Bluebridge
Incubatie- en Innovatiecentrum

METALS, TECHNOLOGIES & INNOVATION

Paper Theme 3: Recent evolutions: innovations, circular economy and deep-sea mining

Prof. dr. ir. Eric Pirard, University of Liège

GHENT UNIVERSITY

LIÈGE université

Content

Disclaimer

This report was prepared in the framework of the think tank ‘Global mineral supply & meeting challenges of future demand’. An event organized on Friday 22nd of October 2021 by Bluebridge under the supervision of a steering committee composed of representatives of Ghent University and Global Sea Mineral Resources. The objective of the think tank is to stimulate the societal debate on mineral supply and demand scenarios, whereby different technology and policy options are considered in an overall framework of sustainable development.

To provide context for the debates, various professors delivered a report based on scientific sources on the various themes.

SUMMARY

Our modern way of living requires huge amounts of raw materials that need to be extracted from the geosphere and turned into high purity metals for ever more demanding applications. The energy transition, encouraged by the Green Deal, relies on the deployment of technologies which will require the raw materials sector to supply even more metals and not only the critical ones. In other words, a dematerialization of our society is not to be expected any time soon unless we drastically reduce our consumption.

It can be easily demonstrated that recycling, although essential, will not be able to satisfy the materials need before several generations. This is particularly the case for many metals which are key for the digital and energy transition but have not been used very intensively until now (Ge, REE, Ga, Li, Co, etc.).

Most geologists would agree that there are enough resources in the Earth crust to satisfy societal needs for a few centuries. But, surprisingly, little if no effort is done to intensify exploration and allow for a resource governance with a horizon beyond the typical twenty years limit. This being said, the most urgent question to address today is not “how much is left” but to which extent the technologies we are manufacturing are depriving future generations from access to metals. In other words, the recyclability of our urban mines is a key concern which obliges us to rethink our products and come to more modular, robust and long-lasting solutions.

The recent recommendation on the “right to repair” is a good step forward, but further improvements are needed to facilitate recycling by establishing a dialogue between recyclers and product manufacturers.

Substitution of one element by another rarely brings a solution and also induces a permanent change in technologies which really impact the development of stable, economic and efficient recycling processes. At last, one should keep in mind that even a very efficient process recovering 95% of the metal content of a product will have dissipated half of the material after only fourteen cycles. Hence, these cycles must be made as long as possible. A recommendation which is best summarized by “slow down the loop”.

THE POWER OF TEN

Before the industrial revolution, each individual roughly needed the equivalent of 3 to 4 manpower per day to satisfy his needs. This could easily be satisfied with basic technologies to capture and benefit from renewable energies such as wooden windmills, hydraulic wheels and charcoal furnaces. Since then, the energy need has increased by at least two orders of magnitude. Our modern way of living, now requires the equivalent of 400 manpower per day for heating, cooling, transportation, grinding, forging, etc. Fossil fuels represent by far the largest amount of resources (by value) extracted from the geosphere.

As for energy, the quantities of metals required by our modern way of living are two orders of magnitude above the ones needed before the industrial revolution. With the notable exception of gold, which is almost useless, all metals have very distinctive properties and are being mined for very specific usages. Some metals play a key role in our technologies since Antiquity (iron, copper, tin,…), others have become prominent only since the mid of the twentieth century (aluminium, nickel, …), whereas many metals had to wait until the seventies to find their way into the anthroposphere[1] (Fig. 1).

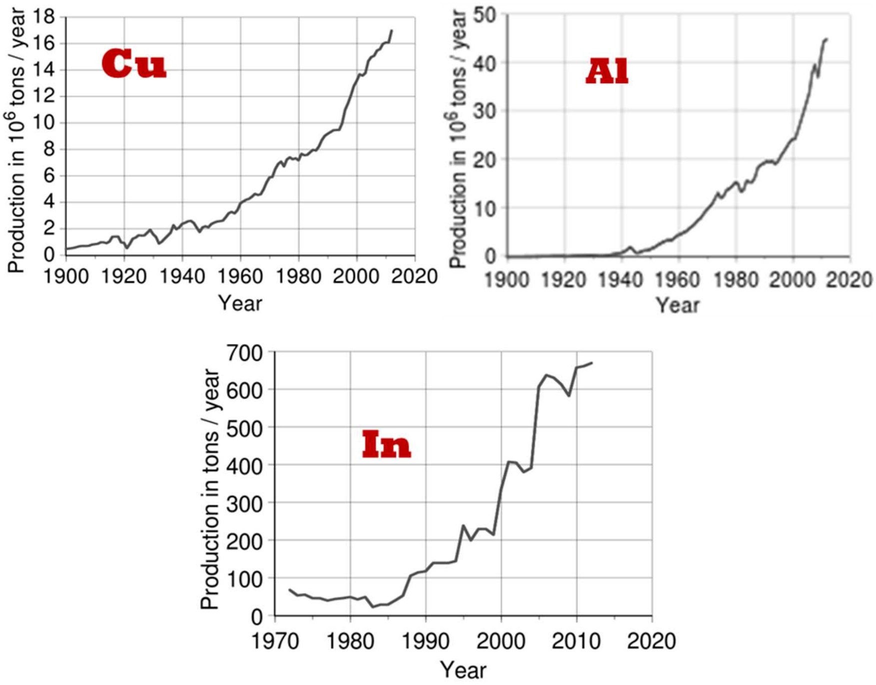

FIGURE 1: Historical chart of the world production of copper (cu), aluminium (al) and indium (in) in tons per year (data from US Geological Survey - https://www.usgs.gov/centers/nmic/commodity-statistics-and-information)

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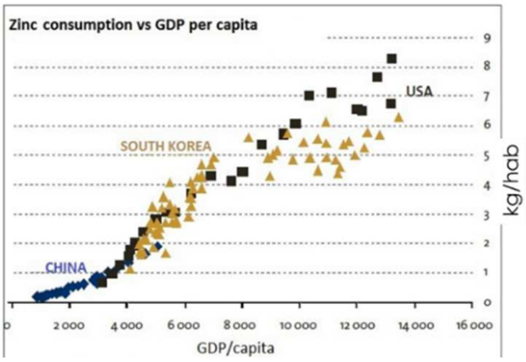
[1] The anthroposphere is materialized by the accumulation of man-made objects, buildings and infrastructures

The exponential increase in metal production during the XXth century is clearly linked to the development of infrastructures and technologies that also led to an increase in the gross domestic product (GDP) of the most technically advanced countries. Figure 2 illustrates that, based on current statistics, a Chinese baby will require throughout his lifetime roughly six time less zinc than an American baby. Similar values have been published for base metals in a major report on mining and sustainable development (IIED, 2002), confirming the orders of magnitude and indicating that the difference with a baby from the less technologically advanced countries in Africa and the Middle East is certainly ten and often thirty times!



	ALUMINIUM kg/cap	COPPER kg/cap	LEAD kg/cap	STEEL kg/cap
United States	22.3	10.9	6.1	458.2
Western Europe	14.2	10.0	4.0	381.1
Japan	17.7	10.8	2.7	562.8
China – India	1.9	1.0	0.3	74.4
Africa–M.East	0.7	0.3	0.2	9.3

Figure 2. Correlation between apparent zinc consumption per capita and gross domestic product (ilzsg.org). Average consumption of base metals per capita for different regions of the world in 2000 (IIED, 2002 chap. 5)

Considering that there is no reason to think that the population growth will notably slow down, one might expect, and even hope, that more regions of the world will access better standards of living. It is therefore undisputable that the exponential growth of metal production will continue for several decades and will probably even accelerate due to the energy transition.

MORE FROM LESS

In recent years, several graphics have been published in the USA, Europe or Japan linking GDP to resource use and energy use. They all tend to show a clear deviation from the almost perfect correlation observed until the end of the XXth century. This apparent decoupling is a key element of the European Green Deal strategy aiming at reducing greenhouse gas emissions by 55% while maintaining a steady rate of economic growth (Fig. 3).

Similarly in the USA, a recent book by McAfee (2019) "More from less" claims, on the basis of figure 3, that "*a great reversal of our industrial age habit is taking place. The American economy is now experiencing a broad and often deep absolute dematerialization*"…

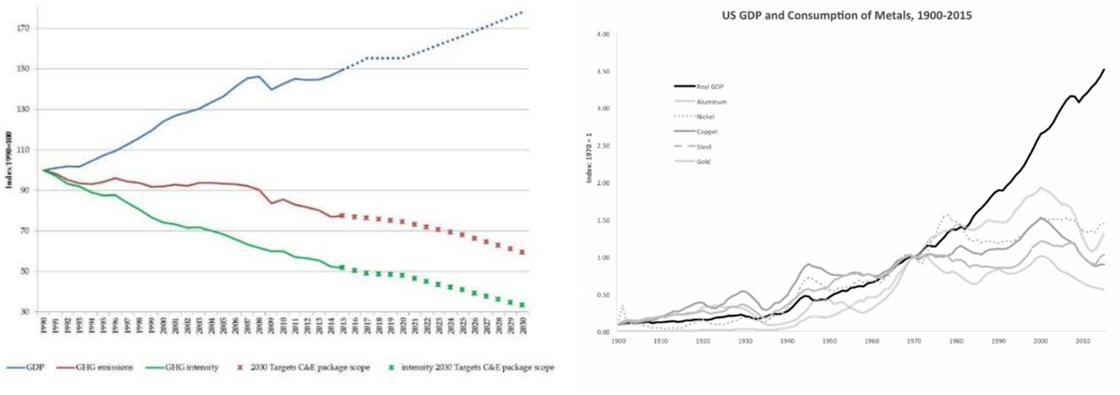


Figure 3. Historic and projected changes in GDP (in real terms), greenhouse gas (GHG) emissions, and emissions intensity of the economy (ratio between emissions and GDP) index (1990 = 100). (European environment agency). Real GP of the US vs metal consumption during the period 1900-2015 (McAfee, 2019)

Dematerialization is often represented using a top-down model linking GDP and resource use (Watari et al., 2018). The data for copper consumption per capita in Japan provide a typical example as it seems consumption has been slowly decreasing since 1990, while the GDP continued to rise. The interpretation of the observed U-shaped curve is often that infrastructure (roads, buildings, railways,…) have reached maturity in technically advanced regions of the world and that the economy is shifting to a service-based economy. Resource efficiency and optimization of manufacturing processes then further contribute to inflect the curve downwards.

The worldwide data for copper consumption vs. GDP plot at the basis of the curve and seem to follow exactly the same ascending trend, which could be interpreted by saying that the rest of the world is enjoying better living standards and that the need for resources will reach a horizontal asymptote within a few decades.

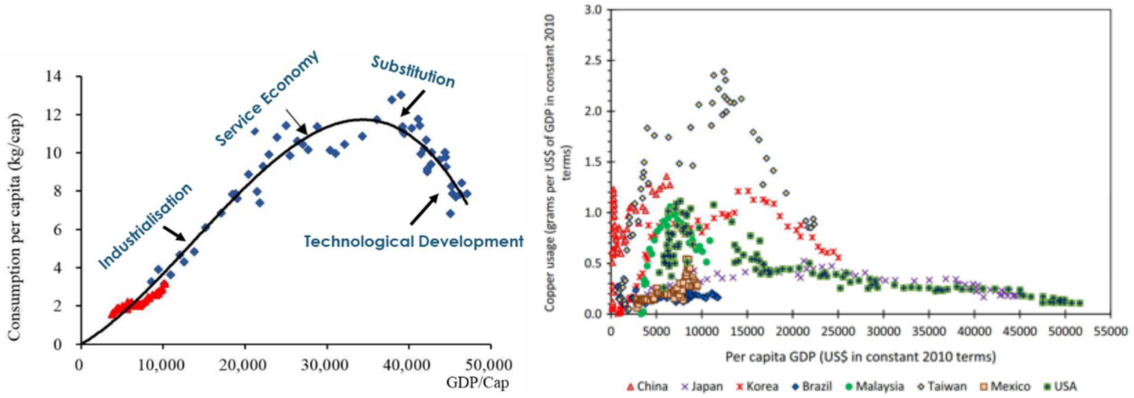


Figure 4. Approximation of the top-down model for copper consumption in Japan (blue ◊) and indication of the world copper consumption vs GDP (red ◊) (after Watari et al. 2018). Same correlation established for individual countries showing notable differences between Japan (blue x), South Korea (red x) or Taiwan (◊) (Crowson, 2018).

It is most probable however that the reality is not that one and that our statistics on flow of metals do not properly take into account the balance of metals present in the manufactured goods that we import massively from third countries. Today, none of the products we buy come together with a material bill. In other words, we know how much sugar is present in our jam and how much palm oil is in our chocolate pasta, but we have no idea how much silver is in our solar panels or how much indium is in our TV screen! When looking closer to the metal production data per capita, we notice that South Koreans consume 21 kg of aluminium per year, whereas Belgians satisfy themselves with "only" 9 kg per year! Knowing that all our batteries are imported and that an ever-larger share of our electronic goods and cars are manufactured in Asia, a closer look to the data is needed.

As correctly pointed out by Crowson (2018), the discussions about the intensity of use of resources are biased because they cover too short a time span and ignore important structural changes in trading relationships during the recent decades. He also stresses the deficiency in the metal consumption statistics which refer to first use of crude steel or refined copper rather than on the amounts of material actually used in final products within a country. Last but not least, data are simply not available for many individual countries and commodities which precludes any form of advanced analysis. As a confirmation of our earlier comment, Crowson (2018) indicates that manufacturing accounts only for 29% of the GDP share in South Korea, whereas it accounts for 90% of its exports!

Interestingly, the author provides a country-based plot of GDP vs copper consumption that clearly shows how different the curve is from one country to the other. Whereas the average world data seems to fit the Japanese curve of figure 4, it is quite evident that this is not the case for individual countries and notably not for South Korea, Taiwan or China.

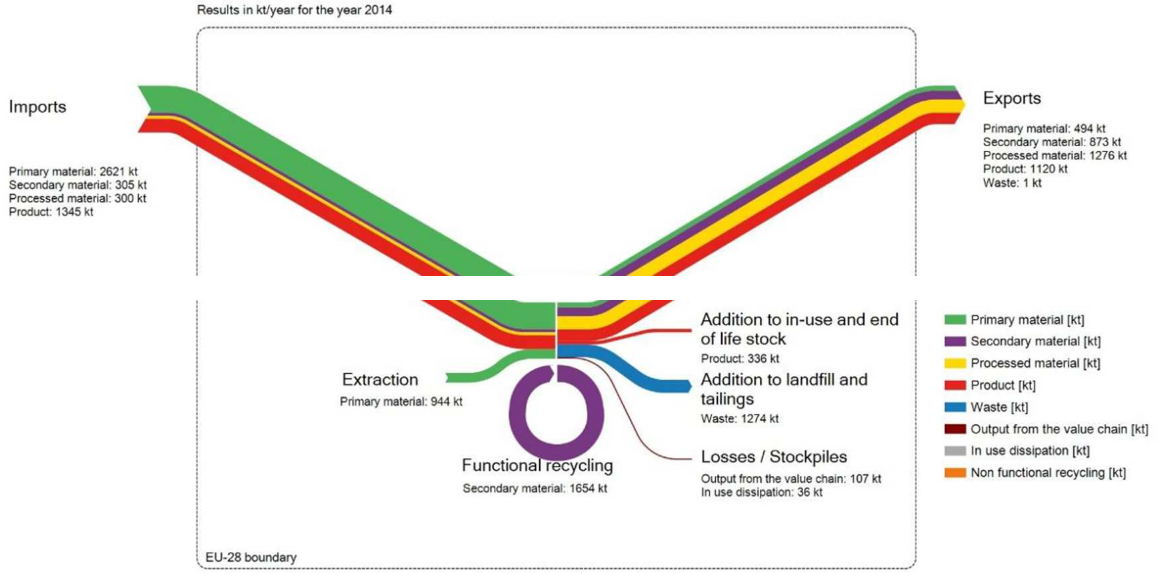


Figure 5. Simplified Sankey diagram for copper flows in the European union (Passarini et al., 2018)

Efforts are being made by the European Commission to improve the quality of statistics and notably to develop a Material System Analysis (MSA) from cradle-to-grave. A recent publication (Passarini et al., 2018) provides a more accurate picture for the flows of aluminium, steel and copper in the EU-28. Figure 5 shows a simplified Sankey diagram for copper indicating that 1345 kt of Cu are present in imported products, whereas 1120 kt of Cu are found in exported products, resulting in 336 kt of Cu being added every year to the in-use and end-of-life stock (Fig. 5). Although these data are probably still very approximate, they represent a real effort to get a better picture of the reality of metal flows and stocks in our society.

By contrast, statistics for important metals such as nickel, silver or tin and even more for essentially for E-technology metals are less well known (see Raw Materials Information System: http://rmis.jrc.ec.europa.eu). Their correlation to GDP follows a different trend and almost certainly one that is still steeply ascending. In order to have some insight into the future, it is interesting to have a closer look at the current technological trends and their appetite for metals.

CRAVING FOR METALS

Since the dawn of time, technological progress has been characterized by radical innovations but also by a continuous optimization in the use of resources. The development of advanced software tools utilizing for example finite element modelling have superseded the limits of conventional calculation and provided many ways to develop resource and energy efficient technologies. The exact amount of concrete required for a bridge or the exact thickness of a steel sheet to provide the desired resistance can be very precisely calculated. Thanks to advanced modelling, combustion engines have managed to provide the same power for much less liters of gasoil and car bodies are manufactured with lightweight materials providing the same safety standards.

Progresses in material sciences and specifically in structural materials have also been spectacular with the advent of high-strength low alloy steels and more resistant aluminium alloys. The first ones typically contain a tenth of a percent of niobium or vanadium, whereas the second ones only need one percent of scandium. Ever more complex and better-performing materials are being manufactured and synthesized using thin coating technology, 3D printing, fiber reinforcement, etc.

However, it can be observed that, almost systematically, any improvement in resource or energy efficiency induces a rebound effect meaning that the possible benefit is quickly sacrificed to provide a gain of performance in terms of comfort or security. This is perfectly exemplified in car manufacturing by comparing the same models at thirty years distance. Although the functional performance (km/liter of fuel) has been significantly improved, the overall weight of the vehicle and hence the amount of material required in the manufacturing has simply doubled (fig. 6)!

In a few other cases, such as polysilicon wafers, it is true that technical developments towards cheaper photovoltaic panels has led to developments where similar performance is maintained while reducing the wafer thickness from 300 µm down to 160 µm. But, this is a minor contribution to the overall resource intensity of the solar panel which also contains structural materials (aluminium frame, glass,…) and an increasing amount of electronics (silver, indium,…).

Figure 6. The same model has doubled in weight after thirty years of improvements in energy efficiency. The thickness of polysilicon wafers used in solar panels shows a downward trend from 300µm down to 160 µm.

The European Green Deal is motivated by the idea to transition towards a fossil fuel free economy. The intention is to intensify the deployment of renewable energies, to develop smart energy storage, to promote e-mobility and to heavily rely on advanced sensors and digitization to optimize all our products and processes. Although, it is barely mentioned, this will not happen without a significant increase in metal production. Needless to say that the transition towards a digital era making intensive use of internet of things (IoT), artificial intelligence (AI), sensors and big data will require huge amounts of technology metals such as Indium (touch screens, diodes,…), Gallium (diodes,…), Germanium (fiber optics,...), Tantalum (capacities,…) etc.

Innumerable studies have tried to compare the relative merits of an ICE (internal combustion engine) vehicle with respect to a BEV one (battery electric vehicle). When considering only the manufacturing stage, most authors agree that the demand for, and the diversity of, metals is significantly higher for BEV’s (Fig. 7 and 8). This is due to the battery pack but also to the ever increasing amount of electronic components on board of vehicles. Several reports indicate that the transition towards electric mobility alone will induce a huge increase in consumption of important metals such as Copper (+20%), Cobalt (+2000%), Nickel (+120%), Lithium, etc. (Mc Kinsey, 2018; EU Commission, 2018).

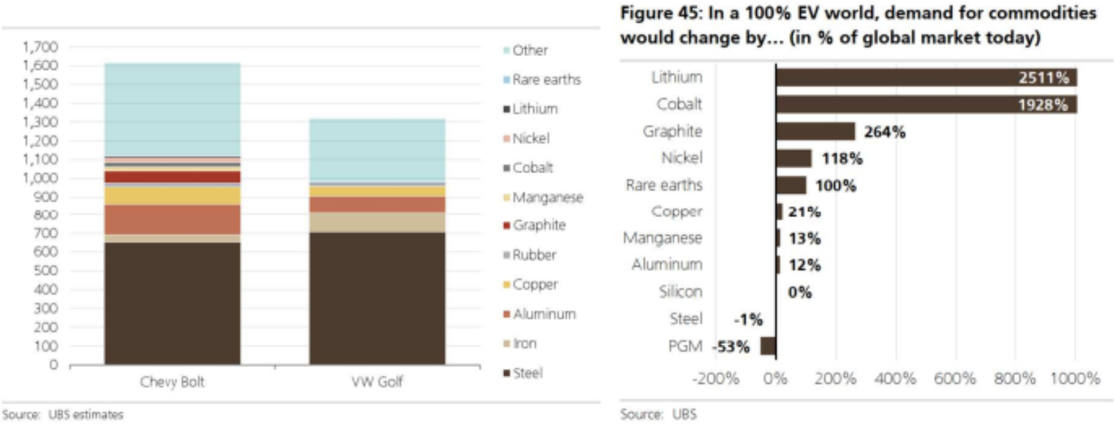
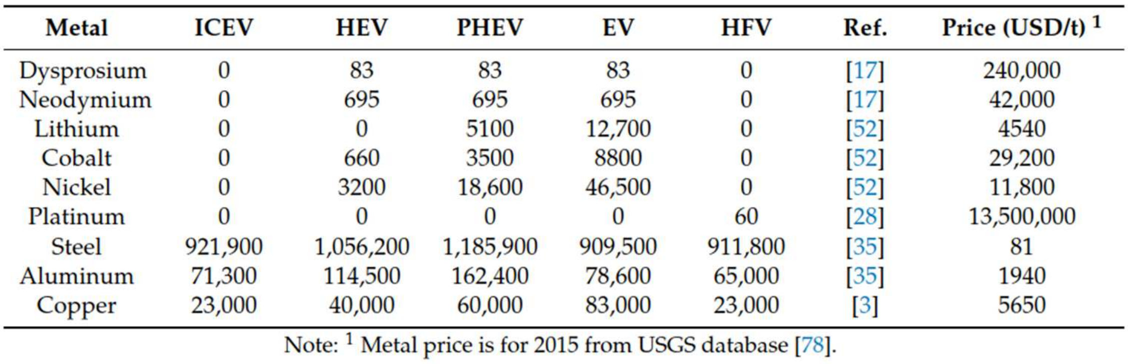


Figure 45: In a 100% EV world, demand for commodities would change by... (in % of global market today)

Source: UBS estimates

Source: UBS

Figure 7. Estimated amount of metals in BEV and ICE cars of comparable size and consequence on the increase in demand for commodities if switching to a full e-mobility (UBS, 2017).



Metal	ICEV	HEV	PHEV	EV	HFV	Ref.	Price (USD/t) [1]
Dysprosium	0	83	83	83	0	[17]	240,000
Neodymium	0	695	695	695	0	[17]	42,000
Lithium	0	0	5100	12,700	0	[52]	4540
Cobalt	0	660	3500	8800	0	[52]	29,200
Nickel	0	3200	18,600	46,500	0	[52]	11,800
Platinum	0	0	0	0	60	[28]	13,500,000
Steel	921,900	1,056,200	1,185,900	909,500	911,800	[35]	81
Aluminum	71,300	114,500	162,400	78,600	65,000	[35]	1940
Copper	23,000	40,000	60,000	83,000	23,000	[3]	5650

Note: [1] Metal price is for 2015 from USGS database [78].

Figure 8. Metal intensity in next generation vehicles in grams (combustion (ICEV), hybrid (HEV), plug-in hybrid (PHEV), electric (EV) and hydrogen (HFV) (Watari et al. 2018)

In fact, whatever the domain we consider, the trend is to move towards ever more complex and sophisticated technologies requiring a wider diversity of metals and embedding them in ever more complex assemblages. To illustrate our purpose, we can use several examples from the most basic technology for water distribution to the most advanced lighting and energy storage solutions.

For centuries, the water distribution system has been relying on pure metals, with the oldest lead pipes being replaced in the sixties by copper or stainless-steel pipes for obvious sanitary reasons. Most recently, so-called multilayer PEX-Al-PEX tubes have quickly penetrated the market with arguments of lower costs and easier doit yourself implementation. Indeed, bending and connecting PEX-Al-PEX tubes is a child’s game compared to copper tubes requiring professional skills. However, their manufacturing is more energy intensive (aluminium, Polyethylene, brass,…) and their recyclability is simply hopeless, compared to the mono-material nature of the copper tubes!

The lead-acid battery is another proven technology which remains unbeaten until today when it comes to storing electric energy and delivering instantaneous power to the starter of a combustion engine. However, considering their low energy density by weight compared to the most recent Li-ion batteries, it is evident that they have no future in e-mobility. With lowering production costs and an attractive “lead-free” labelling, Li-ion batteries will most probably submerge the future electricity storage market even where the energy density per weight is not a critical issue (ex. domestic power banks in the remote countryside of Africa)! But again, when looking at the bill of materials entering into the manufacturing and when considering the efficiency of recycling, there is no hesitation as to which technology is superior and should be promoted wherever possible!

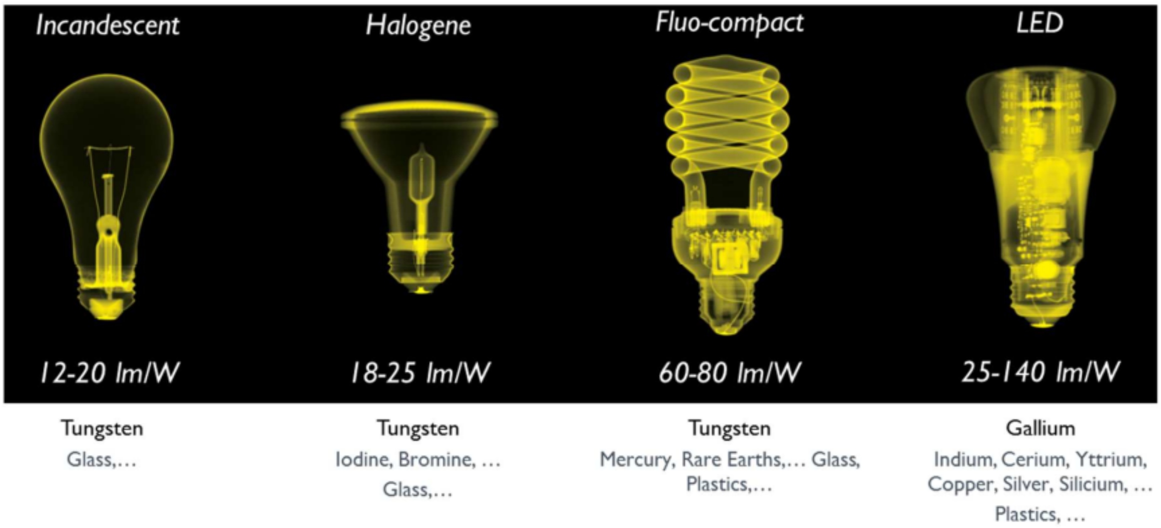


Figure 9. Evolution of the energy efficiency and material bill of a light bulb throughout the XXth century.

Last but not least, the king of the light bulbs throughout the XXth century has been the incandescent tungsten filament promoted by Edison. This wonderful easy-as-pie technology has been banned from the market since 2012 because of its poor energy-efficiency delivering only on average 15 lumens per Watt. Since then, the incredible light emitting powder diode, which earned their inventors a Nobel prize in 2014, has revolutionized the lighting of our cars, houses and streets. Because of its potential to reduce the energy bill to one tenth during its lifetime, LED-lighting is widely advocated by the Green parties. However, when considering the whole life cycle of a light bulb from cradle (sourcing of metals) to cradle (recycling and reuse of the metals/components in new technologies), it readily becomes evident that the superiority of LED-lighting is not really demonstrated and that many efforts are still required, especially in terms of design for disassembly and recycling.

These three examples, among many others demonstrate that while we have done fantastic progress in terms of functionality (usage phase), we have completely disregarded the sourcing and widely underestimated the recyclability of our new technologies. The XXIst century technologies will have to be dramatically redesigned and build for lasting much longer if we want to contribute to a more circular economy in the nearby future. They will also need to privilege metals which are abundant and which have low embodied energy whenever possible.

WHY METALS SUDDENLY BECAME CRITICAL?

The history of mankind is an endless list of conflicts and wars triggered by the quest for resources. Until very recently, leaders of small communities as well as larger countries always kept an eye on their sovereignty in terms of food, energy and materials. However, in the last decades, with increasing globalisation and ever more liberal trade agreements, the most technologically advanced regions of the world lost sight of their sovereignty on mineral resources and stopped worrying about their supply chain. It is only with China's unexpected declaration of a ban on rare earth (2009) that the sudden awareness of a possible supply risk gave birth to the notion of criticality. Since then, Europe in particular, but also Japan and the USA, have regularly monitored and updated the list of the metals they consider as being critical.

The most recent publication (European Commission, 3 Sep 2020) analyses a wide list of metals and based on subjective thresholds identifies thirty of them as being particularly sensitive for the European economy (Fig. 10). Despite a lot of confusion about what criticality exactly means and which mitigation measures should effectively be taken, it is obvious that metals appearing on the criticality list suddenly gain a disproportionate interest in the media and even trigger the launch of scientific publications or the creation of dedicated congresses. First, one should always keep in mind that criticality is variable both in time and space. In other words, a raw material can be very critical for the economy of a region or a given industrial player but have only limited impact in a neighboring region with a different economic ecosystem. Second, criticality is very sensitive to any change in trade relationships between countries and also to the advent of new technologies which heavily rely on an element which is hard or eventually impossible to substitute (ex. the red luminescent phosphors of our screens require yttrium tri-oxide doped with europium… and there is no real alternative!)

In simple terms, criticality is an aggregated index representing several dimensions among which the most important are the supply risk (geopolitics), the economic importance (technology) and to a lesser extent the natural scarcity (geology). Very often, criticality is dominated by the supply risk index since only one country represents a large share of the world production. This is obviously the case for the REE (Rare Earth Elements) and Tungsten which are predominantly mined in China since the end of the eighties, but it is also the case for Niobium (Brazil), Phosphorous (Morocco), Platinum Group Metals (RSA, Russia) and even Strontium produced in… Spain! This focus on geopolitical dependency often hides the real economic impact that a shortage of a less-critical base metal could have. As an example, the non-ferrous industry has regularly insisted that even common metals with a good diversity of supply such as nickel or copper should be a focus of strategic attention.

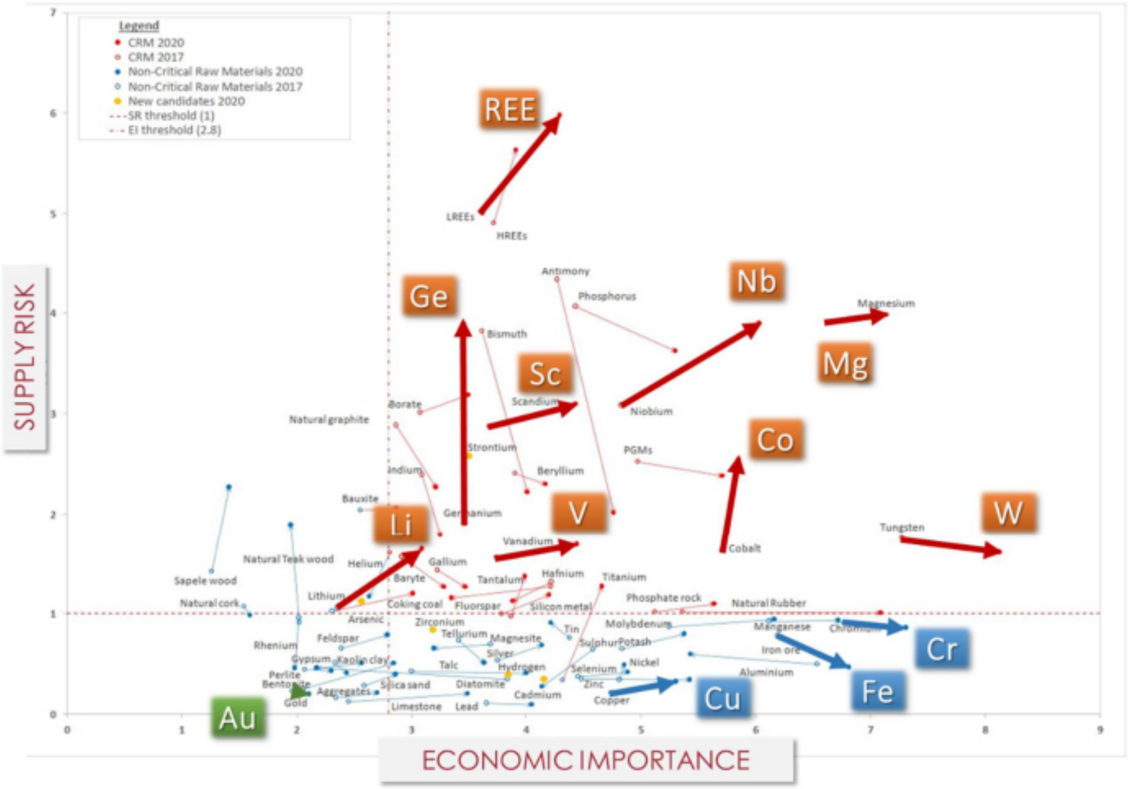


Figure 10. Evolution of the European criticality analysis for a series of metals from 2017 till 2020, visualised in the two-dimensional space of "supply risk" vs "economic importance" (after EU commission, 2020).

As shown on figure 10, the less critical metal of all is … gold! Not only is it mined in many different countries, but most of our technologies could easily do without. Despite this, gold mining is the biggest (metal) extractive activity with a global market of 170 billion US $ ahead of iron and aluminium mining!

As a response to the increase of the number of critical metals and the persisting weakness of the industrial supply chain, Europe has very recently launched the Raw Materials Alliance (ERMA, Sep 29th 2020) with the aim to tackle its resource dependency and support the development of a local supply and manufacturing value chain, especially for supermagnets and, in the longer term, for energy storage technologies. Several important projects have the ambition to manufacture technologies based on a local and/or responsible sourcing of metals (European Battery Alliance, 2020).

It might sound surprising to many, but with a few exceptions, the European basement is largely unexplored and contains most metals necessary for our future technologies including certainly rare earths, germanium, tungsten, etc. The main problem is labour costs and, to say the least, the total lack of social license to operate. Many mining companies have experienced violent opposition by NGO's even before initiating any exploration campaign.

FROM RESERVES TO RESOURCES AND … ULTIMATE RESOURCES

From the above, it is clear that we will need mineral resources more than ever to tackle the energy transition and to satisfy a growing fraction of the world's population. Although it has to be promoted, it should be made very clear that recycling alone will never be able to provide the amount of resources required. This is particularly true for many metals which have not been used intensively in the past and are thus not present in sufficient quantities in the loop. Lithium, Germanium or Gallium, to name a few, are among those metals which are crucially needed in large quantities for batteries, aluminium optics or diodes and which cannot be harvested from the urban mine. Even for base metals, recycling will not substitute mining before long. Let us consider the case of copper. This metal has been used intensively in wires, tubes, printed circuit boards or as brass and bronze in many mechanical devices. On average these technologies have a lifetime of forty years, which means that even if we were able to perfectly collect and recycle all end-of-life products, which is clearly impossible, this would barely correspond to the production of forty years ago… which is only about half of our annual consumption today (Fig. 1).

Mining is the future! Especially in Europe if we want to somehow mitigate the raw materials dependency. But by saying this, the question immediately arises to know whether enough resources will be available in the foreseeable future. The answer is yes, but at the same time all geologists must confess that the exact amount of remaining resources is unknown and that estimates can vary extremely widely from one author to the other.

For non-experts, it is essential to understand that geologists, when reporting their discoveries, make a major difference between two words used in everyday language: resources and reserves.

As shown in fig. 11, resources correspond to the reporting of tonnages and grades of mineralised rocks discovered during the exploration phase. Resources are reported as inferred, indicated or measured depending on the degree of confidence of the geological interpretation. As an indication, it should be noted that the serious evaluation of a significant deposit to establish the existence of indicated and measured resources requires years of efforts and more than 200 km of drill cores!

Reserves are only a small subset of the resources which have undergone a full feasibility study. Tonnages reported by mining companies as being within their proven reserves correspond to volumes of ore for which they have all licences and which can be mined and processed using currently existing technologies. By definition, reserves will generate a benefit given the current operating costs. This means that any change in technology, operating costs or metal prices immediately impacts the volume of existing reserves. A new tax regime can shift proven reserves to probable, but an increase in the metal price can also suddenly unlock resources and bring them into the reserves category.

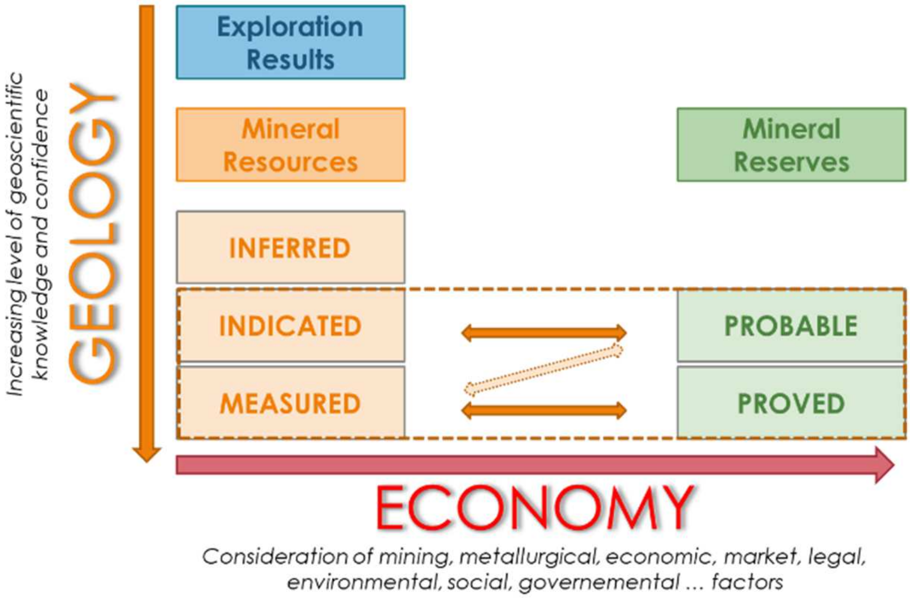


Figure 11. Resources and reserves as reported by geologists following international rules

Resources and reserves data are made public by individual mining companies and are compiled by specialized institutions such as the US Geological Survey. With a few exceptions, reserves represent a total quantity roughly equal to fifteen or twenty years of production at steady state. As a consequence, many alarming publications by poorly informed authors claim that we will run out of lithium, cobalt or even copper within twenty years. This is totally wrong! The only conclusion that could be drawn from these numbers is that the planning of a mine operation is best based on a twenty year period (Fig. 12).

	2000	2016
RESERVES	190 Mt	200 Mt
ANNUAL PRODUCTION	7,75 Mt	13,4 Mt
LIFETIME +5% SCENARIO	16 years	years

Figure 12. Global reserves for zinc vs. Annual production as published in 2000 and 2016 (data USGS)

Geological exploration is a very high-risk activity in terms of financial return. Typically, only one discovery out of 1000 (0,1%) turns out to be an economic deposit. This explains why many mining companies are reluctant to fund exploration campaigns and definitely stop searching for additional deposits once they have secured enough resources for the twenty years to come. It also explains why current reserves are mostly located in brownfield areas and why many regions of the globe are still unexplored. In addition, very large regions of the Earth crust are very difficult to explore because of extensive ice, sand or vegetation cover (Canada, Siberia, Sahara, Australia,..). It is considered that, with a few exceptions, deposits currently known either crop out to the surface or show anomalies within the first three hundred meters of the crust. Despite improvements in geophysical technologies, it is still very difficult to identify mineralization at greater depths and it becomes quickly prohibitive to drill and properly estimate resources (Schodde, 2019).

What is sure is that mining deeper will require an extra amount of energy. Undoubtedly, metals will become more expensive, and their embodied energy will increase. We will definitely need more metals for producing energy, but also more energy to extract metals! Several authors also claim that higher extraction energies will be the result of decreasing ore grades (Calvo et al., 2016; Northey et al., 2014). Indeed, plotting the average ore grade of mine production from 1850 until today shows a spectacular downward trend. But, just like a grade tonnage curve must be used to properly describe a deposit, the average grade curve cannot be considered without putting it in parallel with the exponential increase in tonnage production (Fig. 1) and the occurrence of technological disruptions (blasting, flotation, automation, …). From a geological perspective, every metal should be discussed separately and there is no reason to affirm that metal grades will necessarily go down while going deeper. If our sourcing of aluminium, nickel or lithium will be necessarily different when going to greater depth, there is no good reason to think it will be the case with copper, chromium or rare earths to name a few.

It is the role of public institutions known as geological surveys, to make an inventory of the resources and potential exploration targets of a given country and to contribute to the exploration of the more difficult regions of the earth crust. But in many countries, the geological surveys have very limited human and technical means and in Belgium it has even been integrated into the Natural History Museum!?

As said before, the lack of exploration (and motivation to explore!) makes it difficult to speak and speculate about the ultimate resources. Considering that technically one could probably mine down to ten or fifteen kilometres and given the current mining technologies and geological knowledge, it is reasonable to say that enough resources are left for many generations whatever the metal considered. For copper, a reasonable estimate is at least five hundred years and probably two thousand years at current consumption rates (Arndt et al. 2017)!

The above estimate is valid for resources from the continental crust, including submerged continental plateaus (sea floor resources at depth of 0 to 500 m). It does not take into account the oceanic crust (ocean floor at depth of 3000 to 5000 m). The reason is that the oceanic crust is thinner, has a different composition and offers much less potential for many types of mineralisation due to the absence of deformation, accretion and segregation. In a nutshell, the oceanic crust has potential interest for certain metals linked to so-called mafic magmatic events (Cr, Cu, Ni, Co, Fe, Mg, Mn,…) and it is especially interesting for polymetallic nodules which are easy to harvest with minimal impact on the environment, but it has no interest for Li, W, Sn, Al and other lithophile elements.

Despite many claims and spectacular fund-raising speeches, asteroid mining is complete non-sense. The many reasons are the lack of serious energy sources, the lack of appropriate mining and mineral processing technologies, the prohibitive cost of transportation, but most importantly the fact that the composition of asteroids is by no way exceptional. Two ongoing missions (Hayabusa 2 (JPN) and Osiris-Rex (NASA)) will bring back samples of asteroid surfaces in the upcoming years, but it is already expected that there will be no surprise and the composition will be close to well-known meteorites (chondrites) which show no specific concentrations with respect to the earth crust even for precious metals such as the platinum group elements.

As a conclusion, metals will require ever more energy for their extraction in a foreseeable future. Although it is a matter of concern and vigilance, it is not necessarily a problem if we manage to keep in the long term the level of energy (purity) initially achieved through the metallurgical process. This will be the role of recycling as discussed in the next paragraph.

DESIGNING THE URBAN MINE

It makes no doubt that the circular economy paradigm is essential to help us shape the future of our metal intensive society. The idea of a material cycle, inspired by other natural cycles, was already very well understood by Anaxagoras (500 BC) who said “For nothing comes into being nor yet does anything perish, but there is mixture and separation of things that are. So they would do right in calling the coming into being 'mixture,' and the perishing 'separation”. Our current understanding is such that we know that metals do not disappear nor break down but remain available for those who are capable of extracting them out of the urban mine and bring them back into a new production cycle. By saying so, the circular economy principle tends to overemphasize the role of processing at end-of-life (or recycling) as the main driver of circularity. It is very important to understand that the circular economy will not be circular before long and that a correct representation is given in figure 13. This clearly indicates that the loop still needs to be fed as discussed before and that recycling is the very last option to be considered. It is also important to keep in mind that recycling is energy intensive, can never be 100% efficient and will most often slowly degrade (downcycle) the quality of a material. To put it even more bluntly, an excellent recovery rate of 95% means in practice that half of the material will already be dissipated after only 14 cycles $(95\%)^{14}$ = 49%! If we want to achieve a more circular economy we absolutely need to improve our product design and durability. There is a need to raise consumer awareness in order to slow down the loop. This can be achieved by keeping our goods much longer by privileging care, reuse, repair and a sharing economy.

Figure 13. The circular economy (europarl.europa.eu) of metals is a long term objective, urging us to address four main challenges: feed the loop (mining), optimize the loop (product design), slow down the loop (business models), close the loop (recycling).

With regard to critical raw materials, it is important to spread the message among engineers who are currently designing the future technologies that they should not necessarily worry about the limited availability of resources, but that they should make sure the metals they use will remain available for use by the future generations.

The recent European directive on the “right to repair” is a good step forward to facilitate reuse and repair of products. Further improvements are still needed to develop design for dismantling and design for recycling by establishing a dialogue between recyclers and product manufacturers and by penalising products which do not obey basic rules of recyclability (instead of a value-added tax (VAT), one could think about a value-degraded tax (a VDT!?).

A typical example of a poor design for dismantling is given by Si-based PV panels. These are essentially very thin slices of silicon wafers glued onto a glass support and embedded in an aluminium frame. Silicon being the most abundant element of the Earth crust after oxygen, one might consider that recovering it at end of life is unimportant, but the refinement process of silicon to the level of “photovoltaic grade” is very energy intensive (60 to 200 kWh/kg!) and requires rather scarce high purity silica sources. Recovering pure silicon must be considered as a priority in the development of sustainable PV panels, but the problem is that due to the glued assemblage no PV panel recycling process can avoid breaking and contaminating silicon wafers. The recovered silicon, if any, can only be down-cycled into less demanding applications or the very energy demanding refining process has to be restarted!

Examples of poor design for recycling are unlimited. As mentioned previously, almost any recent innovation has taken the wrong direction. Whereas lead-acid batteries, copper pipes and incandescent bulbs can be very efficiently recycled, we now have a range of products that looks like a dreadful “elemental soup”. We claim those products are recyclable, but the truth is that the recycling process is very energy demanding and poorly efficient. With a few exceptions (e.g. gold from electronic waste, platinum from catalytic outlets or cobalt from Li-ion batteries), a lot of metals cannot be recovered economically due to the very low grades and the low metal prices. Figure 14 explicitly demonstrates that a simple smartphone is not very different from a piece of laterite (African soil sample). Gold, thanks to its high value, is a major incentive to develop a recycling process, but it is important to keep in mind that grade alone is not enough and that tonnages should be guaranteed to secure the long-term operation of a possible recycling plant. Many people do not realize that to compete with an average gold mine (15 tons of gold per year)… the urban mine should collect one billion smartphones every year!

O	35%
Si	21%
Al	11%
Fe	6%
Ni	1,5%
Ga	27 ppm
Pb	15 ppm

Phone + battery	
Cu	10,7%
Au	95 g/t
Co	8,4 %
Li	0,8 %

Figure 14. A piece of African soil (laterite) and a smartphone have a very similar composition with the exception of a few elements, notably copper, gold, cobalt and lithium. These last ones being essentially in the battery.

The permanent evolution of our technologies as exemplified by the light bulbs of figure 9 is another matter of concern. In the event that an efficient recycling process can be designed, the industrial risk of having to deal with a completely different feed material once the process is industrialised is often too high to be taken. An explicit example is given by Solvay's recycling process to recover rare earth from fluo-compact bulbs. The decision to scale up the plant in La Rochelle was never taken because of the low rare earth prices and the advent of LED bulbs with completely different compositions on the market (Delamarche, 2016).

SUBSTITUTION AND TECHNOLOGY EVOLUTION

In order to mitigate the criticality of an element it is often suggested to search for technical alternatives that allow to use a different element offering similar properties. This is known as substitution. A classic example of substitution is the replacement of aluminium by thin sheets of steel in beverage cans, reflectors or car bodies. Whether this is a good or a bad choice is often a matter of (eternal) debate, because the list of advantages and disadvantages is hard to compare even with advanced lifecycle analysis (LCA) studies. Replacing an element by another often means compromising on performance or durability. As an example, high-strength low alloy steel (HSLA) is often based on niobium, but could also make use of vanadium or even titanium which are less critical and more widely available. However mechanical properties are not strictly comparable.

In many cases, critical elements have simply no substitute. We already mentioned the red phosphor in our colour screens that can only be obtained from Eu-doped Yttrium oxide. Similarly, supermagnets are made of Nd2Fe14B wherein only a small fraction of Nd can be replaced by Dy…but both are rare earths and listed as critical.

In recent years, the substitution of cobalt in Li-ion batteries has been the subject of much attention. Cobalt plays a crucial role in terms of charging rates and stability, but researchers have managed to maintain the performance of the battery while replacing an increasing amount of cobalt by nickel. It is now well known that the current Ni5Mn3Co2 technology will be replaced by Ni8Mn1Co1 technology in the upcoming years (Fig. 15). Strangely enough, it is not so obvious that this is a good move for at least two reasons:

- First, cobalt is considered critical because two thirds of the world production comes from a country with a poor governance score (the World Governance index (WGI) is considered in criticality). Cobalt is often pointed out as being the bad boy linked to child labour in Central Africa. But, it should be made clear that only 20% of DRCongo's cobalt is produced by artisanal and small scale mining (ASM) and most of it without any child labour. Banning Congoles cobalt will have a tremendous social impact in one of world's poorest countries, whereas the promotion of responsible mining could lead to a win-win situation.

- Second, cobalt is a metal with a higher cost than nickel. Lowering the cobalt content will lower the cost of batteries for manufacturers, but it might also impact the quality of recycling at end-of-life because of a much lower financial benefit for recyclers.

As a conclusion, substituting an element because it is blacklisted as a critical raw material is not always a good idea. Substitution should be motivated by other factors such as a lower environmental impact (evaluated through a lifecycle analysis), a higher product performance, a longer lifetime, a better recyclability, etc.

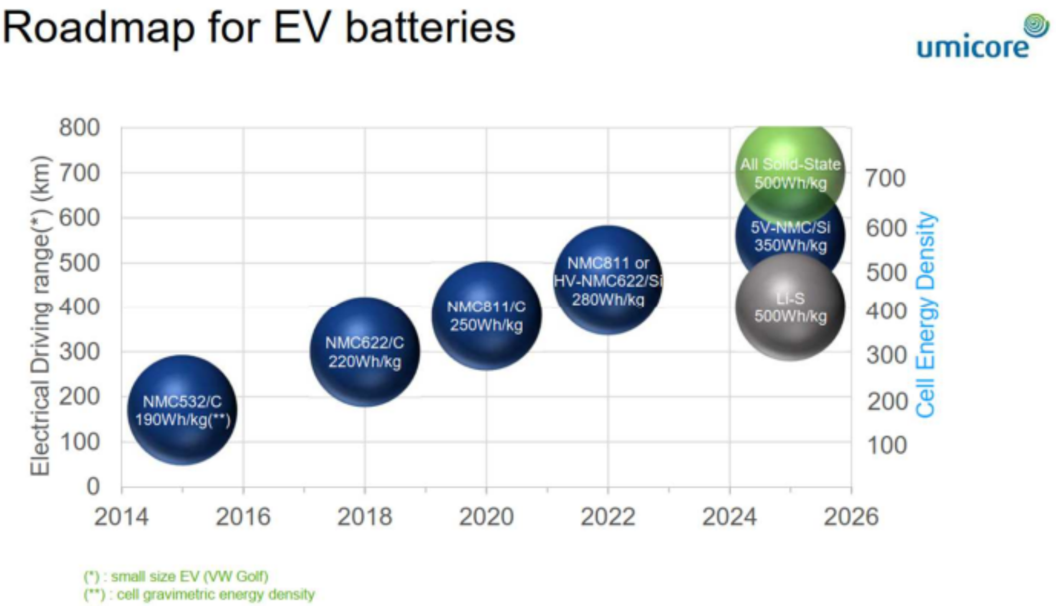


Figure 15. The roadmap for BEV batteries at the 2026 horizon considers the evolution of li-ion batteries towards lower cobalt contents (811) and finally the emergence of solid state batteries such as lithium-sulfur (Stassin, 2018)

CONCLUSION

The road towards a more sustainable, resilient and nature-friendly society is paved with a lot of resource intensive technologies. Mining will be needed more than ever in the upcoming decades if we want a larger share of the world’s population to benefit from decent living standards. Dematerialisation is currently an illusion. If the most technically advanced regions of the world want to lower their footprint, they should consider product design and product durability (longer lasting technologies) as a priority. They should also invite their inhabitants to discover the virtues of a more sober way of living and consuming.

The resources that will be needed for the future generations are below our feet. With the eventual exception of easy-to-harvest deep-sea polymetallic nodules, future deposits are located in the continental crust. Their identification will require a worldwide effort to explore deeper. It should be the mission of an international earth-crust authority to federate all geological surveys in building together a digital twin of the first kilometers of our planet’s surface. With this, a good indication of the potential for future resources could be obtained and a better management of the worldwide resources could be set up. Without this, many metals will remain critical simply because of recurrent political tensions and unavoidable geological uncertainties. Our current understanding of the ultimate resources for most metals is such that no shortage is to be anticipated in the short term (one or two centuries). But, the lack of anticipation, the fast development of new technologies and the increased social opposition to mining, will certainly lead to regular crises in the supply chain of metals.

Developing a more circular economy is absolutely essential. The current take-make-dispose economy promoted by the “BIC generation” is unsustainable as it sends back to nature a lot of toxic but valuable products, components and metals. Reuse, repair and recycling are to be encouraged by all means (legislation, taxation, business models, technical innovation, etc.). The responsibility of manufacturers and product designers should be reinforced. They should not only offer a traceable and responsible sourcing of their raw materials, but also demonstrate their willingness to accommodate recycled materials into their new products.

Cities and regions should take initiatives to better collect end-of-life goods and take care of their final destination. Remanufacturing companies should be supported and advanced sorting technologies should be developed to allow for reuse of components and/or grouping of similar materials and alloys. Recycling facilities should be installed within coherent industrial eco-systems to lower the overall environmental footprint and to make sure recovered materials re-enter into the local production cycle.

Finally, probably the best analogy for thinking in terms of a sustainable raw materials value chain is the modelling clay (plasticine) game. At the very beginning of the game, we benefit from the pure colours of natural resources to manufacture our goods. If we play carefully the colours can still be separated at the end of the day and the resources remain available for the next players. But, if we mix them intensively, the same resources cannot be separated again and the game stops. This can also be expressed in thermodynamic terms with reference to preserving the quality of energy (exergy) and delaying the increase in disorder (entropy).

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