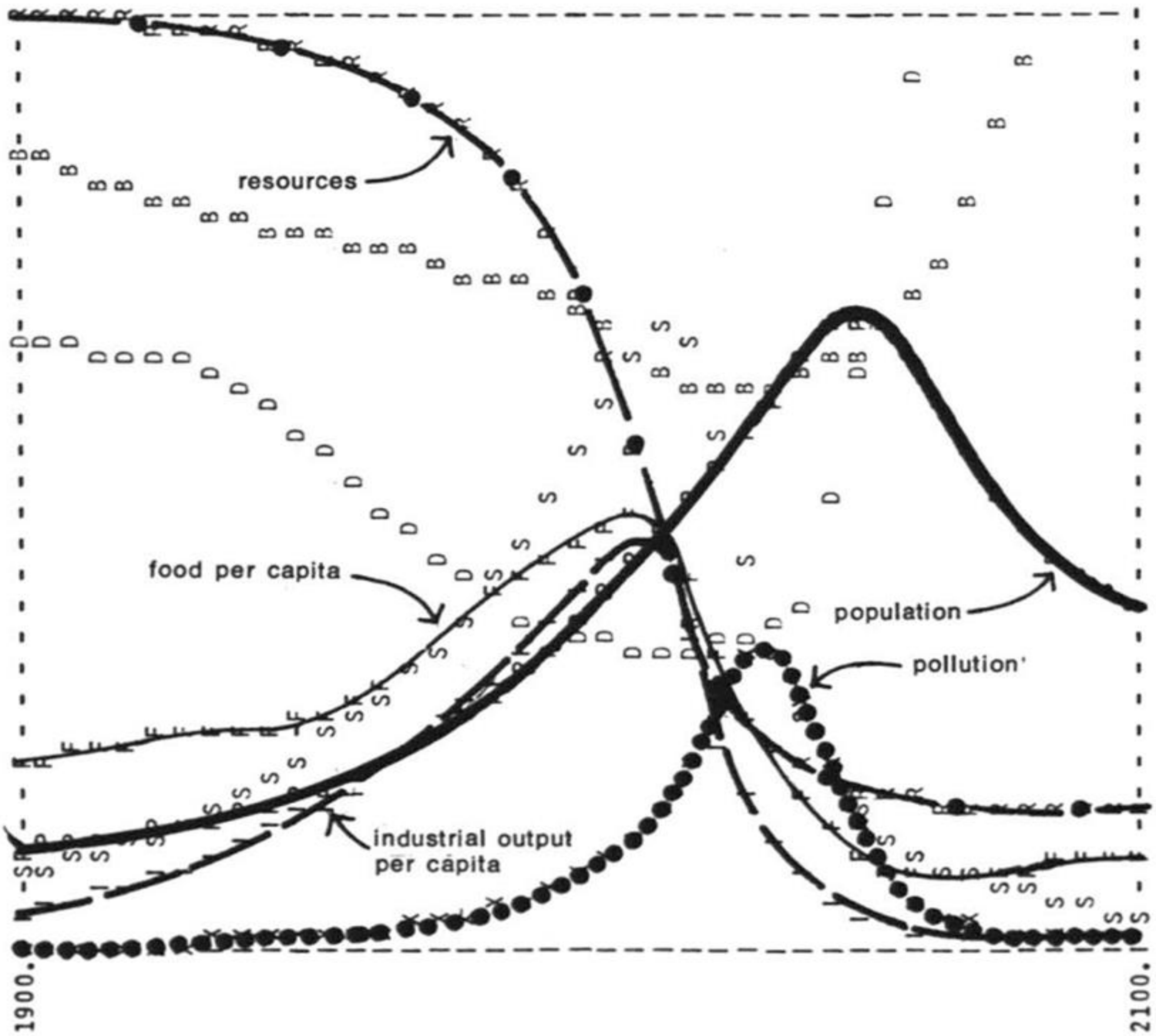


Figure 32. Global annual consumption of mineral resources between the year 2000 and 2018
(Source: USGS data, World Bank data, BP Statistics 2011, BP Statistics 2019)

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 33 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.



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

The implications of Figures 34-36 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.

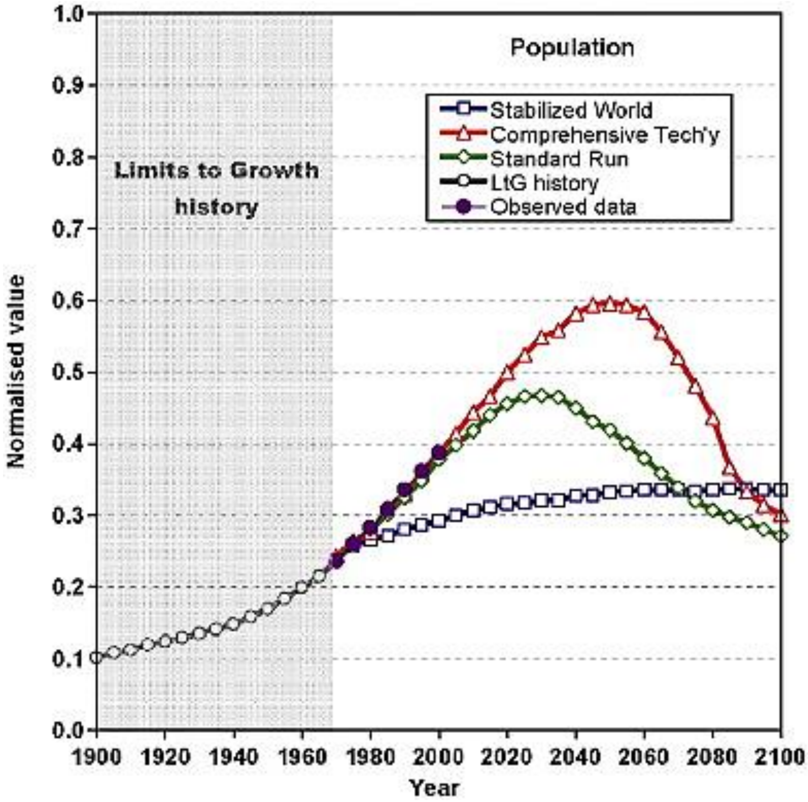


Figure 34. Comparing 'Limits to Growth' scenarios to observed global data – human population (Source: Turner 2008, Copyright granted)

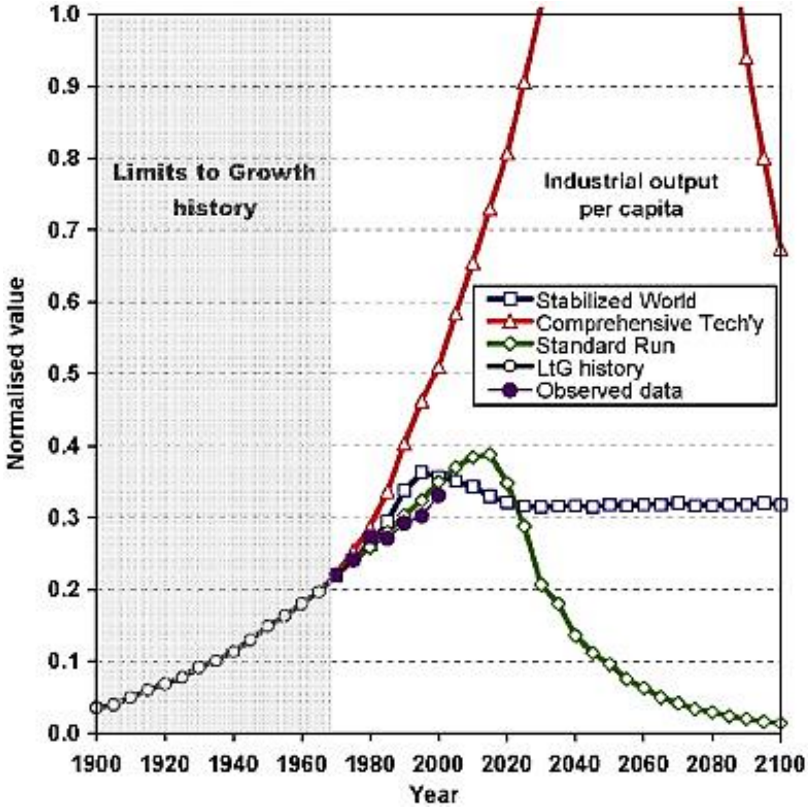


Figure 35. Comparing 'Limits to Growth' scenarios to observed global data – industrial output (Source: Turner 2008, Copyright granted)

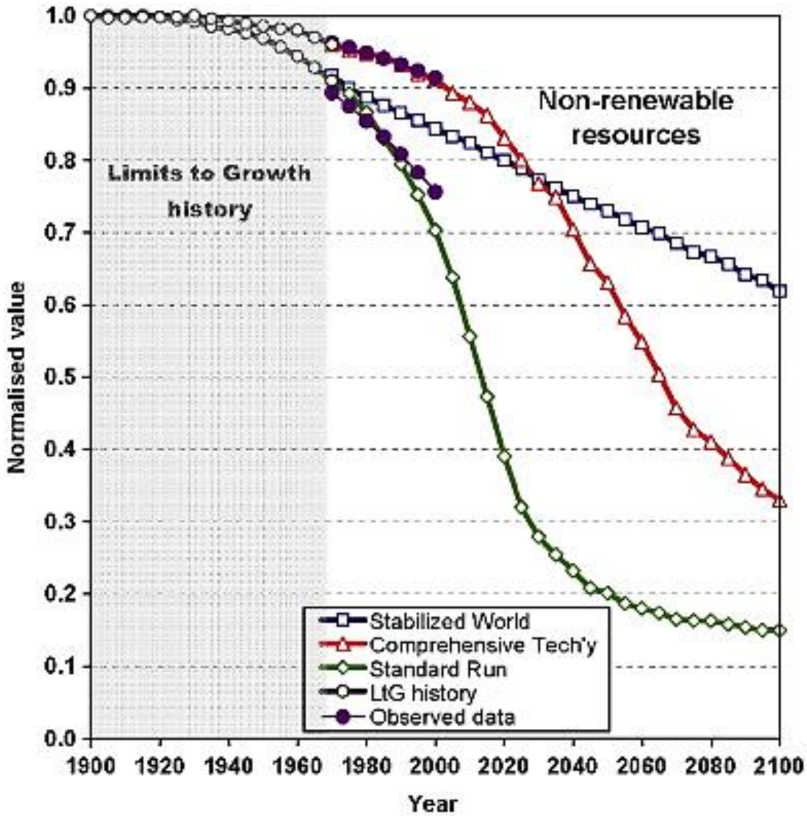


Figure 36. Comparing 'Limits to Growth' scenarios to observed global data – Non-renewable resources (Source: Turner 2008, Copyright granted)

4.10 Other things that need to be addressed in restructuring the Circular Economy

There are a number of concepts that the current Circular Economy does not account for very well in its current form. These issues are relatively minor compared to other priorities. Once a substitution system is constructed, these things would naturally self-organize to a practical solution.

- Zero waste is not practical in any industrial society
- Does not account for the logistics of material transport between disposal and reuse
- 1st and 2nd stage manufacture does not happen in large enough volumes in EU-28

5 RESTRUCTURE THE CIRCULAR ECONOMY

It is now clear that the Circular Economy should be restructured into a new system. The current Linear Economy is unbalanced and is approaching a point where the nodes in the Linear Economy system are showing signs of stress. As the Linear System is fundamentally unsustainable and is reaching planetary scale limitations (human population growth vs. the ability to extract natural resource, change is inevitable. Figure 37 graphically shows a summary of issues raised in Section 4. A change in thinking is required, followed by a change in how society organizes itself.

The question for us all now is: "**are we part of the solution, or are we part of the precipitate?**"

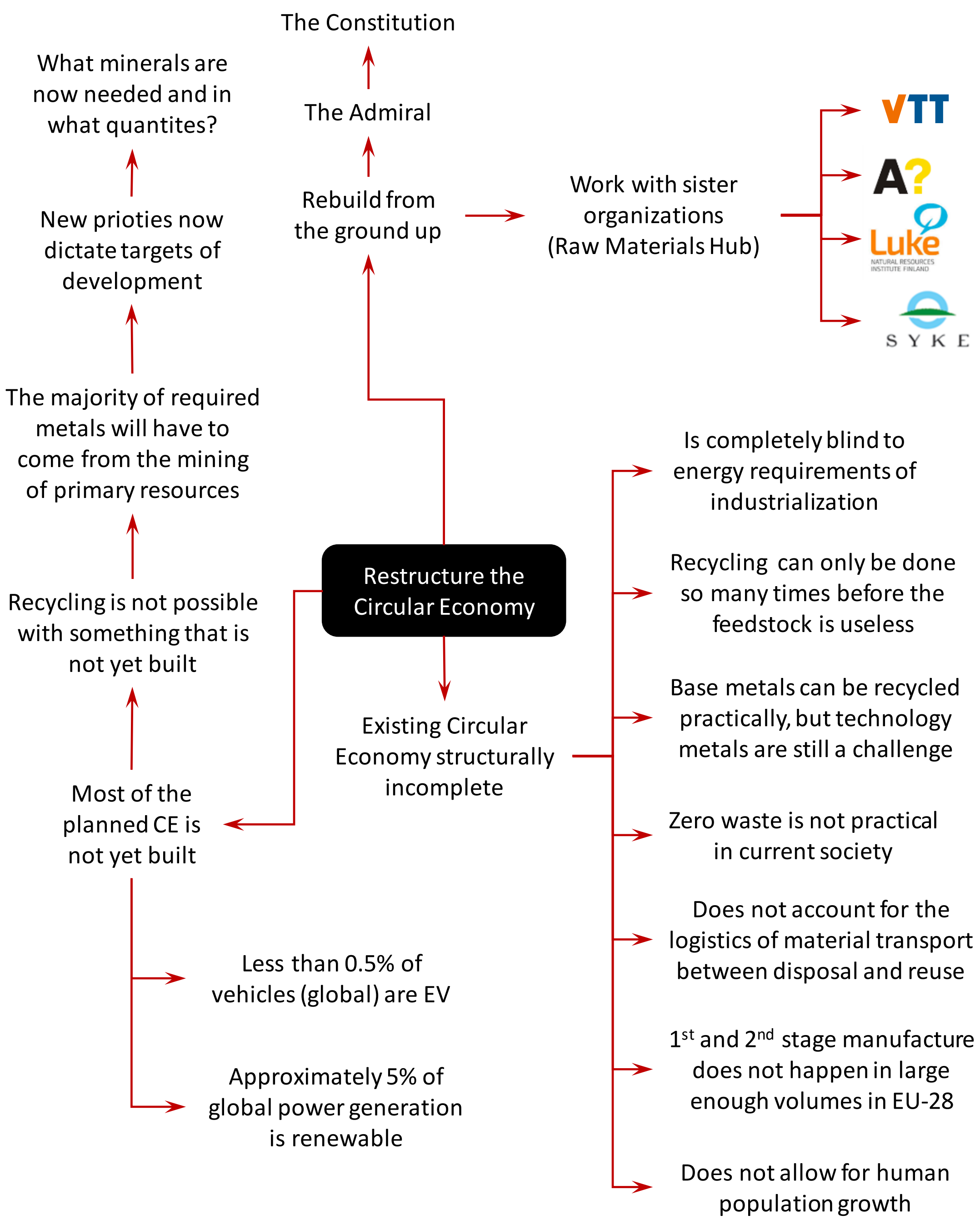


Figure 37. The structural flaws of the Circular Economy
(Image: Simon Michaux)

6 THE RESOURCE BALANCED ECONOMY

The proposed restructure of the Circular Economy is a Resource Balanced Economy (RBE) with the harmonious integration of statistical entropy coupled with material flow analysis of each resource. A Resource Balanced Economy is that of a system where gross industrial output and gross domestic product, is mainly derived from natural resources, but is limited in scope and action by exergy thermodynamics. The objective metrics of this RBE converge around long term sustainability of all stakeholders. Systems network theory is proposed to be the mathematical foundation of the development this form of Resource Balanced Economy (Kossiakoff *et al* 2011 and Dennis *et al* 2009).

The proposed Resource Balanced Economy is an evolution of the Resource Based Economy, with the integration of exergy as a limit derived decision tool. The original concept of the Resource Based Economy was popularized by the Venus Project (https://www.thevenusproject.com/), and its founder Jacque Fresco (Fresco 2018) in the year 2000. Since then it has been through several generations of development. Later, the Zeitgeist Movement (https://www.thezeitgeistmovement.com/) and its founder, Peter Joseph also popularized this concept.

The original concept of the Resource Based Economy is the development of a system over time, where all resources, technology and services are available to everyone in the human population. This would be deployed without the use of money, credit, barter, or servitude of any kind, while maintaining basic human rights like privacy and free speech. For this to be attained, all resources must be declared as the heritage of all humans in a global context. All resources are defined as existing valuable commodities subject to mining, and the waste side stream secondary resources. The proposed Resource Balanced Economy is an evolution of this, which includes a thermodynamical exergy term as a limiting metric to produce a practical system.

A shift in paradigm in how society sees that natural environment is also required. That natural environment allows the long term habitation of our society and should be maintained accordingly. At the same time, all resources that support our society come from that environment. We must change our paradigm, so we see ourselves as part of the planetary environment, not consumers of it (the current Linear Economy paradigm).

What is proposed here is a fundamental restructuring of our entire industrial ecosystem, starting with an evolution of the social contract. The current system is in a state of stress, and much of the planet's leadership are making decisions that could be described as panic based. To meet this challenge of change at a time of stress, it is proposed that the principles of science guided by philosophy is engaged on a scale not seen historically. What is proposed is an unprecedented mobilization of scientific and technical alliances towards problem solving, without the interference of money or politics (implying a replacement system).

How do we develop a system that will converge on a methodology to meet the spectrum of human needs taking into account the most efficient and sustainable processes? The final outcome should be a symbiotic relationship with the natural environment is developed at a planetary scale. The proposed system is geared to maximize economic efficiency and true sustainability together, where the current Linear Economy only maximizes economic efficiency.

There are six dominant considerations that could be developed as structural parts of the economic system.

1. Resource accounting
2. Management of dynamic equilibrium
3. Strategic design
4. Statistical entropy coupled with material flow analysis of each resource
5. Biophysical signatures
6. Technology application evolution/devolution over time

6.1 Resource Accounting

The human population currently administers the global industrial ecosystem as if there are unlimited natural resources. In reality, the planet is a finite dynamically self-regulating system that has been relatively stable for time periods best measured in geological eras. The industrial eco-system has grown very quickly in size and complexity since the start of the first industrial revolution (IR1). The industrial paradigm has only a very limited perspective of approximately 250 years.

So, the global industrial ecosystem habitats a finite closed (mostly) biosphere, and it consumes finite non-renewable natural resources (metal, energy, materials) and renewable resources (sourced from flora and fauna).

Logically, to sustain the environmental habit for future generations, maximizing the use of each and every resource as effectively as possible, is required to leave resources for our descendants. This is the effective and sustainable management of the Carrying Capacity of the planetary environment.

It is recommended that all resources streams are characterized and managed in context of biophysical signatures. The field of biophysical science deals with the application of physics to biological processes and phenomena. This approach could be used to merge non-renewable resources like metals with renewable resources like trees, and industrial resource consumption into a single coherent system.

What is required, is the quantification of the global (and all subregions like Europe and the Nordic Frontier) natural resources in all their forms. We need to understand exactly what our industrial ecosystem requires and in what form. In parallel to this, an understanding on what these resources are needed for and in what applications. A new methodology of resource classification is now needed, as part of routine mapping, there is a dynamic system based link between what resources we have, what they are needed for and where they are needed.

The total global resources need to be mapped in various levels of precision (reserves & resources, etc.). A more sophisticated standard of resource classification is now appropriate where the following needs to be mapped for all useful raw materials

- Quantity (with practical levels of precision)
- Quality (grade, penalty elements)
- Form (mineralized ore, industrial waste product, etc.)
- Renewable or non-renewable character
- Association (what other minerals/metals/materials are in the same stream)
- Mineral/metal/material grain size (implications in energy consumption)
- Extraction profile and process path

These resource mapping parameters need to be in a form where they can be used in an exergy industrial entropy analysis (Reuter *et al* 2006).

6.2 Dynamic Equilibrium

The Linear Economy monetary market model requires as much consumption as possible to keep the growing population employed and the economy operational. The outcome of this approach is obviously sustainable.

To manage natural resources sustainably in the long term, a method is required to track the consumption of resources against remaining quantity and resource regrowth (if possible). To do this effectively, the rates of change and regeneration of all resources and environmental markers need to be tracked to attempt to maintain dynamic equilibrium. For example, trees have a natural growth rate. Human society have been cutting down trees for wood resources for some time now. The cutting down of trees could be managed to be in equilibrium with tree growth.

A systems management protocol in how the data streams for resources is handled is proposed based around eh concept of dynamic equilibrium (Smith & Lewis 2011, Chung & Choi 2018).

Figure 38 shows and example of how dynamic equilibrium could be used to manage the harvesting of wood from forest plantations. The resource accounting of the number of trees and the health of the environment in context the environmental carrying capacity is mapped appropriately. The rate of tree regrowth was managed appropriately. The number of trees being cut down, could be closely managed by optimizing the consumption of wood.

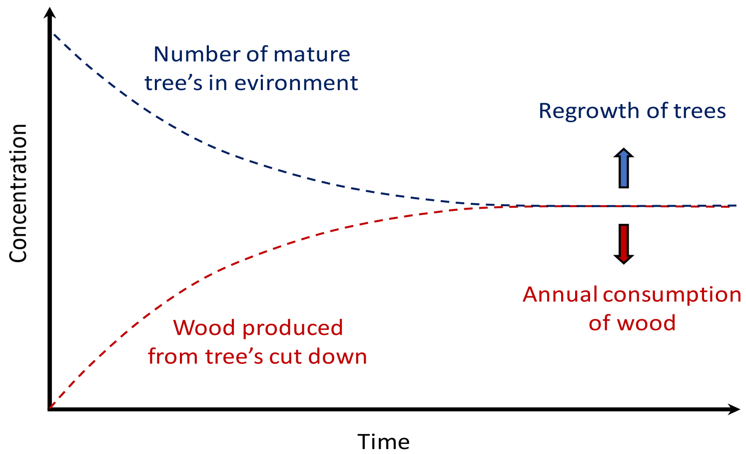


Figure 38. A theoretical example of dynamic equilibrium, wood production from a forest (Image: Simon Michaux)

6.3 Strategic Design

Resource allocation must be optimized strategically and conservatively. This is not done very well currently, where arbitrary monetary realizations are managed in context of what can be afforded by the supplier (cost of production) vs the consumer (commodity price). This is not done in context of the most scientifically efficient and long term strategically sustainable usage could be. The life cycle longevity of each product is currently geared to make money, not last as long as possible. Recycling of those products are not considered at the design phase, where waste disposal is considered someone else's problem (resolved with waste landfill sites). Cost efficiency often results in technological inefficiency. An example of this concept is the European industrial production in context of environmental legislation and minimum wage laws in compassion to the same systems in China. China dominates the global industrial markets because their costs are much lower and environmental legislation regulating industrial pollution are very different.

All of these issues serve as inhibitors for truly sustainable design. In the development of long term strategic industrial ecosystem design the following should be considered where possible.

- Accept lower purity of materials as feedstock, reducing pressure on refining targets
- Design for recycling to be effective
- Design multiple parallel systems resourced by different minerals

6.4 The statistical entropy coupled with material flow analysis of each resource

The case has already been made that energy is the master resource (See Section 4.1). The collection of and the application use of is the very heart of any industrial ecosystem. The current Linear Economy has been made possible with the access to cheap abundant energy. Any new ecosystem will have to have energy as a structural foundation concept.

The development of the Circular Economy has been very effective at collecting the building blocks needed to make a systems replacement. The concept of recycling powered by renewable power systems like wind or solar is a necessary paradigm shift to move away from the Linear Economy. To do this involves a shift in focus away from energy resources (oil, gas, coal, and uranium) to mineral resources to manufacture batteries, solar panels, and wind turbines.

Recycling of metals are theoretically infinitely recyclable, but there are practical limitations based on the complexity in how products are designed. Most products are designed to the optimization of performance, not to be recycled. There is a degradation in quality with each round of recycling. There is an inherent need to develop methods capable of quantifying the efficiency of recycling systems, provide guidelines for optimization of existing technologies, and support the design of new products based on sound, scientific and engineering principles (Reuter *et al* 2006).

A methodology was presented in the literature (Velazquez-Martínez *et al* 2019 and Reuter *et al* 2006) that shows the use of statistical entropy coupled with material flow analysis as a basis for the optimization of separation and purification processes. This example was applied to lithium-ion battery recycling processes. Unlike other efficiency parameters, this approach provides an analysis of component concentration or dilution from a systemic perspective, taking into consideration products, by-products and waste streams. The use of secondary resources through for example recycling involve material losses or generation of undesired by-products. Balancing losses and recoveries into a single and logical assessment is a very useful tool. This methodology introduced an entropic association between the quality of final recoveries and the earlier stages of process separation. In doing so, a true audit of the effectiveness of the process could be conducted.

This approach involves the use of the concept of exergy. Exergy is uniquely suited to use as a global, strategic indicator of the sustainability of mineral resources as it allows direct comparison between all metals, minerals, and fuels. Exergy is the application of thermodynamics to the accounting of natural resources and material fluxes. It examines the real energy costs, that is, the replacement costs, relative to a standard reference environment (RE). Therefore, one can compare in the same units the costs of different industrial operations in context of natural resources: Exergy (in Joules, J).

In thermodynamics, the exergy of a system is the maximum useful work possible during a process that brings the system into equilibrium with a heat reservoir, reaching maximum entropy (Rant 1956). The maximum fraction of an energy form which (in a reversible process) can be transformed into work is called exergy. The remaining part is called anergy, and this corresponds to the waste heat (Honerkamp 2002). Using an exergy standard states makes it possible to express these enthalpy and entropy data as Exergy by using for example the methodology and standard states expressed in Szargut (2005).

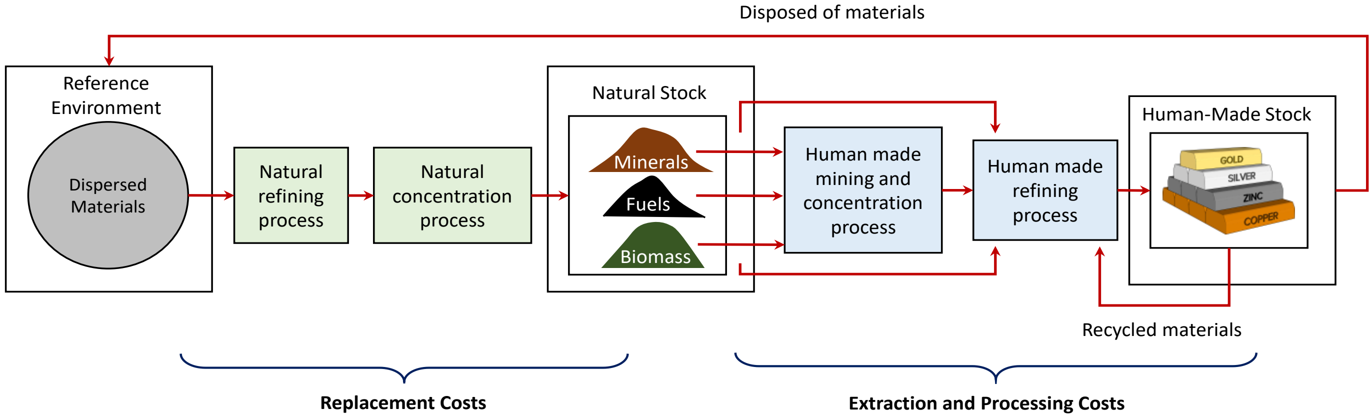


Figure 39. The conceptual process of exergy
(Image: Simon Michaux, ingot image by Craig Clark from Pixabay)

When the surroundings are the reservoir, exergy is the potential of a system to cause a change as it achieves equilibrium with its environment. Exergy is the energy that is available to be used. After the system and surroundings reach equilibrium, the exergy is zero. Determining exergy was also the first goal of thermodynamics. The term "exergy" was coined in 1956 by Zoran Rant (1904–1972) by using the Greek ex and ergon meaning "from work" (Rant 1956 and Grubbström 2007).

Energy is neither created nor destroyed during a physical process, but changes from one form to another (as per the 1st Law of Thermodynamics). In contrast, exergy is always destroyed when a process is irreversible, for example loss of heat to the environment (As per the 2nd Law of Thermodynamics). This destruction is proportional to the entropy increase of the system together with its surroundings. The destroyed exergy has been called anergy (Honerkamp 2002).

It is proposed that the RBE uses the following forms of analysis in the management of resources.

- Mass losses of target element as well as associated elements
- Exergy
- Thermo-economics of industrial entropy
- Biophysical signatures
- Life Cycle Analysis

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. Figures 40 and 41 show 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.

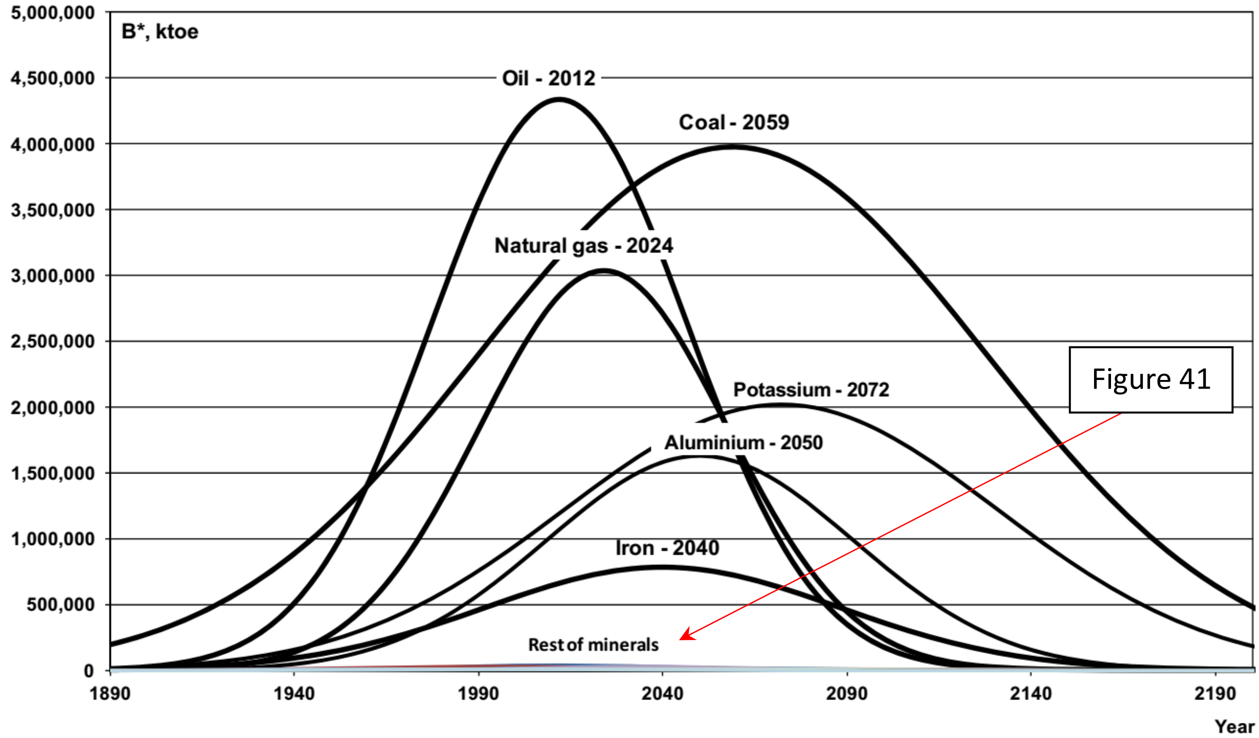


Figure 40. Metals and minerals raw material manufacturing landfill cycle – energy resources (Source: Valero & Valero 2014 - A Thermodynamic Cradle-to-Cradle Assessment) (copyright not secured)

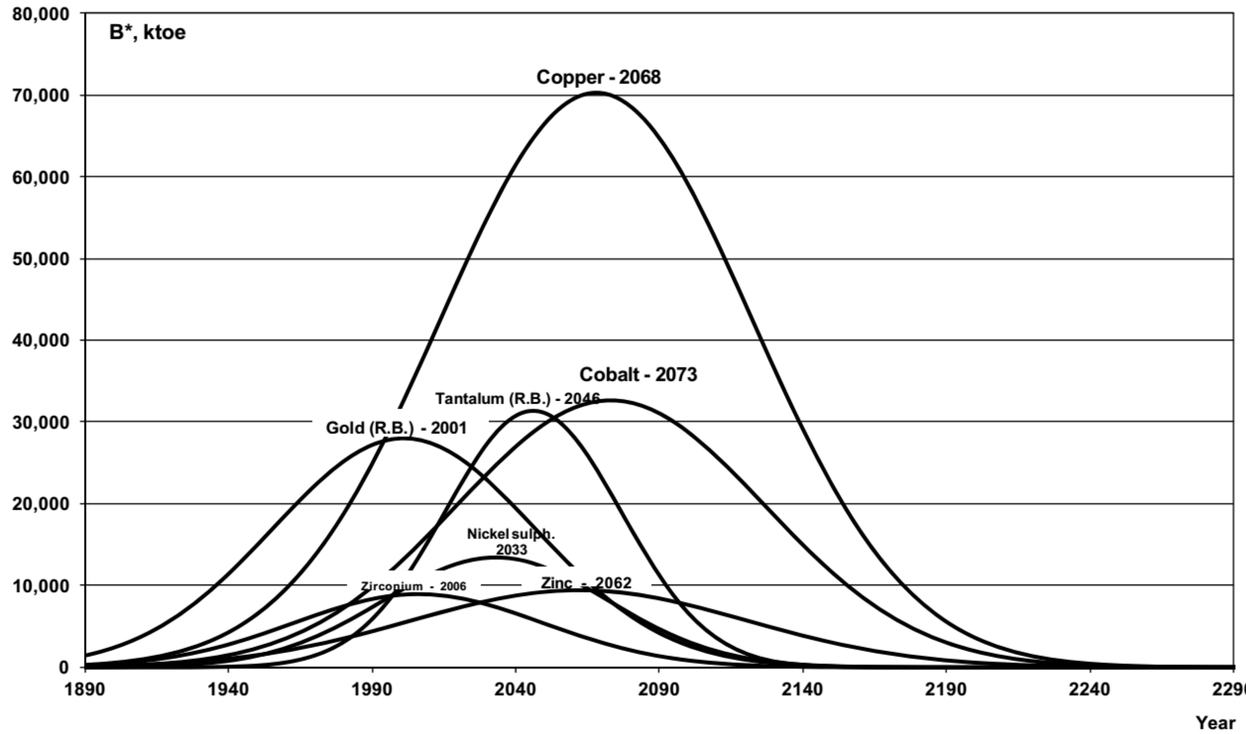


Figure 41. Metals and minerals raw material manufacturing landfill cycle – mineral resources (Source: Valero & Valero 2014 - A Thermodynamic Cradle-to-Cradle Assessment) (copyright not secured)

6.5 The Required Change in the Social Contract

The current Linear Economy has some very serious social imbalances. There is a wealth disparity between the wealthy developed nations and the resource rich economically poorer nations. This has developed over several centuries of time. Each of the wealthy nations are dependent on the import of natural resources, often source from the resource rich economically poorer nations.

So, it can be observed that there is a wealth in some nations and resources in other nations. A case could be made that corporations in the wealthier nations have exploited the poorer nations for their resources (Perkins 2016). At the very least, wealthy nations are happy to continue this circumstance in accordance to the mechanism of the free market, as it makes their tasks much easier.

> "Those nations that are having political instability should manage themselves more effectively, and more democracy is needed to get more competent leadership. We will continue to business with them while they sort themselves out. That they are having difficulties is not our concern."
>
> - a quote from an anonymous civil servant from the European Commission in 2018 (personal communication to the author)

It has been postulated that the escalation of civil unrest, social protest and political instability around the world over the last 20 years is causally related to the unstoppable thermodynamics of global hydrocarbon energy decline and its interconnected environmental and economic consequences (Ahmed 2017). This is not really recognized in developed nations as the paradigm is one of relative isolation. There seems to be a general perception that none of this affects us at all and is really not our problem.

The wealthiest 1% collected 82% of wealth created in the year 2017 (Ratcliff 2018), and the world's richest 1% had more than twice as much wealth as the poorest 6.9 billion people (Oxfam). In 2015, just 62 individuals had the same wealth as 3.6 billion people – the bottom half of humanity. This figure is down from 388 individuals as recently as 2010 (Hardoon *et al* 2016).

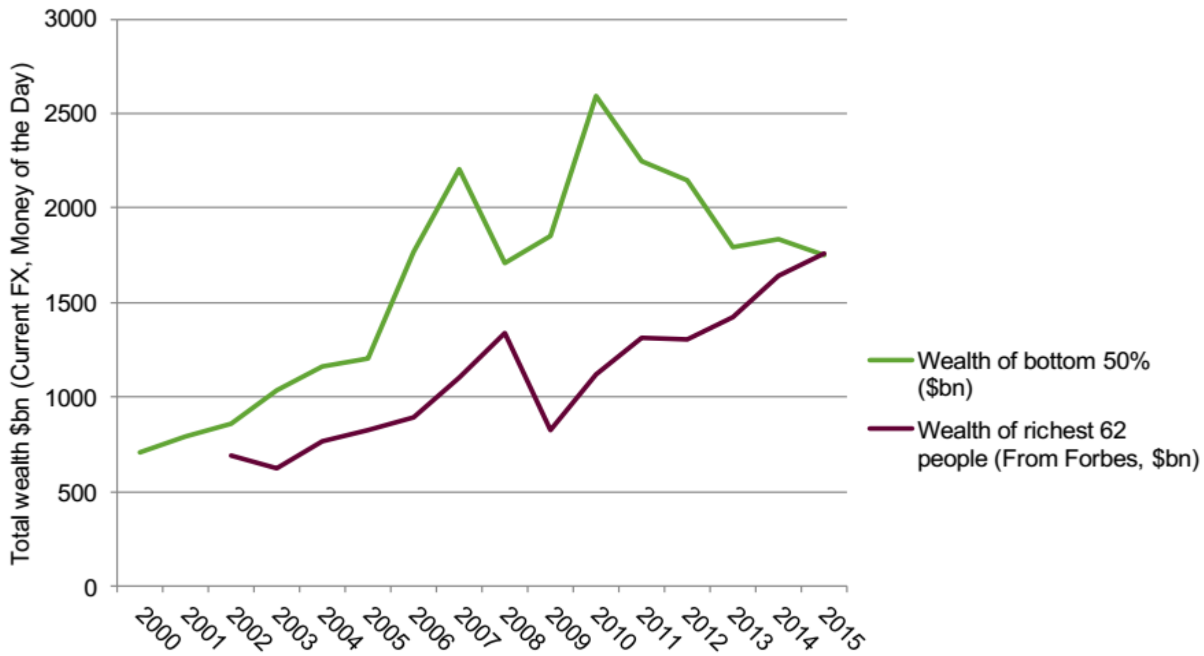


Figure 42. The 62 richest people in the world have an asset value worth more than the poorest 50% of the world's population, and the poorest 50% is stagnating (Source: Oxfam/Forbes, Hardoon et al. 2016) (copyright not secured)

Oxfam did a study to examine the wealth inequality that has been building globally for decades (Hardoon *et al*. 2016). From the Oxfam report:

> *The gap between rich and poor is reaching new extremes. Credit Suisse recently revealed that the richest 1% have now accumulated more wealth than the rest of the world put together. Meanwhile, the wealth owned by the bottom half of humanity has fallen by a trillion dollars in the past five years. This is just the latest evidence that today we live in a world with levels of inequality we may not have seen for over a century. The Oxfam report looked at how this has happened, and why, as well as setting out shocking new evidence of an inequality crisis that is out of control. Oxfam has calculated that:*
>
> - *In 2015, just 62 individuals had the same wealth as 3.6 billion people – the bottom half of humanity. This figure is down from 388 individuals as recently as 2010.*
> - *The wealth of the richest 62 people has risen by 45% in the five years since 2010 – that's an increase of more than half a trillion dollars ($542bn), to $1.76 trillion.*
> - *Meanwhile, the wealth of the bottom half fell by just over a trillion dollars in the same period – a drop of 38%.*
> - *Since the turn of the century, the poorest half of the world's population has received just 1% of the total increase in global wealth, while half of that increase has gone to the top 1%. The average annual income of the poorest 10% of people in the world has risen by less than $3 each year in almost a quarter of a century. Their daily income has risen by less than a single cent every year.*

This Oxfam report was published in 2016. In 2020, the Covid-19 pandemic has resulted in even more wealth disparity. Between 1980 and 2020, billionaires in the United States saw their wealth increase by 1130%, increasing more than 200 faster than domestic median wages. At the same time, the tax obligations of those same billionaires in the United States declined by 78% between 1980 and 2018 (measured as a percentage of their wealth) (Goldin and Muggah 2020). These issues are present in all nation states but seem to be not yet perceived relevant in developed nations at this time.

It was from similar forces and stresses that created the French Revolution. Since the Global Financial Crisis of 2008, there the world has witnessed an unprecedented outbreak of social protest in every major continent (Ahmed 2017). Large sections of the population in the economically poor (but resource rich) countries are in survival mode and are losing faith with the social contract. To make the point again, this has often been happening in nation states that the developed world depends on for the import of resources. That we are in a global system that is imbalanced in terms of wealth and resources is not really recognized by policymakers, the media, as well as social and natural scientists. This is highly relevant for the consideration of any system to replace the Linear Economy. It could be argued that the Linear Economy is now subject to stress and strain as a consequence of deteriorating hydrocarbon resource net extraction (ERoEI). The proposed replacements renewable energy systems (wind, solar, etc.) have a lower ERoEI of what is being used now (fossil fuels). This implies the social contract aspect underlying the replacement system should not be taken for granted that all will be well and equitable.

It is very clear that the challenges facing the global Linear Economy at this time are international in nature and are creating a very serious social disparity that has the potential to disrupt the system. Thus, some kind of change is inevitable, the question becomes into what. Biophysical processes are increasingly driving social unrest and geopolitical instability in parts of the world that other parts depend upon is a signature that world is moving into a new era of social contract, with a changing support industrial ecosystem.

The proposed Resource Balanced Economy would require enormous change. The most fundamental change will be an evolution of the social contract within our society. Changes to the structure of the industrial ecosystem are a function of the change in how society interacts.

The following paradigm shift will have to happen in people systems at all scales (the individual, the family, the community, the city, the nation state, global).

- Move to a growth based economy to a steady state economy. Constant growth is not possible on a finite planet. This would be the end of the Linear Economy.

- Move from a competitive system to a collaborative system. Strategic design cannot be implemented when economic cost efficiency is the defining metric. People have to want to collaborate, not be in a scarcity mindset.

- Move from a diverse system of isolated groups to a more planned inclusive system. Currently, there is no understanding by the average person what resources were used to produce a product (a computer for example), where they came from, what the waste plume was, or what happens when they throw that product away. There is complete isolation (as a function of the free market) between the individual and the consequences of their choices. The information age will resolve this.

- Move from a system of property to a system of access. Remove the monetary system entirely. This may well be the most difficult task to understand, let alone achieve. However, until the nature of monetary systems changes, nothing else will change.

- Move from a property based material value system metric to a dynamic interchangeable resource sharing access management metric approach.

- Wealth inequality needs to be addressed between rich developed nations and Third World nations that have often been subject to geopolitical exploitation (Perkins 2016). Currently the resource rich but economically poor nations

- Move from a system that is geared to consume as many resources as fast as possible in exchange for monetary gain, to a system of strategic access of resources in context of long term management.

6.6 A change how we perceive the natural environment, and what it could teach us

It is now accepted in in the biological and ecological sciences that an organism’s relation to the environment is fundamentally facilitated through the mode and manner by which it extracts energy from the environment, to maintain and improve its distance from thermodynamic equilibrium.

The power source for living systems is the sun. Those living systems can reproduce as well as collect, process, and exchange information. The outcome is the living systems can control and direct energy and matter they receive from their environments (Terzis & Arp 2011, and Hall *et al* 1992).

The industrial ecosystem also has a similar relationship with energy, but the current Linear Economy ecosystem is facilitated by non-renewable finite natural energy resources: oil, gas, coal, and uranium.

Stress points in the Linear Economy also imply that how we perceive the natural environment also needs to change. Much of current thought has a very idealistic view of how the planetary system works. An effective way to understand how the environment functions (and how the industrial ecosystem could sustainably interact with) is to model it as a gigantic complex system (Lovelock 2004). At a macroscale, that system is quite stable, but each and every organism is competing for survival with each other. As the planetary conditions change, different parts of the flora and fauna sub-systems become more effective at surviving, and the previous dominant flora and fauna die off.

This is relevant to understand as this is exactly how the free market is supposed to work, and this is exactly how the Linear Economy was developed. In the Gaia hypothesis, when an animal population grew in size to fast and in excess of the carrying capacity of the local environment, that population was subject to a sharp reduction due to lack of available food (Lovelock 2004). This happens on a small localized scale as a routine method of natural system regulation.

It is pertinent for us to understand how the large macroscale changes happen as well. There have been five mass extinctions in the past geological history (Kolbert 2015). A theory has been put forward in the study of global scale mass extinctions in the planetary environment to try and explain why the form of biodiversity over geological time frames, has long time periods of stability with periodic very short time periods of high stress change (Courtillot 2002). Those very short time periods of high stress change are characterized by the mass die-off of many species and the sharp rise in new species populations. So much so, that the fossil records show a completely different system and are classified as different geological era's (Stanley 1989).

Courtillot has proposed that a correlation between large scale volcanic events and these mass extinctions could explain how the radical in environment required a radical change in the biodiversity flora and fauna. The environment simply did not support the old flora and fauna system, and it died off.

This concept could be used to model what is happening to the Linear Economy and its industrial ecosystem. The supporting energy source is reducing in effectiveness (declining ERoEI). It has exceeded the carrying capacity size of which the global environment can sustain and has started to show signs of plastic deformation strain. The fundamental driver for this is how the Linear Economy consumes resources, and how it maintains its habit. If this is a correct assessment, the Linear Economy is about to be subject to a very sharp reduction in size and relevance (See Figures 33 to 36).

Industrial Ecology (IE) is an excellent approach to develop this idea (Graedel & Allenby 2003, Korhonen *et al* 2004, Allenby 1999 and Cohen-Rosenthal 2000). This describes how Industrial Ecology examines the complex interactions between the so many actors in an industrial material production, use and recycling system, where IE is a science finding its inspiration from nature.

This innovative Circular Economy idea has merit and something like it is required for long term sustainability. That being stated the Circular Economy in its current form is structurally flawed.

The architecture of the proposed Resource Balanced Economy is shown in Figure 43.

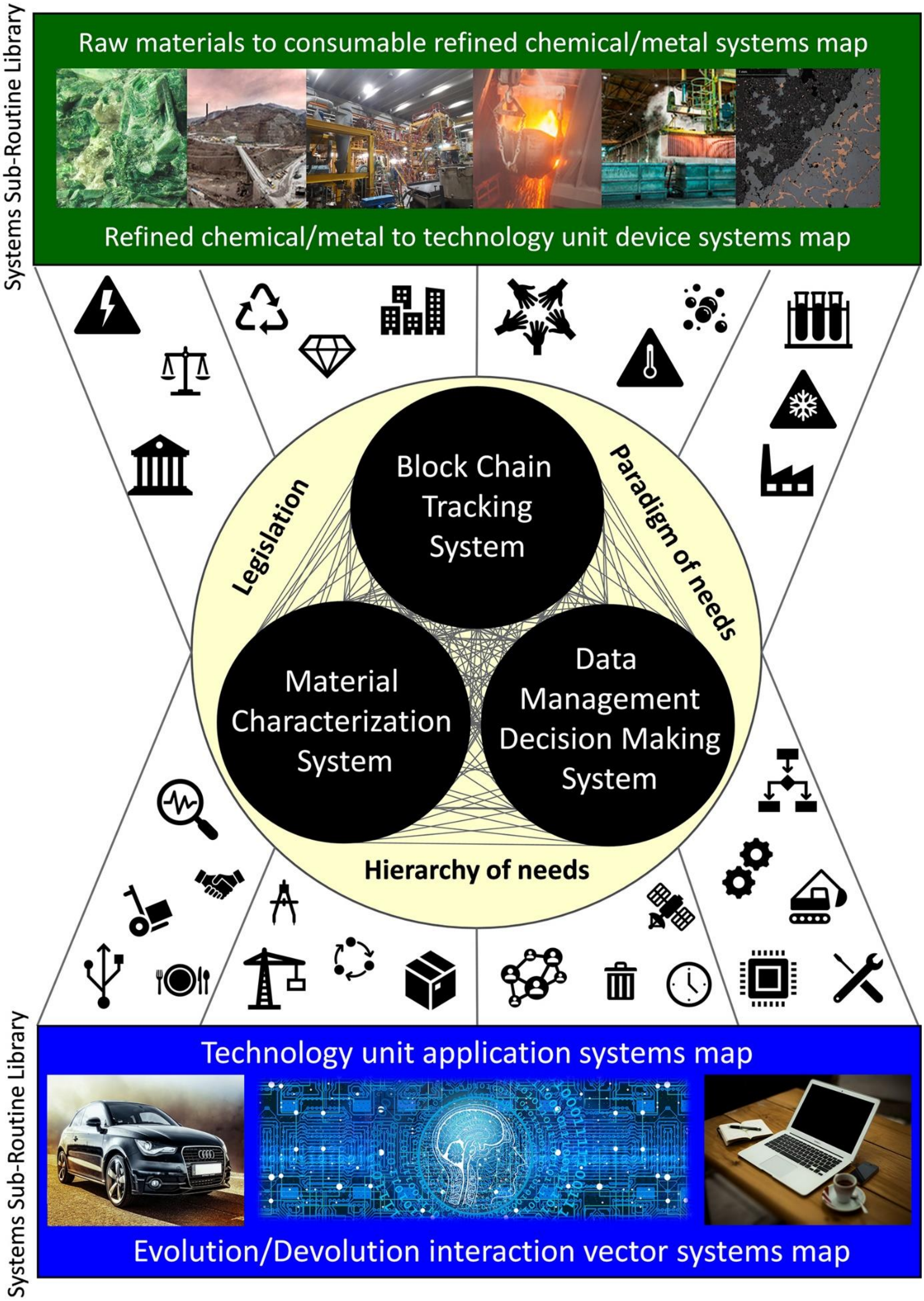


Figure 43. The Resource Balanced Economy (The Constitution)
(Image: Simon Michaux, the car image by Michal Jarmoluk from Pixabay, Gerd Altmann from Pixabay, the smelting images by Codelco flickr, all other images are either GTK, or are copyright free clipart)

7 DEVELOPING THE RESOURCE BASED ECONOMY

Section 7 outlines the start of the development of the Resource Balanced Economy. These are the basic structural components. Clearly, such a complex task cannot be captured so easily in a single report. This is considered to be a starting point of the discussion between relevant people who will do the work suggested here. Figure 44 shows a basic summary of the tasks required.

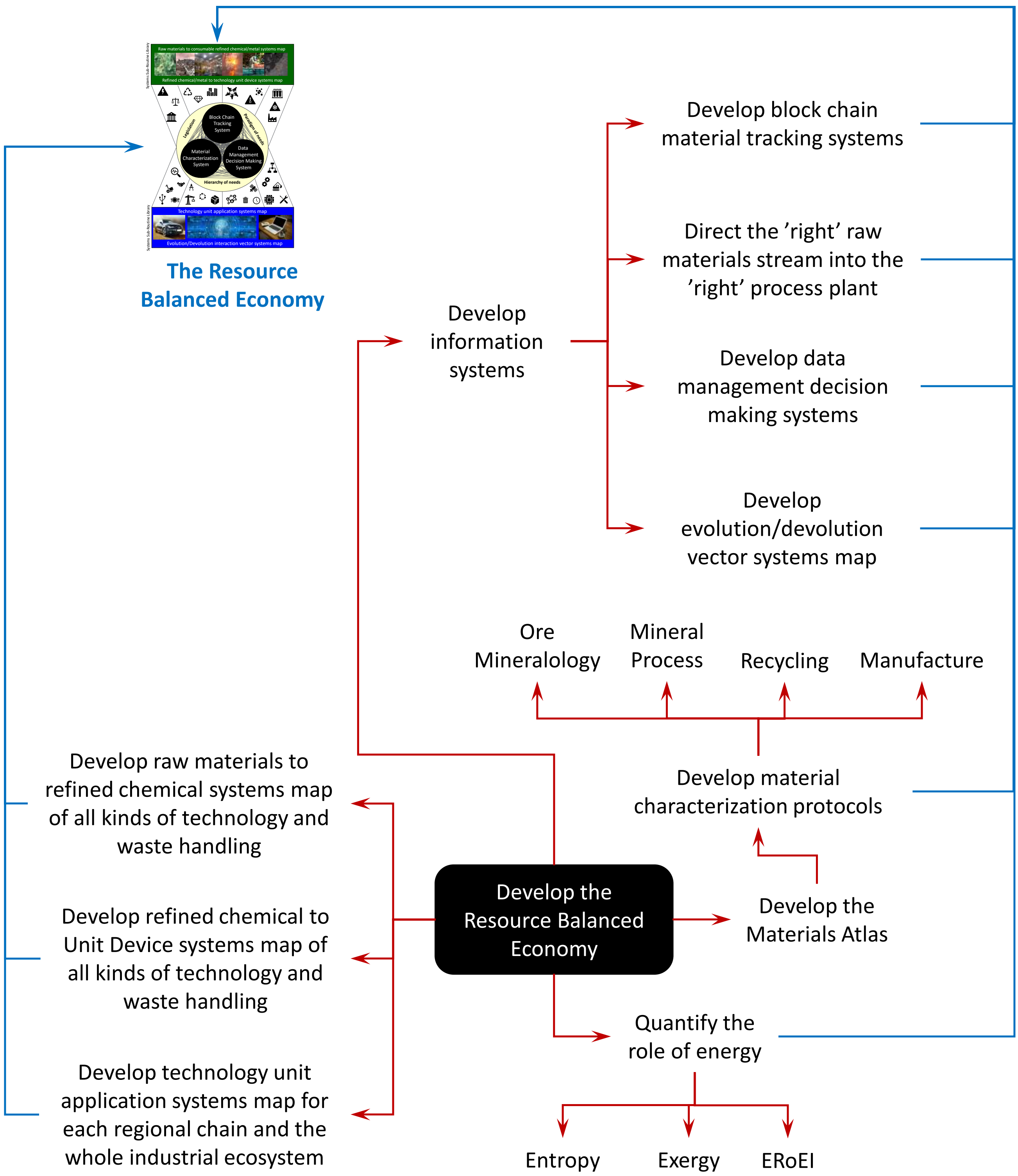


Figure 44. Develop the Resource Balanced Economy (The Admiral)
(Image: Simon Michaux)

7.1 Develop the controlling paradigm

The proposed RBE system is complex and multi-faceted. There are proposals of how raw materials should be mapped and managed. There are proposals for how society could and should use its technology. It is proposed that something like a machine learning A.I. be used to administrate these recommendations.

This would be an administrations system that would serve society (as opposed to the other way around) and would be governed by democratically elected governments.

The question of what is the controlling the ruling paradigm at the very centre if the system is a vital one. Choices can be made but for whom and to what end? Some thought needs to be given to this. There are four questions of primary importance when redesigning a culture.

1. For whom is the culture designed?
2. What are the boundaries of necessity?
3. What ends are to be served?
4. Who will benefit, everyone or a few?

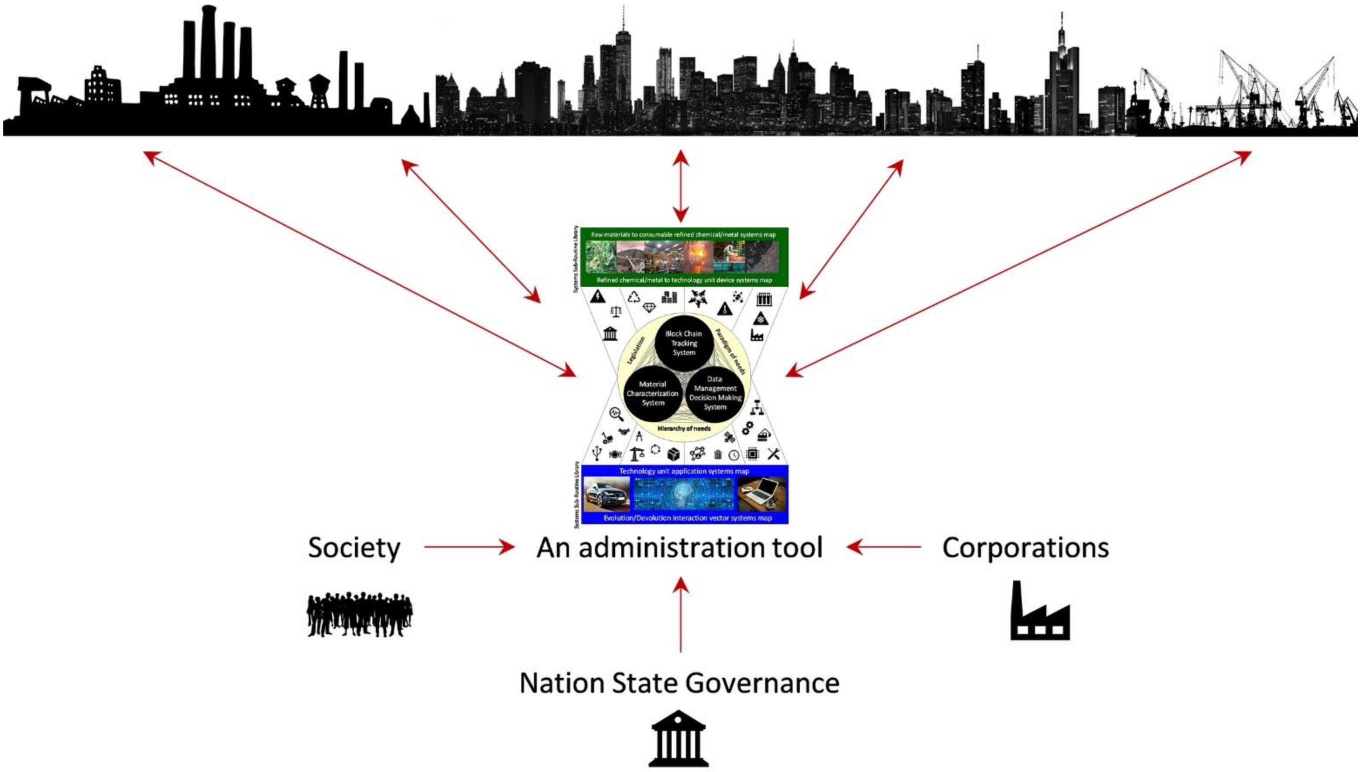


Figure 45. How the Resource Balanced Economy could be used
(Image: Simon Michaux, using copyright free clipart)

It is recommended that this network system follows the same basic profile of a biological system through the use of biomimicry (Benyus 2002). Biomimicry is the emulation of the models, systems, and elements of nature for the purpose of solving complex human problems (Vincent *et al* 2006). This is an appropriate direction of development as it would be easier for the human society and supporting industrial ecosystem resembled the natural environment in architecture more closely at a structural level.

How biomimicry could be used is as follows. There are a series of accepted concepts in the science of biology in the development of a biological network system. The flow of energy through a system acts to organise that system (Morowitz & Smith 2007). the size and complexity of a network is defined by the energy input to that system. Complex systems don't just manifest in complete form, they must evolve and develop from simpler systems over time.

7.2 Quantify the role of energy

As physical work done is a function of energy, and the proposed renewable energy systems have a lower ERoEI than what is currently used, an energy component in each and every resource consumption and technology application is required. It is postulated that the industrial ecosystem is about to move into a low energy future. If this becomes true, then the size and complexity of the industrial ecosystem will be required to be reduced.

To understand the boundary conditions of the limits that will soon be applied to the industrial ecosystem an energy based metric is required. It could be that there will be limitations accessing resources and technological products manufactures too far away geographically.

So, each resource consumption demand could be managed in context of what will be required to access it. An exergy based biophysical term on the resource/product, accounting for logistical transport coupled with a statistical entropy term in context of technological application, could diagnose the boundary conditions for at what point accessing the resource is not worthwhile. Using an exergy standard states makes it possible to express these enthalpy and entropy data as Exergy by using for example the methodology and standard states expressed in Szargut (2005).

One of the implications of a low energy future will be a change from the current global based system that allows the following value chain to be economically viable. Mackerel fish are caught and harvested in a fishery off the coast of Scotland (United Kingdom). That fish is then transported to a canning operation in Vietnam (South East Asia). The tinned fish are then transported back to London for commercial sale and distribution. Some of those tins of Mackerel fish are transported for sale to Edinburgh Scotland to be consumed by the local population. The people who caught the original fish would purchase some of these tins of mackerel from a supply chain based in Edinburgh. This very inefficient system is economically cheaper than canning the fish, at the same harbour the fishing trawler that caught the fish. This is due to a wealth disparity in the costs of production between Scotland and Vietnam. This system is also only possible with the application of cheap abundant energy (fossil fuels).

In a low energy future, it would become more practical to resource the mackerel fish locally and directly. the boundary conditions of what is possible then becomes defined by the ERoEI ratio of the energy systems used to facilitate production.

The outcome in the medium term, could be a transition away from a global system to several fully self-sufficient regional systems. Each of those regional systems would be required to be less complex than the current global system.

The size of each regional system would be defined by what is possible in context of biophysical exergy, and statistical entropy limitations in accessing resources to support vital services to society. This implies that the geopolitical future will be defined, not by current political national boundaries, but with alliances between industrial cluster systems. If taken further, this concept could define the size and form of new nation states in the coming industrial era.

7.3 Quantify the role of automation

What is proposed in this report is a complex system that will require the application of technology in unconventional ways. This could be done in context of the development of the 4th Industrial revolution (Moore 2019). The 4th Industrial Revolution (IR4 or Industry 4.0) is the ubiquitous scale up of automation of traditional existing manufacturing and industrial practices. This is to be done using modern state-of-the-art technology.

What is proposed here is a slight shift in paradigm to what is currently being planned for industrial development, with the suggestion that current thinking has a number of blind spots. Dependency on fossil fuels energy and mineral resources being just two.

The planned 4th Industrial Revolution, characterized by the fusion of the digital, biological, and physical worlds, as well as the growing utilization of new technologies such as artificial intelligence, cloud computing, robotics, 3D printing, the Internet of Things, and advanced wireless technologies (Schwab 2015).

A perceived issue with this approach could be that the individual human and society in general become completely dependent on these technology systems. The individual human as a self-sufficient entity could devolve in capability without the assistance of technological tools.

The high technology automation systems proposed by proponents of the Fourth Industrial Revolution (IR4) will require a very complex industrial ecosystem (Nasman *et al* 2017). The IR4 system will be much more complex than the current Linear Economy system in place now. From a biophysical exergy point of view this will not be practical in scope of complexity. Then there is the question of whether this should be done at all.

There is a lot of debate regarding how society has become dependent on technology and what the long term implications of that could be (Orlov 2017). On one hand, technology application is seen as the path to develop society for the benefit of all. On the other hand, it has been observed how society has become dependent on technology and the average person is now helpless without their mobile phone and the internet.

This debate may well be moot as widespread automation of all of societies tasks is dependent on a complex industrial ecosystem, supplied with vast quantities of natural resources (technology metals in particular) and abundant energy. The current industrial extraction and consumption of resources by the Linear Economy is exhibiting stress signatures. A case can be made that it will struggle to increase in complexity, due to the required increase in mineral resources required.

Orlov (2017) makes an excellent point though. We are required to understand at an individual level and at a nation state level the answer to the following question:

Does the Technosphere serve us, or do we serve the Technosphere?

The role of automation should be optimized for a low energy world, and where the human being is the strongest link in the ecosystem, not the weakest. Our relationship with technology must evolve into something more appropriate. The limitations of exergy and thermo-economics of industrial entropy should define when and where the technology of the 4th Industrial revolution should be applied.

7.4 Quantify the role of surveillance data collection of consumption

What is proposed in this report is a complex system that will require data to be collected in some form to allow optimization to take place. A change in paradigm and a change in architecture is proposed in what data is collected.

The Circular Economy in its current form is advocating of the formation of a nationwide (global if possible) SMART grid, as an outcome of the development of the 4th Industrial revolution. This is often referred to as SMART technology (figure 46). One of the defining characteristics of this concept is the large-scale machine-to-machine communication (M2M) and the internet of things (IoT), which are integrated for increased

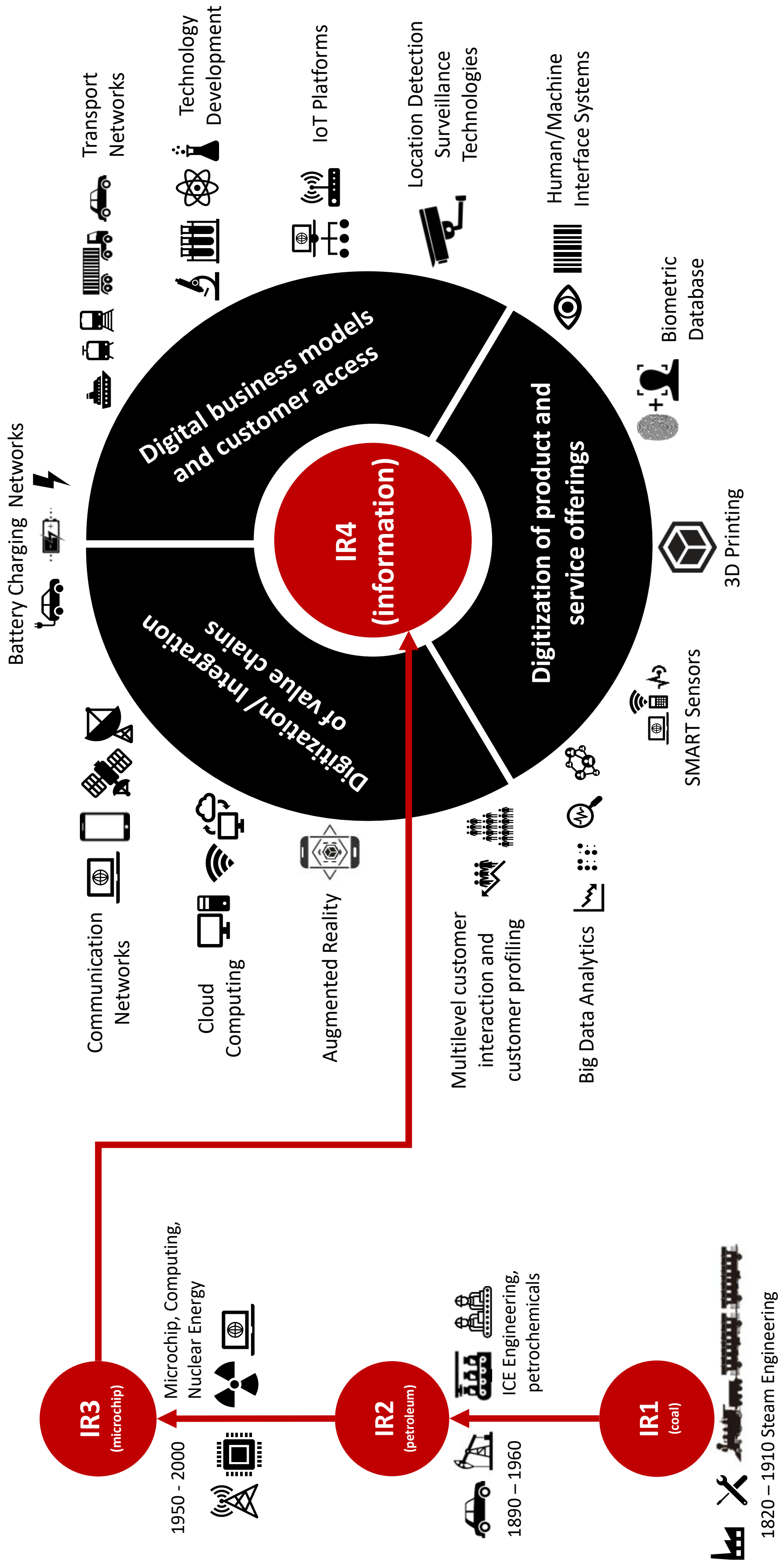


Figure 46. The 4th Industrial Revolution (IR4) has evolved from previous Industrial revolutions IR3, IR2 and IR1 (Image: Simon Michaux, copyright free clipart)

automation, improved communication, and self-monitoring. This would require a whole new generation of technology applied to the production of SMART machines that can analyse and diagnose issues without the need for human intervention.

A SMART city is a city that uses a variety of electronic surveillance methods and sensors to collect data (McLaren & Agyeman). What is planned is the ubiquitous surveillance of all resource consumption by all people, 24 hours a day, 7 days a week. That data is used to manage assets, resources, and services efficiently. In theory, the locally collected data is used to improve the operations across the city.

This includes data collected from citizens, devices, buildings and assets that is then processed and analysed to monitor and manage traffic and transportation systems, power plants, utilities, water supply networks, waste, crime detection (Fourtané 2018), information systems, schools, libraries, hospitals, and other community services. This sensor network has often been referred to as the Internet of things (IoT) describes the network of physical objects (things) that are embedded with sensors and software, for the purpose of connecting and exchanging data with other devices and systems over the internet.

Artificial intelligence (AI) and Machine Learning (ML) is considered the administration tools to develop a decision making system to handle all this data. Artificial intelligence refers to the simulation of human intelligence in software that is programmed to think like humans and mimic their actions (Allen 2020). The stated objective in A.I development is to mimic human ability to apply learning of observed data and problem-solving for future actions.

Machine Learning is the use and development of computer systems that are able to learn and adapt without following explicit instructions, by using algorithms and statistical models to analyse and draw inferences from patterns in data (Ethem 2020).

All of this is a testament to the technological development that has been achieved. There are, however, serious reservations for whether this approach should be used at all (Coombes 2015 & Stanford University Project CS181).

Each time in history that mass surveillance has been used, the human rights of the target society have suffered serious setbacks. An example of this could be the East German Ministry for State Security (also known as the Stasi). The Stasi operated for four decades, where they had complete domination over almost all aspects of life in East Germany with the administration of one of the most intrusive surveillance organizations in human history (Coombes 2015 Amnesty International).

While the scope of activity of the Stasi is quite shocking, modern mass surveillance achieves this omnipresence with a fraction of the manpower. That this is now happening is no longer a theory (Amnesty International & Snowden 2019).

The United States NSA has be engaging in mass surveilling on a global scale using their PRISM system (Planning Tool for Resource, Integration, Synchronization, and Management) for some time (Wikileaks 2013). In the name of national security, 41 nation states routinely exchange mass surveillance data (Privacy international).

What is done with this information is a matter of national security and is unknown. It is believed that sophisticated A.I tools are being applied to manage this data. Artificial intelligence (AI) technology is rapidly proliferating around the world (Feldstein 2019). Yet a growing number of states are deploying advanced AI surveillance tools to monitor, track, and surveil citizens to accomplish a range of policy objectives. Some actions are lawful, others violate human rights, and many of which fall into a legal middle ground (Muižnieks 2016).

AI surveillance technology is spreading at a faster rate to a wider range of countries than experts have commonly understood. At least seventy-five out of 176 countries globally are actively using AI technologies for surveillance purposes. This includes smart city/safe city platforms (fifty-six countries), facial recognition systems (sixty-four countries), and smart policing (fifty-two countries) (Muižnieks 2016 & Saptharishi 2014). Many of the surveillance measures that are currently being done, contradict international human rights law, as established by the European Court of Human Rights (Muižnieks 2016).

The Great Reset as proposed by the International Monetary Fund (Georgieva 2020), among other things, would require the use of the Internet of Things to administer the mass surveillance of society (Hinchliffe 2020).

The question of should we do this, while important, can be avoided by simply changing how data is collected and from where. Figure 47 shows a concept map of the paradigm behind the current surveillance state, the Internet of Things (IoT) and the SMART grid.

The objective is to collect data for resource consumptions of all kinds by all people, in as many places as possible. It is proposed that real time surveillance of all people in their own homes of them engaging in all activities is collected and archived in a central place. This is a much more sophisticated version of what the East German Stasi were doing, but for a different reason. The outcome is the State would micromanage each individual in context of what they did, how and when. The individual would have lost control of their lives. This would be an acceleration of the current actions that contradict international human rights law.

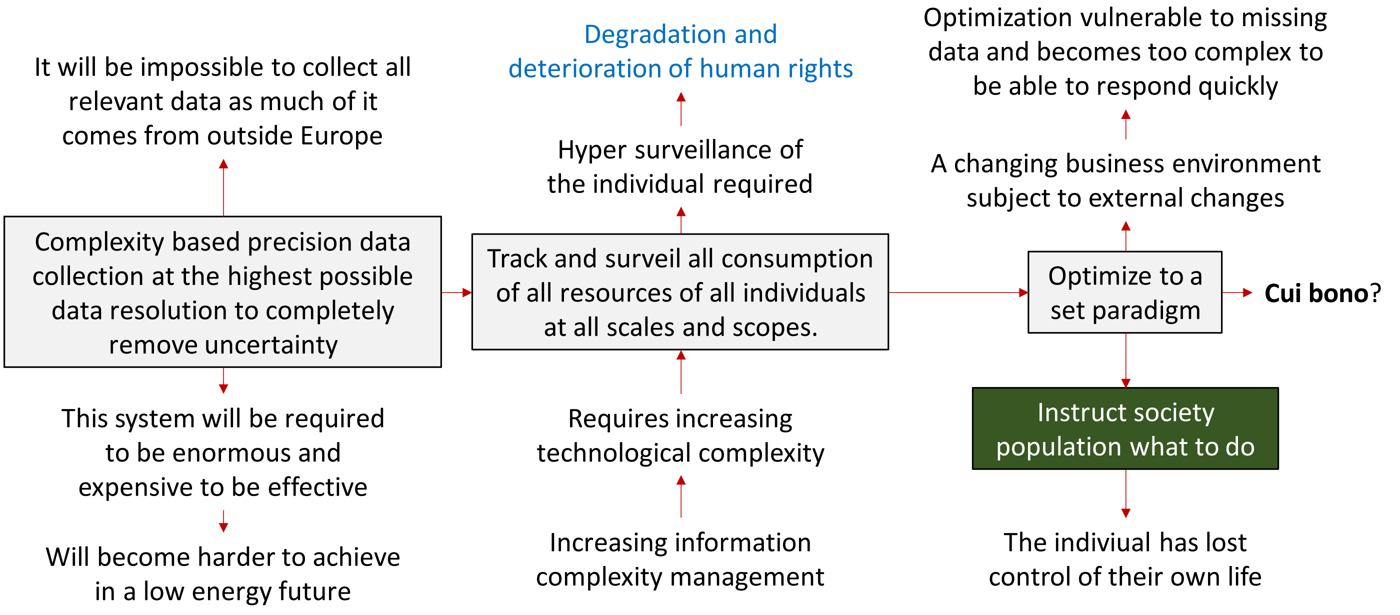


Figure 47. Complexity based precision data collection at the highest possible data resolution to complete remove uncertainty (Image: Simon Michaux)

However, what the Internet of Things is trying to achieve is needed and serves a purpose in context of the optimization if society resource consumption. So, a change in what data is collected and where is proposed in a fashion that completely removes all of the issues of trust and appropriateness of the current mass surveillance.

Figure 48 shows a concept map, where the consumption of resources is tracked at the node point. A node is a device or data point in a larger network. In networking a node is either a connection point, a redistribution point, or a communication endpoint (Kossiakoff *et al* 2011). In this context, a node refers to a goods distribution point where society can access resources. For example: a supermarket for food, a fuel station for fuel, a power station for electricity, etc. The consumption of all resources in and out of each node could be matched against the population catchment the node serves. It is recommended that the network is structured using Fuzzy Logic and/or Neural Network theory. In doing so, uncertainty can be embraced and gives the network greater flexibility in modelling the flow of resources.

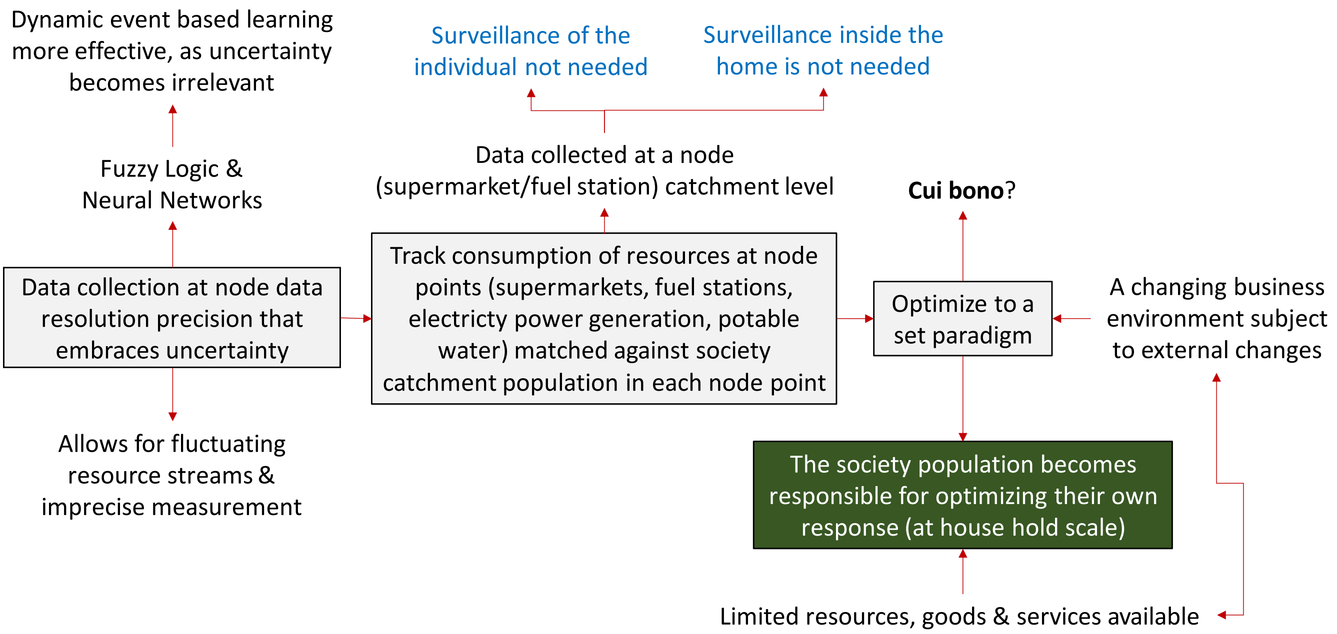


Figure 48. Data collection at node data resolution precision that embraces uncertainty
(Image: Simon Michaux)

As it is projected that there is an incoming low energy future, it is highly likely that there will be limited resources, goods, and services available compared to what is happening now. Each individual, family and household would be required to optimize how they lived with what they had available. While the current mass surveillance system made the State responsible for the micromanagement of people, this solution requires people to attend to their own lives.

The mass surveillance of people in their private homes will no longer be necessary. The concerns for the breach of human rights can be avoided. There would be less pressure on the State to act appropriately in the handling of authority. It is recommended this approach is developed.

7.5 Develop material characterization protocols – The Materials Atlas

A more holistic characterization methodology is proposed to assist in the determination of what to do with each raw material stream. Conventionally, any given resource stream is subject to extraction of one or two metals, and the rest is discarded as waste. What is now required is to extract as many different valuable materials and metals as possible. Figure 49 shows the pictures of three different waste product streams that have been through the first stage stream collection. These waste streams contain many different very useful metals and materials. Which metal or material should be prioritized? Gold or copper? To what metric should this be decided? Economic value or industrially usefulness? Each processing path will have efficiency windows. A polymetallic process path to extract several different metals tends to be very inefficient. How should the various trade-off decision for this be managed? Material characterization can now be done in a systems context, where a unified characterization protocol can be developed for each mineral/metal/material, where it can be understood where in the value chain the sample was collected. The same protocol could be used to examine a recycled waste stream sample and diagnose how many times it has been recycled (concepts developed by Alan R. Butcher).

Figure 49. Three different waste product streams after the first stage of waste collection
(Image: Simon Michaux)

If successful, a model of the evolution of a metal texture across its value chain. If this was done with multiple minerals/metals/materials, it could be termed a Materials Atlas (Figure 50).

It is now appropriate to study each raw material (for example copper, Cu) in all its forms. Traditionally, copper texture in mineralized rock was considered completely separately to how copper texture appears in a recycled waste stream (for example shredded batteries). It is now possible develop a characterization protocol how each target element (in this case copper) appears at each point in the process value chain. In theory, it could be possible to track how the exact quantity of copper in a mineralized ore, would present in a concentrate of that ore, the smelted slag of that concentrate, the refined metal of that slag, the manufactured component of that refined metal, and lastly how that manufactured component would appear as a recycled product.

This task aims at developing engineering parameters based on mineralogical and physicochemical properties, and their treatment with statistical methods, thus allowing the design of recycling systems better suited to the goals of a Resource Based Economy.

The ultimate challenge is to send the 'right' raw material to the 'right' process plant for the most effective recovery. This highlights the importance of the decision in what are the valuable elements to be targeted. Characterization is the foundation of decision making in the Resource Based Economy.

A more sophisticated standard of resource classification is now appropriate where the following needs to be mapped for all useful raw materials. the following needs to be included if possible:

- Quantity (with practical levels of precision)
- Quality (grade, penalty elements)
- Form (mineralized ore, industrial waste product, etc.)
- Renewable or non-renewable character
- Association (what other minerals/metals/materials are in the same stream)
- Mineral/metal/material grain size (implications in energy consumption)
- Extraction profile and process path

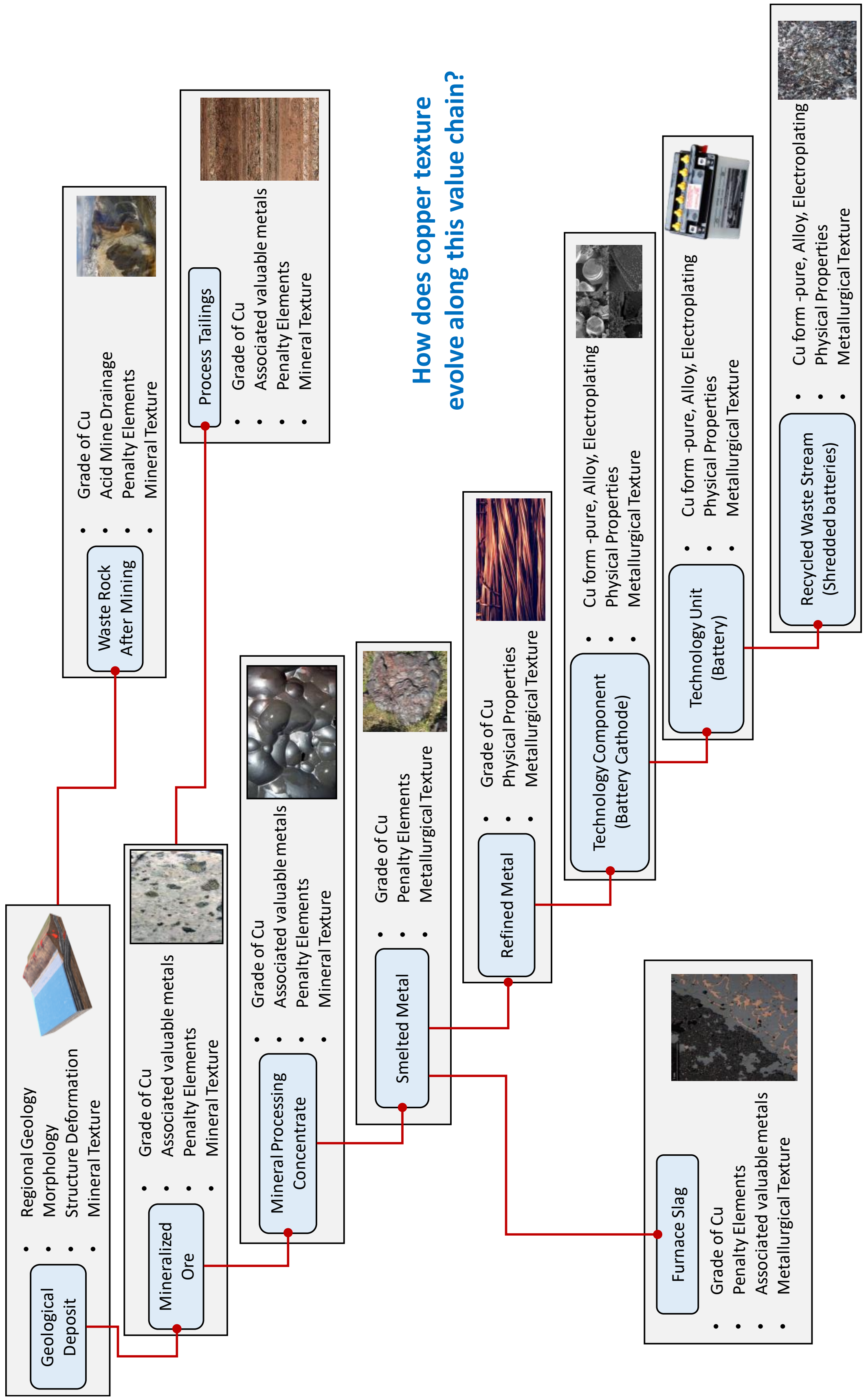


Figure 50. A conceptual characterization of copper texture along the copper value chain – The Materials Atlas (Image: Simon Michaux, sub image by Łukasz Klepaczewski from Pixabay, sub image by Charlie Homerding from Pixabay, sub image by Capri23auto from Pixabay)

7.5.1 Characterization methods for a Materials Atlas

Some thought needs to be given regarding how these characterization methods would be used in this proposed system. To be useful in an operating process plant, characterization measurement of material residues would have to be as close to real time as possible. Image analysis done on material moving on a conveyor belt is a useful tool, but it is to be remembered that measurements are a proxy for mineral content, not actual measurement. Collection of a sample off the belt to be analyzed for bulk mineralogy with for example XRD can be done but would only be useful if the results came back quickly enough to be useful. Residue flowing through a process plant does vary. A measurement could be useful if the result is returned in a window of 8 to 10 minutes.

An understanding of exactly what each of the different characterization methods are and how they relate to the target being mapped needs to be done, then all methods need to be evolved so they can be merged or at least interfaced. The different kinds of measurement could be classified as follows.

- Indirect proxies (trends) – image analysis (textures), hyperspectral spectroscopy
- Direct proxies (rankings) – Handheld XRF & infrared spectroscopy (See appendix B for more information on analytical techniques)
- Direct measures (calibrations) – QXRD, XRF, SEM, FTIR, LIBS & ICP analysis (See Appendix B for more information on analytical techniques)
- Linking models (behaviours) – Process recovery, Process waste output, energy consumption, exergy

Linking models could be process engineering thermochemical simulations (using HSC software) to link the different parts of the Materials Atlas together. Mineralized rock to refined chemical to mostly pure metal.

Figure 51 shows three examples of a copper product from three different parts of the Materials Atlas. Characterization methods already exist to map each of these different products. What is now required is a methodology to merge all three in a holistic fashion where the mechanisms for the texture to evolve between all three can understood. The fundamental signatures of copper that exist in all three also need to be quantified in a way that the Materials Atlas can be navigated.

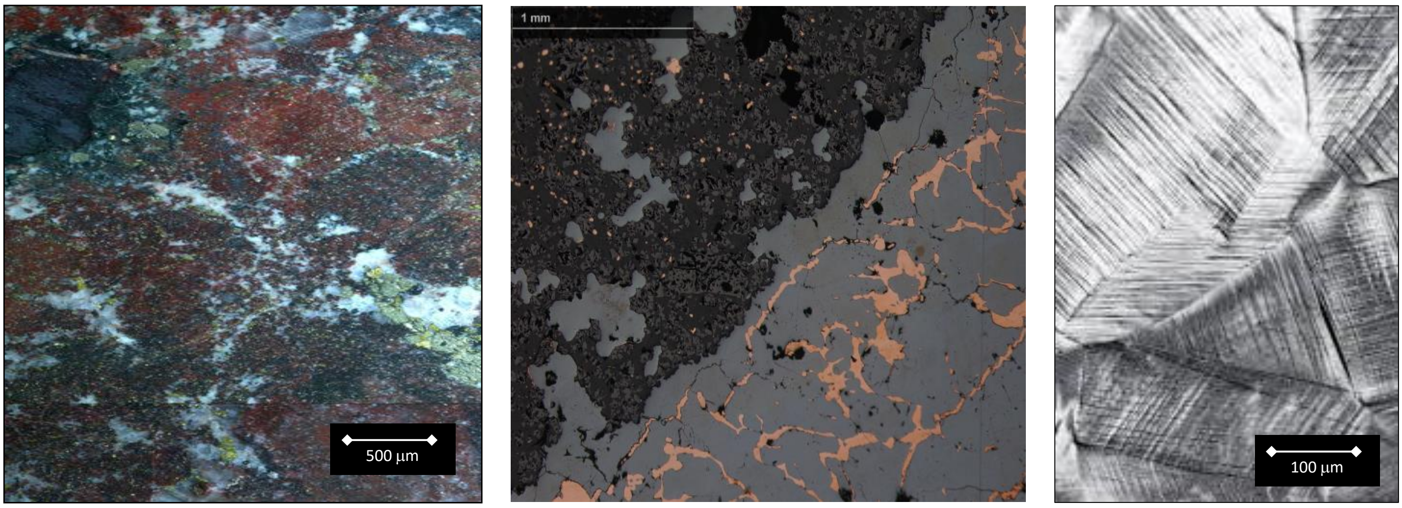
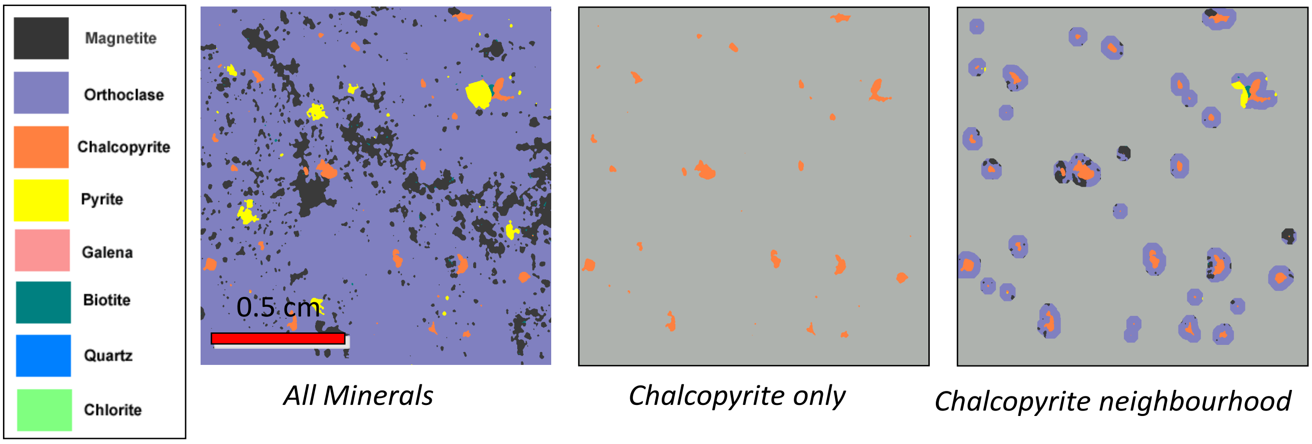


Figure 51. Copper mineralized ore from a mine in the Southern Hemisphere (LHS), Copper EOL smelter furnace bricks (Middle), Refined Copper Metal (RHS) (Images: Simon Michaux)

What data needs to be collected? Usually, the target is the understanding of a specific mineral, mineral of interest (MOI), for example chalcopyrite. That being stated, it is not just the target mineral but what it is associated with and in what mineral assemblage is present. It may not be necessary to map/analyze the entire sample. Figure 52 illustrates different examples of mapping the same mineral texture. The MOI is chalcopyrite, from a comminution aspect, the host mineralogy is a priority, from a floatation aspect, the immediate mineral associations also extremely important. Mineral association is key information when understanding floatation performance, liberation potential and recoveries. All of this has to be considered when developing a unified characterization theory that would later populate the Materials Atlas.



All Minerals *Chalcopyrite only* *Chalcopyrite neighbourhood*

Figure 52. What is really needed in rock texture characterization?
(Image and copyright: Steve Walters, JKMRC, AMIRA)

To understand how copper texture would evolve and change as it moves through the Materials Atlas (Figure 50), automated mineralogy using a Scanning Electron Microscope (SEM) is necessary to map the texture at a 1 micron scale of resolution. The SEM has been the go-to tool for texture measurement. However, it does not map everything efficiently. There are circumstances when optical microscopy is required to diagnose minerals present.

Both meso scale material texture and micro-scale material texture would need to be characterized, across a wide range of very different sample types (from mineralized rock to shredded WEEE waste), with the objective to understand how the texture of one target element would evolve. The form of the target mineral/element as it presents in the matrix material (whatever that is), association of that element to other minerals/elements, and the internal structure of the mineral/element grain, all need to be understood in a unified form across the entire Materials Atlas.

To proceed, how each material characterization methodology is done for meso-texture scales, micro-texture scale, mineralized rock, industrial waste, physical metallurgy and crystallography, synthetic materials, and WEEE electronic waste. Each one of those characterization methods would be done to a different paradigm and subject to different QA/QC requirements. Each one needs to be understood to see what is in common across the whole Materials Atlas and what is different. This could then be done for different elements. For example, does copper behave the same way as lithium? How does plastic and ceramic differ from metals or glass? Experimental methods need to be examined form a fundamental level to a final data outcome.

In doing so, a unified materials characterization protocol could be developed.

The rest of this section outlines some examples of how analytical tools can be used to aid the production of a material atlas with Appendix B describing the full range of, common, commercial analytical methods available to the industry.

7.5.2 Characterization of Meso-textures

Meso texture is scale of examination measured in centimeters (cm). A number of new technological methods have been developed. Figure 53 shows the logic of meso-texture in mineralized rock.

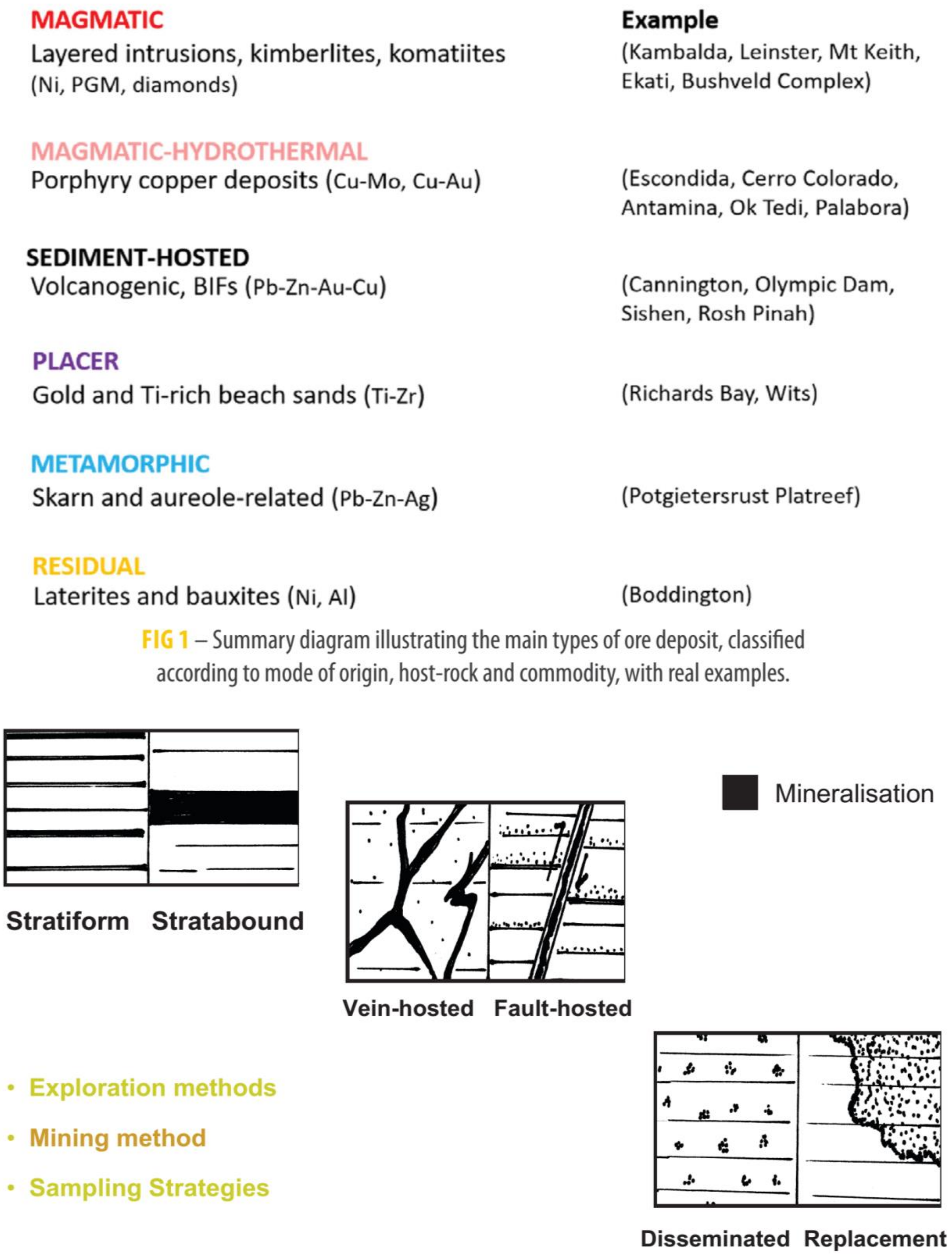


Figure 53. Some examples of meso textures
(Source. Butcher 2019, Image: Alan R Butcher)

7.5.3 Hyperspectral characterization

Hyperspectral imaging is one of these methods and shows great potential for future work. Hyperspectral imaging, like other spectral imaging, collects and processes information from across the electromagnetic spectrum. The goal of hyperspectral imaging is to obtain the spectrum for each pixel in the acquisition area, with the purpose of finding objects and identifying mineralogy, or simply elemental information. The human eye sees colour of visible light in mostly three bands (red, green, and blue), spectral imaging divides the spectrum into many more bands. This technique of dividing images into bands can be extended beyond the visible.

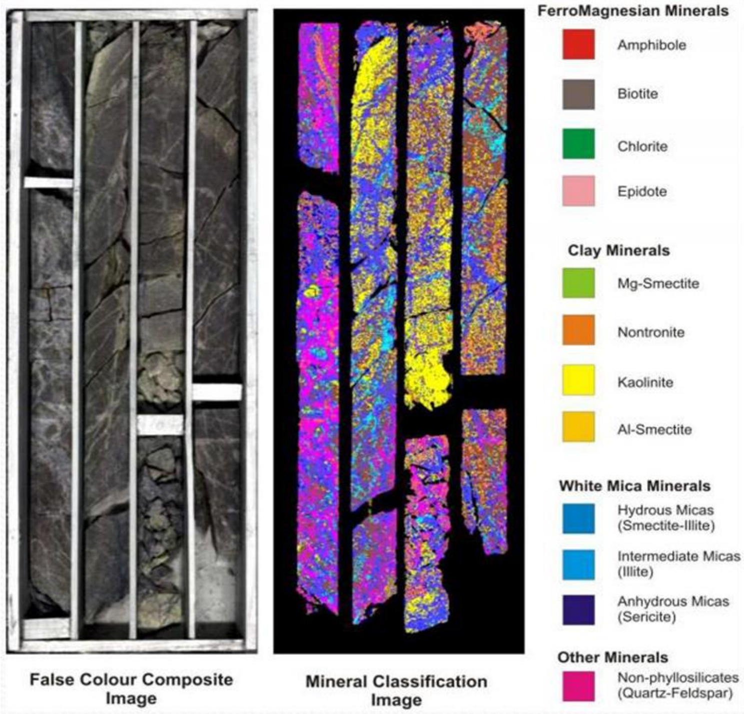


Figure 54. Hyper spectral imaging of drill core
(Source: AMIRA 2009 & GeoTek https://www.geotek.co.uk/sensors/hyperspectral/)

7.5.4 Bulk mineralogy characterization

There are many occasions in which measurement of the bulk mineralogy is useful. In particular, the characterization (mineral phases e.g. quartz) and proportions of gangue mineralogy is useful in understanding process behavior.

7.5.5 Quantitative X-Ray Diffraction (QXRD)

Understanding bulk mineralogy of the sample and deposit itself is a necessary step. XRD is a versatile analytical method to analyze material properties like phase composition and proportions of a powder sample. Identification of the phase s is achieved by comparing the X-ray diffraction pattern obtained from the sample being measured with a reference database. With one single measurement one can identify mineral phases (qualitative) and their concentrations/proportions (Quantitative). X-rays are generated in a laboratory diffractometer using x-ray tubes with a suitable anode material (Cu, Fe, etc).

For example, XRD can distinguish between a sample that contains Fe_2O_3 and Fe_3O_4. It can also distinguish between minerals like calcite, aragonite and vaterite (Chang-Zhong et al 2015, Ruffell & Wiltshire 2004, Tammishetti et al 2015, Potts 1987 and Rollinson 1993).

XRD measurement requires a sample is of crystalline nature and is pulverized and homogenized, pressed in a pellet or back loaded in a sample holder. A powder diffractogram is obtained by counting the detected intensity as a function of the angle between incoming and diffracted x-ray beam. In the diffractogram clay minerals have their distinguished diffracted peaks at very low 2theta angles and analysis of clays required good low angle performance and resolution on the XRD equipment. (FWHM = Full Width Half Maximum).

Amorphous minerals (sample not having any crystals diagnose lattice plains) are particularly difficult to measure and does require expert sample preparation, internal amorphous standards, and knowledge to analyze and process the data.

7.5.6 Elemental analysis

The elemental analytical tools available to produce a Materials Atlas range from Laboratory based tools (e.g. ICP-MS & XRF) through to highly portable field based tools (e.g. handheld XRF). However, the smaller size and increased portability comes a trade off in detection limits (e.g. ~50 elements analyzed to parts per billion levels in a lab based ICP-MS to ~15 element analyzed to ~10s of parts per million in a hand held XRF; Fig. 55).

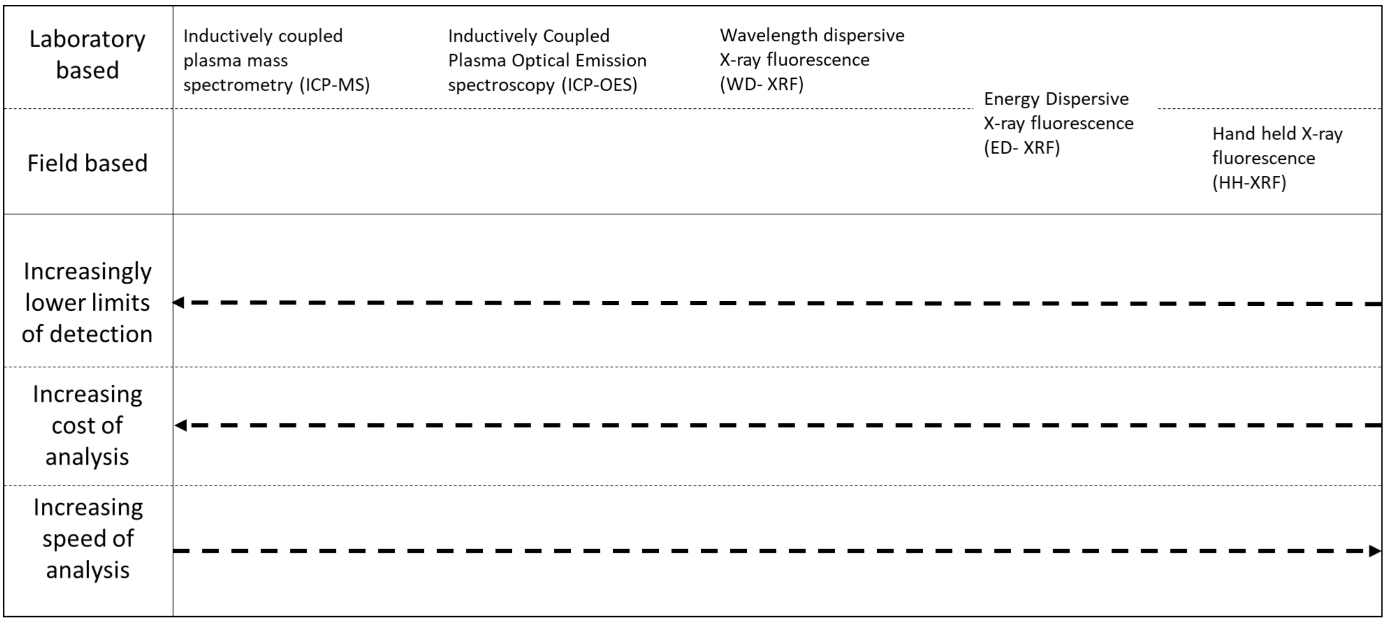


Figure 55. The variation in field based to lab based analytical tools (Finlay et al., in prep).
(Image: Alex Finlay)

This variation makes each technique suited for differing stages of a Materials Atlas. For Example, hand held XRF can be used in early exploration, or quick surveying of recycling centres, whereas ICP-MS can provide full quantification of exact reserves in previously screened material.

7.5.6.1 Wavelength-dispersive (WD) X-ray Fluorescence measurement (XRF)

X-ray fluorescence (XRF) identifies what chemical elements are present and in what concentration by the emission of characteristic "secondary" (or fluorescent) X-rays from a material that has been excited by being bombarded with high-energy X-rays (Fitton 1997, Potts 1987 and Rollinson 1993). For example, if the sample contains iron (Fe) and calcium (Ca) in a measured proportion. An XRF spectrometer is an x-ray instrument used for routine, chemical analyses of rocks, minerals, and sediments (and new tools can analyze fluids).

The most powerful, laboratory, XRF works on wavelength-dispersive spectroscopic methods that are typically used for bulk analyses of larger fractions of geological materials. The relative ease and low cost of sample preparation, and the stability and ease of use of x-ray spectrometers make this one of the most widely used methods for analysis of major, minor and trace elements in rocks, minerals, liquids, solids, oils and sediment.

Virtually any solid or liquid material can be analyzed with and EDXRF or WDXRF spectrometer. There are “standardless analysis software’s” available commercially which can be used when analyzing samples. Using of such a software can give good indication of the elements and their concentrations, however, The best results one can obtain with matrix specific calibrations. For rocks and minerals, typical commercial instruments require a sample constituting at least several grams of material through to 15-20 grams, although the sample collected may be much larger. For XRF chemical analyses of rocks, samples are collected that are several times larger than the largest size grain or particle in the rock. This initial sample then undergoes a series of crushing steps to reduce it to an average grain size of a few millimeters to a centimeter, when it can be reduced by splitting to a small representative sample of a few tens to hundreds of grams. This small sample split is then ground into a fine powder for analysis. Care must be taken particularly at this step to be aware of the composition of the crushing implements, which will inevitably contaminate the sample to some extent. Ideally powdered sample has grain size at 10µm scale, but best results are obtained using glass beads where all grains have been melted in a flux. Sample size for a compressed powder pellet XRF measurement is 10 to 50 grams, but less can be used depending on mineralogical circumstance.

7.5.6.2 Handheld XRF measurement

Portable XRF analyzers are used around the world for monitoring ore grade in active open pit and underground mines. It is also used for QA/QC applications in many refining, recycling, and manufacturing industrial operations. Advantages of using a handheld unit could include rapid indication of potential trace element mineralization through XRF analysis of pathfinder elements in soil, drill cuttings, drill cores, residue particulate, pastes and filter cakes.

7.5.7 Characterization of Micro-texture

Ore micro-texture is the mineral assembly form at the mineral grain scale (1 μm). Understanding what form the ore’s micro-texture takes can be the solution to why a particular process behavior responds the way it does. At the most fundamental level, ores can be considered either equigranular (all grains are the same size) or inequigranular (not all the same size). Mineral grain size is defined by the form of mineralization (Figure 56 RHS).

It is also important to understand the formation process of the ore/metal/material texture in context of geological/industrial events that have produced the final outcome. Figure 57 illustrates some of the geological processes that can change rock texture. Possible changes of the three pristine ore textures is considered (one equigranular and two inequigranular – Figure 56 LHS), which undergo progressively more aggressive modification from left to right (oxidation, hydrothermal alteration to metamorphism).

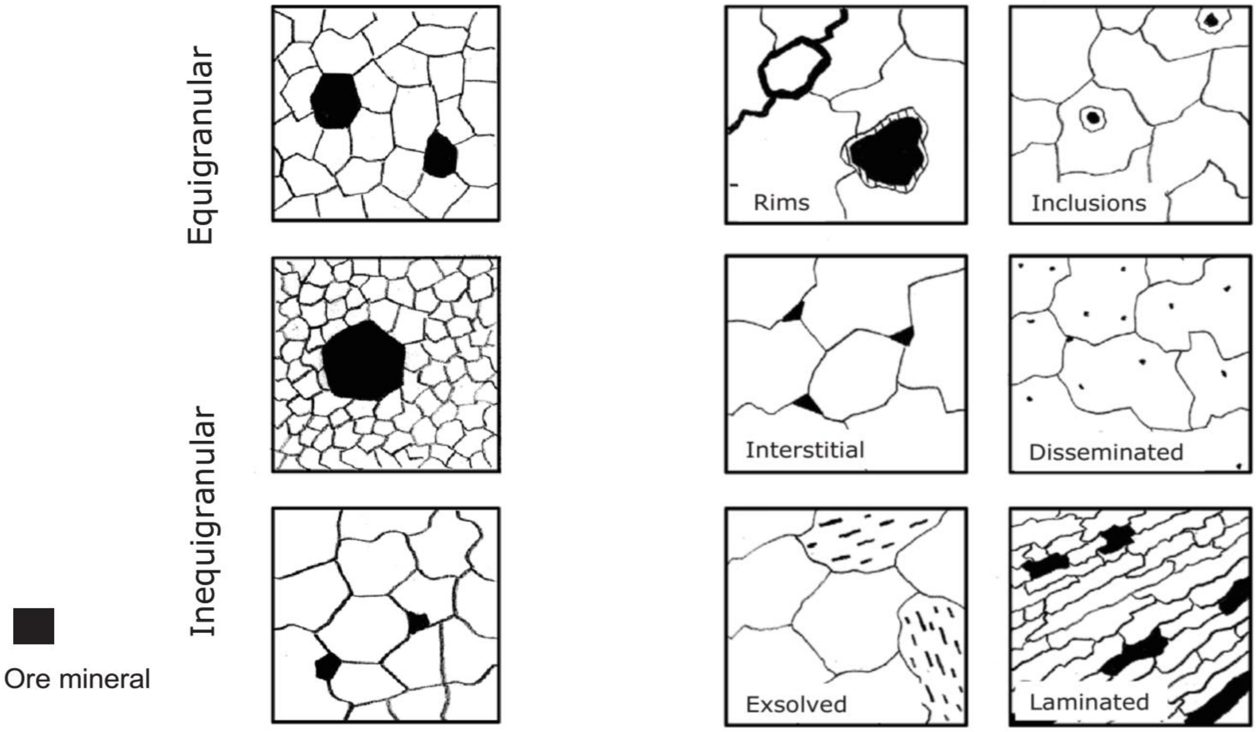


Figure 56. Basic ore textures at a grain size scale
(Source. Butcher 2019, Image: Alan R Butcher)

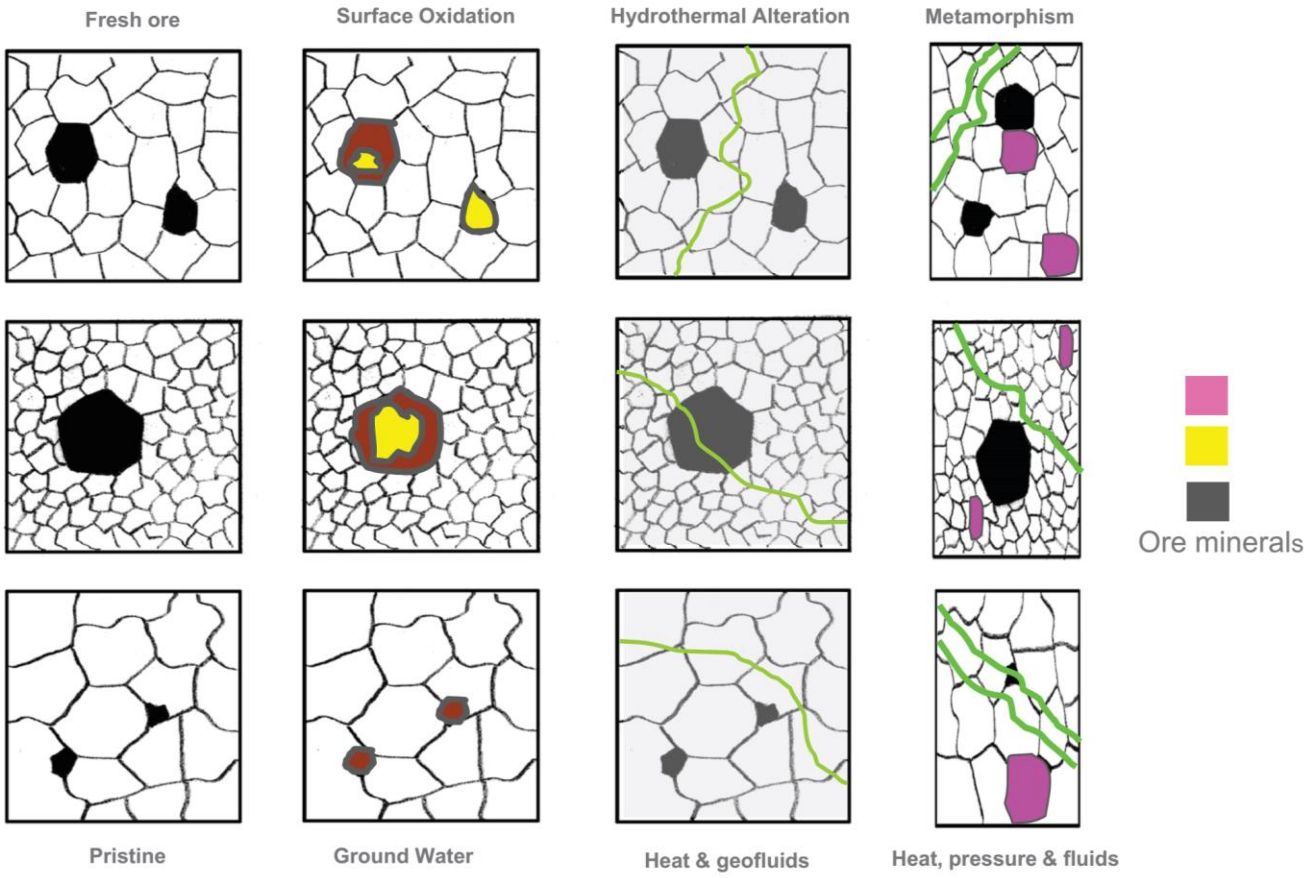


Figure 57. Basic ore textures, at a grain size scale (LHS), textures that influence flotation performance (RHS)
(Source. Butcher 2019, Image: Alan R Butcher)

Figure 58 shows examples of ore micro-textures.

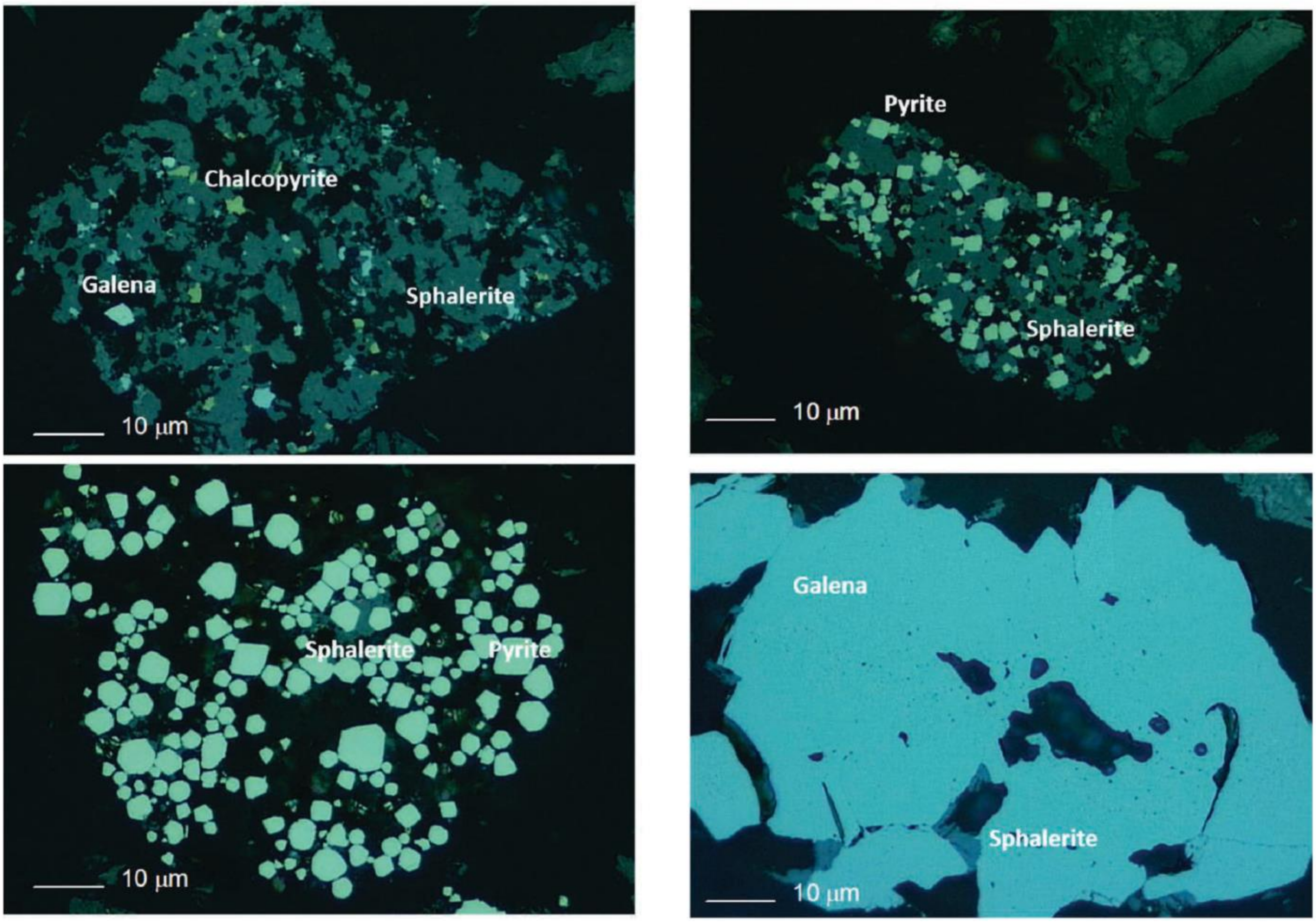


Figure 58. Examples of different ore micro-textures in optical photomicrographs, taken using a digital camera attached to a reflected polarizing petrographic microscope, of processed particles from an Australian lead–zinc operation (McArthur River), which contain textures that historically would have been too fine for conventional flotation, and now require combinations of staged and fine-grinding methods to separate the galena and sphalerite. (Source. Butcher 2019, Image: Alan R Butcher)

Figure 59 shows the mineral mapping of three particles with the chalcopyrite colored blue.

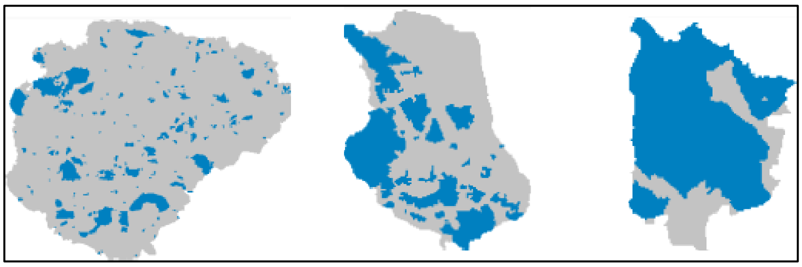


Figure 59. Chalcopyrite micro-texture of three very different forms (Image. François Vos)

If there were three separate samples, with most of the particles in each sample were characterized by one of the images in Figure 59, the process response would be very different for all three samples. The flotation or leaching recovery of each of the above particles would be quite different. Measuring micro-texture in this form allows deterministic conclusions to be drawn which could be used to guide the rest the analysis.

Figure 59 was generated using automated mineralogy (TIMA/MLA etc.). Automated mineralogy as a characterization tool has advanced considerably. Reliable instrumentation, continuously updated software capabilities and faster data acquisition. Samples are mounted into polished resin blocks and are mapped using a scanning electron microscope (SEM). This method can be good for mapping micro-textures, but it is not as effective for gangue mineralogy in some cases, or with mineralogy with very similar back scattered electron grey scales. However, it is best practice to use complimentary analysis to establish good mineral chemistry with probe work and LA-ICP-MS or Raman, depending on the MOI (Hrstka et al 2018, Aylmore et al 2018, and Anderson et al 2014).

Figure 60. In the foreground is the new FEI Quanta 650 field emission scanning electron microscope, in the background is an older MLA equipment. (Image and copyright: GTK)

As gangue mineralogy is also of interest to many industrial analytical questions, automated optical microscopy is useful. This is a cheaper and faster method compared to automated mineralogy but does require expert knowledge and a well-trained user. Figure 61 is an example of a desktop optical microscopy with a resin block and a second image using cross-polarized light (thin section), clearly exhibiting gangue mineralogy in an array of reflected colors.

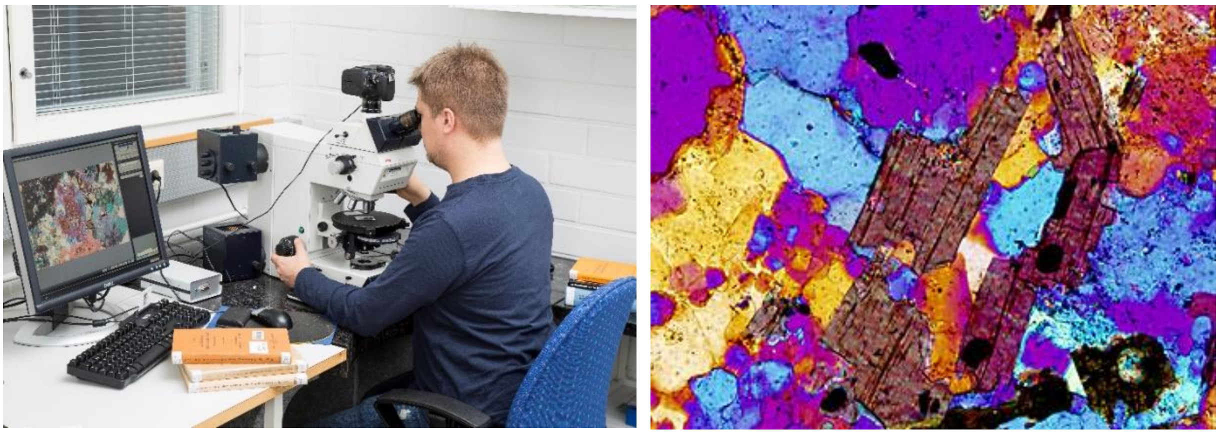


Figure 61. Optical microscopy. Picture shown is an Optical Microscope Nikon MM 40
(Image: GTK)

Table 4. Characterization of different forms of minerals/metals/materials across the value chain – Materials Atlas (Image: Alex Finlay & Tim Pearce, X-Ray Mineral Services Finland)

Mineral to metal						Manufacture		Recycling
Ore	**Concentrate**	**Tailings**	**Waste Slag**	**Mineral**	**Metal**	**Components**	**Product**	**Recycling**
Mineralogical Analysis	Mineralogical Analysis	Mineralogical Analysis	Mineralogical Analysis	Mineralogical Analysis	Mineralogical Analysis	Mineralogical Analysis	Mineralogical Analysis	Mineralogical Analysis
• QXRD	• QXRD	• QXRD	• QXRD	• QXRD	• QXRD	• QXRD	• QXRD	• Hyperspectral
• FTIR	• FTIR	• FTIR	• FTIR	• FTIR	• FTIR	• FTIR	• FTIR	• IR
• Raman	• Raman	• Raman	• Raman	• Raman	• Raman	• Raman	• Raman	• Raman
• SEM	• SEM	• SEM	• SEM	• SEM	• SEM	• SEM	• SEM	• SEM
Elemental analysis	Elemental analysis	Elemental analysis	Elemental analysis	Elemental analysis	Elemental analysis	Elemental analysis	Elemental analysis	Elemental analysis
• ICP-MS & ICP-OES	• ICP-MS & ICP-OES	• ICP-MS & ICP-OES	• ICP-MS & ICP-OES	• ICP-MS & ICP-OES	• ICP-MS & ICP-OES	• ICP-MS & ICP-OES	• ICP-MS & ICP-OES	• ICP-MS & ICP-OES
• La-ICP-MS	• La-ICP-MS	• La-ICP-MS	• La-ICP-MS	• La-ICP-MS	• La-ICP-MS	• La-ICP-MS	• La-ICP-MS	• La-ICP-MS
• WD-XRF	• WD-XRF	• WD-XRF	• WD-XRF	• WD-XRF	• WD-XRF	• WD-XRF	• WD-XRF	• LIBS
• Portable XRF	• Portable XRF	• Portable XRF	• Portable XRF	• Portable XRF	• Portable XRF	• Portable XRF	• Portable XRF	• Portable XRF
• Hand Held XRF	• Hand Held XRF	• Hand Held XRF	• Hand Held XRF	• Hand Held XRF	• Hand Held XRF	• Hand Held XRF	• Hand Held XRF	• Hand Held XRF
• Micro/scanning XRF	• Micro/scanning XRF	• Micro/scanning XRF	• Micro/scanning XRF	• Micro/scanning XRF	• Micro/scanning XRF	• Micro/scanning XRF	• Micro/scanning XRF	• Micro/scanning XRF
Textural analysis	Textural analysis	Textural analysis	Textural analysis	Textural analysis	Textural analysis	Textural analysis	Textural analysis	Textural analysis
• Optical petrographic analysis	• Optical petrographic analysis	• Optical petrographic analysis	• Optical petrographic analysis	• Optical petrographic analysis	• Optical petrographic analysis	• Optical petrographic analysis	• Optical petrographic analysis	• Optical petrographic analysis
• Raman	• Raman	• Raman	• Raman	• Raman	• Raman	• Raman	• Raman	• Raman
• QEMSCAN / SEM	• QEMSCAN / SEM	• QEMSCAN / SEM	• QEMSCAN / SEM	• QEMSCAN / SEM	• QEMSCAN / SEM	• QEMSCAN / SEM	• QEMSCAN / SEM	• QEMSCAN / SEM
• 3D tomography	• 3D tomography	• 3D tomography	• 3D tomography	• 3D tomography	• 3D tomography	• 3D tomography	• 3D tomography	• 3D tomography
Other analysis	Other analysis	Other analysis	Other analysis	Other analysis	Other analysis	Other analysis	Other analysis	Other analysis
• U-Pb geochronology	• U-Pb geochronology	• U-Pb geochronology	• U-Pb geochronology	• U-Pb geochronology	• U-Pb geochronology	• U-Pb geochronology	• U-Pb geochronology	• U-Pb geochronology
• Re-Os geochronology	• Re-Os geochronology	• Re-Os geochronology	• Re-Os geochronology	• Re-Os geochronology	• Re-Os geochronology	• Re-Os geochronology	• Re-Os geochronology	• Re-Os geochronology
• Carbon & Oxygen isotopes	• Carbon & Oxygen isotopes	• Carbon & Oxygen isotopes	• Carbon & Oxygen isotopes	• Carbon & Oxygen isotopes	• Carbon & Oxygen isotopes	• Carbon & Oxygen isotopes	• Carbon & Oxygen isotopes	• Carbon & Oxygen isotopes
• Magnetic susceptibility	• Magnetic susceptibility	• Magnetic susceptibility	• Magnetic susceptibility	• Magnetic susceptibility	• Magnetic susceptibility	• Magnetic susceptibility	• Magnetic susceptibility	• Magnetic susceptibility

The outcome of this task could be used as the data foundation in the next generation of collaborative research work on the use of statistical entropy analysis for the evaluation and design of recycling processes (Velazquez-Martínez et al 2019 and Reuter et al 2006). Figures 50, 62 and Table 4 show a conceptual approach in how this could be developed.

Table 4 shows a summary of the different kinds of characterization tests that could be considered at the different parts of the material types.

To characterize a rock texture, a mineralogist would examine the following (Butcher 2019):

- complete inventory of all known mineral phases present
- detailed modal analysis for major minerals (>5%), minor phases (>1% to <5%) and trace phases (<%)
- textural information on both gangue and ore minerals, which includes:
- grain size estimates (used to determine optimum liberation grain sizes and predict or
- prevent problems such as poor liberation, over-grinding of the valuables, production
- of slimes)
- mineral associations (important for optimizing the separation process, say galena from
- sphalerite, chalcopyrite from sphalerite)
- grain boundary relationships (curved, straight, or irregular boundaries will affect behavior
- during crushing and grinding as this imparts preferential breakage mechanisms – for
- example along or across boundaries)
- elemental deportment information (important for tracking how metals behave during processing
- photomicrographs of typical textures.

Figure 62 shows how all of the different material characterization methods could be integrated into a unified characterization protocol. If this protocol was applied to many different metals and materials, it could be assessed in how each of these materials relate and interact. In mineralized rock, for example, copper is often associated with gold, due to geological fundamentals in how these copper and gold bearing minerals get deposited. In the later part the Materials Atlas, copper is often found in alloys with other metals. This is because the material properties of those alloys are highly useful to technology development.

This means that different element metal value streams will merge with some element metals in one part of the Materials Atlas, but those same metal value steam will merge with completely different metal stream at another part. This needs to be understood and mapped.

Figure 62 shows how the Materials Atlas could be used to interact with other parts of the RBE system proposed in this report.

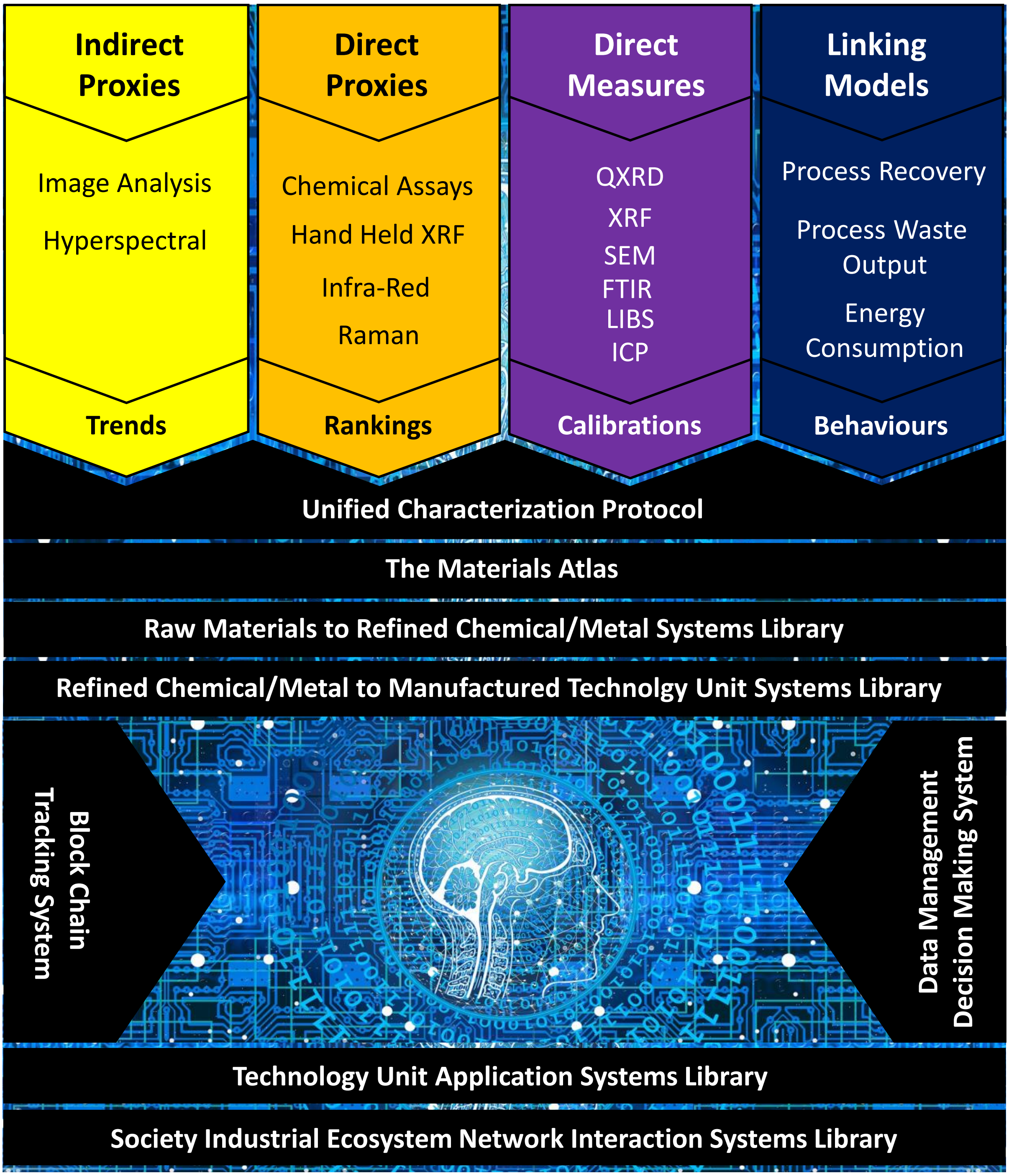


Figure 62. Integration of different forms of materials characterization into a unified characterization protocol in a Materials Atlas, and how that could interact with the rest of the proposed Resource Based Economy
(Image: Simon Michaux, network image by Gerd Altmann from Pixabay)

To do this effectively, a better understanding of what technology metals are needed in what application, then understand how they are sourced. Most technology metals are mined as trace elements associated with other minerals. For example, when indium is demanded, it is zinc mineral that is the primary ore being mined. Indium becomes the hitchhiker metal in the zinc resource stream. This could be why metal price does not correlate with most of these technology metals. This is illustrated with Figures 63 to 65, which show the benefit of characterizing all streams in a holistic context.

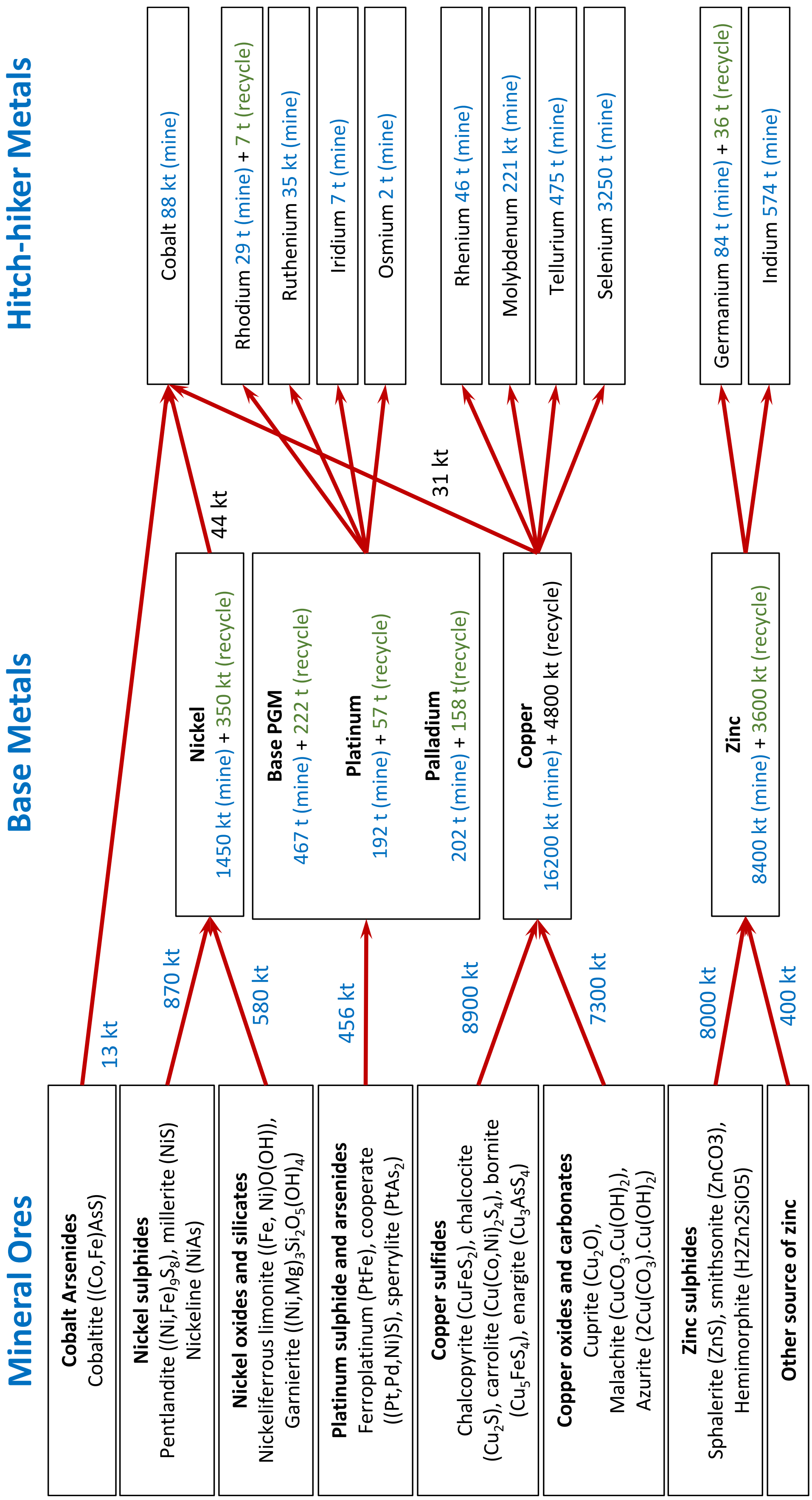


Figure 63. Worldwide production of mineral ores, base and hitch-hiker metals in 2010 – part 1 (Source: redrawn from Talens Peiro, Villalba, Ayres 2012, Rare Metals Recycling)

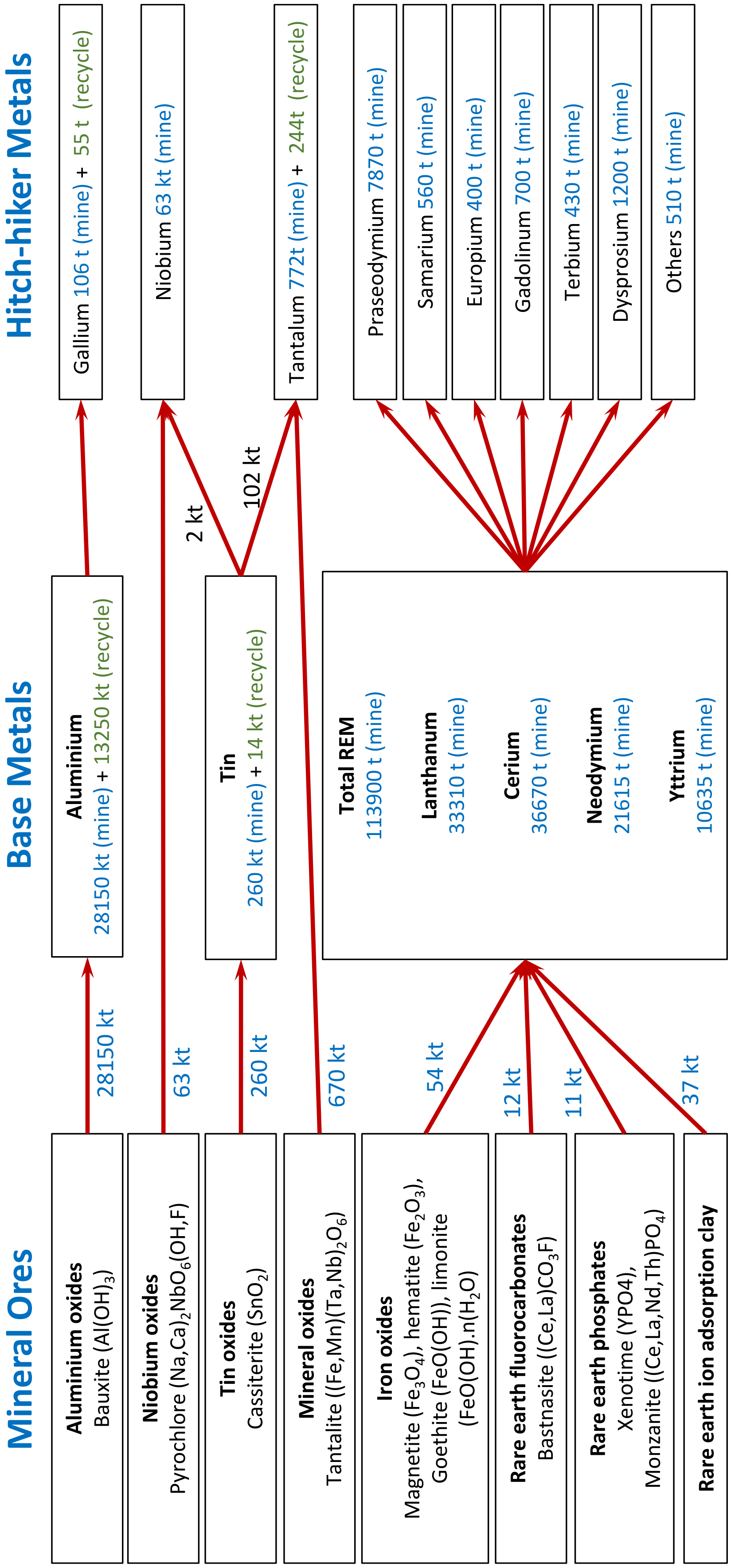


Figure 64. Worldwide production of mineral ores, base and hitch-hiker metals in 2010 – part 2 (Source: redrawn from Talens Peiro, Villalba, Ayres 2012, Rare Metals Recycling)

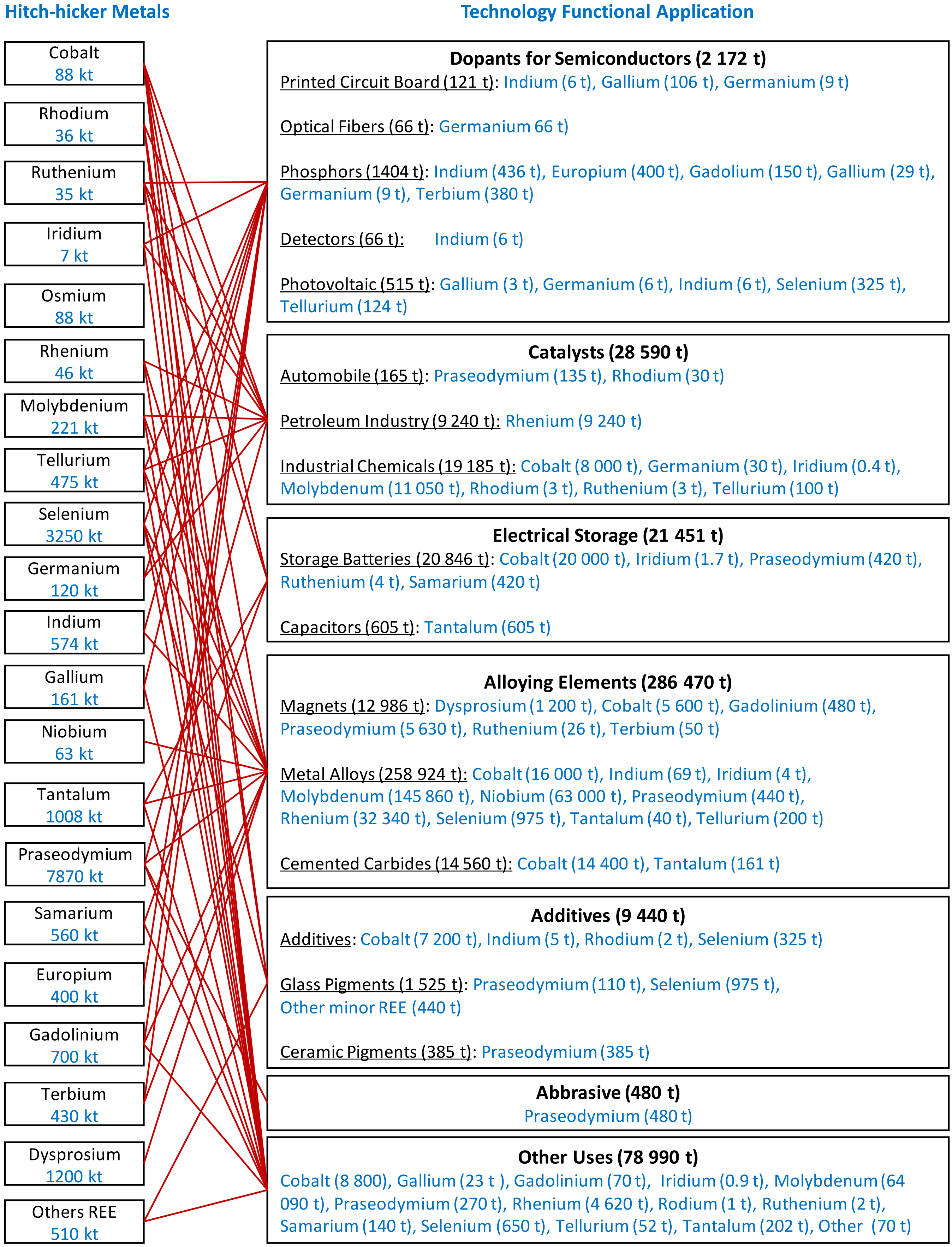


Figure 65. Worldwide production of mineral ores, base and hitch-hiker metals in 2010 – part 3
(Source: redrawn from Talens Peiro, Villalba, Ayres 2012, Rare Metals Recycling)

7.6 Design technology products to be recycled more effectively

Metals are theoretically infinitely recyclable. In practice, the functionality and design of consumer product complicate recycling due to their ever more complex structures producing unliberated low grade and complex recyclates (Reuter 2011). Metallurgical smelting technology is developing in sophistication with the more effective use of thermodynamics and transfer processes to achieve better recovery. The 2nd Law of Thermodynamics provides a limit of what can practically be recycled. This is determined by the complexity of the recyclates.

Process engineering simulation models are a prerequisite to designing sustainable systems as these can predict the metal/materials mass balance for recyclate grade/quality/losses/toxicity of streams (Reuter 2011). This is the link to industrial entropy, and if used appropriately, is the fundamental way of handling complex data from the Materials Atlas.

It will be very difficult to develop a truly closed loop industrial ecosystem that does not extract any resources from the environment, nor discards any waste into landfill. Evolving the industrial ecosystem in the direction of a closed loop is appropriate, however. To do this, a deep understanding of particle property and breakage physics and its relation to product design, metallurgical thermodynamics, and process technology. A series of Industrial Ecological Systems could be designed to link technology product design to metal recovery in metallurgical process recycling of discarded waste residue.

To design technology products in a form that allows for their more effective recycling, an understanding of how a consumer product moves through various stages of processing during which particles/recyclates are created. As these recyclates progress through the value chain, they would be subject to changing phases and compositions, eventually being transformed into molten metal and finished metal products, energy, or extruded plastics. The purpose of the Materials Atlas is to track this evolution.

Both the Materials Atlas and the concept of designing for recycling would be required to incorporate the processes, the complete system with varying material properties, various phase changes of materials as well as the particle physics.

So, the design of the technology products needs to integrate all superior properties of metals/materials with an understanding of which materials are able to be recycled more effectively (in alloy and electroplating context as well as pure metal/material). In order to realize the link between design and metallurgy; and subsequent recycling; requires a detailed knowledge of all technology involved. Using an exergy standard states makes it possible to express these enthalpy and entropy data as Exergy by using for example the methodology and standard states expressed in Szargut (2005).

A product must be designed to:

- Contain the maximum amount of materials that are recyclable
- Be easily recycled through current or newly designed recycling processes
- Be cost effective to recycle whereby the cost to recycle does not exceed the value of its recycled materials
- Be free of hazardous materials that are not recyclable or impede the recycling process
- Minimize the time and cost involved to recycle the product
- Reduce the use of raw materials by including recycled materials and/or components
- Have a net gain in the overall recyclability of the product while reducing the overall negative impact on the environment

To achieve this challenging task, an understanding the link between product design and recycling effectiveness. The character of recyclate grade of the shredded waste products is crucial for maximizing material and energy recovery. Just so, the minimizing energy usage and minimizing the entropy creation of the system in its complexity. This is a key to Design for Sustainability (Reuter 2011). Quantification of all residues and recyclates in terms of their grade/quality ensures that all materials in the system are accounted for. With the available tools, a good indication can be obtained what designs will have a good recyclability and what the thermodynamic limits would be in the recovery of the contained materials and energy.

Sustainability development targets and supporting legislation should have a thermodynamic basis (including the second law), should reflect the limits of technology and well-designed metallurgical, energy recovery and recycling infrastructure (Reuter 2011).

7.7 Develop a series of raw materials to refined chemical/metal systems maps

A systems map of what is involved in producing a unit mass/volume of useful metal/material from source minerals is required to provide a framework for decision making. There is a requirement for pure metals and materials to supply manufacture of technology products. The source raw material to produce such pure metals and materials is almost always very impure and contains contaminants. In most cases, the desired metals and materials are trace elements in the source raw mineral stream.

How the value chain of a given material needs to be understood then quantified in a form that is useful for engineering based decision making. There are three raw material loop cycles to be modelled.

1. RM Loop Cycle A: mining of mineralized ore to manufacture to waste handling disposal
2. RM Loop Cycle B: re-mining of industrial waste dumps to manufacture to waste handling disposal
3. RM Loop Cycle C: recycling of waste disposal products

All three need to be mapped in context of how they interact. Figure 66 shows RM Loop Cycle A. Figure 67 shows RM Loop Cycle B. Figure 68 shows RM Loop Cycle C. All three in an integrated form would be used to describe the full value chain (Figure 69).

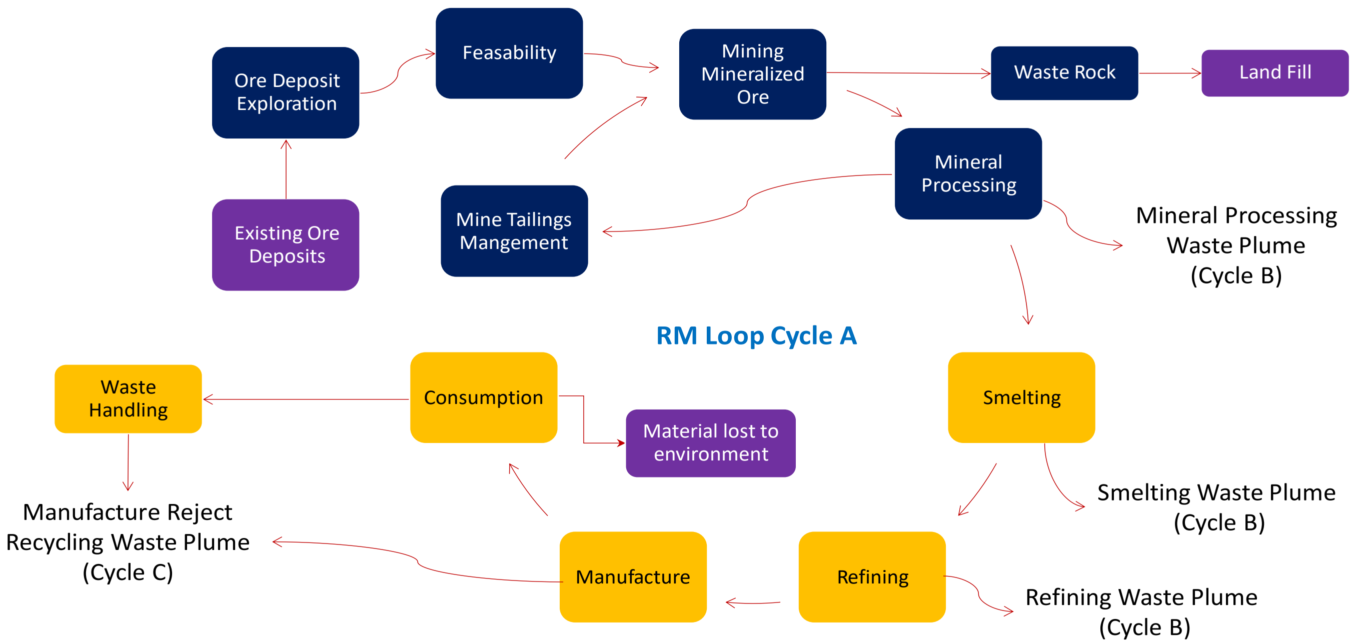


Figure 66 Raw Materials Loop Cycle A: mining of mineralized ore to manufacture to waste handling disposal (Image: Simon Michaux)

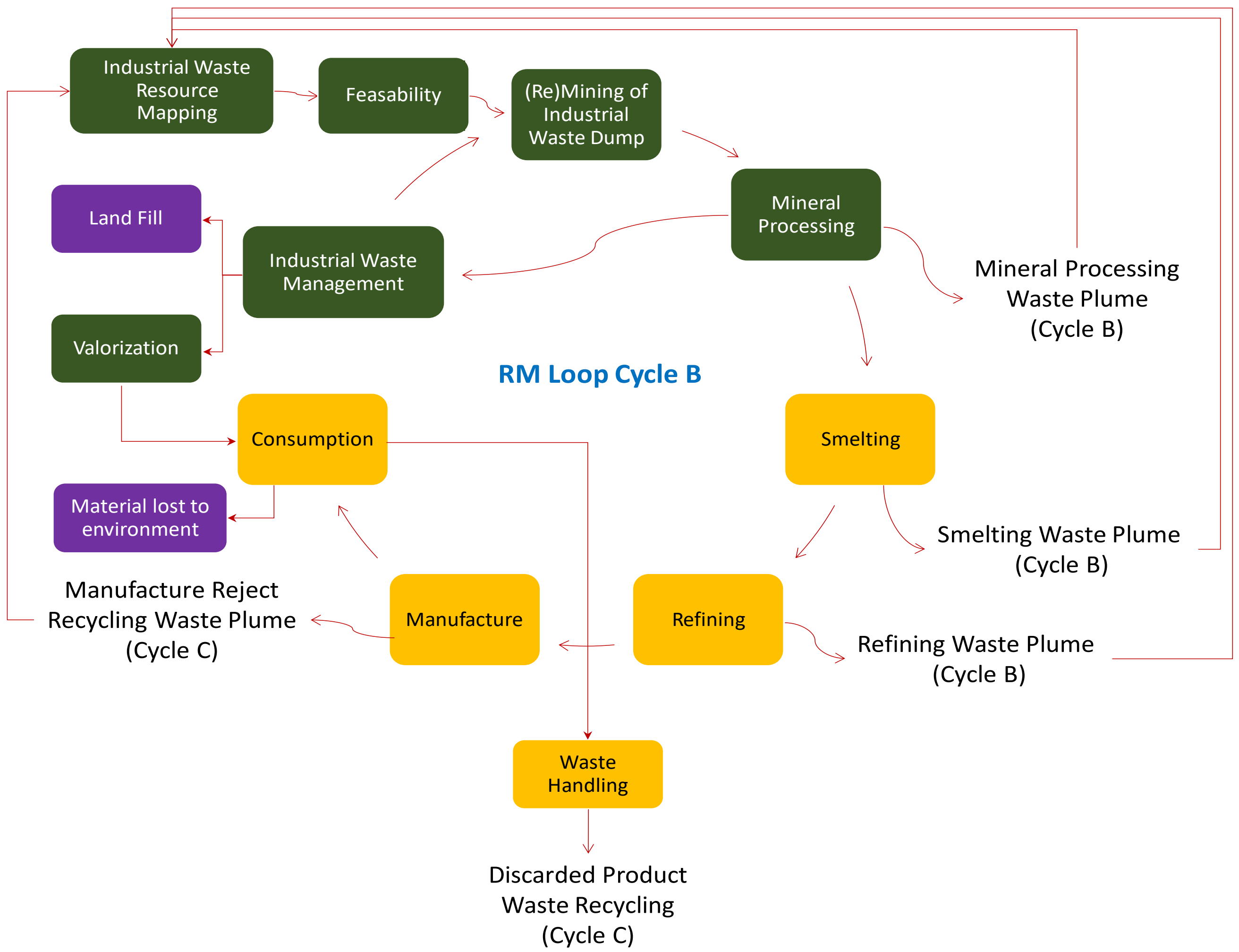


Figure 67. Raw Materials Loop Cycle B: re-mining of industrial waste dumps to manufacture to waste handling disposal (Image: Simon Michaux)

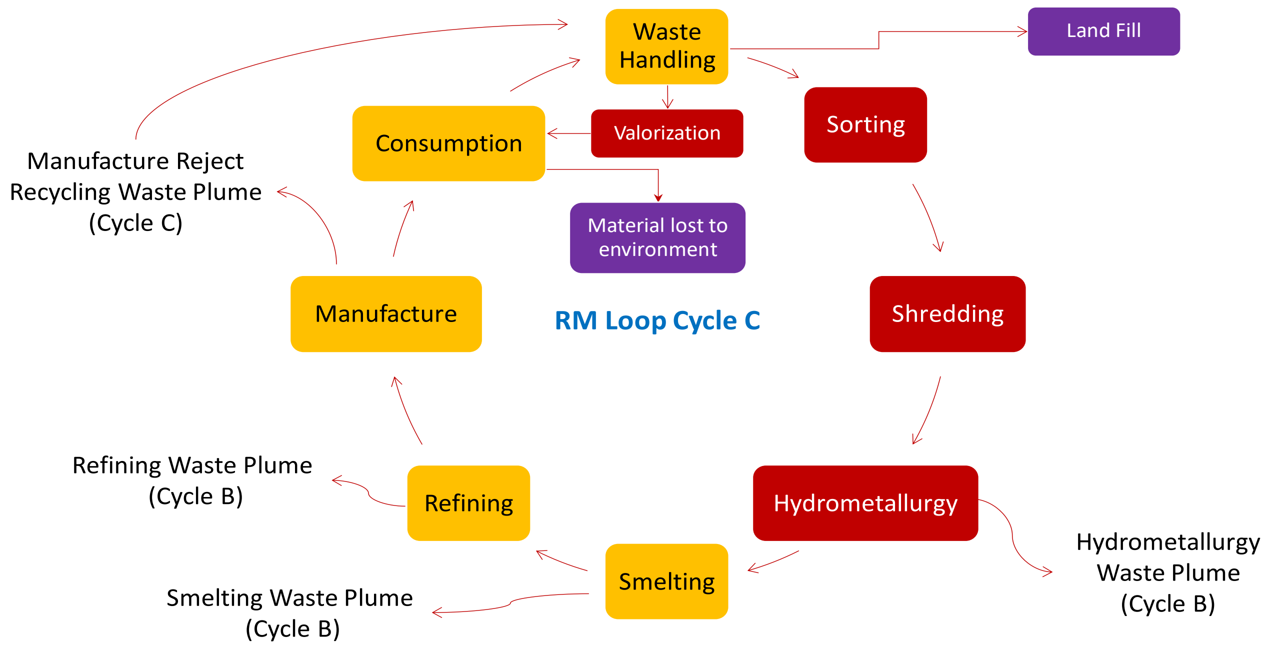


Figure 68. Raw Materials Loop Cycle C: recycling of waste disposal products (Image: Simon Michaux)

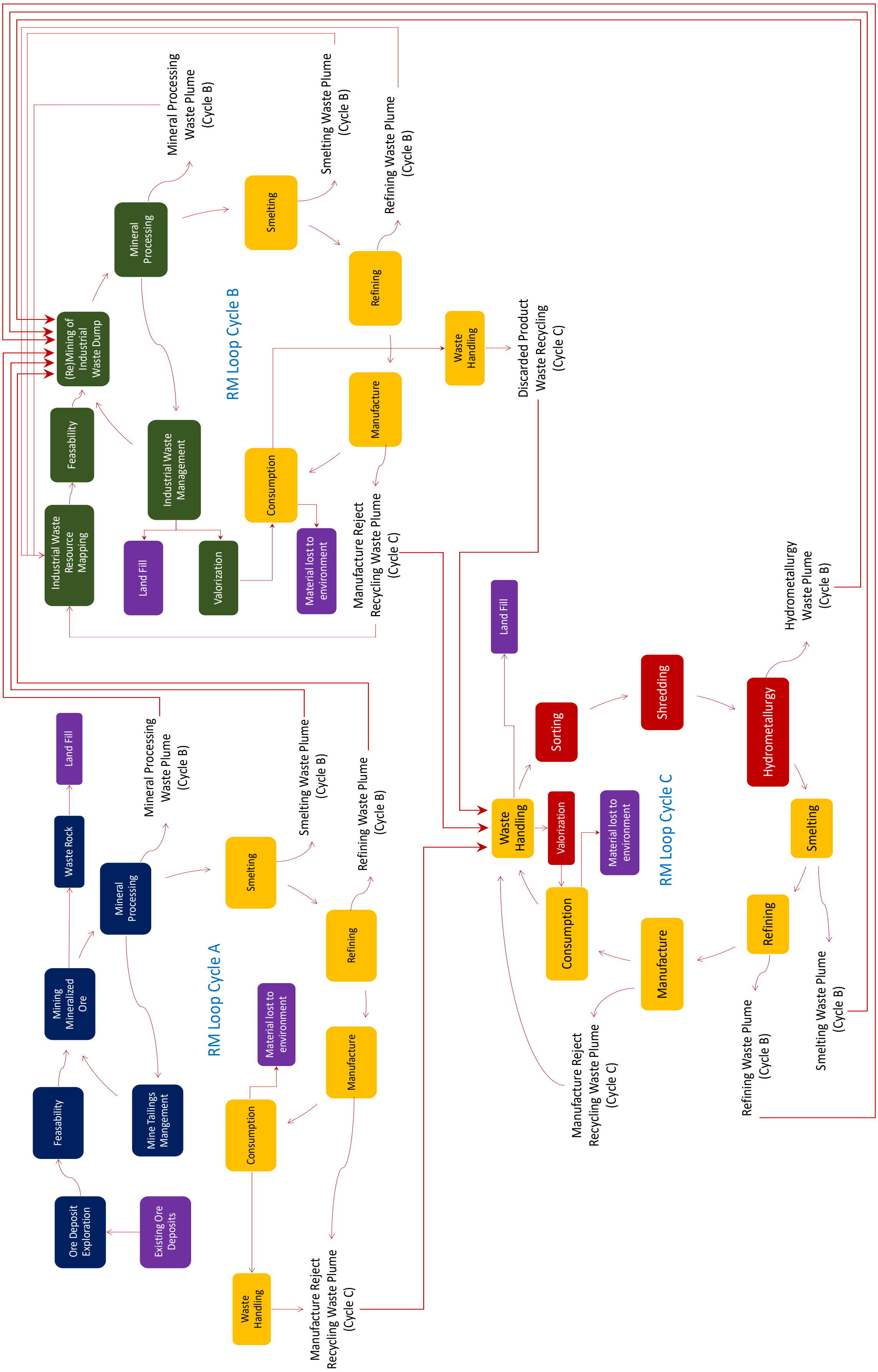


Figure 69. Full materials value chain, RM Loop Cycles A, B and C integrated
(Image: Simon Michaux)

The Linear Economy has a paradigm that focuses on Raw Materials Loop Cycle A, the extraction of resources from the environment. The Circular Economy has a paradigm that focuses on Raw Materials Loop Cycle C, the extraction of resources from recycling of waste streams. Loop Cycle B, the extraction of resources from remining industrial waste streams and dumps, is partially addressed in the Circular Economy, but only partially.

The proposed Resource Balanced Economy in the form shown in this report requires all three Loop Cycles developed, mapped, and operating in an integrated fashion.

Figure 70 shows the same concepts as Figure 69 but from a different perspective. Another way to show this could be done in 3D layers, where each Loop Cycle would be a separate layer.

To process and refine each target metal, a series of process engineering steps are required. This needs to be presented in context of Figure 69. Figure 70 shows a systems map of the industrial steps to produce copper pure enough for manufacture, in context of Loop Cycle A.

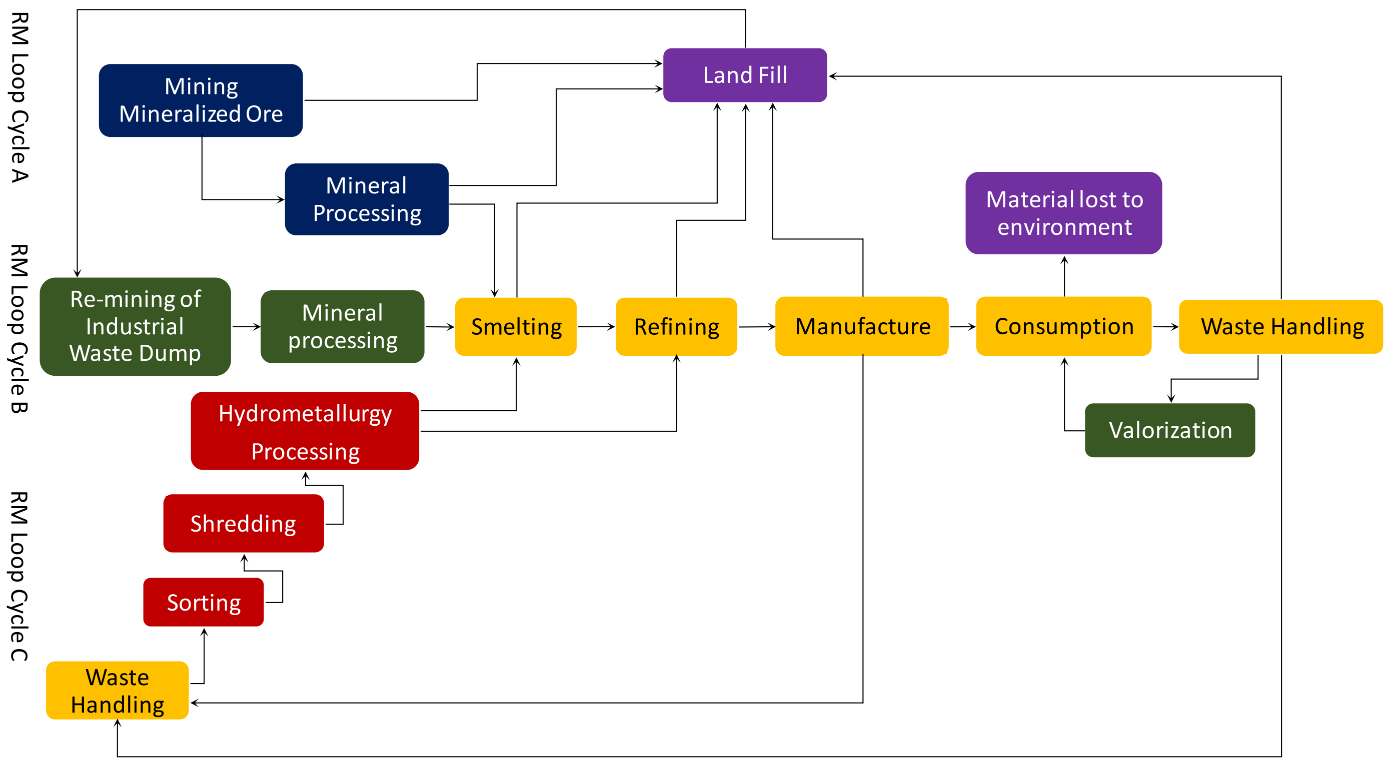


Figure 70. Integration of Loop Cycle A, B and C from a different perspective
(Image: Simon Michaux)

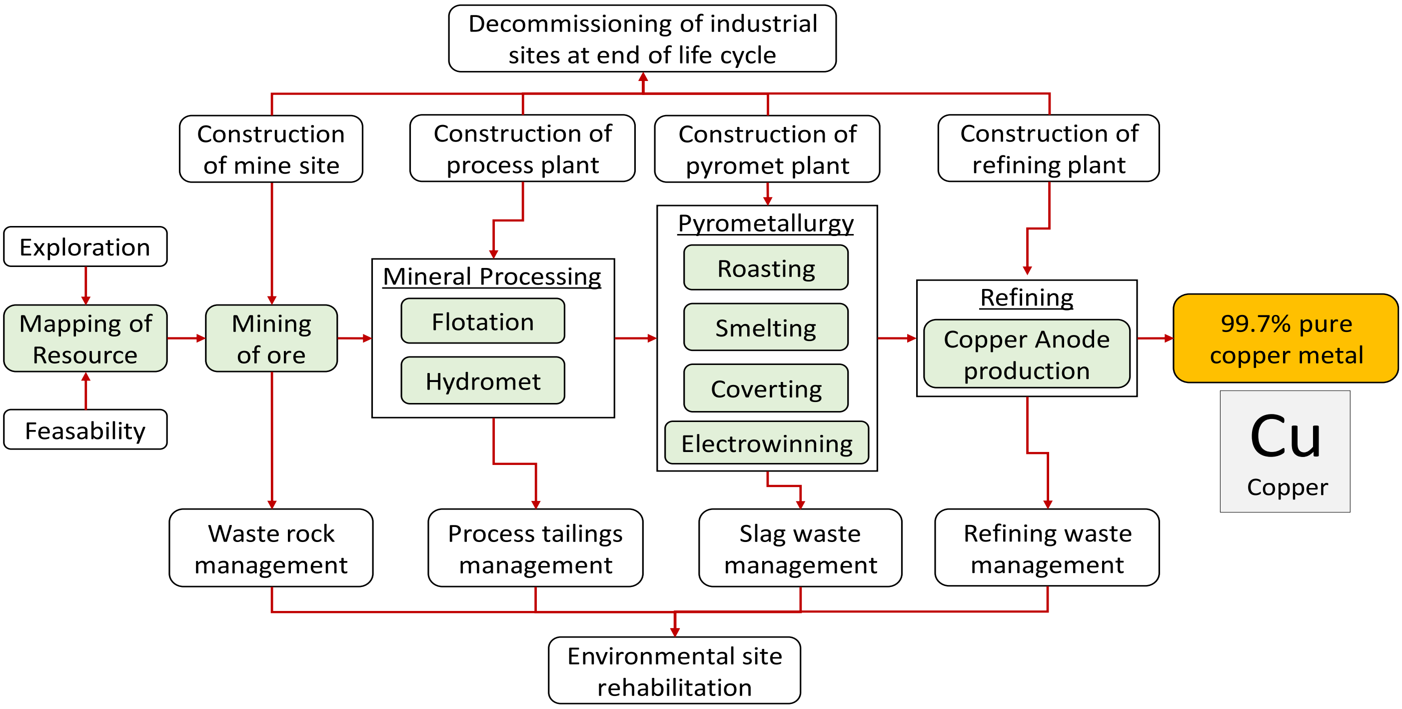


Figure 71. Raw materials to refined metal/chemical systems map – copper
(Image: Simon Michaux)

Each of the green labels in Figure 71 are the industrial steps required. The white labels are the supporting actions for those industrial steps, where each one would require its own systems map. The orange coloured label is the final product of the systems map, which in this case, is 99.7% pure copper. When it comes time to apply characterization of material streams to the systems map of Figure 71, it should be conducted in the manner discussed in Section 7.3. Each of the process engineering steps should be characterized, where a full minerals/metals/materials mass balance can be done between the feed input stream and the combined product outputs streams (Figure 72).

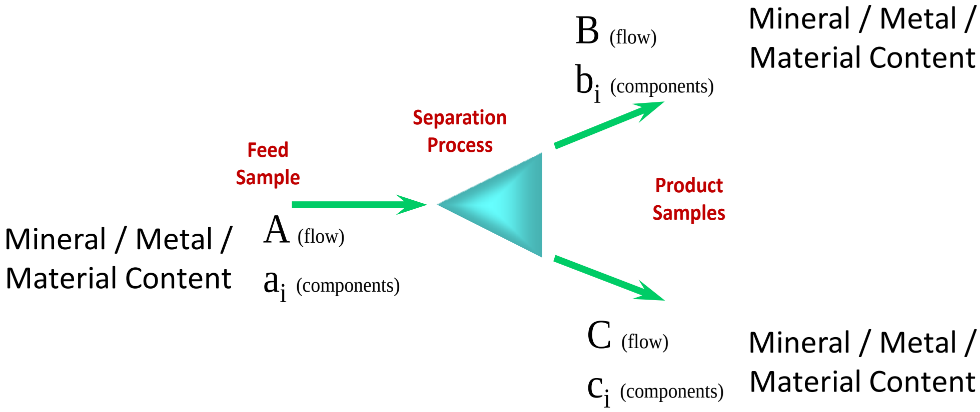


Figure 72. A mineral/metal/material mass balance across all process operations

Figure 71 could be treated as a recipe or a computer programming sub-routine, for the purpose of describing how to transform mineralized ore into copper metal, fit for purpose to be use as manufacturing feedstock. As each mineralized ore has variable content within each deposit, each mineral deposit is unique compared to all others. Each mineralized deposit also has a unique process path engineering flow sheet.

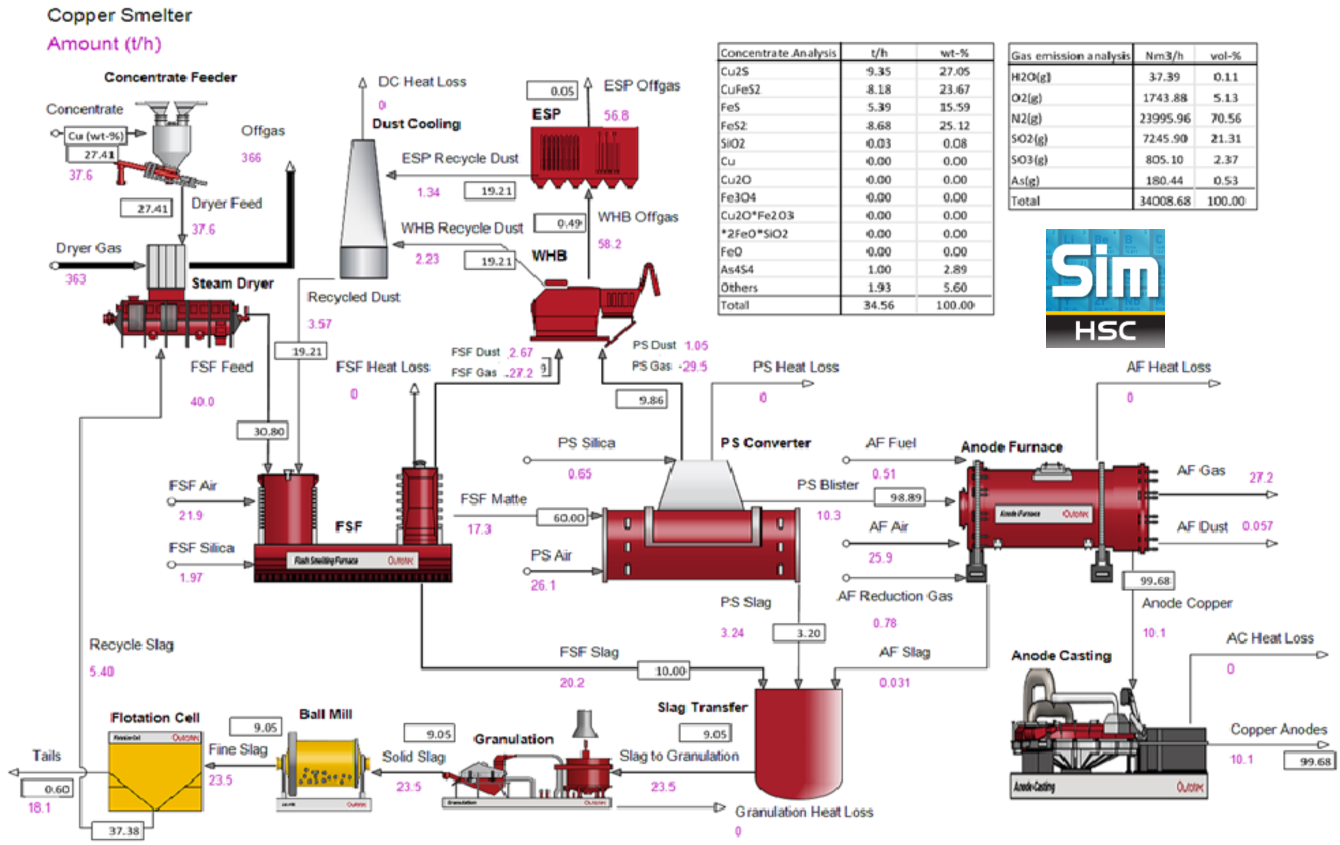


Figure 73. The HSC Thermochemical process simulation tool developed by Outotec (Image and copyright. Outotec)

Where possible, a systems map like Figure 71 could be put into a process engineering flowsheet simulator (like the HSC thermochemical simulation package) to produce something like Figure 73. The input data of these process engineering simulations could be feed mineral characteristics like metal content and grade for multiple valuable elements, engineering efficacy of operation each process unit, energy consumption, chemical consumption, and potable water consumption. The outputs could be used as data inputs fed into all of the relevant system maps.

It is recommended that fuzzy logic or neural network theory to manage the data structures in how the system maps of Section 7.4 interface with the system maps in Sections 7.5, 7.6, 7.7 and 7.8. The range of variation of each parameter could be defined by the extremes produced by a number of examples of Figure 71 & 73 but with different characteristics. This allows for uncertainty could be built into the system. For example:

- Copper produced from mineralized ore – flotation, pyrometallurgy
- Copper produced from mineralized ore – hydrometallurgy leaching, refining
- Copper produced from recycled furnace slag - hydrometallurgy leaching, refining
- Copper produced from recycled waste electrical Waste Electrical and Electronic Equipment (WEEE) - hydrometallurgy leaching, refining

Figures 66 to 73 describe and map how the variety of ways a raw mineralized feedstock could be transformed into a refined chemical or a metal pure enough to be feedstock in a manufacture process.

7.8 Develop a series of refined chemical/metal to Unit Device system maps of all kinds of technology

Now a systems map is required in the steps involved in the manufacture of technology units like cars, computers, or any given technological product. It is the technology products that are used by society, not the raw materials. A dynamic and symbiotic interaction between the extraction refinement of metals from mineralized rock, and the manufacture of complex technology products, has to be developed to a fully functional state of operation.

Figure 74 shows a systems map for the construction of a wind turbine. The turbine is made up of a number of components like turbine blades, power generation unit, gear box, transformer, and control systems. Then there are the structural elements like the tower and foundations. Then there is the connection to the electrical power grid. Each one of these components (which in turn be made up of sub-components themselves) will require their own systems construction map. The feed metals and materials, each subject to material property purity requirements would be manufactured into components. Each factory to manufacture each component will also require a systems map.

This complex value chain is to be mapped with a series systems maps. Each product will have a unique signature, just as each chemical refinement and each recycling process will all have unique signatures. It would be impossible to map this degree of complexity to produce a useful decision making system. It is recommended that fuzzy logic or neural network theory to manage the data structures in a fashion where uncertainty is accounted for. In some cases, this can be an advantage depending on the decision making system architecture.

Each systems map would output a series of parameters, where they would be different between product systems. Those parameters could be used the range between uncertainty could be applied in a fuzzy logic, or even Monte Carlo simulations. This precision is required at some parts of the system network, but not in others.

The complexity of the system would be managed with A.I. and Machine Learning applications (see Sections 7.2 and 7.7).

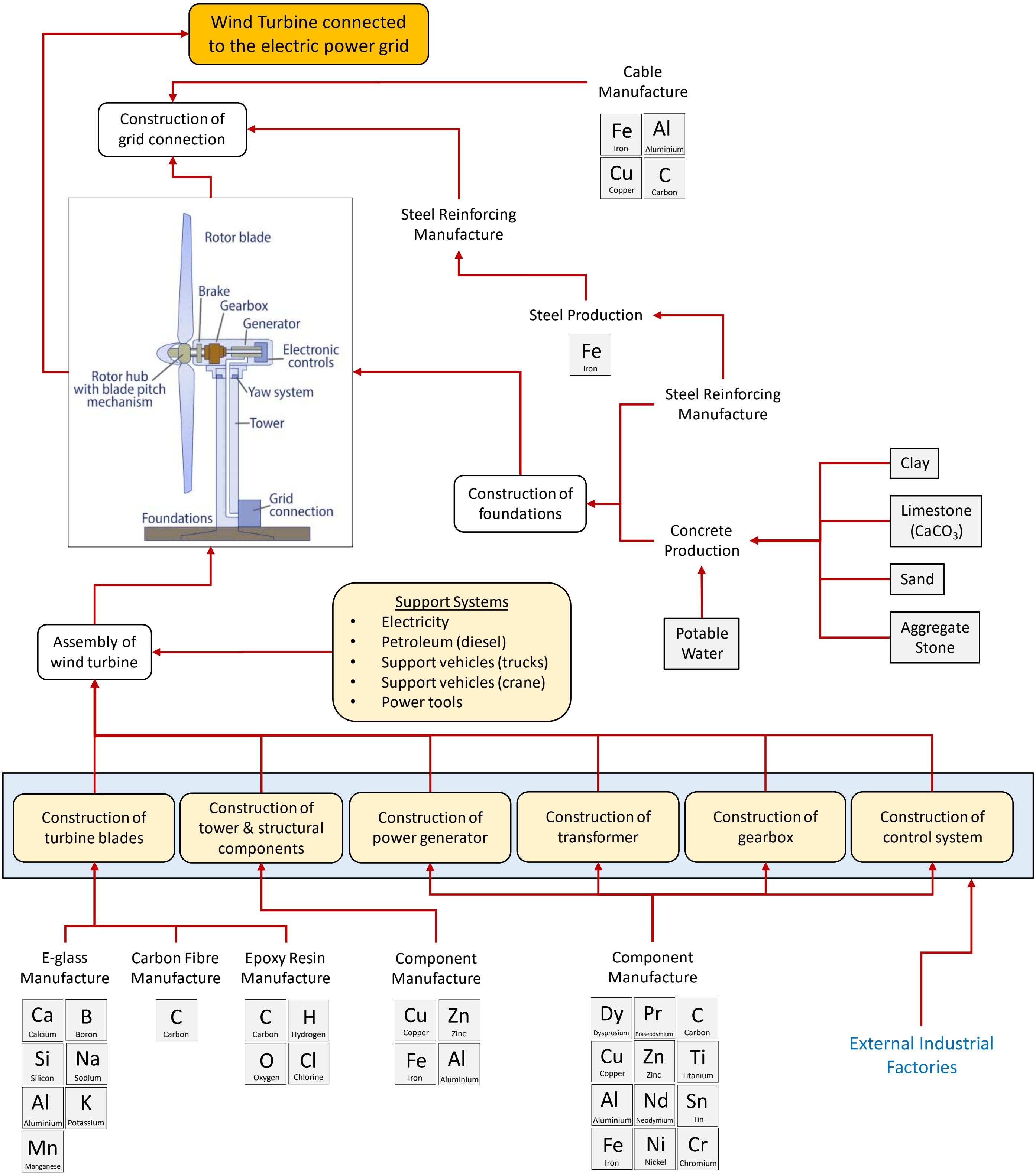


Figure 74. Refined materials systems map used to construct a wind turbine (Image: Simon Michaux) (Copyright for wind turbine: Tania Michaux)

7.9 Develop technology unit application systems map for each region chain and the whole industrial ecosystem

An understanding in how society would use the technology units in applications, then the discard of waste as those technology units reach the end of their useful operational life needs to be put in the same systems architecture as Sections 7.3 to 7.5. Figure 75 shows a simplistic example of how technology units are connected together to provide a service (in this case the delivery of electrical power to industry and the domestic human population for consumption). Each one of these units (with an orange label) would require their own systems maps. The appropriate metrics need to be projected through a map like this for the decision making system (see Section 7.8) to operate. The scope and footprint of influence of how different technologies become obsolete or not viable anymore while new technologies come into the market could be modelled with systems maps like this.

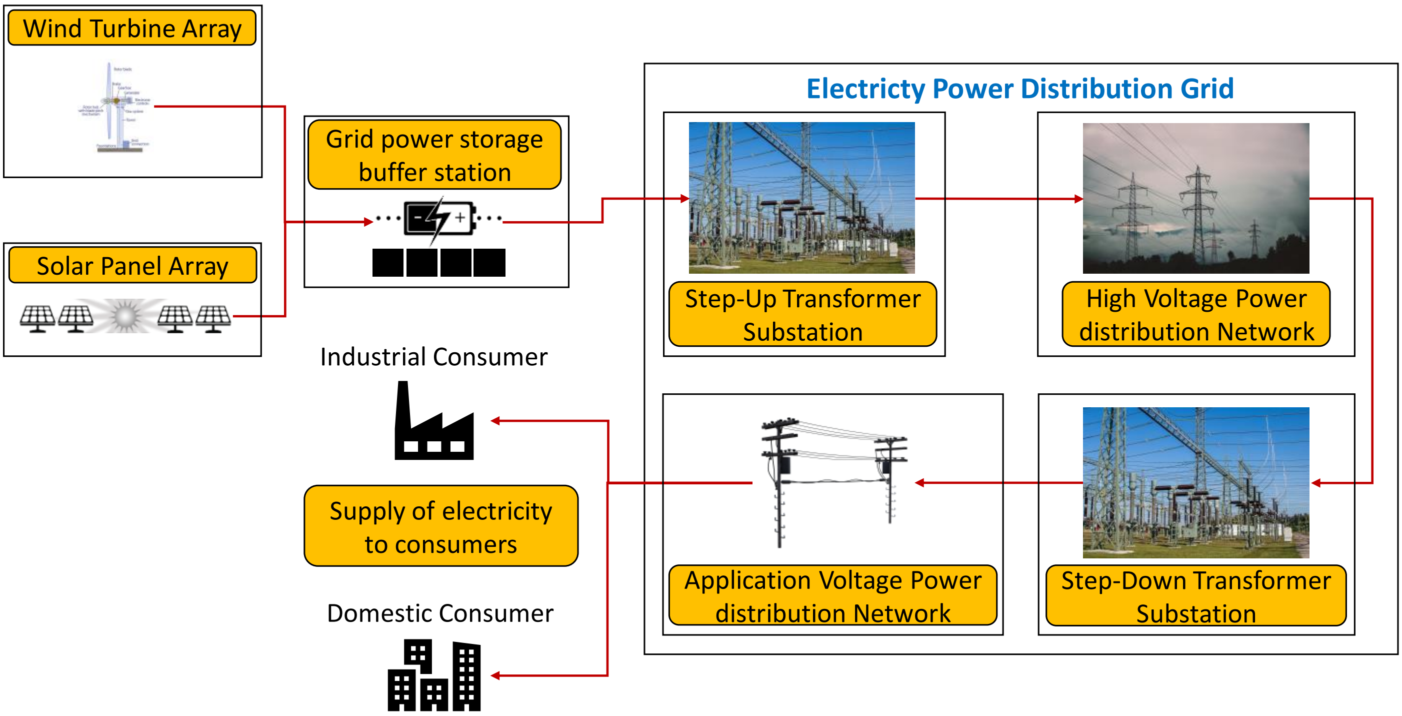


Figure 75. Technology systems map to supply electricity to consumers through the electrical power distribution grid (Image: Simon Michaux)
(Copyright: Tania Michaux, Jazella from Pixabay, Th G from Pixabay and Nicky • ☞ PLEASE STAY SAFE ☜ from Pixabay)

7.10 Develop a network system in how society interacts with technology and resources

Now all systems need to be put together to model how society interacts with technology and the industrial ecosystem. Society is a systems more complex than the industrial ecosystem will ever be. Nevertheless, an interface between society and its industry needs o be developed in a form a decision making system could functionally use in a practical manner.

> *Knowledge of kinds of waste streams can provide a means to determine potential linkages. But this does not link them; decisions by people do*
>
> Cohen-Rosenthal (2000)

Figures 76 to 80 show an example of this with how society could interact with RM Loop Cycle C (recycling), shown in Figure 68. Figure 76 shows different regions (suburbs in a city?) discarding waste after consumption, which is then collected and transported to a number of process plants (Figure 76) where the collected waste streams are processed and refined into useful chemical products. Which waste stream being sent to which process plant is an engineering supported choice based on characterization, to made by the decision making system discussed in Section 7.8.

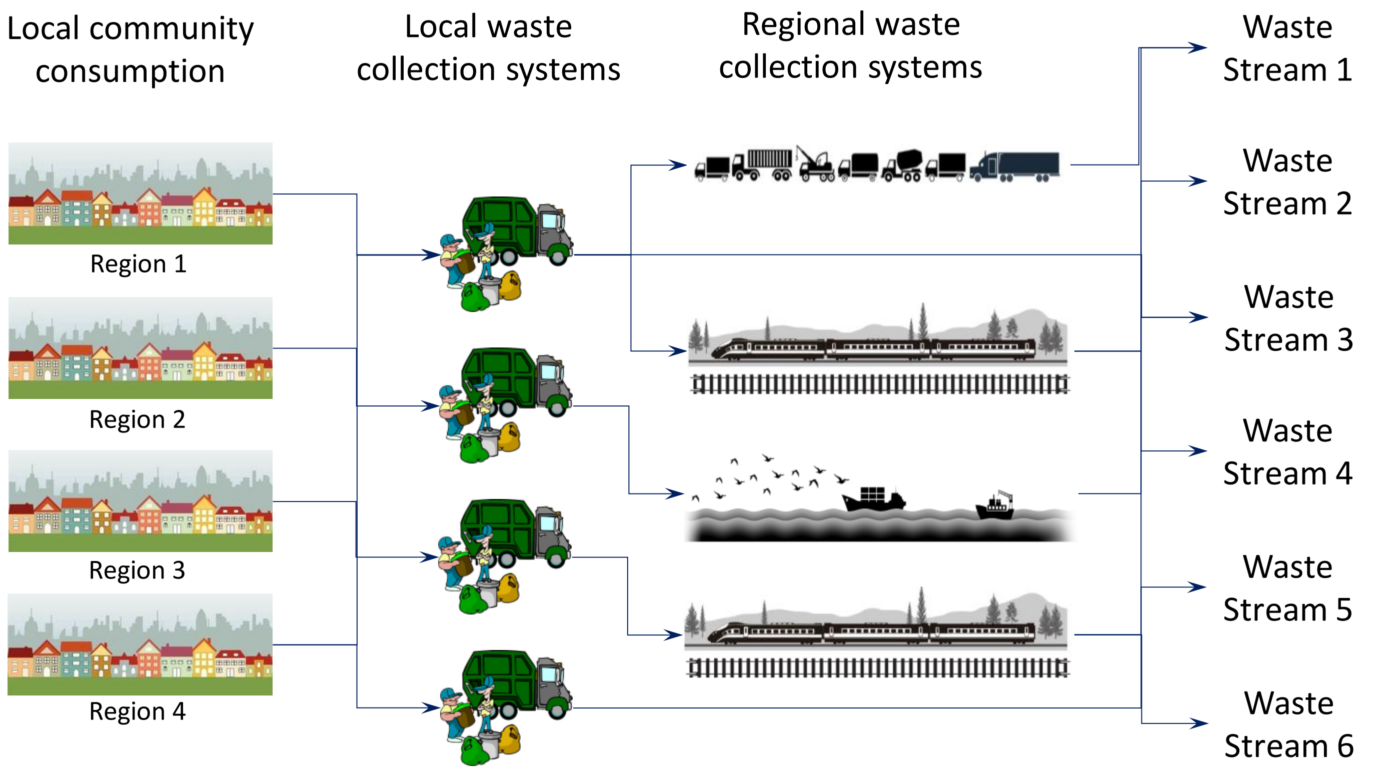


Figure 76. Society human population waste disposal streams systems
(Image: Tania Michaux, and copyright free clipart)

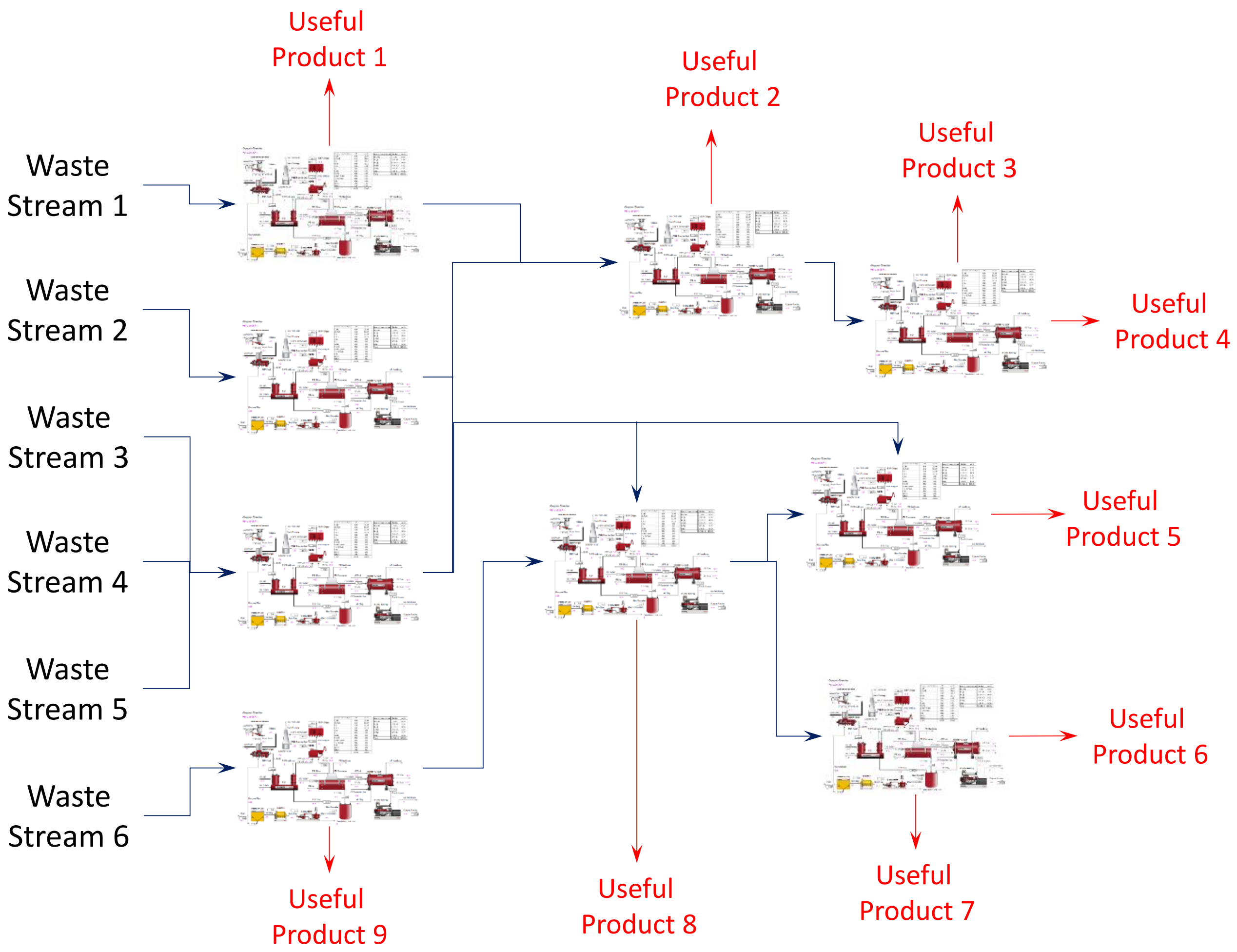


Figure 77. Waste streams to refined products systems
(Image: Simon Michaux) (copyright: Outotec, and copyright free clipart)

Figure 78 continues from Figure 77, where the refined chemicals and metals are manufactured into components and/or finished products. This is a very simplistic view of a very complex process. In reality there would be hundreds or even thousands of different factories and refined chemicals/metals to produce a single technology unit like a computer. Figure 79 shows the distribution of the manufactured products back to society for consumption. The Figure 79 could then flow back to Figure 76, completing RM Loop Cycle C.

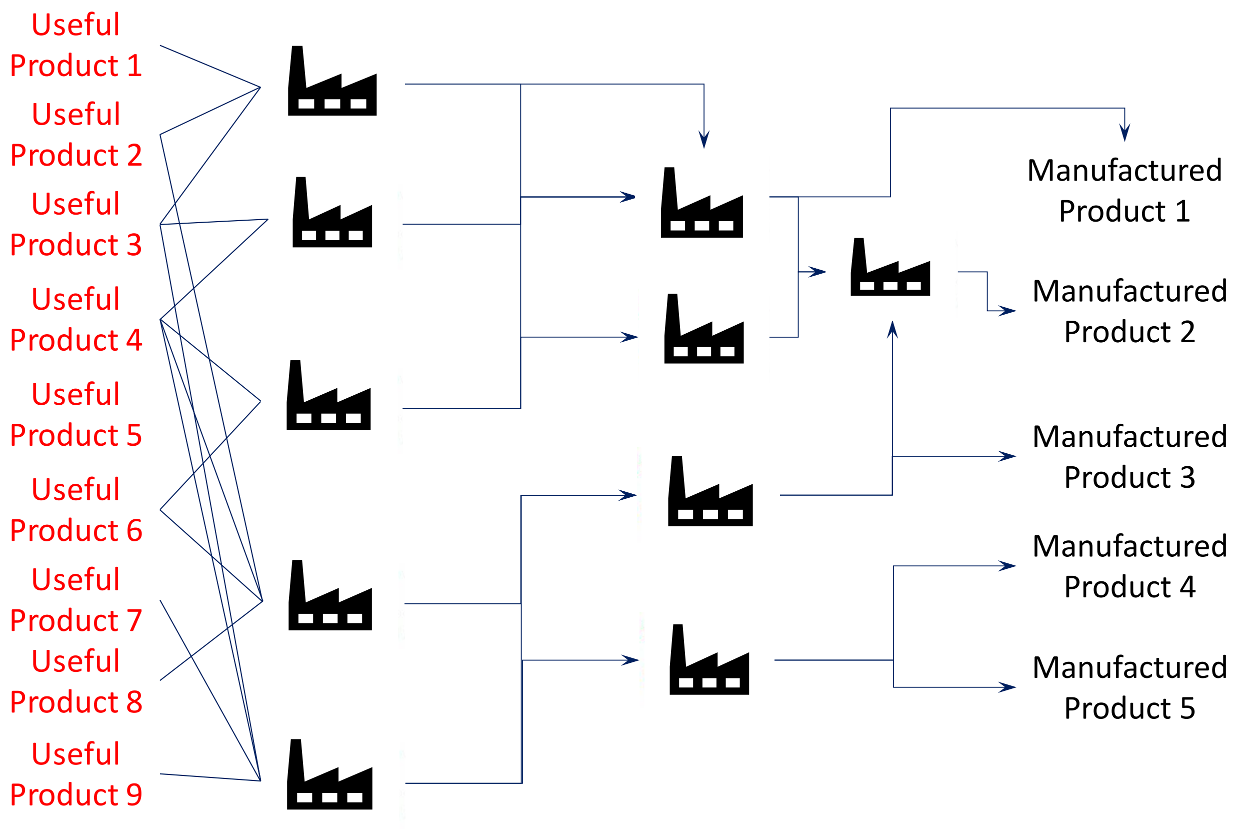


Figure 78. Refined products to manufactured products systems
(Image: Simon Michaux) (copyright free clipart)

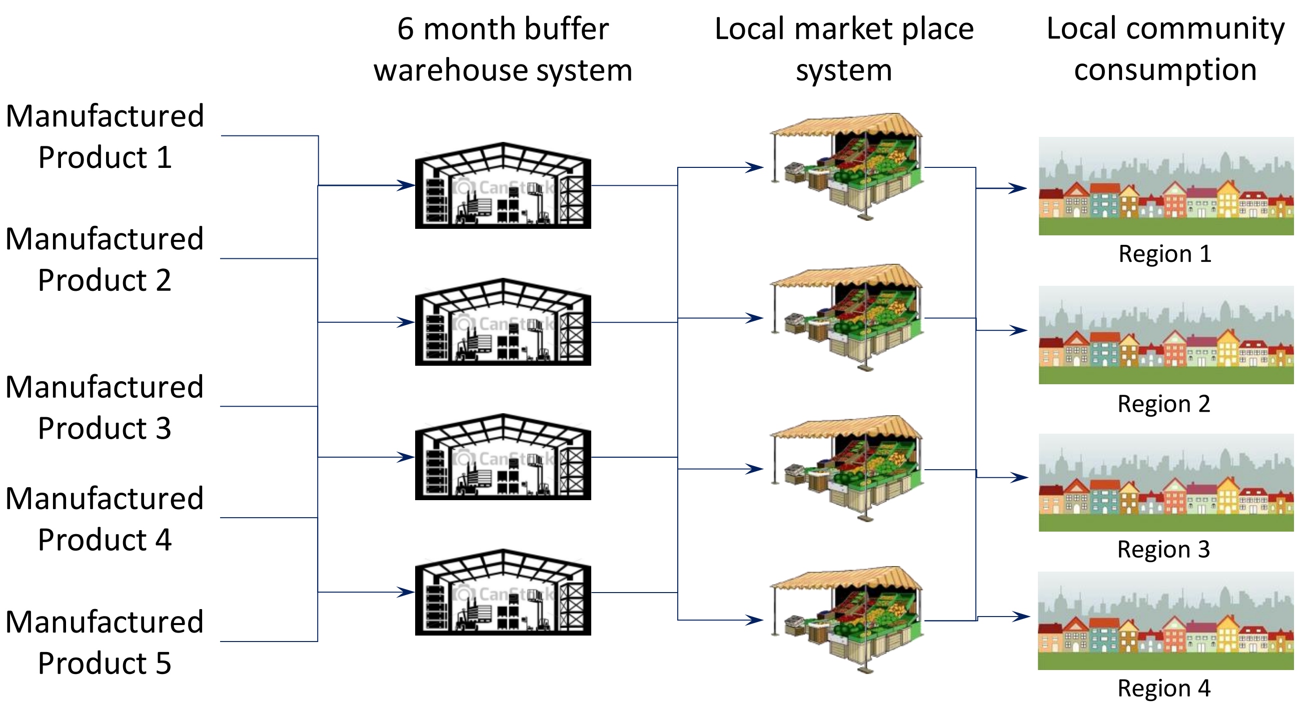


Figure 79. Distribution of manufactured products to human population for consumption
(Image: Simon Michaux) (copyright free clipart)

All of these systems would have to be integrated together. The current paradigm in the Linear Economy is one of a global integration of the whole system. The implications of a low energy future will require a much more effective system design with exergy based thermal entropy limitations. The concept proposed is instead of one giant system, that there is a series of smaller self-sufficient industrial cluster systems that are connected.

Each self-sufficient system could be an industrial cluster organized around an industrial task. For example, a series of refineries and factories that produce building heating units are optimized together. All support industrial systems like electrical power, potable water supply and/or transport networks needed to service those refineries and factories would be optimized as part of the industrial cluster system. The size and boundary conditions of the industrial cluster would be defined by:

- Thermal entropy & exergy of operation
- Importance and influence of the function the industrial cluster system serves

A series of such clusters would be design, connected and optimized together to facilitate the smooth running of the industrial ecosystem. Figure 80 shows a very simplistic example of this concept.

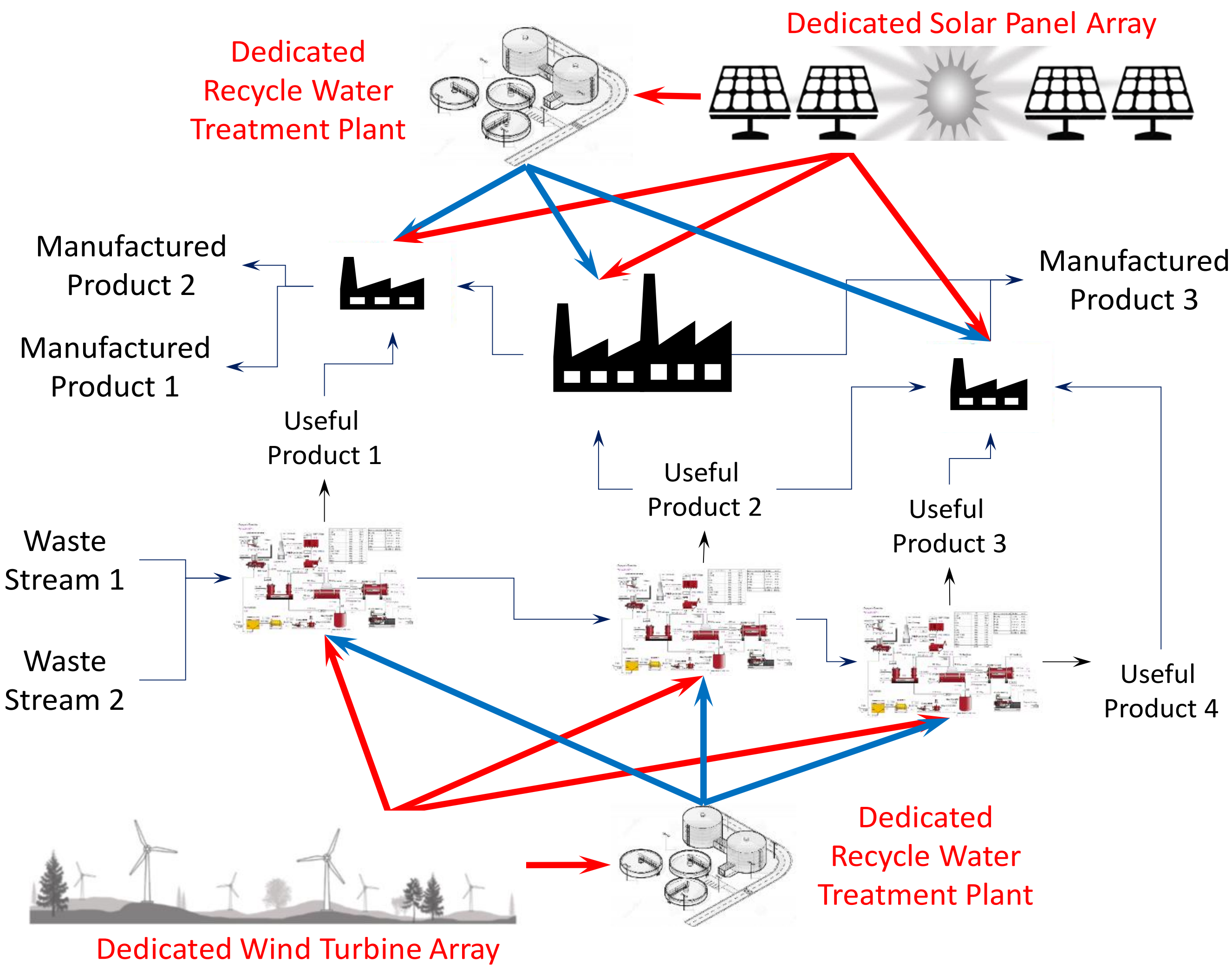


Figure 80. Networked supporting infrastructure
(Image: Simon Michaux) (Copyright: Outotec, and copyright free clipart)

The concept is that this cluster would function to the same principles as a self-sufficient eco-village, operating on the principles of permaculture (Mollison 2002). Residue streams can dynamically flow from one industrial site to another in a network architecture, where all sites are connected and managed by the same dynamic data decision making system. All necessary operations will be in a much smaller geographical area than what is done currently (a global market). For example, all support systems and resources are in a radius of 500 km, where the boundary conditions would have been defined by the thermal entropy of the cluster in operation.

7.11 Develop information data handling systems

To manage a system of unprecedented complexity (even at a small scale of a single city), an information handling system to make choices and give recommendations to government officials is to be developed. What is proposed is a tiered multi-phase system, that uses characterisation methods of all kinds to guide the sorting of raw material, refined material and manufactured goods, into and out of the appropriate process plants, managed by an entropy/enthalpy/exergy based dynamic interactive data decision tree.

The needs of each and every person in the catchment of the RBE cluster is linked and optimized to access to services and goods. Those needs are placed in a hierarchy (access to sanitation sewerage services is placed a greater priority than luxury products access). The goods and services are quantified by a library of system maps in how they work and what resources are needed to support them. All of this would be guided by the controlling paradigm, in context of legislation, administered by the democratically elected governance.

The flow of information through a system of such complexity would need to happen in a timely fashion to make decisions based on that information. Data from the appropriate characterisation of all waste streams, all feed input streams, output streams, side streams and consumption paths, is collected in time to make engineering decisions with what to do for the most effective response.

A system based predictive matrix of models are to use data relationships to make recommendations in how to handle resource streams in the industrial ecosystem. Practical logistical choices could be made from a spectrum of possible outcomes based on dynamic fuzzy logic predictive uncertainty, where potentiality of an outcome is modelled to probability into manifestation at the point of choice. Thus, there is a time component to the management of these proposed systems.

Develop a new business model that underlies the industrial ecosystem, where what is done and, on whose behalf, shifts from making money to a resource based sustainable set of metrics. Some thought should be given to what those fundamental metrics should be. The current Linear Economy uses the metric of maximizing economic value in a globalized market, with the goal of free trade international law. This has led to the ever increasing consumption of resources and now that system is showing signs of strain. The Circular Economy is ultimately embedded in the same underlying paradigm of economic growth. A completely new approach in some form is required. So, what metric of efficiency should guide all decisions? Should just one of the concepts listed below, or should a combination be selected? Should they all be selected? How do we make this practical, as each addition would accelerate the complexity of the system as a whole?

- Economic
- Machine efficiency
- Effective resource use
- Thermodynamics based exergy, enthalpy, and entropy
- Biophysical footprint
- Environmental footprint

A coherent decision making in what to do with a given resource stream according to the controlling paradigm (See Section 7.1).

- What are the most valuable metals/minerals in this stream?
- What is the most effective series of process plants for this stream to pass through?
- Thermal entropy foundation for systems network decision making
- Where are they needed the most and by whom?
- Decide what trade-offs are worthwhile

Artificial intelligence (AI), Machine Learning (ML), and all their variations, could be considered as the administration tools to develop a decision making system to handle all this data. Artificial intelligence refers to the simulation of human intelligence in software that is programmed to think like humans and mimic their actions (Allen 2020). The stated objective in A.I development is to mimic human ability to apply learning of observed data and problem-solving for future actions.

Machine Learning is the use and development of computer systems that are able to learn and adapt without following explicit instructions, by using algorithms and statistical models to analyse and draw inferences from patterns in data (Ethem 2020).

To manage the movement of all the different minerals/metals/materials as they progress through the industrial ecosystem value chain, block chain technology is recommended to be applied. Blockchain technology is a new innovation from the information technology sector. It was originally developed to support a cryptocurrency called Bitcoin. A block chain is a growing database ledger of timestamped records. Each record is called a block and is linked using cryptography (Marvin 2017). Each block contains a cryptographic hash of the previous block, a timestamp, and transaction data (generally represented as a Merkle tree) (Balagurusamy *et al* 2019).

By design, a blockchain is resistant to modification of its data. This is because once recorded, the data in any given block cannot be altered retroactively without alteration of all subsequent blocks (Hyperledger 2019 and Alzahrani 2018).

For use as a distributed ledger, a blockchain is typically managed by a peer-to-peer network collectively adhering to a protocol for inter-node communication and validating new blocks. The blockchain has been could be described as an open, distributed ledger that can record transactions between two parties efficiently and in a verifiable and permanent way.

So, resource mapping could be then link with resource harvesting, using blockchain technology through the application of some ideas shown in Andoni *et al* (2019) and Janssen *et al* (2020) and Ma *et al* (2020).

With the example of a unit of copper at the start of the Materials Atlas, it would be distributed as a trace element in a volume of mineralized rock. That copper would then be concentrated into a smaller volume, leaving some of that copper behind in waste rock and mineral processing tailings. The copper concentrate is then refined into copper anodes (99.7% pure), where some of that copper would report to industrial waste. The pure copper is then used in wide variety of manufactured goods, where copper is made into alloys, electroplating, or is used in its 99.7% pure form. A portion of that manufacture process will have a reject stream, containing some copper. The original unit of copper is split into many different sub-proportions and spread over a wide geographical area. After the manufactured product is used, it is then discarded. If all goes well that product is subject to sorting and recycling. If not, it will be somehow valorised, or in the worst outcome, put in landfill. Some of the original copper unit will go into all three streams. The recycled portion would be shredded, sorted, and refined once more. The cycle repeats.

To track the original copper unit to all the places and sub-product streams was impossible a few years ago. Now with the invention of block chain, it could be possible. The copper unit could be tracked with a block chain ledger if each handling step was audited well enough. The estimated volumes in the block chain could be calibrated by appropriate characterization at important points in the value chain. This could be made much more effective if a way of tracing the origin of the coper material back to the original mineralized ore volume. A sophisticated form of characterization that could diagnose the origin of the copper and the processes it has been subject to would the ultimate goal.

How to design and develop Artificial Intelligence, Machine Learning (and all their variations) and a series blockchain ledgers for all of the target minerals/metals/materials into a coherent system that is of practical use is an enormous task of complexity never attempted before. No one person, or single technical discipline would be able to achieve this on their own. The kinds of information needed and processes to develop would have to be determined through dialog between multiple different technical areas. This is the development of the fourth industrial revolution to a slightly different paradigm to what is now planned.

7.12 Develop evolution/devolution vector systems map

The industrial ecosystem is entering into a phase of comparative change compared to the last 100 years. All existing systems are heavily dependent on fossil fuels (see Figure 12). Those fossil fuel systems are struggling to remain viable (Michaux 2019). The most difficult challenge facing the fossil fuel energy sector is commodity prices well below the cost of production, coupled with persistent stagnant economic growth.

Figure 81 shows that the window of oil market viability is closing, which suggests the resumption of the 2008 correction will be soon. The oil production to meet global demand was dependent on the U.S. Tight oil sector. Rystad studied 40 U.S. shale companies and found that only four had positive cash flow in the first quarter (Rystad Energy 2019). In fact, the numbers were particularly bad in the first three months of 2019, with the companies posting a combined $4.7 billion in negative cash flow. So, before the Covid-19 lockdown, and the short term decline of the oil price, the oil industry was in a state of stress.

Figure 81. 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)

Global oil production in 2020 contracted sharply during the Covid-19 lockdowns. As those energy resource systems deteriorate in quantity of supply, the input energy into the global industrial ecosystem is also decreasing.

The transition away from fossil fuels is not yet established. The vast majority of infrastructure has not been manufactured, nor has the planned substitute electric vehicles. At the time of the writing of this report, a low energy future was probable.

Biophysical limits will become more apparent. Many parts of the global society are showing signs of stress and strain (Ahmed 2017). Civil unrest is becoming more widespread and more frequent in an international context. Wealth inequality is becoming more apparent (Hardoon *et al* 2016).

The year 2020 was a very unusual year. The Covid-19 pandemic brought many challenges. Some of those challenges will affect the financial system. Figure 82 and Table 5 show the M1 monetary supply for the United States dollar (the global reserve currency).

Table 5. Monetary supply of U.S. dollars
(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)

Date	M1 $USD Supply (Billions of US Dollars)
1975-01-06	$273.4
2000-01-03	$1,138.6
2008-05-26	$1,394.0
2015-01-05	$2,934.0
2019-12-30	$3,963.3
2021-01-04	$6,741.8

Figure 82 and Table 5 show some pertinent data. Since the Global Financial Crisis 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.

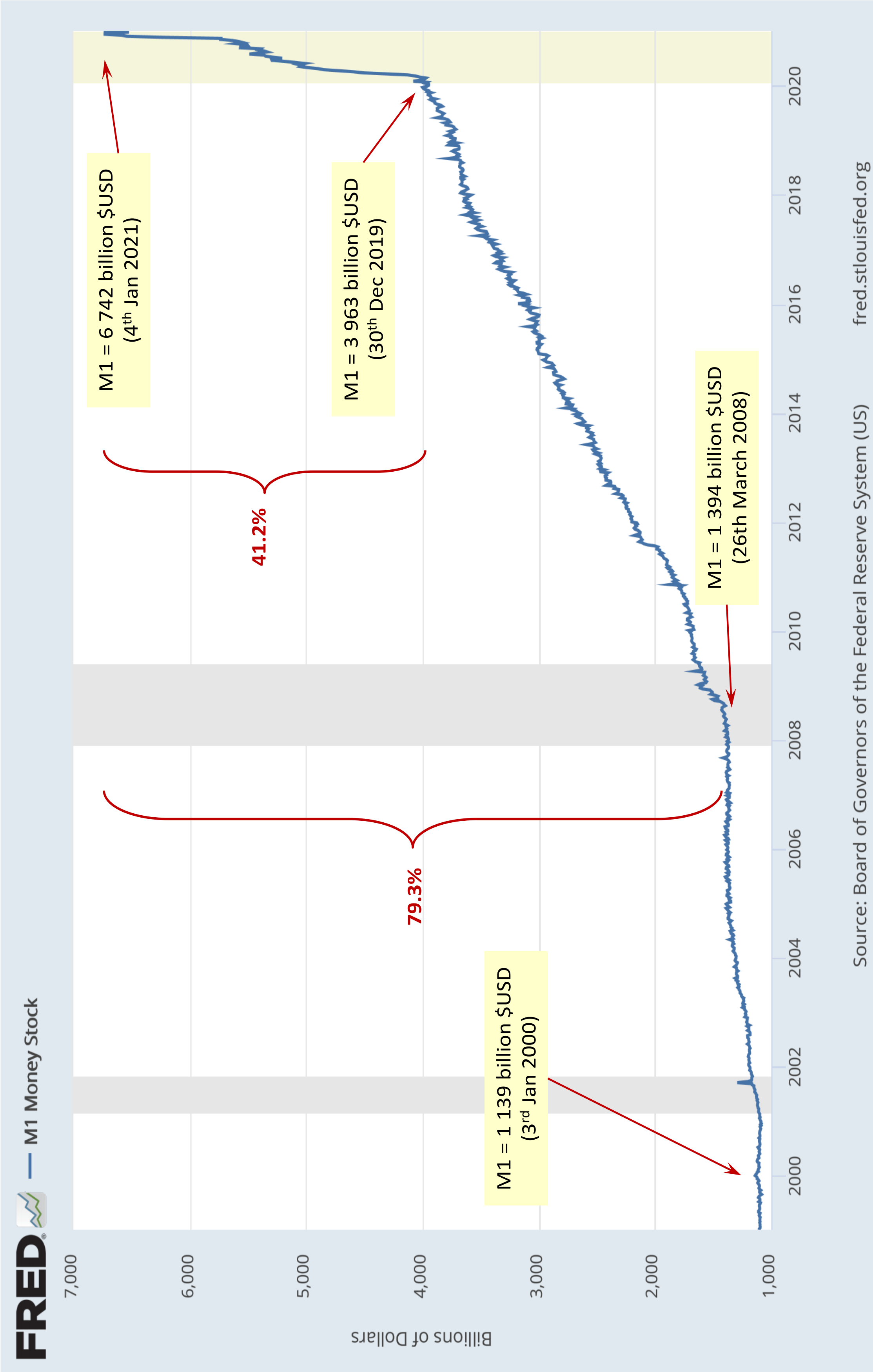


Figure 82. Monetary supply of U.S. dollars, M1, 1975 to 2021, (extracted Jan 2021)
(Source: Board of Governors of the Federal Reserve System (US), M1 Money Stock [M1], retrieved from FRED, Federal Reserve Bank of St. Louis; https://fred.stlouisfed.org/series/M1)

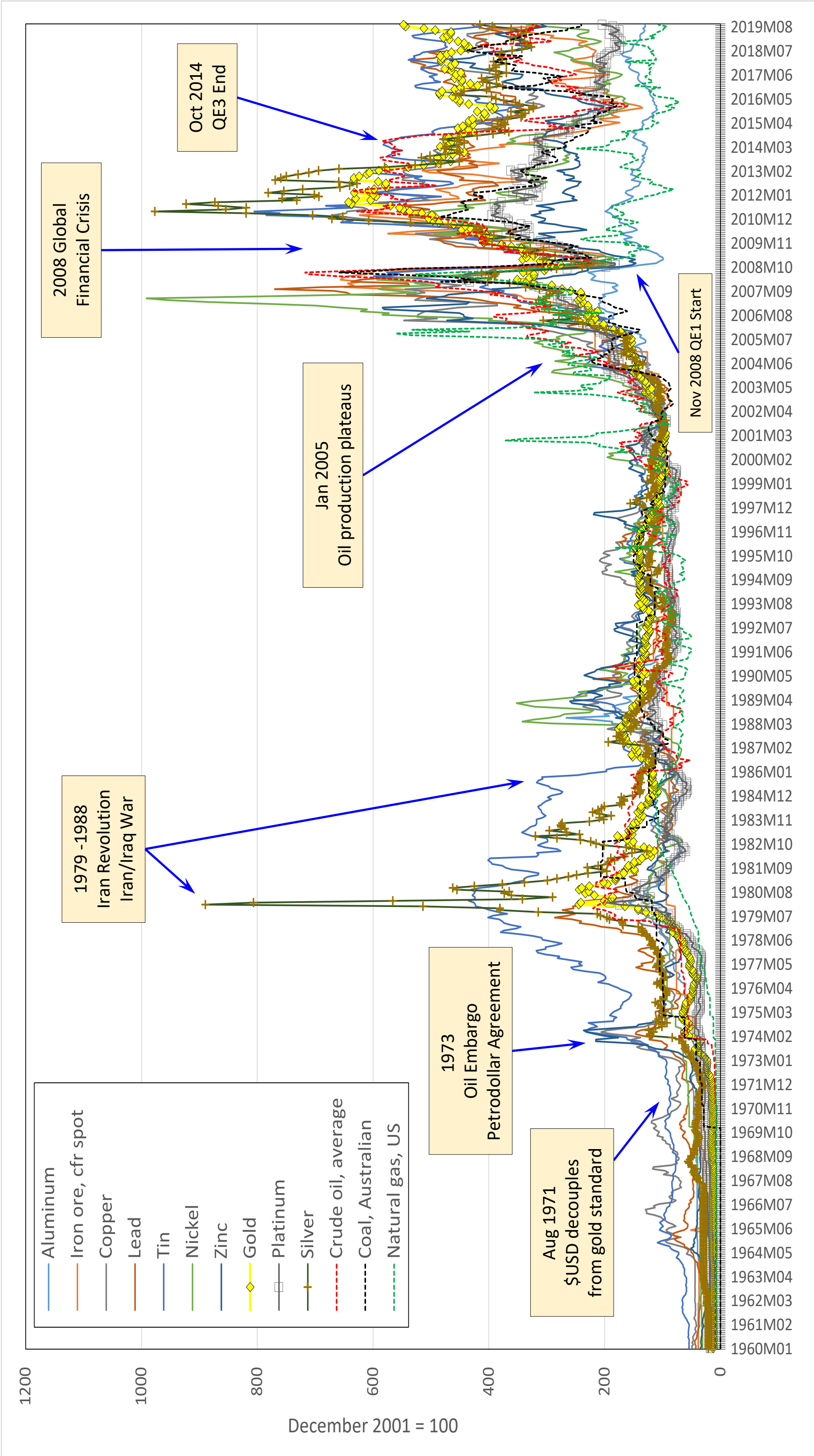


Figure 83. The price of industrial metals, precious metals and energy resources, January 1960 to September 2019, The price of metals Indexed to the year December 2001 = number 100
(Source: World Bank Commodity Price Data used to calculate Indices; monthly data updated Oct 2019)

At the very least, it would appear that the global monetary system is not in a fit state to engage in fundamental industrial reform. As energy systems contract due lack of available credit and contracting oil/gas/coal price, all other systems that energy supports in turn deteriorate.

Figure 83 shows that the industrial ecosystem structurally changed in early 2005, where metal prices blew out. 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. Figures 83 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 for Figure 83. 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 blow in early 2005 is 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.

What this means is many industrial systems that have been considered to be stable and infallible could start to struggle to remain viable. There is a risk of a sharp contraction of scope and complexity of the just in time supply system. This could happen for a number of reasons, the most probable is a contraction of available capital. This has implications for the technology applications systems maps described in Sections 7.7 and 7.8. A number of system maps will become less useful and they would have to change, or new ones would have to take their place.

New products will be developed, based on different limitations of manufacture and operation. They could be manufactured using different raw material resources. They could be manufactured in local factories with more locally sourced supply chains. New system maps for Sections 7.7 and 7.8 would have to be developed.

An understanding how parts of the industrial ecosystem would evolve/devolve in response the current challenges it faces is needed to assist the navigation of this challenging era.

8 HOW GTK COULD RESPOND TO THIS CHANGING MINERALS INDUSTRY ENVIRONMENT

The predicted evolution of how the development of the Circular Economy, EV Revolution, Green New Deal has a series of implications. GTK is well placed to contribute to society (domestically and internationally) in a very relevant manner. While the concepts shown in Figure 84 probably will not be seen for another 4 to 5 years, it would be very useful if GTK understood these concepts ahead of time and was ready to contribute at the relevant time.

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 20 years, 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.

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 (Figure 12). 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.

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. GTK - KTR is well placed to meet this demand. Mineral exploration all over the world will also be required to increase. GTK-MTR and GTK-GFR are well placed to assist in meeting this demand.

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.

Another relevant aspect is what China 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, the Chinese also have a plan. This plan is fundamentally different. In 2019, China directly controlled approximately 80% 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 be a break down in global free trade.

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).

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. This has a number of implications.

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.

8.1 Implications and Opportunities for Unit GFR and Unit MTR

- Minerals Intelligence is highly relevant in context of GTK's capability to navigate this fast-evolving minerals industry.

- Development of a holistic integration of exploration methods to a depth of 3km is now required

- 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.

- GTK could take a leadership role in assisting other survey's getting established to do this kind of work.

8.2 Implications and Opportunities for Unit KTR

- 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. This would have to be done by European operators.

- 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. Projects like GTK's SMART tailings facility have the capacity to place GTK into a world leadership role in this technical area.

- The upgrade and restructure of the GTK MINTEC pilot plant is an opportunity to develop the most sophisticated mineral processing plant the world has ever known. It will be possible to develop capability here that would not be possible in a full scale producing mine site, nor is possible in a bench scale laboratory.

- Developing this site will place GTK in a unique position and have a competitive advantage over all other pilot plants (GTK currently has funding where other operations do not).

- The Circular Economy will have to be rebuilt into something more practical and viable (the subject of this report). The role of energy and the need for raw materials from mining will have to be addressed. A case can be made that mineral exploration is a vital part, and has a role to contribute, not just in mineral supply, but in the design aspect of developing the next generation of the industrial ecosystem.

Figure 84 is an ideas concept map in how the battery EV Revolution and the Green New Deal is predicted to evolve. Reports written so far have serious implications in context of how the EV Battery Revolution, Circular Economy and the Green New Deal will not be rolled out as planned. The black labels are the parts of GTK that may contribute to this fast evolving frontier.

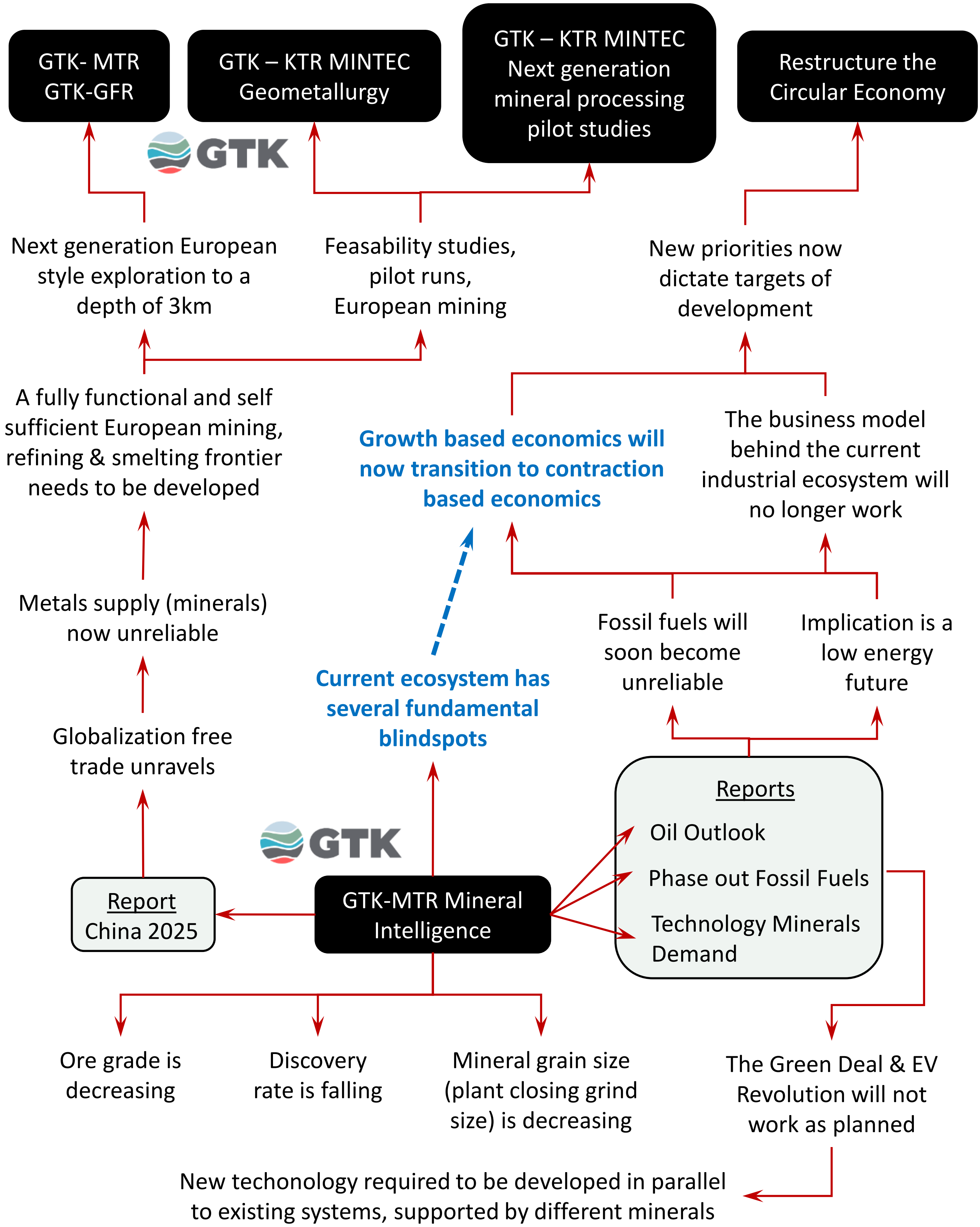


Figure 84. How GTK could interact with the projected "Green New Deal" evolution
(Image: Simon Michaux)

9 CONCLUSIONS

It is recommended to first attempt to develop the Resourced Based Economy for only part of the system that handles raw materials and physical goods first. A simplistic start that could be nurtured into a more complex state.

To start with, bring together technical professionals in the data intelligence parts of these technology sectors (those that understand the concepts in this report). Host a 'Seven Sisters of Industrial Data Intelligence' conference, where a response to this report is presented from each sector.

The Seven Sisters of Industrial Data Intelligence

1. Electrical power supply
2. Building heating systems
3. Transport networks – rail, metro, tram, bus, road
4. Goods distribution and warehouse network
5. Waste handling and recycling systems
6. Industrial Operations (refining of chemicals, smelting of metal, manufacture)
7. Raw materials supply (petroleum gasoline, natural gas, minerals, chemicals, metals, biomass, plastics, ceramics, glass)

From the conference list of participants, assemble a development team of people and start the process of creating this conceptual data management system. Plan the development of the proposed RBE from there.

Once the fledgling RBE evolves to a state of stability (most material streams are mass balanced and relatively sensible outcomes are produced), the developed RBE industrial ecosystem could be merged with other networks to include communications, food supply, potable water, sewerage sanitation and monetary financial systems.

It is recommended that development of the proposed RBE starts very small and propagates in size once stable. Start with a systems approach to city design and the resource plume stream of that city, using construction and maintenance methods that emphasize the conservation of resources. The approach would be to construct a single very small city from scratch and use it as a learning laboratory to establish what works and what does not in context of long terms sustainability. The managed development could follow a similar structure as a biological organism in how it balances power source and function.

From this point a decision tree can be developed to guide recommendations in all other systems. It is so very important to get this developed in context of all four questions above.

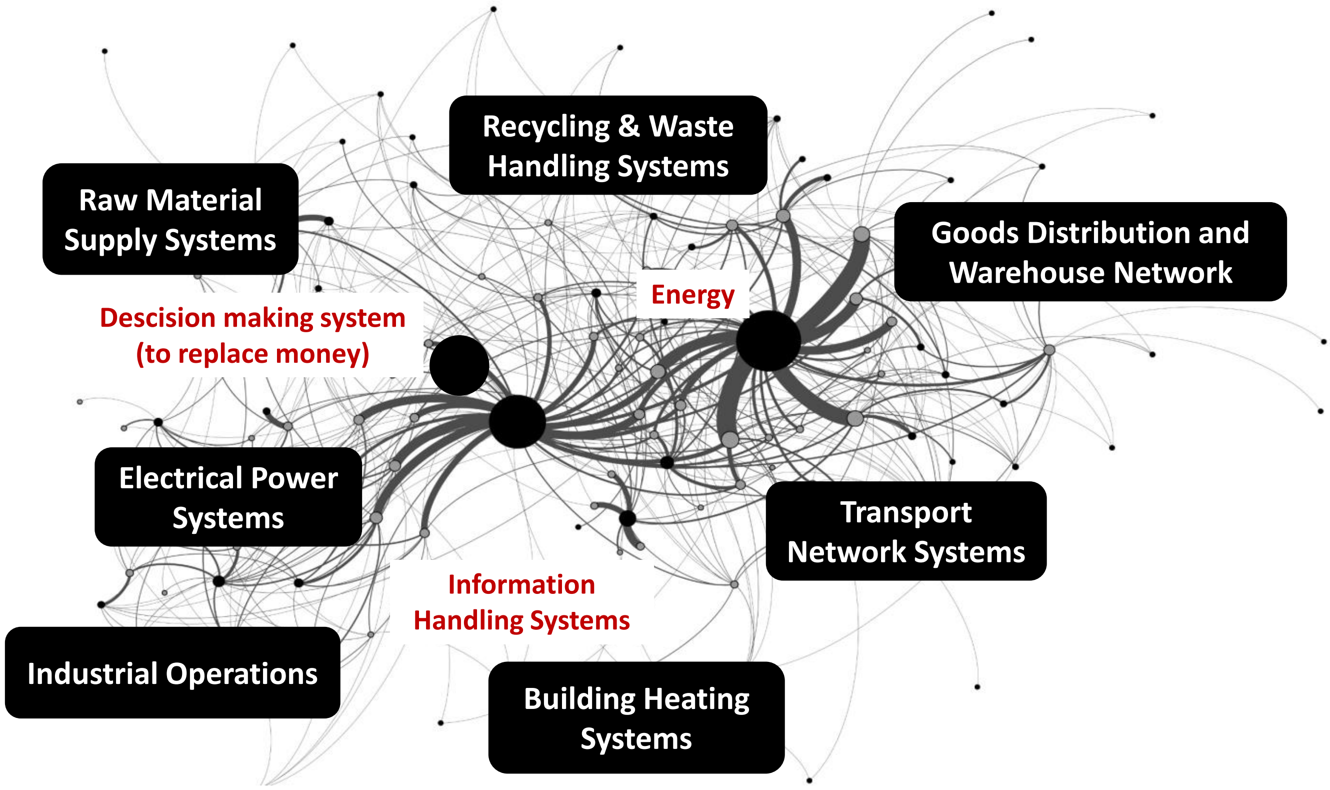


Figure 85. The Seven Sisters of Industrial Data Intelligence come together
(Image: Simon Michaux)

10 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)

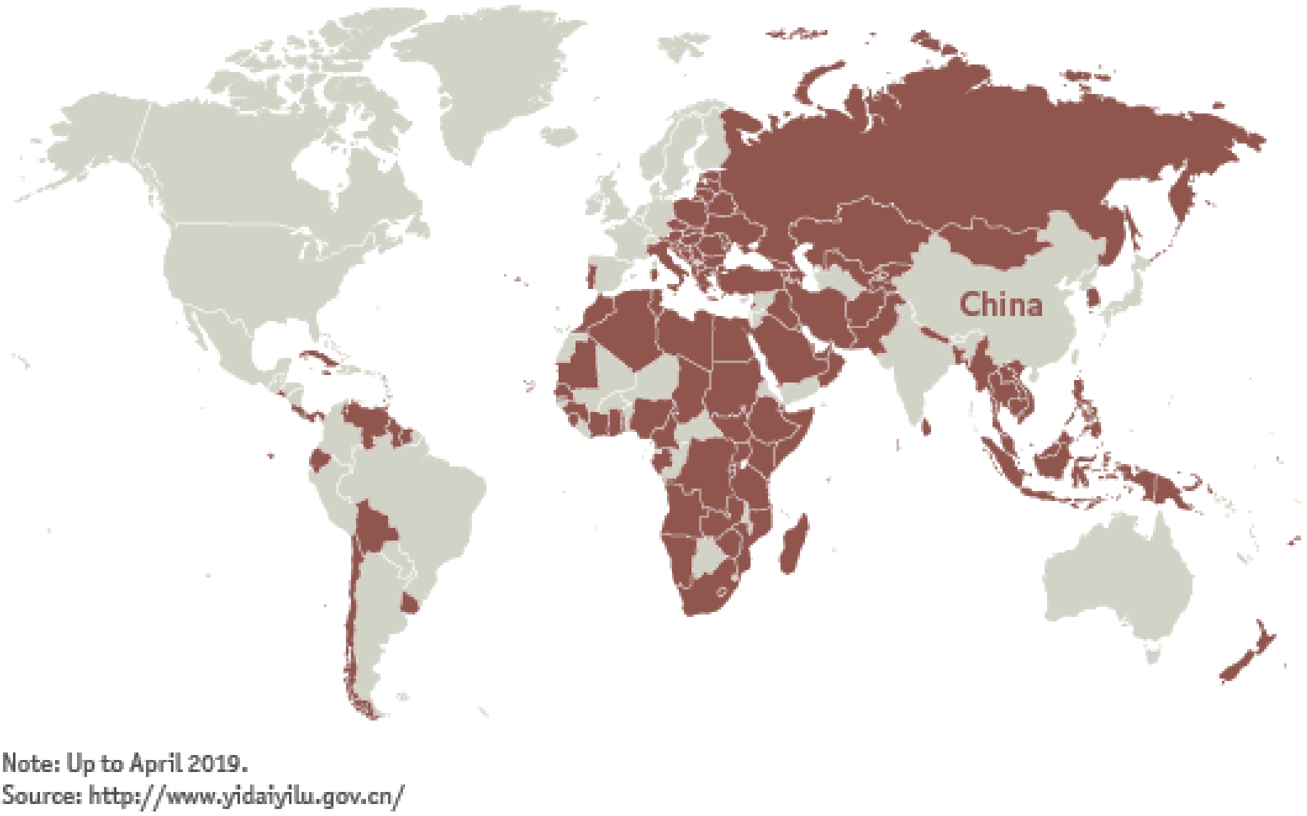


Figure A1. China Going Global 131 countries have signed China Belt and Road Initiative by 04/2019
(Source: Economist 2019, and CCP Belt and Road Portal, , https://www.yidaiyilu.gov.cn/xwzx/bwdt/13764.htm)

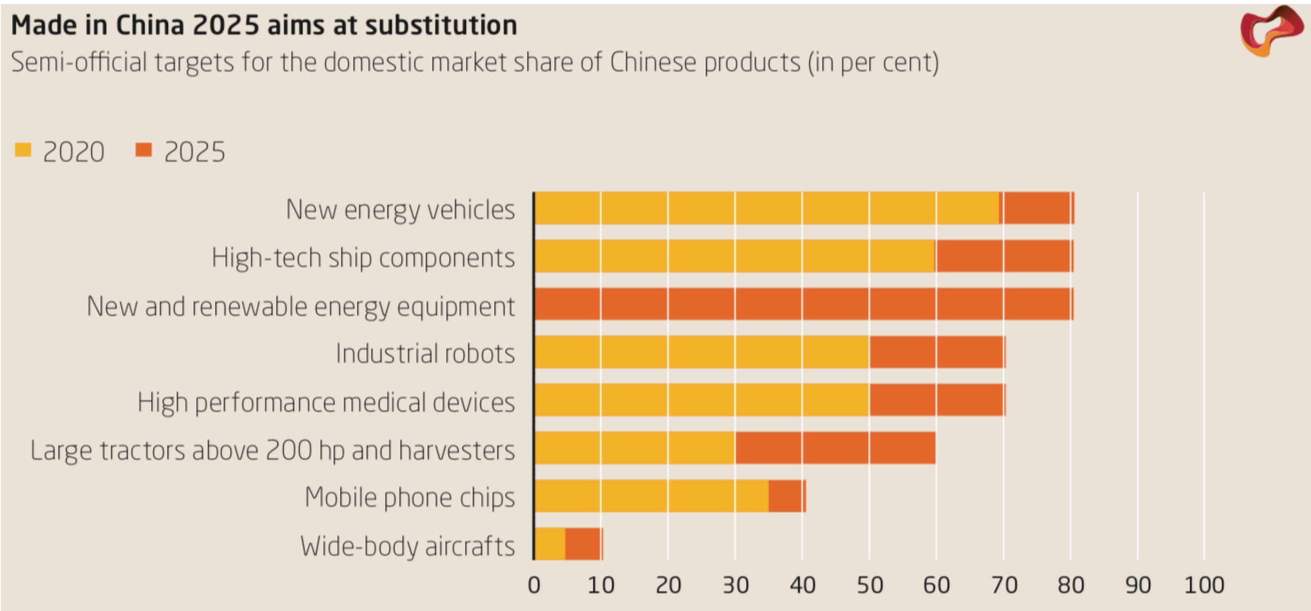


Figure A2. Semi-official targets for the domestic market share of Chinese products
(Source: MIC 2025 Green paper 2015 and MERICS 2016)

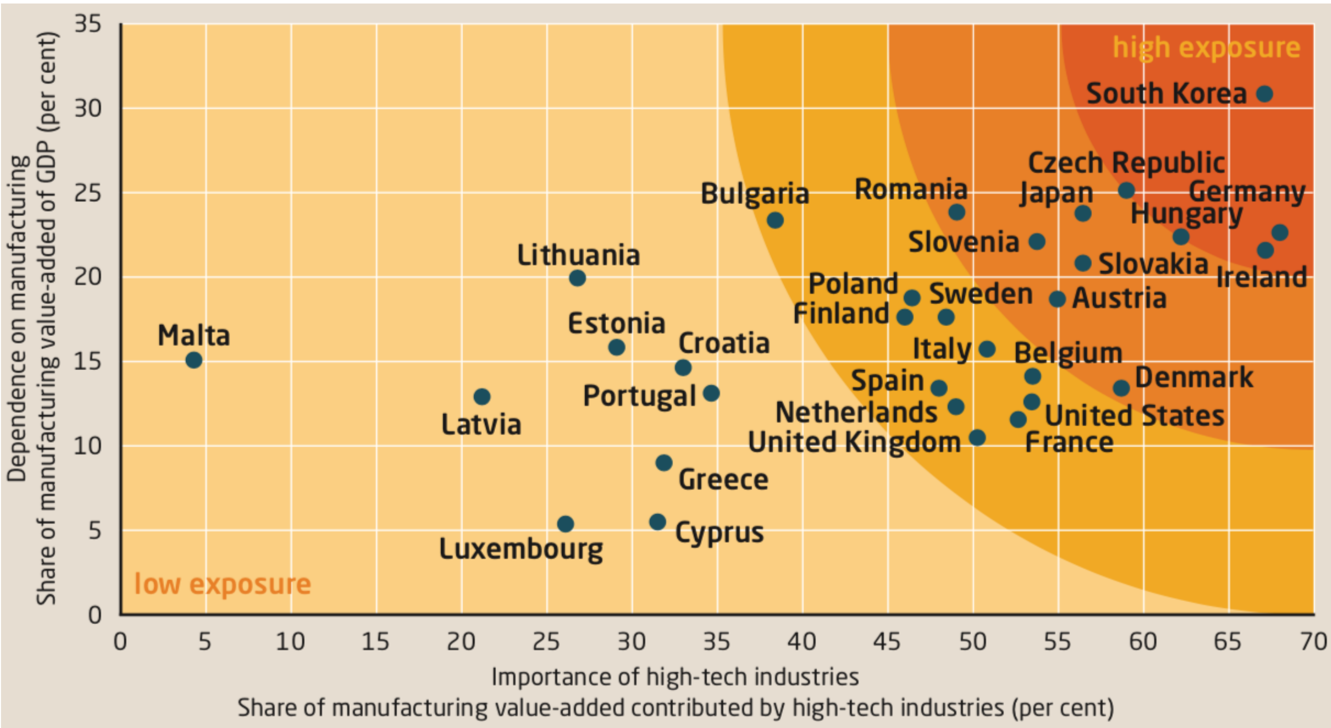


Figure A3. Level of risk exposure to Chinese corporate investment
(Source: Malkin 2018)

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

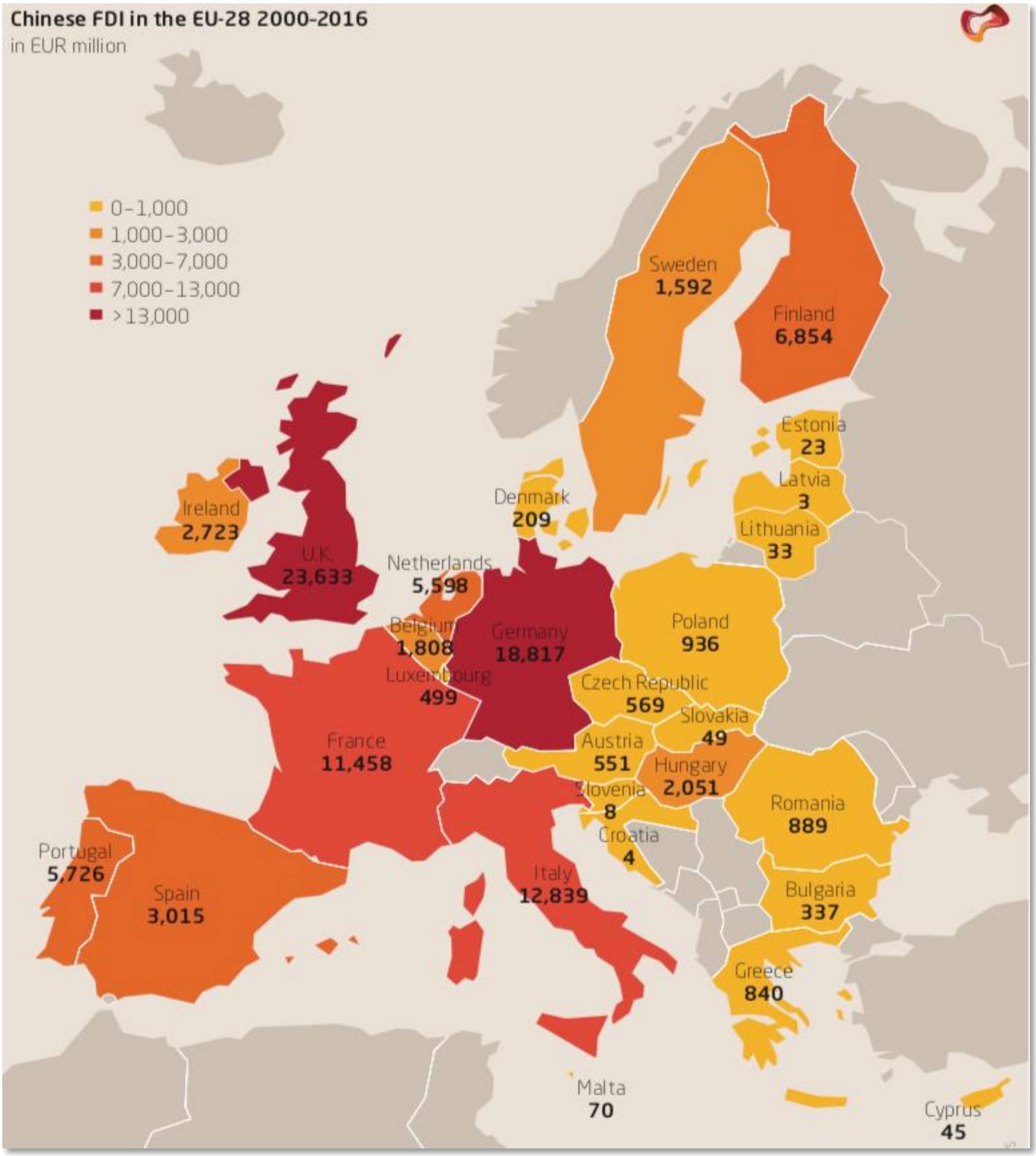


Figure A4. Chinese FDI in the EU-28 2000 to 2016
(Source: MERICS & Rhodium Group 2017)

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.

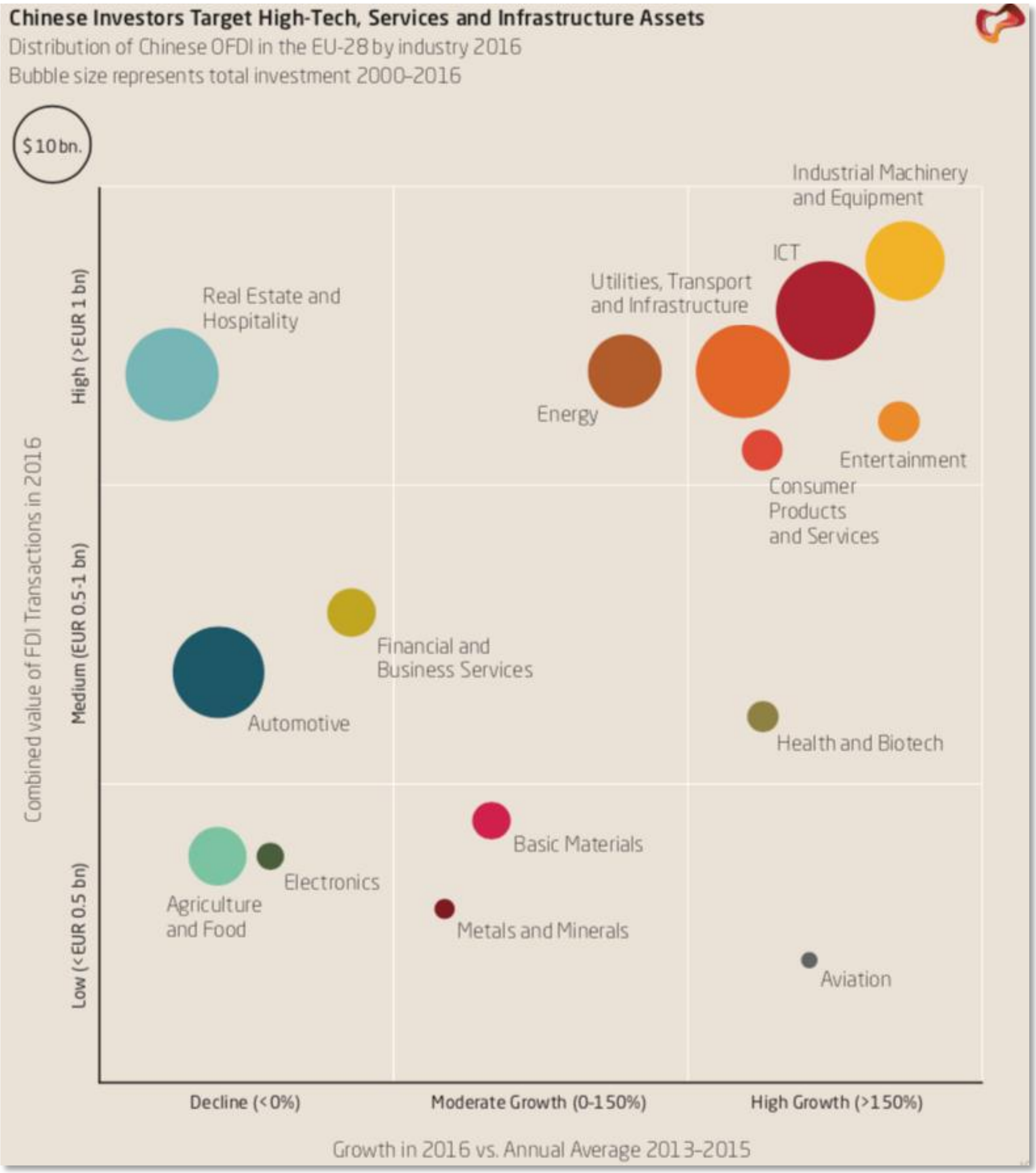


Figure A5. Chinese Investors Target high-technology, services and infrastructure assets
(Source: MERICS & Rhodium Group 2017)

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

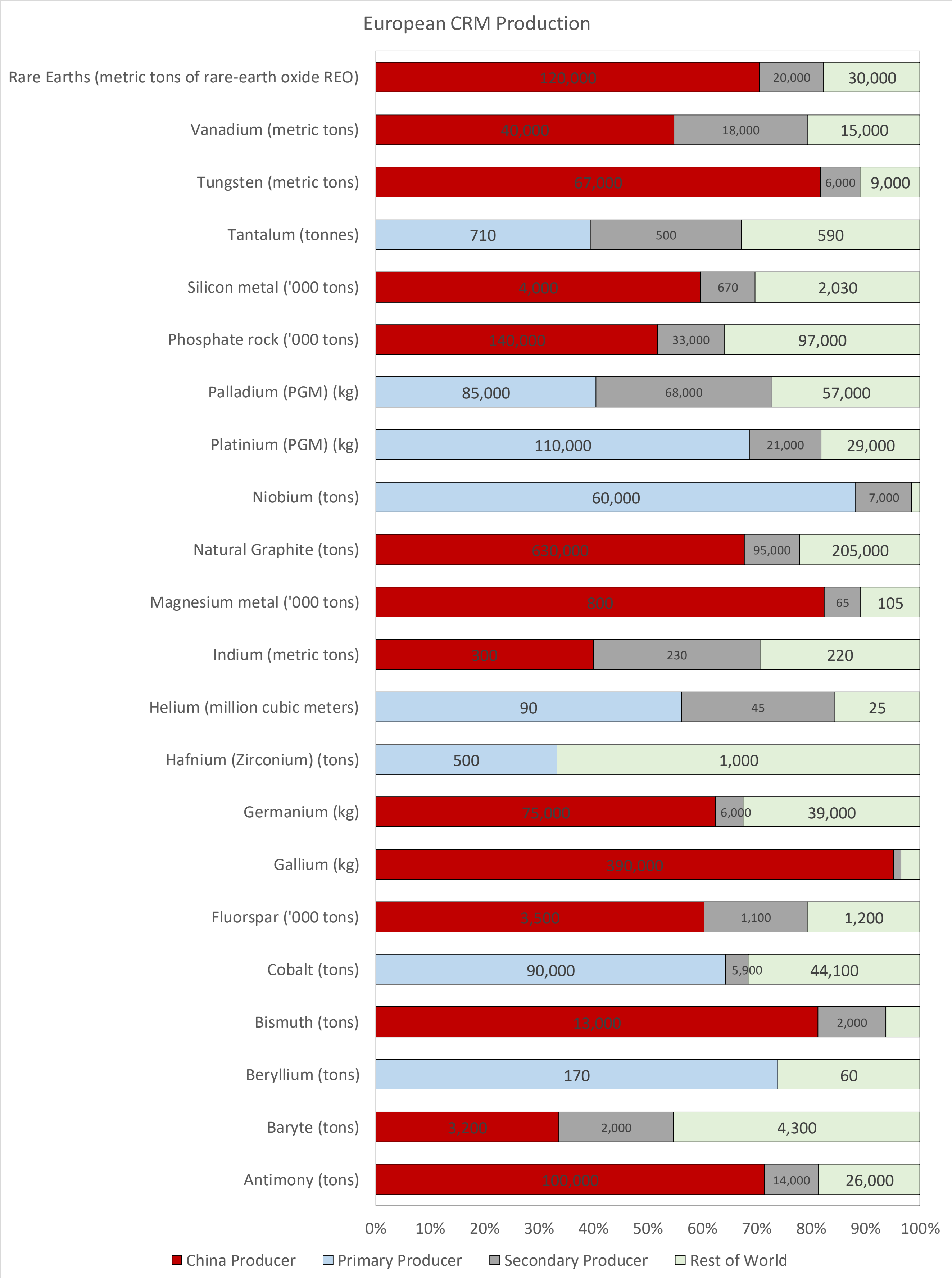


Figure A6. Chinese global market footprint of CRM raw material supply
(Source: USGS data)

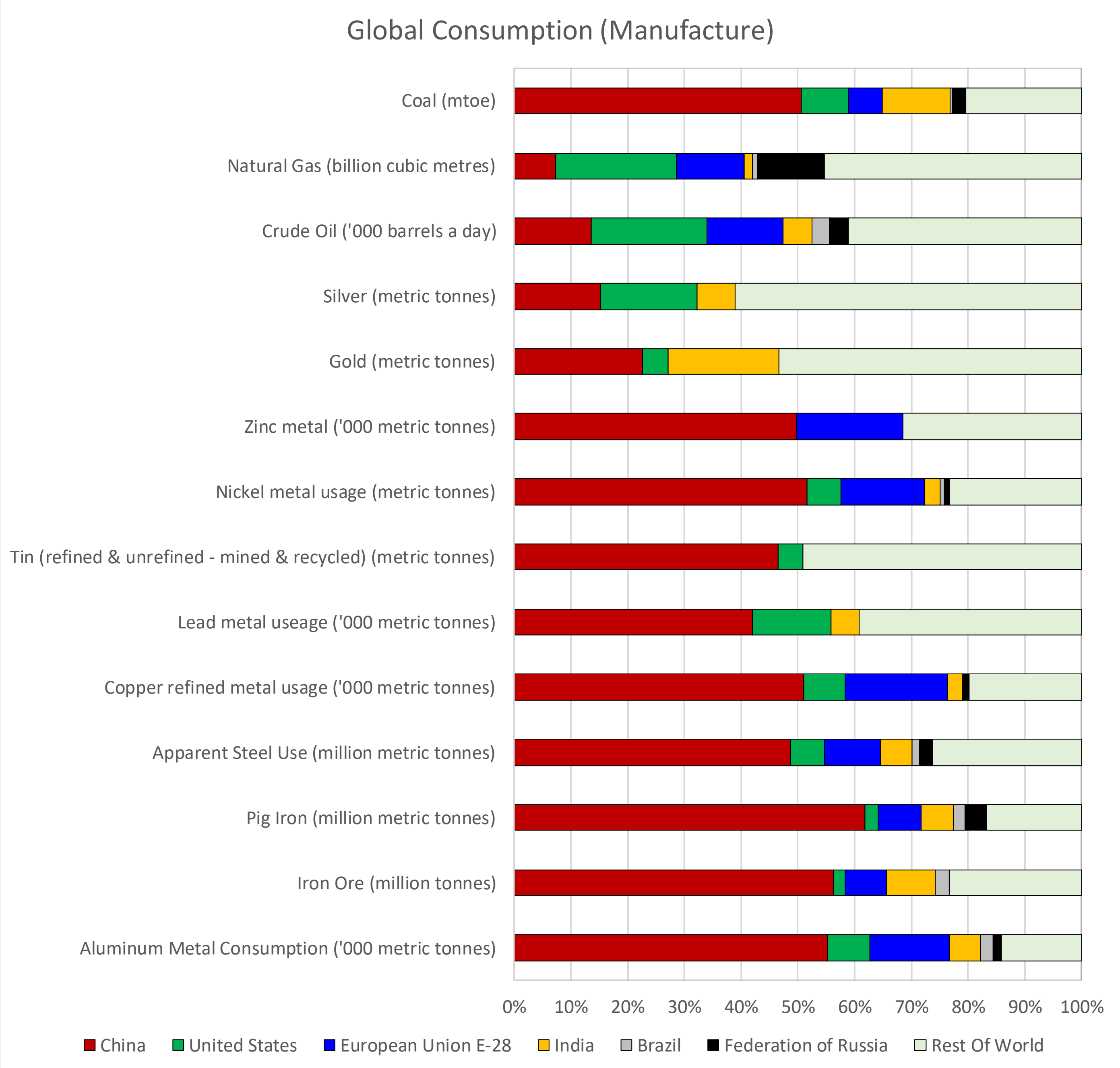


Figure A7. Chinese global market footprint of metal consumption
(Source: Data taken from World Coal association, World Gold Council, World Silver Council, BP Statistical Review of World Energy 2019, International Zinc Association, The Nickel Institute, International Tin Association, International Lead Association, International Wrought Copper Council, World Steel Association, Australian Aluminium Council, USGS)

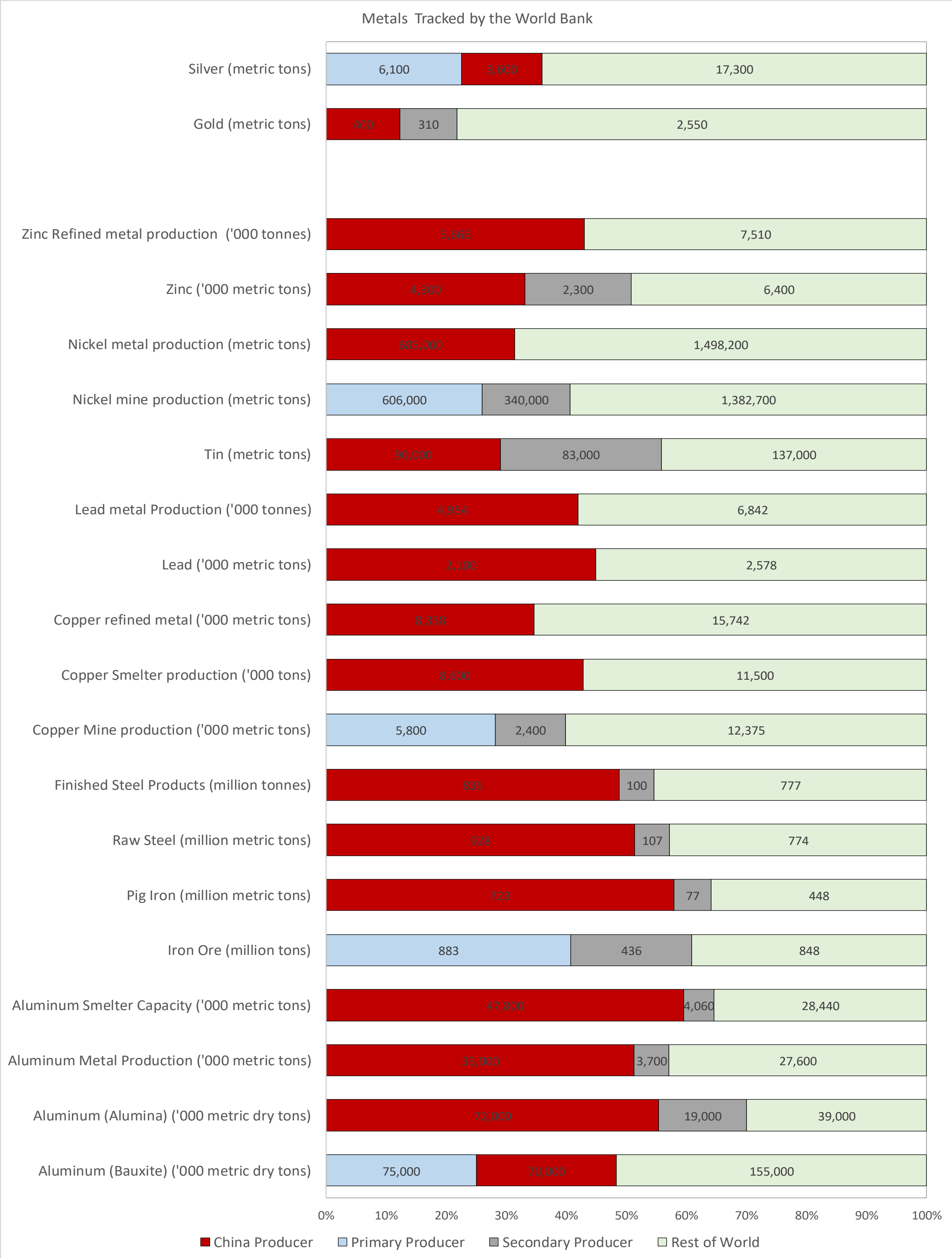


Figure A8. Global consumption of metals tracked by the World Bank
(Source: same data sources as Figure A7)

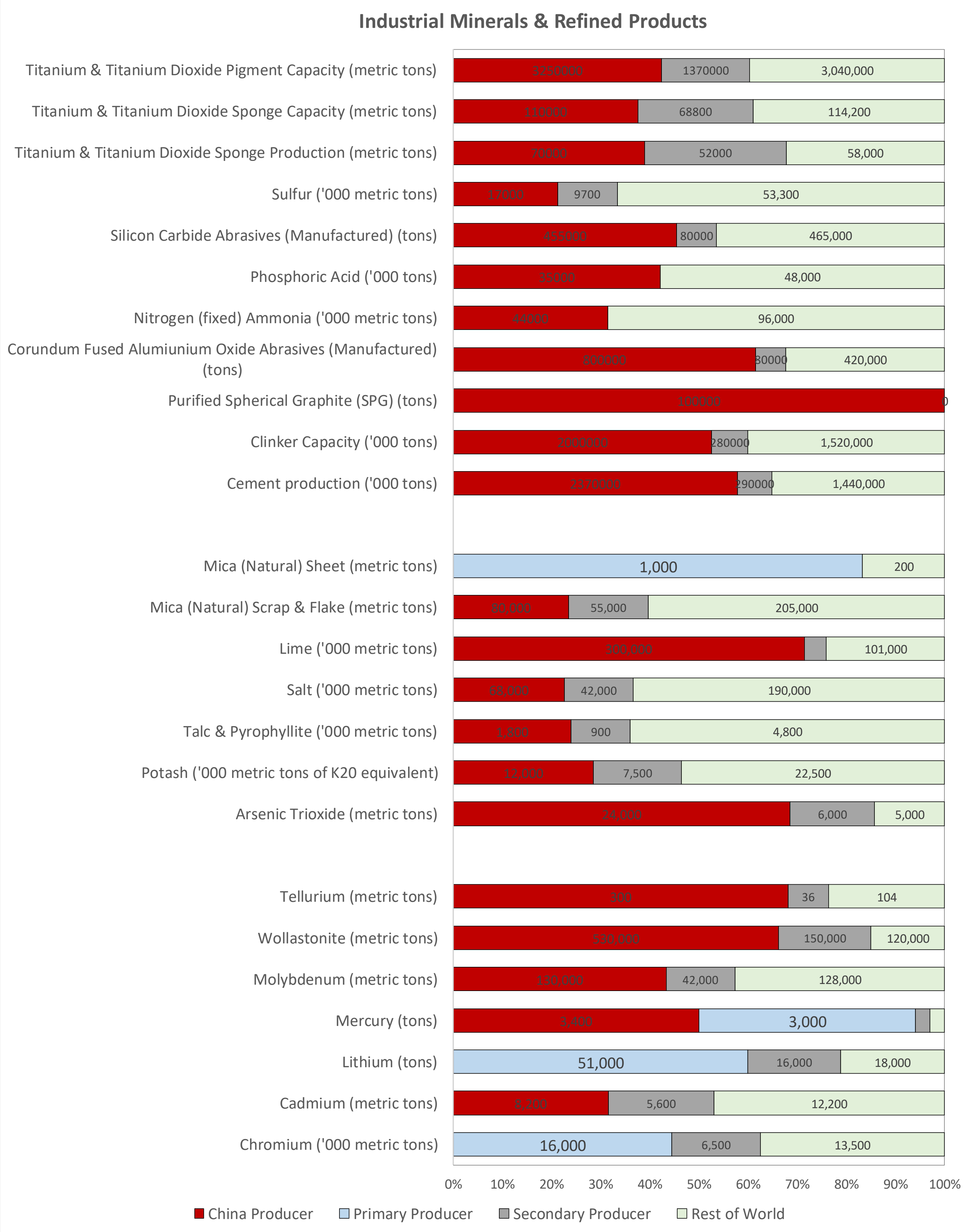


Figure A9. Chinese global footprint in industrial mineral supply
(Source: USGS data)

11 APPENDIX B – COMMON ANALYTICAL TECHNIQUES THAT CAN BE APPLIED TO PRODUCE A MATERIAL ATLAS

Dr. Alexander Finlay & Mr Luke Morgan, Chemostrat Ltd.

Inductively coupled plasma optical emission spectrometer (ICP-OES) and inductively coupled plasma-mass spectrometry (ICP-MS): ICP-OES & ICP-MS are our standard, laboratory based, elemental tools. The combination of ICP-MS and OES are capable of providing data for ten major elements, (>0.1 wt% of the rock) and ~forty minor and trace elements (<0.1% - >100ppm and >100 ppm), depending on lithology. The high sensitivity of the ICP tools make them ideal for analysing clean sands and carbonates.

Energy dispersive X-ray fluorescence (ED-XRF): ED-XRF analysis is a rapid, highly portable, yet powerful closed source X-Ray tool that can be used in a lab setting or offsite. Dependant on lithology it provides data for up to 45 elements, importantly including both Cl and S making it the ideal tool for working with evaporates.

Handheld X-Ray Fluorescence (HH-XRF): HH-XRF is an open source ED-XRF tool that is capable of providing rapid elemental data. Dependant on lithology it provides data for up to 23 elements, from Mg to U including both Cl and S. The HH-XRF is non-destructive, which combined with it being an open source instrument, makes it capable of high spatial resolution analysis making it the ideal tool for use in core stores or outcrop studies

Stable Isotope Services

Stable isotope analysis provides rapid, cost-effective, data that is relevant to a wide variety of geological questions, making it a valuable tool for the petroleum industry. Each stable isotope ratio reflects different depositional and diagenetic processes. Common ratios utilized for sedimentary geology include carbon ($\delta^{13}C$), oxygen ($\delta^{18}O$), and strontium ($^{87}Sr/^{86}Sr$). These analyses are most commonly applied to sedimentary organic matter and carbonate.

Carbon and Oxygen isotope chronology: $\delta^{13}C$ & $\delta^{18}O$ vary systematically over a time scale equivalent to or sometimes below biostratigraphy resolution. Furthermore many $\delta^{13}C$ & $\delta^{18}O$ profiles have been studied and dated on geochronological constrained sections. Therefore, a profile of an unknown section can be compared to a known section and ages assigned to the $\delta^{13}C$ & $\delta^{18}O$ excursions.

Strontium isotope chronology: $^{87}Sr/^{86}Sr$ isotopes vary systematically over millions of years and have been highly studied, enabling the formation of a composite Sr-isotope curve linked to the geologic timescale. It is therefore possible to analyse unaltered carbonate for its Sr isotope composition, compare it to the sea-water curve, and establish the age of formation. This method is particularly effective in post-Triassic sediments.

History of carbonate/cement formation: Within a well-constrained depositional system, the comparison of $\delta^{18}O$ and $\delta^{13}C$ values of carbonate cement can be used to differentiate marine and freshwater carbonates. Furthermore, the data can be utilised to identify the causes of diagenetic alteration, be it hydrothermal fluids, subaerial exposure or methanogenic cements. This can be used on both limestones/chalks as well as cements or mineralized bands within a reservoir to understand the processes driving cementation and reservoir fluid composition.

Residual salt analysis: Strontian isotope analysis can also be carried out on reservoir water or residual salt found extracted during the drilling process. The present $^{87}Sr/^{86}Sr$ value is often distinct, depending on the reservoir it is extracted from. Therefore, compartmentalization of different fluids within a reservoir will be reflected by distinct strontium isotope values.

Sedimentological, petrographic, mineralogical and reservoir quality services

Chemostrat offer sedimentological, reservoir quality, diagenetic and mineralogical analysis using a broad series of techniques that can identify the primary depositional environment, secondary diagenetic controls and their effect on reservoir quality. Integration of the different techniques can provide a detailed and powerful dataset answering a wide variety of questions. For example, mineralogy is largely controlled by provenance and weathering but the depositional environment determines sediment distribution, grain size and sorting. These parameters can be characterized and, if a proper calibration data set is available, by linking them to depositional features predictions and assessments of reservoir quality trends are possible.

X-Ray Diffraction (XRD): XRD is a technique that identifies the crystalline minerals within a rock based on their crystal structure. Each mineral provides distinctive X-ray diffraction spectra and so a pattern of an unknown rock sample can be compared to standard patterns to identify the presence of minerals within a bulk rock sample. Basic clay minerology is provided by bulk rock analysis, however, if different clay species are to identified then a separate clay XRD analysis is needed. In addition to identifying the presence of minerals within a bulk sample it is possible to provide a semi-quantitative analysis that looks at the proportion of the major minerals within a sample through Rietveld analysis. If a semi quantitative clay analysis is needed this has to be carried out separately to the bulk fraction again and can either be done via Rietveld or full pattern peak fitting methods.

Fourier Transform Infra-Red Minerology (FTIR): FTIR also produces a semi quantitative minerology data for quartz, feldspar, clay, carbonate, pyrite and organics content. While XRD undoubtedly remains the gold standard for mineralogy when time or sample location is no issue, FTIR can supply comparable data and it can readily be transported to a core warehouse, separate lab, or wellsite. Furthermore it is significantly quicker than XRD making real time analysis possible at wellsite, and the production of bulk mineralogical data possible. It is important to note that if an FTIR study is undertaken in a new area a model will have to be created using XRD on a subset of samples.

Chemical Minerology (ChemMin): Using an extensive global database of XRD and whole rock geochemical data, derived from separate aliquots of a sample, Chemostrat have developed an in house method to predict the mineralogical composition of a rock based on its elemental abundance. If only elemental data is available, ordinary least squared or random forest regression methods are utilised to predict the mineralogy for a sample based on the in-house global dataset. If quantitative mineralogical data is available it is possible to train this data, increasing the confidence in the produced mineralogical data.

Thin section petrography: Thin sections are described in detail with a breakdown of litho-types and representative photomicrographs provided. In addition if quantitative data is required, a detailed textural determination, point counting (~250 grains for modal composition) and heavy mineral and lithic clast (connected grains/crystals) characterization is undertaken. Detrital quartz grains are subdivided in to several separate monocrystalline and polycrystalline sub-categories. Furthermore, lithic igneous rock fragments are dived in to 4 sub-categories: volcanic (basic to intermediate), volcanic (acidic), plutonic (basic to intermediate) and plutonic (acidic). Metamorphic rock fragments, sedimentary rock fragments and chert grains are also recorded within the lithics category. Phyllosilicate grains are separated into muscovite, biotite and chlorite varieties and accessory grains such as phosphatic matter and bioclastic material were also recorded in the count. Non-framework components are broken down into a detailed differentiation of authigenic cements, authigenic clays and detrital matrix.

Scanning Electron Microscopy (SEM) petrography: SEM petrography is carried out in the same way as thin section petrography; however, it is capable of recording smaller features than optical petrography. High resolution images are captured showing the detailed structure, morphology and porosity of the analysed sample. If required, the SEM is fitted with an Energy Dispersive X-ray Spectroscopy (EDS) tool that captures the chemical composition of each analysed mineral and so can produce a quantitative minerology for the sample. One caveat for this technique is that minerals of similar composition (e.g. Pyroxene and Amphibole, or Rutile and Anatase) cannot be differentiated. Furthermore, image analysis software can also provide quantitative textural data from the SEM image. Typical SEM EDS analysis takes ~1hr to analyse a section at a ~75µm resolution.

Quantitative Evaluation of Minerals by Scanning electron microscopy (QEMSCAN): QEMSCAN is a high resolution SEM with multiple EDS detectors capable of performing high resolution (down to 1µm) analysis of a sample. The QUEMSCAN has an extensive mineral database enabling the automated identification of scanned minerals to be undertaken. QUEMSCAN is typically utilised to collect high resolution data where an SEM is used to get large amounts of data.

Cathodoluminescence analysis (CL): CL is used in mineral identification and mineral distribution because many minerals have diagnostic luminescence properties within a suite of rocks. Small mineral grains (such as apatite and zircon) and differing carbonate cements may be readily identified by CL when they cannot be identified by optical microscopy due to their small size or when obscured by alteration effects in transmitted light. CL is commonly utilised in carbonate studies. Accompanying the CL analysis will be 2-3 photomicrographs, descriptions and summary of cement timing, oxidizing vs. reducing diagenetic environments.

<u>Source rock and graphite screening</u>

Rock-Eval 6 Pyroloysis (Rock-Eval): Rock-Eval used to measure richness and maturity of potential source rocks. Rock-Eval measures the free hydrocarbon in a rock (S1), remaining hydrocarbon in a rock (S2), CO2 yield during breakdown of kerogen (S3), and the maximum rate of hydrocarbon generation during pyrolysis as a maturity indicator (Tmax). This enables the calculation of the total organic carbon (TOC) and mineral carbon (MinC), Hydrogen index (HI), Oxygen Index (OI), and Production Index (PI) of the rock.

<u>Radiogenic Isotope Geochronology</u>

The Uranium – lead (U-Pb), Argon – Argon (Ar-Ar) and Rhenium – Osmium (Re-Os) isotope systems are commonly utilised by Chemostrat to produce isotope ages for a wide variety of geological events.

U-Pb dating: All U-Pb techniques undertaken by Chemostrat utilise Laser ablation (LA) ICP-MS analysis making them cost effective and capable of producing data on a commercial time scale. U-Pb dating can be undertaken on a variety of minerals, and is only limited by the minerals being present within a rock and containing sufficient U for analysis.

- Multiple zircons are analysed to isotopically date the eruption and deposition of ash bands and the crystallisation of felsic igneous units. An uncertainty of 1-5% is expected on the age.

- Baddeleyite, Monazite and Titanite are commonly analysed to date the crystallisation of mafic igneous and metamorphic units. An uncertainty of 1-5% is expected on the age.
- Carbonate can also be dated via U-Pb to provide a crystallisation age of the analysed material (primary carbonate, or dolomite, altered carbonate or dolomite and vein filling cement. In samples containing 100ppb U an uncertainty of ~5% is expected.

Ar-Ar dating: Ar-Ar dating is capable of producing extremely precise ages (~1% uncertainty) however is both time consuming and costly. It is regularly used to date the ages of feldspars and mafic igneous units.

Re-Os dating: Re-Os dating different from the other routine dating techniques in that instead of dating specific minerals, it is carried out on organic matter. Furthermore the data produced by Re-Os geochronology can be used to identify the source of oil.

- Re-Os dating of Sulphides directly dates the formation age of the analysed sulphide material (e.g. Molybdenite)
- Re-Os dating of shales analyses the organic fraction of shale and provides a depositional age with an expected uncertainty of ~2-10%.
- Re-Os dating of oil analyses the asphaltene fraction of oil and produces an age of generation. The uncertainty of an age cannot be predicted before analysis due to the wide variety of variables associated with petroleum generation, but a 5-10% uncertainty is hoped for.

X-RAY MINERAL SERVICES UK

__Provenance services__

Provenance analysis provides information on the sediment enabling the reconstruction of the origin of the sediment, in terms of lithology and age of the geological terrains. This data can then be applied to studies ranging from sub field scale sand differentiation, correlation and reservoir quality studies through to mega-regional palaeogeographic reconstructions, source to sink and tectonic reconstruction studies. Chemostrat regularly integrate provenance studies with the stratigraphic framework of the study area and other contextual information available and provide a succinct provenance interpretation for each individual study.

Provenance studies have traditionally been carried out on sands, however, Chemostrat have developed a new range of analytical techniques enabling provenance studies on silts to be undertaken. Provenance studies can be undertaken using a single analytical technique or, ideally, the integration of multiple tools. For example, studies based on heavy mineral analysis use the evidence that many heavy minerals occur only in a limited number of metamorphic and igneous rocks. Thus, the occurrence of these heavy minerals directly points to provenance from the corresponding parent rocks. However, heavy mineral abundancies within a sedimentary rock can be affected by processes such as hydraulic sorting and weathering, masking the original provenance signal. Therefore, the addition of other techniques (e.g. detrital zircon geochronology to identify the age of the source of the sediments) can confirm if the heavy mineral data.

Detrital Zircon U-Pb analysis: The determination of up to 100 detrital zircon ages within a sample via laser ablation - inductively-coupled plasma - mass spectrometry analysis (LA-ICP-MS). This data provides age information to link the sediment to its source (i.e., geological terrains having the same crystallization/metamorphic ages of analysed zircon grains) as well as to determine the minimum age of sediment deposition.

Heavy mineral analysis (HMA): The determination of the abundances of HM occurring in the analysed sample. Raw counts, percentages, maturity index and provenance-sensitive indices – which have been successfully used as correlation method – are given. Chemostrat uses two methods to undertake HMA:

1. **Optical HMA**: identification of non-opaque HM and of colour, roundness, and dissolution features of key individual HM species, used to interpret sediment provenance, reworking and recycling, weathering and diagenesis.
2. **Automated Raman HMA**: Automated identification of HM abundances as well as the typologies of garnet and zircon grains. Traditionally this has only been achievable through the use of multiple techniques (e.g., optical HM analysis coupled with expensive and time consuming electron microprobe analysis). The technique can be applied to sandstones and siltstones.

Single grain geochemistry: The measurement of the elemental composition within a single mineral species (e.g., Cr-spine, feldspar, rutile). For example, rutile geochemistry gives information on parental rocks, including their metamorphic facies.

Provenance focussed petrography: A specific point counting petrographic methodology focusing on quartz, feldspar, and lithic fragments within sediment. This enables provenance to be reconstructed on the basis of the proportions of these components. Furthermore, the description of morphology of the grains/clasts provides information on sediment maturity.

QEMSCAN/SEM automated mineralogy: digital petrological analysis via scanning electron microscope for calculating mineralogy, pore types and pore-size distribution.

<u>Stratigraphic Services</u>

Elemental chemostratigraphy

Chemostratigraphy involves the characterisation, correlation or differentiation of sedimentary rock successions based on stratigraphic variations in their elemental geochemical data. This geochemical data is controlled by changes in the mineralogical and organic content of the rock. These changes in clay mineralogy, heavy mineral content and organic material, can be linked to changes in palaeoclimate and palaeoenvironment, sediment provenance and any weathering or diagenesis that may have occurred. The mineralogical/lithological controls on chemostratigraphy means that it is a technique that can be used on any lithology, including those barren of biostratigraphy, for example clean sands, red beds, barren shales and carbonates.

In addition to providing a correlation, the geochemical data can be assessed in terms of lateral variations which can be mapped to produce isocon maps that can provide a wide variety of geological information. For example, mapping the concentrations of elements such as Zr, Nb and Ti can display changes in heavy mineral abundance, which can provide some insights into sediment dispersal patterns and changes in provenance. Mapping elements like U and Mo reflect the presence and abundance of organic matter that, together with biostratigraphic information, enable the reconstruction of depositional environments. Furthermore, Chemotrat are able to model the geochemical data to produce information such as chemical gamma, minerology and lithology.

Stable isotope stratigraphy (SIS) is based on the observation that the stable isotopic ratios display similar trends in coeval sections and vary systematically throughout geological time. Owing to the relatively short mixing time of the atmosphere and hydrosphere, a major shift in the abundance of a given isotope will manifest itself in far-flung depositional environments instantly in geological time. Therefore recognition of diagnostic, time-specific variations can provide the basis for chronostratigraphic correlation at field, basin, and sometimes global scale. The variation of $\delta^{13}C$ & $\delta^{18}O$ are linked to climate and primary productivity, making them applicable for correlation at or below the resolution of biozones (including barren sections), whereas, $^{87}Sr/^{86}Sr$ reflects large-scale tectonic shifts, applicable for chronostratigraphy at the level of geological stages. $\delta^{13}C$ can be undertaken on organic material whereas $\delta^{13}C$, $\delta^{18}O$ & $^{87}Sr/^{86}Sr$ analysis can be undertaken on carbonate material.

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