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DIGITAL ECONOMY GROWTH AND MINERAL RESOURCES

Implications for Developing Countries

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Digital economy growth and mineral resources: implications for developing countries[1]

Abstract: *This technical note examines the link between growing digitalization of the world economy and the demand for various elements. It feeds into the overall research work of the UNCTAD E-commerce and Digital Economy (ECDE) work programme.*

The study focuses on the following issues in view of the growing use of digital technologies: What metals/minerals will be more demanded as a result?; What changes in demand can be expected compared with today's situation?; Which mineral-rich developing countries are likely to be most affected by the growth in demand of different metals and minerals?; Which are the main actors (including possibly new actors such as digital companies) involved in the extraction, smelting and refining of these minerals and metals?; and How recyclable will these "new" metals be and to what extent may they be adding to the problem of "e-waste"?

Based primarily on desk top research, complemented by a few interviews with representatives from industry and academia, the study deals primarily with the functional parts of computers and other devices, which are at the core of the digital economy. Demands for raw materials from the structural parts of the devices and the networks necessary as well as their energy supply and the consequences of the transition to a fossil free world are not covered.

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[1] This technical note was prepared by Magnus Ericsson, Olof Löf and Anton Löf of RMG Consulting, with contributions and guidance from Torbjörn Fredriksson. Valuable comments were received from Shamika N. Sirimanne. The note was commissioned by the ICT Policy Section of UNCTAD as background for the E-commerce and Digital Economy work programme. Financial contribution from the Government of the Netherlands is gratefully acknowledged.

Contents

Executive summary

The fast-evolving digital economy demands an increasing number of elements for devices such as computers, mobile phones and networks. This study focuses on seven *information and communications technology (ICT) elements*: gallium, germanium, indium, rare earth elements (REEs), selenium, tantalum and tellurium. They are all "functional elements" that are essential raw materials for the building blocks for all ICT hardware, such as microchips and integrated circuits.

These ICT elements have become widely used during the past decades but mostly in minute quantities. Of the seven elements, only the REEs are produced in more than a few thousand ton globally every year. Even the REE production amounts to less than 200,000 ton compared to, for example, the 60 million ton of aluminium or 2 billion ton of steel. Aluminium and steel are "structural elements", used to house the functional parts of a computer and for the infrastructure around its core, such as energy storage, electric motors, etc. Together with the so-called battery metals (cobalt, nickel and others) these structural elements have been extensively studied and are not examined in this review. All the seven ICT elements have a wide range of uses outside the ICT sector. However, for gallium, germanium, indium and tellurium the ICT sector dominates. In 2018, the total value of the production of the ICT elements was around $5 billion, or 0.77% of all mined elements (metals and industrial minerals) excluding coal.

While REEs and tantalum are primary products from specific mines, the other five elements are by-products from copper, bauxite, lead/zinc or coal mines, extracted at later process steps of smelting or refining. The supply of these elements is in general not an issue. Only limited parts of what could potentially be extracted from the total volumes of the primary products is currently utilized. The small absolute production volumes needed make it realistic to cover also large future increases in demand for all the seven elements with limited investment and within short time frames, possibly with the exception of REEs.

The mines from which the seven elements originate are located all around the world. Among developing countries (excluding China), the Democratic Republic of the Congo (DRC), Rwanda, Brazil, Nigeria, India, Madagascar, Ethiopia, Thailand, Viet Nam and Burundi have the highest economic value of production of the ICT elements, ranking from $315 million in the DRC to as little as $10 million in Burundi. For Rwanda, the production of tantalum accounts for 68% of the total value of all metals produced there, making it the country in which ICT metals contribute the most to the national economy relative to GDP. For the other African countries mentioned above, ICT elements contribute 23% of the value of total mine production in Burundi, 15% in Ethiopia, 13% in Nigeria and 7% in Madagascar. In all these countries, tantalum is the most important element.

Meanwhile, China and in high-income countries host most of the smelting and refining steps, which are the most important in the global value chains related to the ICT elements. The ICT elements are often needed in extremely pure form, 99.999% (five nines or more, 5N+) purity, and a few such high-tech production units are enough to cover world demand. Chinese producers dominate production with around 90% of global output of gallium and germanium and some 70% of the REEs. For indium and tellurium, they account for half the world output while their share is below 25% for selenium and tantalum.

Traditional transnational mining companies do not have the tight control over the production of the ICT elements as they have over base metals, such as iron ore and bauxite. Relatively small and highly specialized companies account for the final and most important refining steps. The small volumes of production and the fragmented ownership structure make the related markets fairly opaque. The Chinese producers of ICT elements are often privately held which adds to the difficulties of finding data. The strategic importance for military purposes of some of the ICT elements have added another layer of secrecy, which makes it difficult to track who produced what and even more difficult to trace ownership of the companies involved. It is, however, clear that vertical integration remains limited in this sector.

Among the transnational companies, a handful are central to the entire sector: Umicore (Belgium), Teck (Canada), Indium Corp. (USA), Mitsubishi (Japan), Dowa (Japan). A few others are scattered around the world.

Opportunities for developing countries to benefit from increased demand for ICT elements are quite limited, mainly because of the small volumes demanded and the limited value of these elements in absolute terms. African production of tantalum represents 78% of total production and this is the only one among the seven ICT elements where mines in developing countries excluding China play a key role. For selenium, African production accounts for 11%, for indium 5% and for the remaining elements the share is negligible.

The present trade conflict between China and the United States and other high-income countries might lead to some restrictions of exports of ICT elements from China and possibly open up further opportunities for other countries. However, given the need for specific production facilities, skills and know-how to produce these elements, such a development would require significant investment in capacity development over several years.

The recycling rates of the ICT elements are high in that the amount of primary scrap recycled is considerable. However, recycling of end-of-life products, such as smart phones, is miniscule. New approaches with design for recycling and reuse and improved collection of used computers and smart phones will become necessary to change this situation.

Introduction

The pace of digitalization in the world economy is steadily increasing (McKinsey 2015, DERA 2016, UNCTAD 2019). Information and communications technologies (ICTs) are given a central role in these developments. Computer application software, in particular algorithms, have gradually come to influence life for billions of people around the world. The number of smartphones sold annually was about 1.3 billion units in 2019 (Mongardini and Radzikowski, 2020). In 2018, 9 billion items were connected to the Internet of Things and with an expected growth rate of 17% annually the number could exceed 22 billion in 2025 (McKinsey 2016, European Commission JRC 2020, DERA 2016). The amount of information and data produced, stored and exchanged is expected to grow even faster. Increasing at a breakneck speed by more than 500% between 2018 and 2025, when 175 ZB (zettabyte [2]) may be handled globally (European Commission JRC 2020). Some followers of these developments claim that when transitioning to 5G and 6G, demand for speed, capacity and new hardware will explode and possibly increase speed of change even more (Ny Teknik 2020). But even if computers, tablets and smart phones have become smaller and smaller but more powerful, following Moore's law, the sheer number of hardware items also creates a significant demand for a wide range of materials including many elements which have so far been of narrow scientific interest. The equipment for storage and distribution around the world of giant dataflows add to the raw materials demand.

Even in the emerging world of e-commerce and the digital economy, the hardware will retain a central position as will the surrounding infrastructure and support systems, in particular energy supply, and create additional demand for materials. The necessity to reduce the use of fossil fuels in global energy systems has speeded up the transition to renewable energy sources and new energy storage solutions. While the impact on the demand for metals and minerals by the transition to a fossil-free future has been relatively well studied (World Bank 2017 and 2020, UNCTAD 2020), the demand for raw materials created by hardware (such as computers, fibre optical cables, computer chips and its building blocks such as capacitors and others, diodes and screens etc) is less examined. It is this "core" of the digital economy that is in focus for this report, recognizing that also when expanding out of this core into the broader scope including e-commerce, e-mobility, industry 4.0 with robots, microprocessors and process control etc., these sectors will require huge additional amounts of raw materials. The digital sector is further enabling change and development in almost all other parts of national and global economies, thereby indirectly generating new demand for raw material.

The analysis contained in this report can be seen as a pre-study of the likely impact on demands and what implications this might have for mineral rich developing countries. It sheds light on the following five questions:

- What elements will be most affected by increased demand?
- What changes compared with today's situation can be expected?
- How will mineral rich developing countries be affected?
- Which are the main actors (including possibly new actors such as ICT companies) involved in the raw material supply for these elements?
- How recyclable will these elements be and to what extent are they adding to the problem of "e-waste"?

[2] One zettabyte is 10^{21} or one billion trillion transactions.

But before going into these questions, it will be useful to make a brief introduction to some basic chemical definitions.

Elements, metals and non-metals

The elements are the building blocks of all matter, whether the earth's crust, the oceans, the atmosphere, all man-made materials including textiles, plastic products and metal alloys or biological material and living matter. There are over 100 elements which are systematically organized in the periodic table according to their inner structure. Each element has been given an atomic number[3] according to how the number of protons it contains. Thus, elements close to each other in the periodic table often have similar properties.

The elements can be divided into metals and non-metals. Metals are typically elastic, ductile and strong, with good conductivity for heat and electricity (Enghag 2004). The remaining elements form the non-metals including gases, such as hydrogen, nitrogen and oxygen, and a range of other elements on the right-hand side of the periodic table (*Figure 1*). The border between metals and non-metals is not sharp, however. Elements along the borderline show both metallic and non-metallic properties. They are called metalloids or semi-metals. Many of the elements that are important for the production of various ICT goods belong to the semi-metals and are interesting exactly because they have this dual character and can behave as semiconductors. Silicon (Si) and germanium (Ge) in group 14 (column in the period table) are semiconductors but also elements on both sides in group 13 and 15 have semiconductor properties. Gallium (Ga), and indium (In) combined (doped) with phosphorous (P), arsenic (As), and antimony (Sb) give semiconductors with specific properties.

Figure 1 Periodic table metals, non-metals and semi-metals

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 La*	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 Ac**															

* *Plus lanthanides (period 6, group 3)* ** *Plus actinides (period 7, group 3)*

Shaded squares indicate nonmetals

Squares with double frames or indicate semimetals (metalloids) and semiconductors

Source: Enghag 2004.

[3] The figure in the top left corner for each element in the periodic table.

In the crust of the earth, elements are found mostly as minerals, which are combinations of elements. When these minerals are concentrated enough to make mining economically and technically viable, a mineral deposit is created. The traditional four main steps of metal production can start: mining, processing, smelting and refining. Many of the ICT elements are demanded in ultra-pure qualities which makes it necessary to refine to 99.999% and higher (5N, five nines) levels of purity and a second refining step is added which is often done by specialized companies with the required expertise. These final process steps treat very limited volumes of material, often only kg quantities, in each batch and under particular conditions, for example, a helium atmosphere.[4]

What elements will be covered in the study and why?

A computer could for simplicity be divided into two main parts: A structural part using mostly metals and polymers and a functional part with components including metals and semimetals/semiconductors.[5] Among the structural metals, aluminium, tin, nickel, steel, magnesium and lead are the most common. These are all widely used in many other applications and the use in computers mostly only accounts for a small part of their total usage.[6] The functional elements are often used in small quantities and include a large number of elements. Many of these have only found wide usage, even if in minute quantities in each smart phone or portable computer, during the past decades. As noted above, the focus in this paper will be on the functional metals and semimetals most directly related to ICT hardware.

Table 1 lists twenty-four elements which could be considered important for the digital future. It could be argued that additional elements should be included in the table. The explosion of elements that are present in a smartphone compared to a traditional fixed line telephone from the mid-twentieth century is frequently used as an illustration of the complexity of modern IT products (see for example Achzet et al 2012). The screen alone is made up of at least 14 elements (see *Figure 2*). Different memory technologies use aluminium, antimony, arsenic, chromium, cobalt, germanium, hafnium, indium, iridium, manganese, neodymium, nickel, platinum, ruthenium, selenium, silicon, tantalum, tellurium, tungsten, zirconium in all 21 elements mostly in minute amounts (European Commission JRC 2020). Given the nature of this brief study, however, it is not possible to analyze all of them in depth, and the use of, for example, aluminium in computer magnetic RAM memories is of no importance whatsoever on the overall aluminium markets or the potential for developing countries economies (Ku 2018).

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[4] Such new demands for helium have made that element potentially a critical resource and necessary for the production of ICT products but it is not covered in this study.

[5] The study does not deal with the polymers (plastic) which are mainly built by hydrocarbons (oil and gas) although they could also be produced based on plant and forest raw materials.

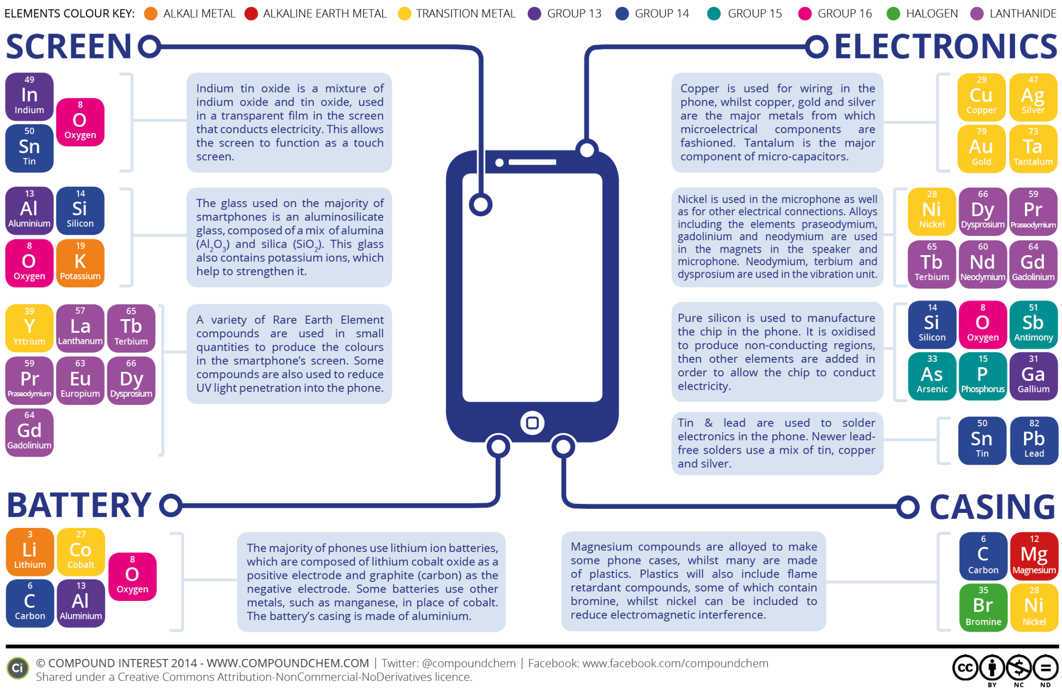
[6] It should be noted that the energy transition is not the main driving force behind the increase in demand for most high-volume metals, which will principally be generated by general economic and social developments caused by the growing global population and its generally increased standard of living. It is realistic to anticipate that these long-term underlying trends will continue.

Table 1 Elements important for the digital economy

Element	Symbol	Usage in ICT
Antimony	Sb	Alloying element in lead batteries.
Beryllium	Be	Electric contacts, communication satellites
Boron	B	Dopant in semiconductors.
Bromine	Br	Flame retardant in plastics cases for cell phones.
Cesium	Cs	Photoelectric cell components.
Chromium	Cr	Alloys.
Cobalt	Co	Rechargeable batteries.
Copper	Cu	Electric connections.
Gallium	Ga	Integated circuits, LED, photovoltaics.
Germanium	Ge	Fibre optics, IR technology.
Gold	Au	Microelectrical components, electric connections.
Graphite	C	Rechargeable batteries.
Heavy REEs (atomic number 63-71, for example dysprosium)	Dy	Magnets for microphones and loud speakers, displays.
Helium	He	Protective, shielding gas.
Indium	In	Displays.
Light REEs (atomic number 21, 39, 57-62 for example praseodymium and neodymium)	Pr, Nd	Magnets for microphones and loud speakers, displays.
Lead	Pb	Solder.
Lithium	Li	Rechargeable batteries.
Magnesium	Mg	Alloys for cell phone cases.
Manganese	Mn	Rechargeable batteries.
Nickel	Ni	Microphone, electrical connections.
Niobium	Nb	Alloys.
Platinum Group Metals (PGMs)	Pd, Pt, Rh, Ru, Os, Ir	Alloys
Selenium	Se	Photovoltaics.
Silicon	Si	Integrated circuits.
Silver	Ag	Microelectrical components.
Tantalum	Ta	Capacitors.
Tellurium	Te	Photovoltaics.
Tin	Sn	Lead free solder.
Tungsten	W	Dielectric materials, filaments.
Vanadium	V	Rechargeable batteries.

Sources: USGS, BGS, Enghag.

Figure 2 Elements of a smartphone



Source: Compound Interest 2014.

Against this background, the study does not include an analysis of the following elements:

- *Antimony* used to be an important alloying material in lead acid batteries but is nowadays mostly used as a flame retardant and hence not of key relevance to this study.
- *Beryllium* has properties that make it suitable for use in aircraft and space applications. It is an electric insulator with good heat conducting properties and is also used in high-density electronic circuits. The dominating use of beryllium is, however, as a minor component of copper-beryllium alloys with many applications in industry.
- *Cesium* is perhaps best known for its use since 1967 to define time in the cesium clock. Its industrial use is diversified but only marginally in ICT industries.
- *Platinum Group Metals (PGMs)*, in addition to ruthenium (discussed below), platinum and palladium are used for hard disks and multilayer ceramic capacitors. The main usage of both platinum and palladium is, however, as catalysts in, for example, catalytic converters for exhaust gases from petrol engines. The ICT industries generate only 10% of total palladium demand.
- *Rhenium,* although one of its important applications is as a material in electric switches, this is mostly for high-voltage applications. Further, rhenium is mainly used for alloys working at extreme temperatures such as rocket motors.
- *Ruthenium* is one of the PGMs, which is mainly used as an alloying element for platinum and palladium making them harder. A three-atom thick layer of ruthenium between two magnetic layers can improve the storage capacity of hard disks.
- *Silicon* is clearly of key interest as it is a semiconductor and is widely used because of this property as a foundation for integrated circuits. Silicon Valley that stands as a symbol for the entire ICT industries of the world is named after this element. A single crystal of silicon is cut extremely thinly and these wafers, semiconductor plates are used to manufacture chips with miniature electronic components such as transistors, diodes, resistors and capacitors. However, silicon is used in many other applications including

glassmaking, as an alloying metal in steel and cement and solar cells. Silicon is also the main components in quartz, which is used as an abrasive and as a flux material in metal production processes. It is not possible to find and separate out production statistics useful for the purpose of this analysis and hence, unfortunately, silicon cannot be usefully analysed here.

- *Tin* is one of the oldest known metals. A very thin tin layer improves corrosion resistance of copper, nickel and in oxygen free atmosphere such as in cans. Tin is also used in a range of alloys for example with copper in bronze. In electronics it is used in lead-free solders and in a thin film which conducts electricity used in touch screens. All of these applications in the ICT industries are however again marginal to other uses of tin.

Copper, gold and silver, which are used for their excellent electrical conductivity together account for more than 50% in value terms of a computer (Dedryver 2020), are also excluded. Only a marginal part of their production is used in the ICT sector and their supply situation and importance for developing countries are already well understood (Addison, Roe 2018).

There will be continuously increasing demands for elements in the batteries necessary for the energy supply of all mobile and hand-held types of equipment and as energy storage equipment to balance the swings in production of wind and solar and other renewable generation of electricity. Batteries are undoubtedly often an integral part of a computer but they are only mentioned here in passing. For details, readers are recommended to consider other studies (for example, UNCTAD 2020, World Bank 2020, Ericsson Löf 2020). The most important elements for present and future battery technologies are expected to include chromium, cobalt, copper, graphite (a naturally occurring crystalline form of carbon), lithium, manganese, molybdenum, nickel, niobium, platinum group metals, rare earth elements, tantalum, vanadium. In this study, only tantalum will be in focus as it is crucial also as a functional material.

With these exclusions, the seven elements that will be analysed below in more detail are: gallium, germanium, indium, rare earths (dysprosium, neodymium and praseodymium), selenium, tantalum and tellurium (see *Figure 3*). The rare earths constitute the bulk of the seven elements with 0.59% of the total value of all mine production of non-fuel minerals (3/4 of the total value of the seven elements alone) and the remaining six only 0.18% (1/4). In this study they are referred to as the *ICT elements*. A brief overview and presentation of the main applications of these seven elements are provided below.

Although all these seven elements are minor in terms of both volume and value of production, their role in making the digital transformations happen is of major importance (*Table 2*). The total value of all metal production (at the mine stage) in 2018 was around $660 billion. Iron ore, gold and copper - in that order – accounted for over 60% of that amount and other metals 39%, while the seven elements identified together only represented 0.77%.

Table 2 Selected elements for the digital economy

Element	Mobile phones	PCs	Flat screen TVs	Laptops and notebooks	5G networks	Rechargeable batteries	Fiberoptics	Main ICT usage
Gallium	X	X	X	X			X	LED, microchips, photovoltaics
Germanium	X	X		X			X	Infrared optics, fibre optics, solar
Indium	X	X	X	X				Flatscreens, photovoltaics, solder, semiconductors
REEs	X	X	X	X	X			Magnets, displays, LED
Selenium						X		Electronics
Tantalum	X		X	X				Capacitors, "sputter targets"
Tellurium						X		Solar, thermoelectrics

Sources: Dedryver, Bakas et al., DERA, USGS.

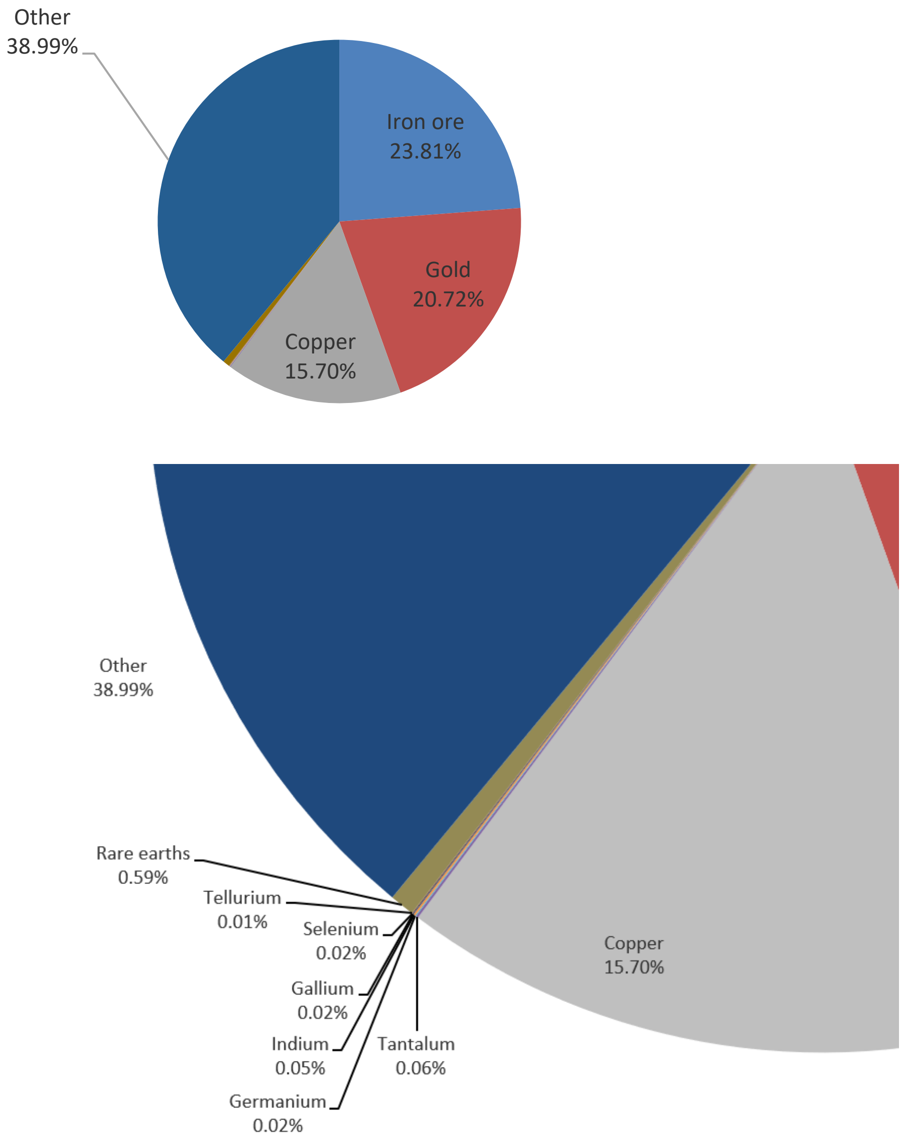
In terms of production volumes, the share of these 7 metals is even smaller, as most of them command a high price per ton. Total world production of metals was around 1 600 Mt (metal content) in 2018. The seven elements together amounted to 0.17 Mt, of which REEs accounted for around 95%. All the others are produced in miniscule amounts, from germanium around 100 ton up to 3,000 t of selenium (*Table 3*). The ICT elements thus represent only a tiny fraction of total use of all metals but for some of them, the digital economy accounts for 80-90% of total usage (Malmodin et al. 2018).

Table 3 Production volumes (t) and values (MUSD) for elements for the digitalized economy 2018

Metal	Value (MUSD)	Volume (t)	ICT usage 1) (% of total usage)
Gallium	160	323	81
Germanium	155	101	80
Indium	310	835	90
REEs	3,900	164,000	20
Selenium	125	2988	16
Tantalum	790	1799	32
Tellurium	40	524	70

Note: ICT includes also entertainment and media sectors.
Sources: RMG Consulting, BGS, USGS, DERA 2016, Naumov, Malmodin et al.

Figure 3 Production value of digitization metals 2018 (% of total value of all mined elements, excl. coal)



Source: Raw Materials Data, RMG Consulting, BGS, USGS.

Properties of the seven ICT elements

This section provides a brief description of the properties of the seven ICT elements.

Gallium metal is liquid near room temperature. Its melting point is at 30º C. It forms semiconductors together with arsenic and phosphorous. The gallium-based semiconductors have an advantage over silicon in that they generate less heat. Gallium is also used in optoelectronic devices such as light emitting diodes (LED), laser diodes and solar cells.

Germanium is nowadays used in fibre optics, infrared optics and solar cells. Germanium is transparent to infrared (IR) radiation like glass is to light and this makes it suitable for IR optics.

At the end of a fibre optical cable, the light signals are decoded by a germanium-based semiconductor. A substitution of gallium-arsenide for germanium-silicon is taking place.

Indium alloyed with gallium is liquid at room temperature and has a very low friction coefficient, which is the basis for its use as a lubricant without oil. Indium-tin oxide (ITO) is used for liquid crystal displays (LCD). Indium phosphide serves as a special semiconductor, which makes the fastest frequency synthesizer available.

Rare earths, both some of the “heavy” (HREEs with atomic number 65 and over) elements (mainly terbium, dysprosium, and the “light” (below 65) elements (mainly lanthanum, praseodymium, neodymium, europium, gadolinium) have a range of usages in electronic components and computer screens. The special electron configuration of the rare earth metals forms the basis for their special chemical, optical, magnetic and electromagnetic properties.

Selenium was previously a widely used element in electronics and is nowadays mostly used as a colour in glass and as an alloying element to improve machinability. Its ICT usages include thin-film photovoltaics.

Tantalum has excellent corrosion resistance due to a passive and thin layer of tantalum oxide which is naturally formed on its surface. This layer is also responsible for its dielectric property which is utilized in capacitors made of tantalum. More than 60% of its total production is destined for capacitors.

Tellurium is chemically resembling selenium, both of which are semiconductors. Antimony and bismuth containing tellurium compounds are used in thermoelectric cooling devices. A small but promising for the future, part of tellurium production is used in solar cells.

What changes in demand can be expected?

Projections into the future are always subject to uncertainty, and this applies especially to estimates of future demand for elements in the digitalization of the world economy. Further complexity is added by the current transition to a low-carbon future running at an increased pace, for two main reasons:

- First, many of the technologies that are applied when digitizing are either newly developed or not yet developed and proven, and will most probably change in the future as greater knowledge is accumulated. Speed of technological development has also been revved up.
- Second, substitution is often possible and will take place when the potential alternatives can provide the same or improved properties at an acceptable cost. Given that the price sensitivity for increased raw material costs in most cases is very low (as the amount of material included in the final product is marginal), huge swings in price can be accommodated and does not necessarily make demand change as dramatically as prices might do.

The growing acceptance and use of the concept of criticality and critical materials by politicians and industry have made the risks of future imbalances in supply and demand of these elements come into focus at an early stage in the development cycle. In Europe, China, Japan and the

United States, broad R&D programmes have been started to shed lights on all possible aspects of demand and supply of critical elements. Research topics include the search for possible substitutes, ways to increase supply and how alternate technologies could be facilitated and future deficits with concurring price swings avoided. All these efforts should hopefully result in reduced risks. Improved rates of recycling will also influence the demand for virgin materials and with the present emphasis on sustainability, such aspects have become more important.

Selenium is but one example of how demand for ICT metals has changed dramatically over short periods of time. Selenium was once greatly used in photocells and photo copiers for its photoconductivity, it is a good conductor in light but poor in darkness. But since the 1980s, organic compounds have replaced selenium as photoreceptors (Enghag p. 1069). Germanium is another example, which with the invention of the transistor in 1947 became an extremely important element from previously having been known only to a few specialists. But the period of prosperity was short. Already in the 1960s, silicon was the favoured semi-conductor material and replaced germanium (Enghag p. 932). Similar developments could very well be projected for other elements.

The small volumes demanded of the seven elements and the low grades in possible ores make specific mines impossible for all except rare earths and tantalum. There are a handful of rare earth mines around the world. Tantalum is often found in ores which also contain tin and the two metals are produced together. The other elements are only identified as a by-product at the smelting/refining stage (see *Table 4*).

Table 4 Origin of seven elements

Metal/ element	Product of mine or smelter/refinery	Primary / by-product	Origin
Gallium	Smelter/refinery	By-product	Alumina production, previously mostly zinc processing.
Germanium	Smelter/refinery	By-product	Zinc processing, coal (lignite) or fly ash.
Indium	Smelter/refinery	By-product	Mainly zinc processing, some copper and tin ores.
REEs	Mine	Primary product	REE ores.
Selenium	Smelter/refinery	By-product	Electrolytic refining of copper.
Tantalum	Mine	Primary product	Tin/tantalum ores. increasingly by-product lithium mining
Tellurium	Smelter/refinery	By-product	Electrolytic refining of copper.

Sources: Dedryver, RMG Consulting.

The story of tellurium production in the Swedish Kankberg goldmine illustrates how development of new production processes can affect the entire world market of these small volume elements. The Kankberg gold deposit was not exploited for many years because it was difficult to process the ore and extract the gold due to its high tellurium arsenic content.[7] After a long period of development, a new process route was designed and successfully tested. In addition to the desired gold, 40 t annually of tellurium was obtained as a completely unintended by-product. This amount, equal to 5-10% of world annual production, suddenly came onto the market from this very small gold mine.

[7] Interview with industry executive November 2020.

Many of the ICT elements have special and unique properties and are applied in very low volumes, sometimes layers only a few atoms thick, other times as alloying elements or additives to a crystal gitter, with only a few atoms or extremely low concentrations. Nevertheless, they are not solely used in ICT applications but also as alloying elements, food additives and many other applications. Pure ICT demand is usually not accounting for the largest share even of these highly specialized elements.

It is highly likely that the increase of elements used in small amounts in ICT applications will continue into the future. In the past couple of years, hafnium, arsenic, ruthenium and bismuth have increasingly attracted attention. Even accounting for the quick expansion of transactions on the Internet and the increasing use of computers and smart phones in all parts of the world, the volumes of a material demanded by the digital economy are generally small and should not cause much alarm. Geographical and corporate concentration patterns could of course increase risks. The present geopolitical situation with China's growing ambitions and the stand-off with the United States has prompted more interest in the security of supply and sustainable supply chains, for example, in the European Union (European Commission 2020, Trump 2020). The case of Chinese control over REEs production, which came to the fore in the early 2010s, with export quotas imposed by China resulting in strong price hikes, is but one example of how serious these issues are considered to be.

As has been pointed out, it is difficult to estimate future demand for the metals in new technologies in general and in the ICT sector in particular. Nonetheless, some estimates do exist. For example, by 2035, it is projected that an additional 5.3 Mt of copper (in comparison with total demand in 2013 of 21.4 Mt) will be necessary to cover the demand created in 42 emerging technologies (including around 10 ICT-related ones) (DERA 2016). Demand for lithium alone will equal almost four times total 2013 production, for cobalt 45 times and for PGMs platinum and palladium together the growth in demand will be 50%. From the same source, *Table 5* provides information related to the ICT elements in focus in this report.

Table 5 Potential future demand for ICT elements

Metal	Production total 2013 (t)	Demand from 42 technologies 2013 (% of total)	Demand from 42 technolgies 2035 (t)	Growth %	Growth (t)
Gallium	350	25	130	46	40
Germanium	145	39	118	111	62
Indium	790	29	361	55	128
Heavy REEs Dy/Tb	2300	85	7400	370	5400
Yttrium	5500	0.3	1054	659	1038
Tantalum	1300	38	2070	416	1570

Note: Selenium and tellurium were not included in the German study.
Source: DERA 2016.

In a study from 2018 of material implications from the Internet of Things (IoT) of emerging data storage technologies, the demand over 5-10 years period starting in 2016 for germanium was expected to grow by 0.35 t/year, indium 0.004 t/year, selenium 0.1 t/year, tantalum 8.3 t/year, tellurium 0.2 t/year. These are all very minor amounts, fractions of a percent of total production in 2016 except for tantalum where the figure was 0.75%. Of all elements covered, the PGMs iridium and platinum were projected to grow (in these applications compared to total production 2016) by 2,500% and 137% respectively (Table 6).

Table 6 Potential future demand for ICT elements by Internet of Things

Metal	Use in the EU 2015 (t)	Apparent consumption (% of total)	Use in 2035 (t)	Growth (%)	Growth (t)
Gallium	4	5	5	25	1
Heavy REEs dysprosium	9	5	12	33	3
Tantalum	80	80	110	38	30

Note: Germanium, indium, selenium and tellurium are not included in the European Commission JRC report.
Source: European Commission JRC.

Which mineral-rich countries are likely to be most affected by the demand growth by digitalization?

Table 7 lists the producing countries of the seven ICT elements. In Figure 4, these countries are placed on a world map. China is by far the dominant producing country, mainly because of the large volumes of REEs mined there. Australia and the United States follow, also because of their REEs production. Among the 15 most important producing countries, 5 are in Africa, 4 in Asia, and Brazil is the only significant producer in Latin America. The remaining two countries are Canada and the Russian Federation. China reaches over $3 billion. For the Democratic Republic of the Congo, the tantalum production is valued at $315 million. For most countries, however, the value of production is less than $100 million annually.

Table 7 List of producing countries of seven elements 2018 (MUSD)

No.	Country	Gallium	Germa-nium	Indium	REEs	Selenium	Tantalum	Tellurium	Total MUSD	Mine/ smelter/ refinery
1	China	154.9	138.9	148.1	2760.0	31.4	38.3	24.3	3296	m/s/r
2	USA		3.1		414.0	5.0		4.0	426	m
3	Australia				483.0		9.8		493	m
4	DRC						314.9		315	m
5	Rwanda						179.1		179	m
6	Brazil				25.3		106.4		132	m
7	Russian Fed.	3.0	9.3	1.5	62.1	7.7	16.2	3.6	103	m/s/(r)
8	Korea, Rep.of	1.5		88.1					90	m/s
9	Nigeria						85.1		85	m
10	India				66.7	0.7			67	m
11	Japan	1.5	3.1	26.2		32.1		4.3	67	s/r
12	Madagascar				46.0				46	m
13	Ethiopia						29.8		30	m
14	Canada			21.8		3.5	0.0	1.3	27	m/s/r
15	Thailand				23.0				23	m/s
16	Viet Nam				21.2				21	m
17	France			16.1					16	s/r
18	Belgium			7.5		8.4			16	s/r
19	Germany					12.5			12	s/r
20	Burundi						9.8		10	m
21	Mozambique						0.0		0	m
22	Sweden					1.7		3.6	5	m/s
23	Ukraine	3.0	1.5						5	m
24	Finland					4.6			5	s/r
25	Mexico					4.5			4	m/s/r
26	Philippines					4.2			4	m/s
27	Peru			1.9		2.3			4	m/s
28	Poland					2.8			3	m/s
29	Uzbekistan					2.0			2	m/s
30	Italy			1.9					2	s/r
31	Serbia					1.2			1	m/s
32	Kazakhstan					0.4			0.4	m/s/r
33	Bulgaria							0.3	0.3	m/s
	Total MUSD	**164**	**156**	**313**	**3901**	**125**	**789**	**41**	**5490**	

Sources: WMC, BGS, USGS, RMG Consulting.

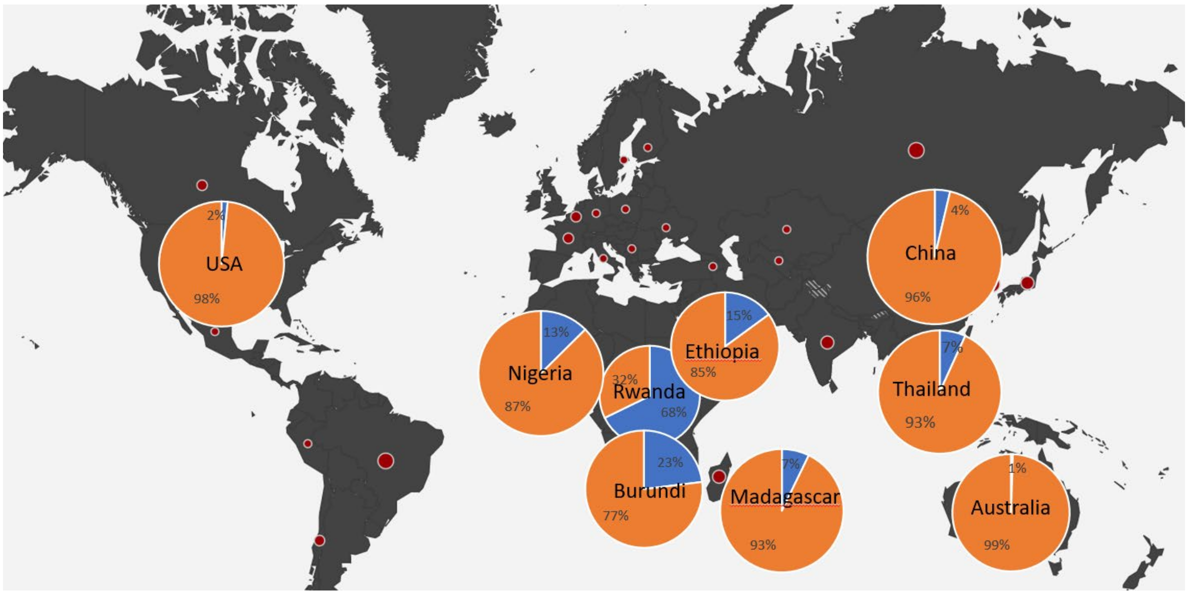
Figure 4 Production of seven ICT elements 2018 (millions of US dollar)

Sources: WMC, USGS, BGS, RMG Consulting.

Japan is among the top 15 but has no mine production of its own. All its production originates from imported ores and the metals are produced in Japanese copper and zinc smelters and alumina plants. Further down the list are other countries without mines but with sophisticated processing capabilities, such as Belgium, France, Germany and Italy.

The importance of the production of the seven ICT elements compared to total mine production in each country is highlighted in Figure 5. In the African producers, they accounted in 2018 for between 7% in Madagascar and 68% in Rwanda. In most other countries, the production represents only a small part of the total value of mine production.

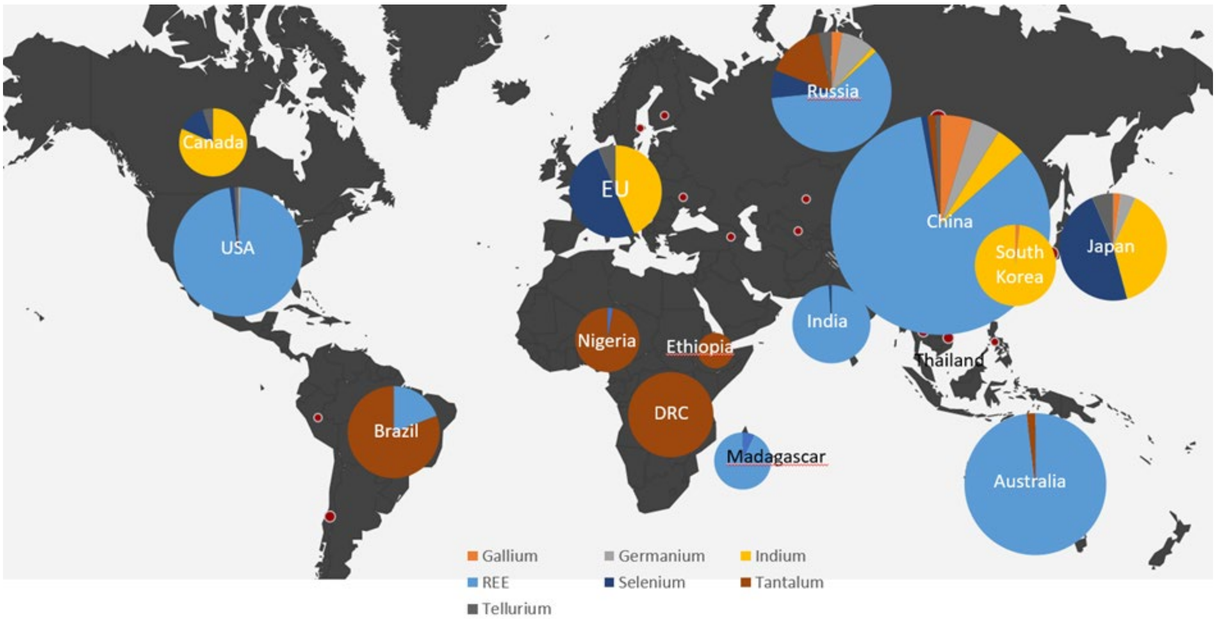
Figure 5 Relative importance at the mine stage of seven ICT elements 2018 by value (MUSD)



Sources: WMC, USGS, BGS, RMG Consulting.
Note: The full circles represent total value of mine production in each country, blue is the share of the seven elements under study.

From Figure 6 it is clear that most countries, apart from China, Russian Federation and Japan, are producing only one or two of the seven elements. Canada, USA and the European Union report production of three elements each. African countries are producing tantalum, except for Madagascar, which mines REEs. In Europe, there is limited production based on domestic mines mostly in Sweden, Finland and Poland, but several smelters/refineries use imported concentrates for production of the ICT elements.

Figure 6 Production (all stages) of seven ICT elements 2018 by value (MUSD)



Sources: WMC, USGS, BGS, RMG Consulting.

Resources and reserves

Reserves and resources are two concepts describing how much of an element that could be mined and processed with a profit at today's prices and technology. The reserves are clearly defined and studied in detail while resources are sufficiently well known in terms of size and quality to make an estimate. The conclusion for Table 9 is that there is no scarcity of the ICT elements in the earth's crust. For the elements lacking in the table, gallium, germanium and indium, the reserves and resources are gigantic. They are proportional to the resources of bauxite (for aluminium production), zinc and copper ores, all of which are produced in millions of tons every year and hence are available in huge quantities. See Table 9 Resources and reserves of seven ICT elements in Annex.

Which are the main actors?

Reduced dependencies and diversified supply to achieve resource security is a mantra repeated by many countries around the world, in particular during the pandemic disrupting global supply chains (European Commission 2020, Trump 2020). Supply risk analysis usually focuses on country level concentration of global production of critical raw materials. Dependence on imports from China is sometimes singled out as "particularly concerning" (Trump 2020). From Table 7 it is clear that China is the largest supplier of several of the seven ICT elements, producing 95% of global gallium, 89% of germanium, 71% of REEs, 7% of tellurium, 47% of indium, 25% of selenium and 5% of tantalum.

While country concentration is an important aspect of supply security it is rarely "countries" that mine, refine or process raw materials. This is done by companies acting on the world markets. Transnational mining companies make decisions about localization of production, new investments and production levels, all important decisions about how much is to be produced and where. There are several state-owned companies in mining, smelting and refining but their market shares and hence importance have been dwindling since a peak in the 1980s. Corporate concentration hence is an important part of the analysis of supply security. Within the narrow scope of this report, it sheds some light on this aspect of mining and refining of the seven ICT elements.

As already noted, the production processes for the ICT elements differ from the major base metals and some of the battery metals in that they are mostly by-products (see Table 4). It is only REEs and tantalum of which at least a sizeable share of production originates from mines specifically dedicated to the production of these two elements. The by-product base means that it is the viability of the main metal in a mine that decides whether there will be any by-product recovery. The by-product does of course give a certain economic contribution, but it is of minor importance and will usually not warrant major investments, process alterations and generate much less focus on optimization and maximum recovery. There will further be limited marketing and sales efforts.[8] A mining executive summarized this concerning cobalt from copper concentrates: "you get the cobalt the process gives you"[9], and the same is valid for the by-product ICT elements. Most of the ICT metals are usually lost during the value chain, for example, only 15-20% of the indium content of a zinc ore is estimated to be recovered into 99.7% indium metal (Lokanc et al. 2015).

The recovery and production of the ICT elements usually do not take place during mineral processing at the mine but at a later stage during smelting and refining. The skills and technology to recover these elements are highly specialized and unique. They are mostly developed and maintained within a small number of companies in developed economies. At present, when prices for most of the ICT metals are relatively low, process R&D and innovating activities are limited, but if prices rise, activities will restart.[10] Mineral-rich developing countries will usually not be able to benefit more than marginally from such content of their ores and concentrates exported. In particular, the content and extractability of by-products are often not well known and the refineries extracting these metals are not always open about their capabilities. A seller must have thorough and deep metallurgical skills in order to be able to realize the customer value of the product. Often, the presence of these elements does not increase the price of a concentrate at all as the number of buyers is limited and the markets far from transparent and competitive. Selenium and tellurium are extracted during copper processing. Germanium and indium are obtained mainly from zinc refining and gallium during the production of alumina from bauxite ores, a process step in the chain to aluminium. The smelters and refineries with capacity to extract these elements usually buy concentrates from a range of mines around the world and it is difficult or impossible to track the origin to the final pure elements.

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[8] Interview with industry executive November 2020.

[9] Interview with industry executive October 2020.

[10] Interview with process metallurgist October 2020.

These industries are characterized by a paradox in that they are in general opaque and secretive as to key facts such as production volumes, capacities and origin of raw materials. On the other hand the companies themselves have an interest in trying to share important information and data among themselves in order to avoid over production and market disturbances, in particular, as production volumes are small and individual companies can have a strong impact on market balance and prices. Price volatility is already high because of rapid technological developments and changes in demand.

Gallium

Gallium is yet another by-product ICT metal, most commonly obtained from the alumina production step in the value chain from bauxite to aluminium. Some gallium is also recovered in processing of zinc ores. Large production volumes of alumina hence give the potential for high gallium production. Chinese companies are the dominating alumina producers and hence also the largest gallium producers. See Table 10 Major companies producing gallium in Annex.

Around the turn of the century there was an oversupply of gallium and production facilities in Australia and France, and later in Hungary and Slovakia, were closed down. There is still considerable over capacity in primary gallium 700-800 ton/annum (tpa) compared to actual production around 300 tpa.

In addition to the companies listed above, Japanese Dowa Electronic Materials Co, Sumitomo Chemicals Co, Rasa Industries Ltd and Nippon Rare Metals Inc, have considerable capacity. Dowa and Sumitomo, for example, have estimated production capacity of around 100 tpa.

Germanium

There are two major sources of primary germanium: zinc concentrates and lignite or fly ash from burning lignite in the proportions two thirds zinc concentrates one third lignite. Chinese companies dominate both these process routes (Moskalyk 2003). The lignite route is dominated by a few Chinese and Russian companies. There are two Chinese lignite areas (Lincang and Wulantuga) with considerable amounts of germanium. One of the most important Chinese producers is Yunnan Lincang Xinyuan Germanium Industrial Co. Ltd in south China, which has a fully integrated production process from mine to wafer. The Russian production is based on lignite deposits in the east of Siberia on the Pacific. See Table 11 Major companies producing germanium in Annex.

Indium

As mentioned, indium is mainly recovered as a by-product from zinc mining and to a lesser degree from copper, lead tin and silver deposits. Zinc companies with good grades of indium in their ore resources hence theoretically control the mine output of this element. Most mining companies do not, however, extract indium but sell a concentrate to a smelter/refiner which has the necessary equipment to extract indium and produce an indium sponge.

Chinese companies account for around half of the world's indium production. There are no detailed production figures available from China but all Chinese mining sectors including zinc and indium are more fragmented than their competitors outside China (Ericsson, Löf & Löf 2020). In 2010, the 25 largest zinc mining companies in China produced only a third of the total

Chinese production, and even the largest was only a tenth of the top transnational company, Glencore. Since then, some consolidation has taken place but the Chinese companies are still much smaller than global leaders. Among the indium producers the situation is similar with 20 companies sharing export quotas and the largest, Hunan, having 12% of the total 233 t in 2011. There was no access to more recent figures but in view of the slow pace of consolidation in China in the past decade, the situation is likely to still be similar. See Table 12 Major companies producing indium in Annex.

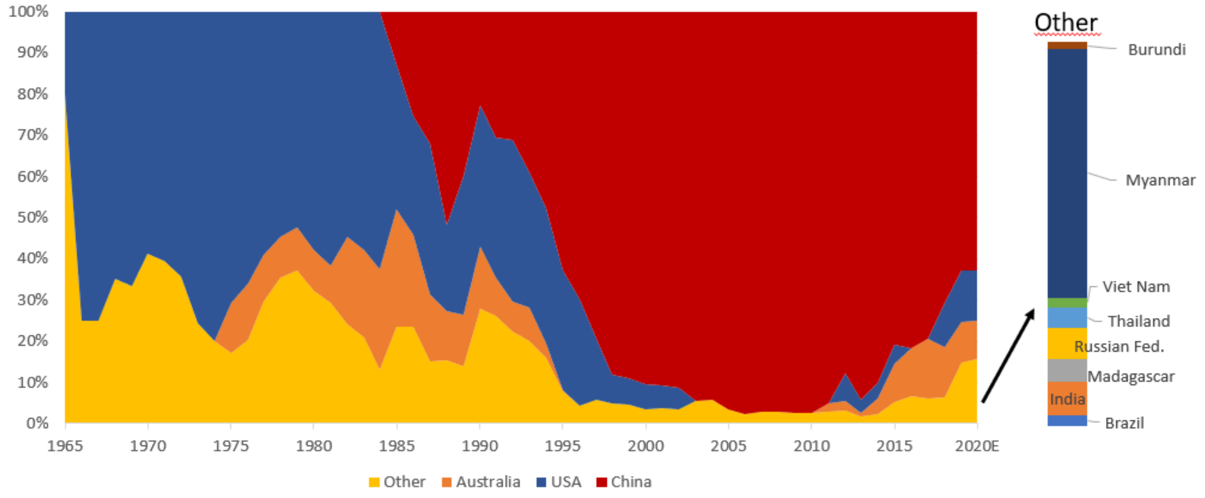
Depending on their facilities these companies refine indium to at least 95%. The final conversion into higher purity 5-7 N and into saleable products is done by a dozen of companies such as: Indium Corp of America, MCP Metal Specialities, ESPI and AIM Speciality Materials (all United States), Umicore Group (Belgium), Zhuzhou Keneng New Material (China) and Teck Resources (Canada).

Rare earth elements

The rare earths came into political limelight in 2010 when prices skyrocketed as a result of China briefly halting exports during a dispute with Japan (Shen et al. 2020). At that time, Chinese producers controlled around 90% of total world production at the mine stage and probably even more of the refined production. The initial global up-roar resulted in political statements and also some exploration projects. However, as prices fell back, the rare earths left the centre of attention. Gradually, the Chinese dominance has been reduced. In 2019, China controlled an estimated 60% of global mine production, while Chinese refinery production is probably as high as 10 years ago or even higher.

In the 1970s and 1980s, the United States dominated global rare earth production (Figure 7). The Mountain Pass mine in California was a major producer controlled by the oil company, Chevron. The process to extract and separate the rare earths from the ore is difficult because the rare earth elements are chemically very similar to each other. The process can also be heavily polluting. When environmental demands grew, new investments were necessary to reduce emissions, production costs increased and profitability dwindled. It was at the time not seen as a major issue that Chinese small-scale producers gradually became the main suppliers of REEs, in view of the environmental and health problems of the production processes (Rao 2016).

Figure 7 Rare earth elements production 1965 – 2020



Sources: RMG Consulting, USGS, BGS.

The top Chinese producer is the Baotou I&S company, which mines an REE-rich iron ore deposit in Inner Mongolia. Over the past decade, Chinese authorities have begun to crack down on the environmental and health problems caused by production of rare earths there and elsewhere in China. The many small producers also created problems in that some did not have the necessary mining permits, and illegal exports both reduced government income and made the use of rare earths as a potential political weapon difficult. Central authorities have set about to restructure the industry in China and have created 6 major groups of companies in charge of REEs mining (Rao 2016, Shen et al. 2020). Chinese companies control most of the production from Mynamar all of which is exported to China.

In the United States, the Mountain Pass mine restarted production in 2019 after having gone bankrupt in 2015, and produced a 26 kt of rare earth oxide, amounting to 12% of world supply. This mine is owned by MP Materials, in which China's Shenghe Resources Holding holds a 10% stake. All the rare earth oxides from the Mountain Pass mine are treated and refined in China. Lynas Corporation, the third biggest controlling company, produced 14.6 kt of rare earth oxide in 2019 from the Mount Weld mine in Australia (Johnson, Gramer 2020).

After the crisis in 2010/11, additional production has come on stream in new countries, such as Myanmar, Madagascar, Viet Nam and Thailand, although all of them deliver relatively small amounts. Projects are underway in many other countries, but in general with much poorer ores, high production costs and low recoveries. So, in spite of the political rhetoric, China still dominates, in particular, when considering the entire supply chain. The worries about the supply of REEs may be more political than reflecting the flow of raw materials. See Table 13 Major companies producing rare earth elements in Annex.

Selenium

Anode slimes recovered from electrolytic refining of copper ores is the main source of selenium. Production, price and market conditions for selenium are to large extent dependent on the copper market. Many copper refineries have the capacity to extract selenium but for most companies this is a minor side activity. See Table 14 Major companies producing selenium in Annex.

Tantalum

The tantalum market has for a long period been dominated by a few industrial scale producers in Australia and Brazil, and a larger number of small-scale, artisanal producers in the Great Lakes Region countries, DRC, Burundi and Rwanda. The latter region has supplied 50-60 % of world production around 1,900 t/a (Ta_2O_5).[11] The growing demand for batteries in electric vehicles has triggered exploitation of a number of new lithium mines, which also deliver as a by-product tantalum in large quantities. In 2019 alone, new lithium mines in Australia increased the supply of low-cost tantalum by some 10% of world production. If this trend continues, the market domination by the African producers will be challenged – an example of the strong unintended market impact by-product elements.

A number of traders have been and are operating in the DRC: Halcyon, Traxys, Rash et Rash, CDMC (John Crawley).[12] Their influence on the market is difficult to assess with any precision, but their activities add to low transparency in the tantalum industry. See Table 15 Major companies producing tantalum in Annex.

Tellurium

Like selenium, tellurium is extracted from copper anode slimes but there are also three primary mines: one in Sweden (Kankberg) run by the Boliden company, and two in south east China (Dashuigou and Majiagou), close to each other on the Tibetan plateau. At one stage in the early 2010s, they were both controlled by the US company Apollo, but their present ownership is not known. It is even unclear if they are still producing. Exploration activities to find other ores with economically viable tellurium content have been under way for the past decade but so far with no success. Tellurium has historically been a by-product of gold production in, for example, Australia but this process route is no longer in operation.
Some copper refineries, for example, Russian Norilsk and Ural Mining and Metallurgy, have capabilities to recover tellurium. See Table 16 Major companies producing tellurium in Annex.

New actors

So far, the almost logarithmic growth of the digital economy has produced a number of giant companies, such as Alibaba, Amazon, Apple, Facebook, Google, Tencent and Microsoft (UNCTAD, 2019), but also new industrial companies such as automotive producer, Tesla. The concepts of supply security and traceable value chains are buzzwords heard frequently in corporate communications. But what actions have been taken? Have the digital giants tried to engage themselves also in mining and refining of the ICT elements? The quick answer is no. The supply of ICT elements is dominated by two types of companies:

- A number of small, newly established Chinese, often private, companies and
- A few specialized companies based in Europe, North America and Japan which have since long been processing by-products from the base metal production of transnational mining and refining companies.

11 The most common deposits are pegmatites where tantalum is present together with lithium.

12 Interview with industry executive October 2020.

There is only limited incursion by other new competitors.

Particular focus has been on cobalt and the serious problems of child labour and war lords in the DRC. ICT companies have chosen not to engage themselves directly in mining and refining but mainly to conclude long-term supply contracts with guarantees of origin and processing. The US Dodd Frank act[13] nay have been an important factor in this case. The Act is binding for publicly listed US companies and its suppliers and has had important effects for the transparency of trade in some of the ICT elements, notably tin, tantalum and tungsten. Many of the activities of the giant ICT companies seem to be focused on the future supply of fossil free energy and not primarily on issues and problems created by such a focus.

A fund led by Bill Gates has been reported to invest in new lithium mining technology and in technology intended to use AI and new exploration technologies to find new deposits. KoBold Metals, is one example, exploring for nickel in Canada in the vicinity of another major nickel discovery, Raglan. While new technologies might be applied the choice of target areas for exploration is traditional close to existing know mineral deposits in "safe" countries, with low sovereign and financial risk, rather than in mineral rich developing countries. Countries for which the potential opening of a new mine could have much greater economic impact than it would have in Canada.

There is a clear difference in approach to securing the supply of mineral raw materials between United States and European companies, on the one hand, and Japanese and Korean ones, on the other. Japanese manufacturing companies, which have long suffered from a lack of domestic raw material supply, have developed a model of joint financing of mining projects around the world together with traditional mining companies. This model secured the supply of raw materials, for example, iron ore with long-term contracts which secured the market for the miners and loans to finance expansions and new mine projects. A win-win situation. Later this model was also adopted by Korean manufacturing companies. The Japanese sogo shoshas have, for example, since the 1970s invested in iron ore, copper, coal and other mineral raw materials.[14]

Summary

Corporate concentration is in general low for all the seven ICT elements. This is the case both at the mine stage and the refinery stage. One important reason for this is the dominance of Chinese companies, most of which are smaller than their foreign competitors. This is partly a historical inheritance which is characterizing all Chinese mining industry. In spite of attempts by Chinese authorities (at least during the past decade) to consolidate the mining sector, it remains fragmented. In the rare earth sector, Chinese central authorities have actively pushed for restructuring and this is gradually succeeding. Beijing wants to reduce environmental problems caused by small operators that are often operating in a grey zone without all proper permits (Shen et al. 2020, Rao 2016). There may also be diverging interests of regional,

[13] The Dodd-Frank Wall Street Reform and Consumer Protection Act is its full name. It was enacted in 2010 to overhaul financial regulation in the aftermath of the Global Financial Crisis in 2009. The Act also contains provisions for other areas including "Disclosures on conflict materials in or near the DRC".

[14] Toyota is among the few automotive companies that have invested directly in the lithium mining industry through Australian lithium producer Orocobre. Toyota's investment in the Argentinian lithium operation is done in cooperation with the provincial government and the Australian company where Toyota is also the sole marketer of the lithium material.

provincial and central governments. The strategic importance of, in particular, the rare earth elements has also raised Beijing's interest in tightening the control over these mines.

The vertical integration in the production chains of these ICT elements is also low. Mining companies often sell their concentrates to smelters/refineries that extract the elements as by-products. The common case is a second break in the value chains when a highly specialized company refines the, by common base metal standards, already pure product into 9N+ to meet the exacting demands from wafer producers and manufacturers of computer chips, etc. The refining companies usually treat not only primary concentrates, slags and slimes but also different types of secondary raw materials, making it even more difficult to disentangle the flows in the industry.

There are a few examples of co-ownership of mines and processing units between Chinese companies and companies from other countries. These include both operations inside and outside of China. The most common situation is, however, that ownership is separated. One such joint venture partner is a listed United States company and hence some information is available through its reports to the SEC. Among the risks for the future are included the escalating trade conflicts between China and the United States. If Chinese exports of some of these ICT elements in some way would be restricted, opportunities for new companies outside of China could expand.

How recyclable will these elements be and to what extent may they be adding to the problem of "e-waste"?

As of 2020, less than 1% of the ICT elements are recycled at their end of life. There are tiny fractions of these metals in ICT devices. For example, in an ordinary PC the average content of gallium (weight share) is only 0.00004% (Bakas et. al. 2016). With a price of "only" $570 per kg (2019), the value per unit is low and, if calculated per kg computer, only around $0.02 cent. By comparison, the gold content in a computer is much higher both in terms of volume and value. Average gold content is 0.130% (weight) and at a price around $50-60,000 per kg (2020), it equates to some $60. Thus, it is no surprise that more than 50% of the gold in what is often called e-waste (Waste Electrical and Electronic Equipment, WEEE) is recycled (Bakas et al. 2016, Malmodin et al. 2018).

The economic incentives for recycling the ICT elements are very low and it is also technically challenging to do so. Recycling rates tend to increase when there are relatively large quantities of hardware that is easy to collect or when the value of the metals is high. Still the grade of these special metals can be higher in e-waste than in virgin ores. At the moment, there are few economically viable technologies to recover all ICT elements, but research is underway and the e-waste recyclers in Europe and Japan are progressing.[15] The German study previously referred to has estimated the recyclability of elements in future high-tech applications. For the elements covered in this study, the potential in 2035 has been considered either limited or nil (DERA 2016).[16]

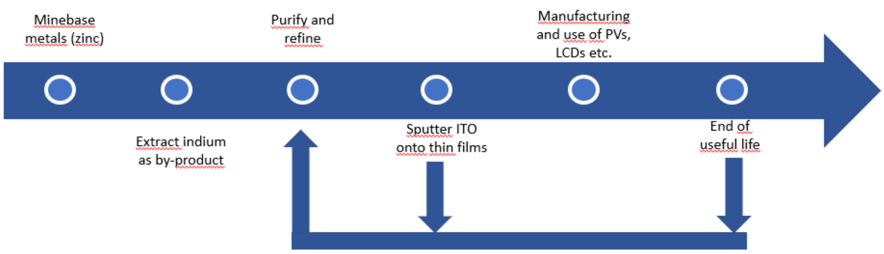
[15] Interview with process metallurgist October 2020.

[16] An update is expected in 2021.

Design for recycling will be crucial. Many ICT products contain an increasing number of elements in small volumes and their recycling will be difficult and costly if the products are not designed at the outset for recycling. There is a growing understanding of this situation. For example, battery producers are designing their products and processes to facilitate recycling from the start.

At present, the recycling rates for end-of-life products are abysmally low, at best a few percent. The production processes are often ineffective and there is substantial primary recycling. In Figure 8, the loop to the left illustrates the primary recycling of material which has not reached final customers.

Figure 8 Recycling of ICT elements - indium as an example



Note: ITO indium-tin oxide.
Source: Lokanc et al.

Table 8 Recycling rates for ICT elements (in bold) and battery metals

Element	End-of-life recycling rates (%)	Global average recycled content (%)
Gallium	**<1**	**10–25**
Germanium	**<1**	**25–50**
Indium	**<1**	**25–50**
Tantalum	**<1**	**10–25**
Beryllium	<1	10–25
Cobalt	>50	25–50
Gold	>50	25–50
Lithium	<1	<1
Palladium	>50	25–50
Ruthenium	10–25	>50
Silver	>50	25–50
Tungsten	10–25	25–50

Notes: EOL-RR, percentage of metals in discards that is recycled. RC, the fraction of secondary metal in the total metal input to metal production.
Source: Bakas et al., Malmodin et al.

The problems with e-waste dumped in developing countries will remain serious as long as the value of scrapped computers and smart phones is as low as it is. The introduction of additional elements and continuing digitalization will not change this.

Conclusions

A wide and increasing range of elements will be demanded in the digital economy, including for e-commerce and IoT, to run all computers and keep all of them inter-connected. Most of the ICT elements will, however, be demanded in very small quantities, despite the rapid speed of digital transformation. The infrastructure around the core of computers and smart phones will demand much larger quantities, in particular, for electric vehicles, renewable energy production and storage. Of the seven ICT elements studied (gallium, germanium, indium, rare earths, selenium, tantalum and tellurium), only rare earths are produced in more than a few thousand ton annually and only for a few of these elements is direct ICT demand the most important use.

Demand for these ICT elements will undoubtedly grow rapidly but the multiple uncertainties about technological shifts, substitution, market preferences and growth of the world economy complicate making forecasts. In any event, even high relative growth in demand is possible to meet with limited investments and within reasonable time frames.

Only two of seven ICT elements are primary products from a mine (rare earths and tantalum), the others are by-products from smelting and/or refining (gallium, germanium, indium, selenium and tellurium). For most of these elements, this means that there are huge resources theoretically available, of which only a part is used for the extraction of the minor by-products. The recovery of these ICT metals is not optimized, as the main product is in economic and technical focus. As a result, most of the by-product ICT elements end up in the mine tailings or refinery slags. This also means that there are potentially vast amounts available for extraction without having to be mined from new deposits.

Most metal smelting and refining takes place in developed countries. Concentrates are produced in both high-income and low- and middle-income countries. Most of the concentrates and ores are exported from mineral-rich developing countries to high-income countries to be smelted and refined. The actual production of the ICT elements hence takes place mostly in developed countries. Producers from developing countries might not even get paid for the contents of the ICT metals, particularly if the content in concentrates is low or not precisely known. The tin/tantalum output by African countries is the most important production which influences directly a number of developing countries.

The digital economy in itself will not create huge opportunities for mineral-rich countries, neither in developed nor in developing economies, except possibly for a limited number of small very specialized mines and refineries. The infrastructure surrounding the computers and the smart phones – batteries, electric vehicles, wind farms, robots etc. – will probably be more important and should be carefully monitored by countries seeking to benefit from any opportunity which might arise.

The traditional transnational mining companies do not have the same tight control over the production of the ICT elements as they have over, for example, iron ore and bauxite. Relatively small and highly specialized companies, often privately held, do most of the final and most important refining steps to produce the ICT elements of the extreme high purity that the makers of computer chips and other electronic components require. The small production volumes and the ownership structure make the markets quite opaque. The strategic importance of some of the elements for military purposes have added another layer of secrecy. It is difficult to trace who produced what and the ownership of the companies involved. Chinese producers account for considerable market shares for some of the ICT elements. These companies, which are often private, sometimes cooperate with local and regional governments, adding another barrier to finding data and information.

Among transnational companies, a few in Japan, Europe and North America are central to the entire sector. There a few producers in the Russian Federation, and a handful companies in Germany and the Nordic countries. African countries could possibly try to leverage production of some ICT elements by using the potential competition between European/North American and Chinese buyers to improve their bargaining position. At the same time, it is important not to push capacity too far as an over-supply situation can easily develop, in particular as total production volumes are small.

The digital platform giants, or entrepreneurs such as Elon Musk and Richard Branson, have so far not ventured into the raw material supply to the ICT sector. While there has been some recent press coverage of some forays into battery metals, it seems as if these newcomers may not fully appreciate the high risks of exploration. It is doubtful if they will see any need or opportunity of entering into the mining and production of ICT elements as the markets and the potential profits are likely to be small. Automotive companies have worried about the supply of battery metals, but in this field, most have favoured long-term contracts with specific focus on traceability and proven sources of ores and concentrates rather than direct investments into mining operations.

The recycling rates of the ICT elements are high in that the amount of primary scrap recycled is considerable. However, that is partly a reflection of the low productivity in the production of screens, etc., only a fraction of the material produced is of a quality that meets the customers' demand and hence a lot of material is recycled. Recycling of end-of-life products on the other hand is miniscule. It will remain both economically and technically difficult to recycle all the elements of a smart phone. New approaches with design for recycling and reuse and improved collection of used computers and smart phones will become necessary to change this situation.

Bibliography

Achzet B., Reller A., Zepf V., Rennie C., Ashfield M., Simmons J., 2012, Materials critical to the energy industry. An introduction, University of Augsburg, Germany.

Addison T., Roe A. Eds. 2018 Extractive industries – the management of resources as a driver of sustainable development, Oxford University Press 2018.

Bakas I., Herczeg M., Blikra Vea E., Fråne A., Youhanan L., Baxter J. 2016, Critical metals in discarded electronics – Mapping recycling potentials from selected waste electronics in the Nordic region TemaNord 2016:526.

Bundesanstalt für Geowissenschaften und Rohstoffe 2018, Gallium Rohstoffwirtschaftliche Steckbriefe Gallium (in German).

BGS, British Geological Survey, World Mineral Production, various years.

Cui R., Guo J., Yin L., Huy D., Liedtke M. 2016, Supply and demand of lithium and gallium, Information Center of Ministry of Land and Resources (PRC) and Federal Institute for Geosciences and Natural Resources (German).

Dedryver L. 2020, La consommation de métaux du numérique: un secteur loin d'être dématérialisé, Document de travail, France Stratégie No 2020-05 juin (in French) .

Deutsche Rohstoffagentur (DERA) 2016, Rohstoffe für Zukunftstechnologien, DERA Rohstoff informationen no 28 2016.

Enghag 2004, Encyclopedia of the elements – Technical data, history, processing, applications Wiley-VCH 2004.

Ericsson M., Löf O. 2020, Extractive dependency in lower-income countries Evolving trends during the transition to a low-carbon future, WIDER Working Paper 2020/120.

Ericsson M., Löf O., Löf A. 2020, Chinese control over African and global mining – past present and future, Mineral Economics Vol 33 pp. 153-181.

European Commission 2020, Critical raw materials resilience: Charting a path towards greater security and sustainability, COM(2020) 474 final.

European Commission, Joint Research Centre 2020, Critical raw materials for strategic technologies and sectors in the EU – A foresight study.

Hund K., La Porta D., Fabregas T.P., Laing T., Drexhage J. 2020 Minerals for climate action: The mineral intensity of the clean energy transition, World Bank Group.

Johnson K., Gramer R. 2020 U.S. falters in bid to replace Chinese rare earths, Foreign Policy, https://foreignpolicy.com/2020/05/25/china-trump-trade-supply-chain-rare-earth-minerals-mining-pandemic-tensions/.

Ku A. 2018, Anticipating critical materials implications form the Internet of Things (IOT): Potential stress on future supply chains from emerging data storage technologies, Sustainable Materials and Technologies, 15 (2018) pp. 27-32.

Kul'chitskii N.A, Naumov A.V. 2015, Modern State of Markets of Selenium and Selenium-Based Compounds, *Izvestiya Vuzov. Tsvetnaya Metallurgiya (Universities' Proceedings Non-Ferrous Metallurgy)*, 2015 No 3 pp. 40-48 (in Russian).

La Porta D., Hund K., McCormick M., Ningthoujam N., Drexhage J. 2017, The growing role of minerals and metals for a low carbon future, World Bank Group.

Larichkin F.D., Cherepovitsyn A. E., Novosel'tseva V.D., Goncharova L.I. 2017, State and prospects of Russian and world gallium market, News of the Ural State Mining University 4 (2017) pp.108-114 (in Russian).

Liedtke M., Huy D. 2018, Rohstoffrisikobewertung Gallium – Marktüberblick, DERA presentation at DERA Industrieworkshop Gallium, Berlin, June 5, 2018 (in German).

Linden J. 1995, Tantalum raw material supply, TIC Bulletin No 86 June 1996 pp. 5-11.

Lokanc M., Eggert R., Redlinger M. 2015, The availability of indium: the present, medium term and long term, National Renewable Energy Laboratory (NREL).

Malmodin J., Bergmark P., Matinfar S. 2018, A high-level estimate of the material footprints of the ICT and the E&M sector, EPiC Series in Computing, Vol 52 pp. 168-186.

McKinsey Global Institute 2015, The internet of things: Mapping the value beyond the hype.

McKinsey Global Institute 2016, Digital globalization: The new era of global flows.

Melcher F., Buchholz P. 2012, Current and future Germanium availability from primary sources, DERA presentation at Minor Metals Conference, Cologne, April 24, 2012.

Mongardini J., Radzikowski A. 2020, Global smartphones, sales may have peaked: What next? IMF Working Paper WP/20/70, International Monetary Fund.

Moskalyk R. R. 2003, Review of germanium processing worldwide, Minerals Engineering Vol 17 pp. 393-402.

Naumov A.V. 2010, Selenium and tellurium: State of the markets, the crisis and its consequences, Metallurg 2010 no 4 pp. 19-21.

Ny Teknik 2020, Glöm 5G – det stora skiftet är 6G, Ny Teknik No 43 22 October 2020 (in Swedish).

Rao Z. 2016, Consolidating policies on Chinese rare earth elements, Mineral Economics Vol 29, pp. 23-28.

Raw Materials Data, production and ownership database Stockholm various years.

Reichl C., Shatz M. 2020, World Mining Data 2020, Federal Ministry Agriculture, Regions and Tourism, Republic of Austria.

SEC, see US Securities and Exchange Commission.

Shen Y., Moomy R., Eggert R.G. 2020, China's public policies toward rare earths, 1975-2018, Mineral Economics, Vol 33 pp.127-152.

Trump D.J. 2020, Executive Order on addressing the threat to the domestic supply chain from reliance on critical minerals from foreign adversaries, www.

UNCTAD 2014, Commodities at a glance – Special issue on rare earths, No 5.

UNCTAD 2017, The 'new' digital economy and development, TN/UNCTAD/ICT4D/08.

UNCTAD 2019, Digital Economy Report 2019, Value creation and capture: Implications for developing countries.

UNCTAD 2020, Commodities at a glance – Special issue on strategic battery raw materials, No 13.

USGS, United States Geological Survey, Mineral Commodities Summaries various elements and years.

U.S. Securities and Exchange Commission, Southern Copper Corp. 10K report 2018.

WMC, World Mining Congress see Reichl & Schatz.

World Bank see Hund et al. and La Porta et al.

Annex tables

Table 9 Resources and reserves of seven ICT elements

Country	REEs (Mt)		Selenium (t)		Tantalum (t)		Tellurium (t)		Indium (t)		Germanium (t)		Gallium (Mt)	
	Reserves	Resources	Reserves	Resources	Reserves	Resources	Reserves	Resources	Reserves	Resources	Reserves	Resources	Reserves	Resources
World total (rounded)	**120**	**4,000**	**99,000**		**>90,000**		**31,000**		**15,000**	**50,000**	**3,100**	**35,000**	**1.4**	**4**
Australia	3.3	77			55,000									
Brazil	22	3			34,000									
Bulgaria							NA							
Burundi					NA									
Canada	0.83	15	6,000				800					88		
China	44	340	26,000		NA		6,600		10,000	20,000	3,100	10,900		
DRC					NA							4,250		
Ethiopia					NA									
Greenland	1.5	262												
India	6.9													
Madagascar	NA	600												
Malawi		6												
Mexico												150		
Myanmar	NA													
Namibia												530		
Nigeria					NA									
Peru			13,000											
Poland			3,000											
Russian Fed	12	19	20,000		NA		NA			5,000		17,500		
Rwanda					NA									
South Africa	0.79	44												
Sweden		63					670							
Tanzania	0.89	170												
Thailand	NA													
United States	1.4	2.7	10,000				3,500					2,500		
Vietnam	22	10												
Other countries	0.31		21,000				19,000							

Note: NA not available. Sources: USGS, BGS, RMG Consulting.

Table 10 Major companies producing gallium

Company	Country	Smelter/ Refinery	Country	Production 2018 (t)	Share of world total (%)	Controlling company	Home country
World total				**323**			
Total identified 3)				**118**	**37%**		
Aluminium Corporation of China Ltd.	China	Guangxi, Guizhou, Henan, Shandong, Shanxi 1)	China	160*/100e	31%	Chinalco 100%	China
Zhuhai SEZ Fangyuan Inc.	China	Chongqing, Guangxi, Henan, Shandong, Shanxi 1)	China	140*			China
East Hope Mianchi Gallium Industry	China	Henan 1)	China	80*			China
Beijing JiYa Semiconductor Material Co. Ltd.	China	Shanxi 1)	China	65*		AXT Inc. 39%	USA
Guangxi Tiandongjinxin Rare Metals	China	Guangxi 1)	China	60*			
Shanxi Zhaofeng Gallium Co. Ltd.	China	Shanxi 1)	China	20-40*		Shanxi Zhaofeng Aluminium (Yangmei group), Beijing JiYa, Chalco	China, USA, China
Xiaoyi Xingan Gallium Co. Ltd.	China	Shanxi 1)	China	50 ->130* 2)		Hangzhou Jinjiang Group, AXT Inc. 25%	China, USA
Beijing ZhuoLung Yuan Technology	China	Guangxi 1)	China	50*			
Aluminium Oxide Stade and Chemicals Ltd	Germany	Stade Alumina	Germany	30*/0	-	Dadco	UK
Dowa Electronics	Japan	Iijima	Japan	10*/3e	1%		
Korea Zinc	Korea, Rep. of	Onsan refinery	Korea, Rep. of	10*/3e	1%	Yuong Poong Corp.	Korea, Rep. of
Aluminium of Kazakhstan	Kazakhstan	Pavlodar alumina 1)	Kazakhstan	25*/0e	-	Euroasian Natural Resources Corp.	Kazakhstan
Pikalyovsky alumina plant	Russian Federation	Pikalyovo alumina 1)	Russian Federation	10*/6e	4%	Rusal	Russian Federation
Nikolaiev alumina plant	Ukraine	Nikolaiev alumina	Ukraine	15*/6e	-		

Notes: e estimate, * capacity. Capacity figures are often not for 2018 but latest available. Figure after / indicates actual production.
1) Locally mined raw materials. 2) Expansion to 130 t announced. 3) Most of the remaining approximately 200 t are produced by the Chinese companies listed.
Sources: Raw Materials Data, BGS, USGS, company websites, DERA 2018, Cui et al., Larichkin.

Table 11 Major companies producing germanium

Company	Mine(s)	Country	Smelter/ refinery	Country	Production 2018 (t)	Share of world total	Controlling company	Home country
World total					**101**			
Total identified 2)					**9**	**9%**		
Yunnan Chihong Zn & Ge Co.	Huize zinc mine	China		China	10-30*		Chinalco	China
Yunnan Jinding Zinc Industry Co. Ltd.	Lanping zinc mine	China		China	10*		Hanlong group	China
Zhongjin Lingnan Nonfemet Co. Ltd.	Fankou zinc mine	China		China	15-30*		Nonfemet	China
Nanjing Germanium Technology Co. Ltd.		China		China	30*			China
Yunnan Luoping Zinc & Electricity Co. Ltd.		China						China
Xilingol Mengdong Germanium Technology Co. Ltd.	Wulantuga lignite mines	China	N/A	China	60 * Susp. 2019			China
Xilingol Tongli Germanium Refinery Co. Ltd.	Wulantuga lignite mines	China	N/A	China	Suspended 2019		AXT Inc. (25%), China Energy Investment Corp.	USA, China
Yunnan Lincang Xinyuan Germanium Industrial Co. Ltd.	Lincang lignite mines	China	N/A	China	60*			China
Umicore	-	-	Hoboken, Olen	Belgium				Belgium
Gecamines	Various (slag)	DRC	Lubumbashi	DRC	Suspended		State of DRC	DRC
JSC Germanium	Lignite (now closed?)	Russian Federation		Russian Federation	20*/0e	-	State of Russian Federation	Russian Federation
GEAPP	Spetsugli lignite mine	Russian Federation	Novo-moskovsk		20*/6e	6%		Russian Federation
Boliden	Various	Sweden	Kokkola	Finland	15*/0	-	Boliden	Sweden
Teck	Red Dog	USA	Trail	Canada	28*/3e	3%	Teck	Canada

Note: e estimate. 1) Germanium plant. 2) Most of the remaining approximately 90 t are produced by the Chinese companies listed.
Sources: Raw Materials Data, BGS, USGS, company websites, Melcher & Buchholz, Liedtke & Huy.

Table 12 Major companies producing indium

Company	Mine(s)	Country	Smelter/refinery	Country	Production 2018 (t)	Share of world total (%)	Controlling company	Home country
World total					**835**			
Total identified					**522**	**63%**		
Korea Zinc	Imports from various countries	NA	Onsan	Korea, Rep. of	235e	28%		Korea, Rep.of
Nyrstar	Imports from various countries	NA	Auby	France	40e	5%	Nyrstar 1)	Belgium
Hunan Nonferrous Metals Corp. Ltd	Huanshaping mine	China		China	50e	6%	China Minmetals 51%	China
Yunnan Hualian Zinc & Indium Stock Co., Ltd.	Dulong mine	China		China	60e	7%	China Rare Metals & Rare Earths Group Corp.	China
Teck Resources	Red Dog mine	USA	Trail	Canada	58e	7%	Teck Resources 2)	Canada
Dowa Mining	Imports from various countries	NA	Akita	Japan	23e	3%	Dowa	Japan
Mitsui Mining & Smelting	Imports from various countries	NA	Onsan, Hachinohe, Kamioka	Japan	23e	3%		Japan
JX Nippon Mining & Metals	Imports from various countries	NA	Mikkaichi, Saganoseki	Japan	23e	3%		Japan
Ural Mining & Metallurgical Co	Various local mines	Russian Federation	Chelyabinsk	Russian Federation	4e	0.5%	Ural Mining	Russian Federation

Note: e estimate. 1) Nyrstar has been acquired by Trafigura in 2019. 2) Teck has both Japanese and Chinese major shareholders.
Sources: Raw Materials Data, BGS, USGS, company websites.

Table 13 Major companies producing rare earth elements

Company	Mine(s)	Country	Production (kt) 2019	Share of world total	Controlling company	Home country
World total			**210**			
Total identified 1)			**135**	**64%**		
Baotou Iron & Steel Rare Earth Co.	Baiyunebo (Bayan Obo) Rare Earths Mine	China	70e	33%	Baotou I&S Group	China
MP Materials	Mountain Pass Rare Earth Mine	USA	26	12%	MP Materials	USA
Lynas Corp	Mt Weld	Australia	14.6	7%	Lynas	Australia
Shandong Weishan Lake Rare Earth Co, Ltd	Weishan Shandong (Micro Hill) Rare Earths Mine	China	13e	6%		China
IREL (former, Indian Rare Earths Ltd)	Chavara Rare Earths Mine, Orissa Sands Complex Rare Earths Mine	India	2.9	1%	State of India	India
Lovozersk Mining Co	Lovozero Rare Earths/Tantalum Mine	Russian Federation	2.7	1%		Russian Federation
Ganzhou rare earth	Ganzhou	China	2e	<1%		China
Jiangxi Copper	Maoniuping	China	2e	<1%		China
Tantalum Rare Earth Malagasy 2)	Tantalus project	Madagascar	2e	<1%	ISR Capital	Singapore
Minmetals rare earth	Jianghua	China			China Minmetals	China
Chalco	Chongzuo	China			Chinalco	China
Xiamen Tungsten	Sanming	China				China
Various	Clay deposits	China				China

Notes: e estimate. 1) Most of the remaining approximately 75 t are produced by the Chinese companies listed. 2) It is not clear if production has started but according to national statistics some production takes place.
Sources: Raw Materials Data, BGS, USGS, company websites.

Table 14 Major companies producing selenium

Company	Country	Mine(s)	Smelter/refinery	Country	Production 2018 (t)	Share of world total (%)	Controlling company	Home country
World total					**2988**			
Total identified 1)					**1875**	**63%**		
Retorte GmbH Selenium Chemicals & Metals	Germany	No mines	Hamburg, Lünen	Germany	300e	10%	Aurubis	Germany
Umicore	Belgium	No mines	Hoboken, Olen	Belgium	150e	5%		Belgium
5Nplus	Canada	No mines	Montreal, Tilly	Canada, Belgium	130e	4%	5Nplus	Canada
Mitsubishi Materials Corp.	Japan	Various 2)	Naoshima	Japan	330*	11%		Japan
JX Nippon Mining & Netals	Japan	Various	Hitachi	Japan			Eneos Holdings Inc.	Japan
Shinko Kagaku Kogyo	Japan	No mines	Amagasaki	Japan				Japan
Sumitomo Metal Mining	Japan	Various	Toyo	Japan				Japan
Vital Materials Co. Ltd.	China	No mines		China			Privately held	China
Jiangxi Copper	China	Various		China	120e*	4%		China
Yunnan Copper	China	Various		China	80e*	3%		China
Jinchuan Group	China	Various		China	36e*	1%		China
Tongling Nonferrous	China	Various		China	30e*	1%		China
Daye Nonferrous	China	Various		China	20e*	1%		China
Baiyin Nonferrous	China	Various		China	15e*	0.5%		China
KGHM Polish Copper	Poland	Polish mines	Glogow refinery	Poland	66e	2%	State of Poland	Poland
Boliden	Sweden	Aitik and imports	Rönnskär, Harjavalta refineries	Sweden, Finland	149	5%	Boliden	Sweden
Minera Mexico	Mexico	La Caridad mines	La Caridad refinery	Mexico	107e			
Southern Peru Copper Corp.	Peru	Cuajone mine	Ilo refinery	Peru	52e 279e	9%	Grupo Mexico	Mexico
Asarco	USA	Various	Amarillo refinery	USA	120e			
Philippine Associated Smelting and Refining Corp.	Philippines	Various	Leyte refinery	Philippines	100e	3%	Glencore	Switzerland
Norilsk Nickel	Russian Fed.	Polar division	Nadezhda	Russian Fed.	80e	3%	Norilsk Nickel	Russian Fed.
Ural Mining Metallurgical Co	Russian Fed.	Various	Pyshma, Svyatogor, Sredneuralsk	Russian Fed.	110e	4%	Ural Mining	Russian Fed.
Basen Bor	Serbia	Bor mines	Bor refinery	Serbia	28e	1%	Zijin Mining Group Co	China

Notes: e estimate. 1) Most of the remaining approximately 1 000 t are produced by the Japanese and Chinese companies listed. 2) "Various" means mines controlled by the controlling company sometimes in several countries.
Sources: Raw Materials Data, BGS, USGS, company websites, SEC, Kul'chitskii & Naumov.

Table 15 Major companies producing tantalum

Company	Mine	Country	Production (t) 2018	Share of world total (%)	Controlling company	Home country
World total			**1799**			
Total identified 2)			**221**	**12**		
Global Advanced Metals (GAM)	Woodgina, Greenbushes	Australia	30e	1	Privately held	Australia
Pilbara Minerals Ltd.	Pilgangoora	Australia	1)			Australia
Mineracao Taboca SA	Pitinga	Brazil	100e	6		Brazil
AMG	Mibra (Nazareno)	Brazil	50e	3		Brazil
Lovozersk Mining Co	Lovozersk	Russian Federation	41e	2		Russian Federation
Soc. Miniere Bisunzu	Bisunzu	DRC				DRC
Sinomine	Tanco	Canada				Canada
Ethiopia Mineral Development Enterprise	Kenticha	Ethiopia	Suspended			Ethiopia
High African Mining Company	Marropino	Mozambique	Suspended			Mozambique
Yichuan Tantalum Co.	Yichuan	China				China

Notes: e estimate. 1) Most production in 2018 sold to GAM. 2) Most of the remaining 1 500 t are mined in DRC and Rwanda by small scale operators.
Sources: Raw Materials Data, BGS, USGS, company websites, Linden.

Table 16 Major companies producing tellurium

Company	Mine(s)	Country	Smelter/refinery	Country	Production (t) 2018	Share of world total (%)	Controlling company	Home country
World total					**647**			
Total identified 2)					**237**	**37**		
5N Plus	No mines	Canada			25e	4	5N Plus	Canada
Vital Materials Co. Ltd	No mines	China	Qingyuan, Guangdong	China			Privately held	China
Xiandao Rare Metal and Chemical Co.		China					Privately held	China
Emei Semiconductor Material Co.	No mines	China					Dongfang Electric Corp.	China
Shenzhen Jiangton Southern Co	Various 3)	China		China	60e*	9		China
Zhuzhou Smelter Group	Various	China	Zhuzhou Lead/Zinc smelter	China	60e*	9		China
Shinko Chemicals	No mines	Japan	Amagasaki plant	Japan				Japan
Kisan Kinzoku Chemicals	No mines	Japan		Japan				Japan
JX Nippon Mining & Metals	Various	Japan	Saganoseki refinery	Japan			Eneos Holdings Inc.	Japan
Kazzinc	Various	Kazakhstan	Ridder, Ust-Kamenogorsk	Kazakhstan	17-18*	3	Glencore	Switzerland
UGMK	Various	Russian Federation	Pyshma, Svyatogor, Sredneuralsk	Russian Federation	30*	5		Russian Federation
Boliden	Kankberg	Sweden	Rönnskär refinery	Sweden	45	7		Sweden
JSC Almalyk MMC	Kalmakyr	Uzbekistan	Almalyk Refinery	Uzbekistan	1)		State of Uzbekistan	Uzbekistan

Notes: e estimate. 1) Almalyk has report capacity but it is unclear whether any production takes place. 2) Most of the unidentified 400 t are produced by the Chinese and Japanese companies listed. 2) "Various" means mines controlled by the controlling company sometimes in several countries.
Sources: Raw Materials Data, BGS, USGS, company websites.

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ICT Policy Section
Division on Technology and Logistics
www.unctad.org/ict4d
ict4d@unctad.org