Critical minerals: their nature, occurrence, recovery and uses

R. Dhana Raju

Critical minerals (CMs) are metals and non-metals which are vital for the economic well-being of society. However, their supply may be at risk due to geological scarcity, geopolitics, trade policy, vulnerability and other factors. CMs include REEs, PGEs, Li, Be, Ga, Ge, In, W, Co, Nb–Ta, Mo, Sb, V, Ni, Te, Cr, Sn, Th–U, Zr, Hf, Se, Te, Re, phosphate, potash, etc. They occur in three sources, viz. primary – in ore deposits; secondary – in waste, like the electronic (e)-waste, and tertiary – in imports. Currently, many CMs (like REEs, PGMs, Cr, W, Co, Cd, Ge, Se, Te and Re) are recovered primarily during the mineral processing of ores of major commodities, such as Cu, Pb, Zn, Ni and Au. Some CMs like Au, Ag, Pt, Co, Sn and Al are being recovered and reused by recycling the environmentally hazardous, but valuable e-waste that contains ~50 chemical elements. The CMs thus recovered are in much demand in diverse industries based on conventional, high-tech and cutting-edge technologies.

Keywords: Critical minerals, e-waste, industrial uses, ores.

CRITICAL minerals (CMs) are metals and non-metals that are considered vital for the economic well-being of the world's major and emerging e-economies. Yet their supply may be at risk due to geological scarcity, geopolitical issues, trade policy and other factors. CMs ranked as most critical for the world's major industrial economies (plus their use in futuristic developments in energy, health, construction and transportation sectors as well as in space, nuclear, defence and artificial intelligence) of USA, Japan, Republic of Korea, European Union and the UK include rare earth elements (REEs), platinum group metals (PGMs), lithium (Li), beryllium (Be), gallium (Ga), germanium (Ge), indium (In), tungsten (W), cobalt (Co), niobium–tantalum (Nb–Ta), molybdenum (Mo), antimony (Sb), vanadium (V), nickel (Ni), tellurium (Te), chromium (Cr), tin (Sn), thorium–uranium (Th–U), zirconium (Zr), hafnium (Hf), selenium (Se), rhenium (Re), phosphate, potash, etc.[1]. From the perspective of each country, the list of CMs may change. For example, USA lists 35 CMs that are considered critical to its economic and national security[2,3]. For Australia, its critical commodities include Sb, Be, C (graphite), He, In, Li, Mn, Mo, Nb–Ta, Th, Sn, Ti, W and Zr, besides phosphate and potash used in fertilizers[1]. In India, 10 strategic minerals (S, Pb, petroleum, Zn, Hg, Pt, Ni, graphite, Sn and ferro-tungsten) have been identified; their present status and future challenges are discussed by Randive and Jawadand[4]. The nature, occurrence and recovery during mineral processing of diverse ores and recycling of electronic (e) waste, and major uses of CMs, together with the 33 CMs suggested here from the Indian perspective are presented in this article.

R. Dhana Raju is in the 1-10-284/1, Brahmanwadi Lane 5, Begumpet, Hyderabad 500 016, India.
e-mail: dhanaraju.reddi@gmail.com

Nature of critical minerals

CMs are both metals and non-metals, which are vital for the economic well-being of society and national security, but their supply may be at risk due to geological scarcity, geopolitics, trade policy, vulnerability and other factors. Their list (i) varies from country to country and should be arrived at after in-depth discussions amongst major stakeholders of a nation, like the geoscientific, mining and mineral industrial organizations as well as user organizations, (ii) is dynamic, (iii) needs to be updated periodically, taking into consideration the new mineral discoveries, geopolitics, mineral trade trends and policies, advances in mining, mineral processing, extractive technologies from ores and waste, vulnerability and national security. Generally, CMs include REEs, PGMs, rare metals such as the Li, Be and Nb–Ta, Ga, Ge, In, W, Ni, Co, Cr, V, Mo, Sb, Sn, nuclear fuels – thorium (Th) and uranium (U), Se, Zr–Hf, Te, Re and fertilizer commodities of phosphate and potash. Usually, CMs are the by-products of ores and some are extracted from waste material like the e-waste. Thus, many CMs (e.g. Co, Cd, Cr, Ge, PGMs, REEs, Se, Te, Re and W) are recovered as by-products from the processing of ores of major commodities such as Cu, Pb, Zn, Ni, U, Th and Au. Among the CMs, there are metals and semi-metals used in the manufacture of mobile phones, flat-screen monitors, wind turbines, electric cars, solar panels and many other hi-tech applications. The production of many CMs is strongly dependent upon the production of major commodities; as a consequence, there are opportunities to recover them from ores in which CMs may be enriched, but have not been extracted. For example, germanium can be recovered due to its enrichment in the Mississipi Valley-type and Mount Isa-type zinc and lead ores; indium can be processed from the zinc concentrates[1] and lithium can be obtained from the rare metal pegmatites and salt lakes[5]. Furthermore, concentrations of copper, zinc, silver, cadmium, indium, tin, antimony, mercury, lead and bismuth are found higher in the soil from some e-waste recycling sites like in Bengaluru, Karnataka and Chennai, Tamil Nadu, India, from which some CMs can be extracted[6]. Similarly, CMs like nickel can be obtained byphyto-mining or extracting minerals from hyper-accumulating plants. One example of this is in Borneo, Indonesia[7], where about 700 plants flourish in metal-rich soil, which makes hundreds of thousands of other plant species flee or die. The roots of these plants act like magnets. Slicing open one of these trees or running the leaves of these plants bush-cousin through a peanut press produces a sap that oozes a neon blue–green juice that is actually one-quarter nickel that is far more concentrated than the ore feeding the world's nickel smelters. These plants could be the world's most efficient solar-powered mineral smelters. Though this type of extracting minerals from plants cannot fully replace the traditional mining techniques, the technology has the additional value of enabling areas with toxic soils to be made productive[7].

Occurrence and recovery of critical minerals from primary sources

The CMs occur in three major sources: primary – in different minerals/ores that are extracted from the earth; secondary – in waste materials such as e-waste, and tertiary – in imports.

Occurrence and recovery from primary sources

The primary source materials for CMs are different minerals/ores that occur in diverse rock types/ore deposits on earth (Table 1; suggested from the Indian perspective). These primary sources – ore deposits, hosted by the magmatic, sedimentary and metamorphic–metasomatic rocks, all affected by diverse mineralization processes that include hydrothermal activity, syn-/dia-/epi-genetic affects, remobilization–recrystallization, weathering, transportation (as in placers), etc. are mined conventionally after (i) comprehensive mineral exploration by the geological–geophysical–geochemical and related laboratory-based studies, and (ii) establishment of a cost-effectively exploitable resource-base in a deposit[8,9]. CMs are usually recovered from such ores as by-/co-products and occasionally as major products by mineral processing, which comprises pre-concentration, beneficiation and extractive metallurgy like hydro-/pyro-metallurgy, followed by smelting and purification. The mineral industry usually focuses on the extraction of the main product(s) of ores, with little importance to their potential by-products like many CMs. For example, in the diverse types of U-deposits in India, the emphasis is more on the extraction of U and less on its possible high-value CMs like Au, Ag, Mo, Co, V, etc.[10]. To extract the main product(s) and co-/by-products, like some valuable CMs from different ore deposits as well as from their waste, generated during mining and ore-processing, it is better to synergize the mineral-, chemical- and nano-technology, after comprehensive characterization of different ores by state-of-the-art analytical techniques like electron micro-probe analysis, to identify both qualitatively and quantitatively different constituent metals in different ore minerals[11].

Secondary source of CMs, processing, recycling and extraction

Amount, nature and environmental impact of e-waste

The secondary source of CMs is waste materials of different types. According to the World Bank, more than 1.3 billion people in India, led by Delhi, generate the highest amount of waste globally – more than even China[11]. Among different types of waste, e-waste is considered as the fastest growing waste stream in the world with 44.7 million tonnes generated in 2016, which is equivalent to 4500 Eiffel towers. In 2016, Asia generated 18.2 metric tonnes (Mt) of e-waste, followed by Europe (12.3 Mt), USA (11.3 Mt), Africa (2.2 Mt) and Oceania (0.7 Mt). Though Oceania as a region generated the lowest amount of e-waste, it was the largest generator of e-waste per capita, with an average of 17.3 kg/inch (2.54 cm), followed by Europe (16.6 kg/inch), America (11.6 kg/inch) and Asia (4.2 kg/inch)[12]. In 2018, an estimated 50 million tonnes of e-waste, valued at about US$ 62.5 billion, was reported; the United Nations referral to it as a 'tsunami of e-waste'[13]. E-waste includes discarded electronic and electrical devices, used electronic components that can be used for refurbishment, reuse, resale, salvage recycling through material recovery or disposal. It is generated at the end of the useful life of an electronic or electrical product. Every minute a large amount of e-waste is generated due to the rapid expansion of technology and the consumption-driven society, resulting in 'e-waste mines' from which many metals, including a few CMs can be extracted. The European 'Waste Electric and Electronic Equipment' (WEEE) Directive classified e-waste into 10

Table 1. Critical minerals (CMs), their common host minerals/ores and occurrence in diverse deposits

CMs/metals	Common host minerals/ores	Occurrence (some Indian examples)
Antimony (Sb)	Stibnite, native Sb, cervantite	Stibnite and lead ores (Rajasthan, AP)
Arsenic (As)	Arsenopyrite, enargite, tennantite, realgar, orpiment	Ores of Au, Ag, Cu, Pb and Zn (Hatti, Malanjkhand, Zawar, etc.)
Beryllium (Be)	Beryl, chrysoberyl, helvite	Rare metal pegmatites, Sn–W ores (Bastar)
Bismuth (Bi)	Native Bi, bismuthinite, Bi-ochre	Fissure veins, hydrothermal/tin deposits
Caesium (Cs)	Pollucite	Rare metal pegmatites (Bastar pegmatite belt)
Chromium (Cr)	Chromite	Chromite in ultramafic igneous rocks (Odisha)
Cobalt (Co)	Linnaeite, cobaltite, smaltite-chloanthite	In copper, silver, lead and zinc ores (Malanjkhand, Zawar, etc.)
Fluorspar	Fluorite	Fluorite veins, cavity fillings, replacements
Gallium (Ga)		As by-product of Cu and Zn ores, coal ash
Germanium (Ge)	Germanite, argyrodite	Zinc-refinery slimes (Rajasthan)
Gold (Au)	Native gold, minor in Au-tellurides, electrum and amalgam	Hydrothermal, metasomatic and placer-residual concentration of Au-deposits (Kar, Ker)
Graphite (natural)	Crystalline/amorphous graphite	Graphite deposits (Eastern Ghats – AP and Odisha)
Hafnium (Hf)		In zircon of placer mineral sands (AP, TN)
Helium (He)		Extracted from natural gas (Krishna–Godavari basin, AP)
Indium (In)		Zinc residues (Rajasthan)
Lithium (Li)	Spodumene, lepidolite, amblygonite	Rare metal granite pegmatites (Bastar belt), subsurface brines
Nickel	Pentlandite, pyrrhotite	Ultramafic–mafic igneous complexes (Odisha), laterite, meteorite, earth's core and mantle
Niobium (Nb)	Pyrochlore, columbite, fergusonite, samarskite, betafite	Rare metal granite pegmatites (Bastar), carbonatites and A-type granitoids (TN)
Platinum group metals (PGMs)	Alloyed with Fe, native form	Ultrabasic magmatic rocks, PGM-placers
Potash	Sylvite, glasserite, leonite	Marine evaporites, salt lakes, vegetation
Rare earth elements (REEs)	Bastnaesite, monazite, xenotime	REE–Nb–Fe ore deposits, shoreline/fluvial placers (AP), alkaline group pegmatites, veins
Rhenium (Re)		In Mo-(molybdenite roaster flute dust) ores (TN), Cu-ores (Malanjkhand) and coal ash
Rubidium (Rb)		Rb-rich K-feldspar of granite pegmatites
Scandium (Sc)	Euxenite, gadolinite, thortveitite	RE- and U-compounds and minerals
Selenium (Se)	Related to tellurium	Copper ores, flute dust in soil
Silver (Ag)	Native Ag, argentite, cerargyrite, polybasite, proustite, pyrargyrite	Hydrothermal, fissure vein-type Ag deposits, Au-, Cu-, Pb- and Zn-deposits
Strontium (Sr)	Celestite, strontianite	Celestite in vein deposits of galena, barite, calcite and as beds with gypsum; strontianite as alteration product of celestite and as replacement of limestone
Tantalum (Ta)	Tantalite, microlite, yttrotantalite, euxenite, polycrase,	Rare metal granite pegmatites, carbonatites, A-type granitoids (Chg, TN)
Tellurium (Te)	Closely related to selenium	Cu-ores/refining sludges, native form
Tin (Sn)	Cassiterite, stannite, teallite	Sn-placers/stockworks/veins/replacements
Titanium (Ti)	Ilmenite, rutile, anatase, titanite	Beach/stream placers and anorthosite (TN)
Tungsten (W)	Scheelite, wolframite, ferberite, huebnerite	Fissure veins, replacement, contact-metasomatic and placer W-deposits (Chg)
Uranium (U)	Uraninite, coffinite, U^{6+} minerals	Uranium deposits of hydrothermal, sandstone, unconformity–proximal and carbonate-hosted types (Jharkhand, AP)
Vanadium (V)	Patronite, roscelite, vanadinite, carnotite	Carnotite deposits, oxidized Ag–Pb–Mo ores, sedimentary phosphate rock
Zirconium (Zr)	Zircon	Zircon in mineral sands (Odisha, AP, TN)

AP, Andhra Pradesh; Chg, Chhattisgarh; Kar, Karnataka; Ker, Kerala; TN, Tamil Nadu.

categories, namely large household appliances (cooling and freezing appliances – air-conditioners and refrigerators), small household appliances, IT equipment (including monitors), consumer electronics (including TVs), lamps and luminaries, toys, tools, medical devices, monitoring and control instruments, and automatic dispensers. Such waste includes used electronics and secondary raw materials such as copper, steel and plastic[14]. The Partnership on Measuring ICT for Development divides the e-waste into six categories – (i) temperature exchange equipment like air-conditioners and freezers; (ii) screens and monitors like TVs and laptops; (iii) LED lamps; (iv) large equipment, e.g. washing machines and electronic stoves and (v) small IT and (vi) telecommunication equipment like mobile phones and printers[12]. Depending upon the age and type of the discarded item, the chemical composition of the e-waste may vary. Most e-waste comprises a mixture of metals, like Cu, Fe and Al, and is hazardous to the environment. It is important to dispose such e-waste with an R2-certified recycling facility[15]. Some of the major impacts of e-waste on environment are: (i) toxic materials like Pb, Zn, Ni, flame retardants, Ba and Cr found in computers and most electronic items, if released to the environment, can cause damage to humans affecting blood, kidneys as well as the central and peripheral nervous system; (ii) damage caused by the warming up of e-waste releasing toxic chemicals into the air and affecting the atmosphere is one of the biggest environmental impacts, leading to a number of airborne diseases; it also increases the toxicity of air, making it unfit for breathing and living; (iii) e-waste, which is often thrown out into landfills releases toxins that usually seep into groundwater, affecting both land and sea animals and (iv) in Guiyu, PR China, which is the largest e-waste disposal site in the world, receiving shipments of e-waste from all over the world, many people living around the site exhibit substantial digestive, neurological, respiratory and bone problems[16]. Similar sites exist in India (e.g. Delhi, Bengaluru and Chennai), Ghana, Nigeria and the Philippines. For example, the local people and migrant workers in Delhi scavenge discarded computer equipment and extract base metals, using toxic and unsafe methods[17]. Bengaluru has a growing informal e-waste recycling sector. It was found that e-waste workers in the slums had higher levels of V, Cr, Mn, Mo, Sn, Tl and Pb in their blood than workers at an e-waste recycling facility[6,18]. E-waste can be disposed of by burial, burning, or dissolution and recovery of metals. Repairing of e-equipment is one way to quantitatively reduce e-waste. To manage e-waste, recycling is an essential element, as it greatly reduces the leakage of toxic materials into the environment and mitigates the exhaustion of natural resources. Less than 20% of e-waste is formally recycled and the rest 80% ends up in landfills or is informally recycled, thereby exposing workers to hazardous and carcinogenic substances such as Pb, Hg and Cd[19]. In an effort to globally manage and control such hazardous ‘e-waste mines’, the United Nations Environment Management Group lists key processes and agreements (~14), made by various organizations[20], and the readers can refer to this for details.

E-waste processing

For the processing of e-waste, the first step is dismantling the e-equipment into various parts, like metal frames, circuit boards, power supplies and plastic, either by hand and or using automatic shredding equipment. In an alternative bulk system, a hopper conveys material for shredding into a mechanical separator, with screening and granulating machines to separate constituent metals and plastic fractions, which are sent, to smelters and plastic recyclers respectively. Magnets, eddy currents and trammel screens are employed to separate glass, plastic, and ferrous and non-ferrous metals, which can be separated by a smelter[21]. Cu, Au, Pd, Ag and Sn are some of the CMs sold to smelters for recycling. An ideal e-waste recycling plant combines dismantling for the recovery of components with increased cost-effective processing of e-waste. Reuse is an alternative option to recycling, because it extends the lifespan of a device. Recycling raw materials from end-of-life electronics is the most effective solution to the growing e-waste problem. Additionally, recycling reduces greenhouse gas emissions, caused by the production of new products[22].

Recent processes of recycling e-waste

E-waste contains about 60 chemical elements, and presently, only about 10 are being recovered. The rest ends up in waste landfills that represent real ‘urban mines’ or ‘e-waste mines’, which are potential deposits for those who know how to exploit them. Recycling e-waste means separating materials, molecules or chemical elements so that they can be sold as raw materials for the manufacture of new materials. This involves dismantling the materials and components, their sorting and grinding, and finally separation of the materials, usually by incineration and then by solution-based chemical processes. As the e-waste is complex in nature, it is difficult to automate this step and, hence, disassembly is mainly carried out by costly manual methods. Sorting aims to minimize the chemical complexity of the mixture to be treated and its variability. The most common approach amongst recyclers, before chemical treatment, is grinding at the scale of the device or module, followed by the steps of separation by physical methods using the differences in density and magnetic properties. Depending upon the purity of the powders obtained, thermal or chemical treatments are then used to refine the composition of the final products. In the chemical treatment, the most commonly used process in the separation of chemical elements is the ‘liquid–liquid extraction’. This process involves first dissolving the metals or their oxides in an acid like nitric acid, then making an emulsion that is vigorously mixed with an organic solvent like kerosene in an extraction column, and one or more molecules (mustard) having the property of transfer of certain metals from acid to solvent. This separation step is repeated in series many a time so as to obtain the desired purity. To increase both the number of chemical elements recycled and their recycling rates, new processes are being developed. For example, to reduce the time and cost of developing new extraction processes, scientists in the SCARCE (Singapore CEA Alliance for Research in the Circular Economy) laboratory, Singapore have miniaturized and integrated with a single device ‘microfluidics’ automated all the equipment necessary for a process study. Using this modular microfluidic approach and following the two specific extracting molecules process, they have recovered some CMs, namely REEs from mobile phones with an efficiency 100 times greater than the efficiency of extractions with molecules used separately. Furthermore, they have demonstrated efficient extraction at acid consumption 10–100 times lower than that used in the industry, thereby generating less pollution[23].

Examples of e-waste recycling plants to extract some high-value CMs

At Skellefte, Sweden, a giant industrial smelter operated by Boliden is one of the world's largest e-waste recycling companies. In 2017, it smelted ~80,000 Mt of scrap e-waste, much of it circuit boards cut from European computers and mobile phones, to extract Cu, Au, Ag and other precious metals, with no vats of acid and acid fumes. The automated process operates according to the European environmental and health and safety standards. It is equipped with systems to clean process gases and prevent dust release. Waste heat, generated during smelting, is circulated for heating local buildings and the scant leftovers from smelting are buried in purpose-build stores under the site.

Another example is the company Umicore in Hoboken, Belgium, getting most of its raw materials from e-waste. Here, the smelters can extract 400 g of Au from 1 Mt of mobile phones, along with Cu, Ag, Pb, Sn and In. After smelting, the metals in the waste stream are chemically separated. The plastic casings go into the smelter, where they are burned to provide most of the fuel for the facility. Here, over 95% of the feed is turned into useful products, with the rest 5% that includes toxic elements like Hg and Cd that have to be disposed of 'in a safe way', plus slag that is used for constructing flood-protection dykes along the Belgian coast. Furthermore, companies like Dell have been collecting old electronic equipment to pass on to recyclers for the extraction of precious metals, while Apple rolled out a robot able to dismantle iPhones, sorting components for ease of recycling so as to recover materials that traditional recyclers cannot. The company claims to recover Al, Co, Cu, W, Sn, Ag, Ta, Au, Pd and various REEs. It appears that Cu and Al, together make up more than half the value in e-waste, and are now often cheaper to obtain from jettisoned products. Thus, 'urban mining' of e-waste is becoming more cost-effective than virgin mining. It appears that there is more Au in a tonne of mobile phones than in a tonne of ore from a gold mine, and according to an estimate all the e-waste discarded annually around the world contains >300 tonnes of gold[24].

Scientists at the University of New South Wales (UNSW), Australia, have developed a prototype modular system micro-factory to turn e-waste into reusable materials. The discarded electronic devices were collected and robotically processed by first breaking them, before being sorted by a special robot. The useful components are placed inside a furnace and subjected to precisely controlled temperatures, thereby extracting valuable materials, including metal alloys and a range of micro-materials. The UNSW micro-factory has also found use for plastics by converting them into filaments employed in 3D printing. Due to their modular set-up, the micro-factories can operate on sites as small 50 m^2. The different stages in the system can be tailored to those materials being processed, saving space and improving efficiency. Due to the small size of the micro-factories, they can be easily set up wherever waste is generated or stockpiled. This provides local commercial opportunities as well as dealing with waste problems at the source itself. It benefits remote and rural areas which face prohibitive logistical costs in transporting their waste for communities to deal with their rubbish themselves. Micro-factories like those developed at UNSW keep costs low, while extracting valuable materials for use in new and usable resources[25].

Uses of the critical minerals

The CMs, listed in Table 1 have many uses because of their important role in several industries, based on the conventional, high-tech and cutting-edge technologies, to meet diverse needs of the society (Table 2). Thus, they play an important role in both conventional industries like metallurgy and in the production of steel, ceramics, refractories, automobiles and jewellery, and high-tech industries such as nuclear, space, telecommunications, consumer electronics, super-alloys and defence.

Critical minerals in the Indian scenario

In India, a study, the first-of-its-kind framework for the country and supported by the Department of Science and Technology, Government of India (GoI) while assessing the impact of CMs on the manufacturing sector, has identified 12 CMs that include beryllium, germanium, rare earths (heavy and light), rhenium, tantalum, etc. having specialized uses in a range of industries with modern applications, such as aerospace, automobiles, cameras, defence, entertainment systems, laptops, medical imaging, nuclear energy and smart phones[26]. According to the Press Information Bureau, the Ministry of Mines, GoI, will set up a joint venture company, namely Khanij Bidesh India Ltd (KABIL) to ensure consistent supply of critical and strategic minerals to the Indian domestic market and to help in realizing the overall objective of import substitution. For this, KABIL would carry out identification, acquisition, exploration, development, mining and processing of strategic minerals overseas for commercial use and meeting the country's requirements of these minerals. The new company will help in building up partnerships with other mineral-rich countries like Australia and those in Africa and South America, where Indian expertise in exploration and mineral processing will be mutually beneficial bringing about new economic

Table 2. Societal applications of CMs

CMs/metals (atomic no.)	Uses*
Antimony (Sb, 51)	In batteries and flame retardants
Arsenic (As, 33)	Lumber preservatives, pesticides and semiconductors
Beryllium (Be, 4)	As metal: as an alloying agent in aerospace and defence industries; X-ray window, as canning material in nuclear reactors; for high-speed computers and audio components. As oxide: electrical insulator, in microwave communications, alloys (Be–Cu in electrical and electronic industries; Be–Al as hardener in Al–Mg alloy melting)
Bismuth (Bi, 83)	In medical and atomic research; its low melting point alloys with Pb, Sn, Fe and Cd are used in fire detectors and extinguishers
Caesium (Cs, 55)	In research and development (R&D) used as a catalyst in hydrogenation of a few organic compounds; metal in ion propulsion systems; in atomic clocks; 'getter' in electron tubes, photoelectric cells and vacuum tubes and IR lamps
Chromium (Cr, 24)	Primarily in stainless steel and super-alloys
Cobalt (Co, 27)	Co-oxide nanoparticles in Li-ion batteries for electric vehicles and Co in super-alloys
Gallium (Ga, 31)	For integrated circuits and optical devices like LEDs
Germanium (Ge, 32)	For fibre optics and night-version apparatus
Gold (Au, 79)	For jewellery; in electronics and computers, medicine and dentistry, and medals and statues
Graphite (natural; C, 60)	For lubricants, batteries and fuel cells
Hafnium (Hf, 72)	For nuclear control rods, alloys and high-temperature ceramics
Helium (He, 2)	For MRIs, lifting agent, inert shield for arc welding, refrigeration, gas for aircraft, coolant for nuclear reactors, medicine and cryogenic research; to detect gas leaks
Indium (In, 49)	Mostly used in LCD screens
Lithium (Li, 3)	Primarily for Li-ion/polymer batteries for electric vehicles; in ceramics and glass industries; nuclear fusion and for many chemical compounds
Nickel (Ni, 23)	For alloys, batteries, coins, cars, mobile phones, jet engines, cutlery and bathroom taps and shower heads
Niobium (Nb, 41)	For making steel; Zr–2.5% Nb alloy for pressure tubes in heavy-water nuclear reactor, Zr–Nb–Cu for garter springs, SS super-alloys, superconductors, micro-alloyed steel; magnetic films of Fe–Nb nitride used in corrosion resistance
PGMs (Pt-78, Pd-46, Os-76, Rh-45, Ru-44 and Ir-77)	Pt as catalytic converters, oxygen sensors and spark plugs in automobiles; Pd in almost all electronics; Ir to make high-purity crystals that have applications in medical, petroleum and security industries
Potash	As fertilizer in agriculture; in the manufacture of K-bearing chemicals such as detergents
REEs (La-57, Ce-58, Pr-59, Nd-60, Pm-61, Sm-62, Eu-63, Gd-64, Tb-65, Dy-66, Ho-67, Er-68, Tm-69, Yb-70, Lu-71, Y-39)	Primarily in batteries and electronics; for superconductors, permanent magnets, metallurgy, nuclear, ceramics, chemicals, electronics (LED displays on smartphones and TVs, energy-efficient light bulbs, disc-drives in laptops), power steering in cars, space, lasers, phosphors, fibre optics, misch metal, renewable wind-energy, defence, etc.
Rhenium (Re, 75)	For lead-free gasoline and super-alloys (in jet engines and in W-/Mo-based alloys, as filaments for mass spectrographs and as an electrical contact material.
Rubidium (Rb, 37)	For R&D in electronics; in vacuum tubes as a getter and in the manufacture of photocells and in special glasses; as a propellant in ion engines on spacecraft
Scandium (Sc, 21)	For alloys (Al–Sc alloys for aerospace industry components and sports equipment such as bicycle frames, fishing rods, etc.) and fuel cells; Sc iodide in Hg vapour lamps
Selenium (Se, 34)	Has antioxidant properties – antioxidants protect cells from damage; may reduce chances of prostate cancer; plays a key role in metabolism
Silver (Ag, 47)	In electronics, coins, jewelry and medicine
Strontium (Sr, 38)	For pyrotechnics and ceramic magnets
Tantalum (Ta, 73)	In electric components, most capacitors; transmitting and vacuum tubes, heating elements and heat shield; carbides for tools, magnetic films of Fe–Ta nitride used in corrosion resistance
Tellurium (Te, 52)	To improve the machinability of Cu and stainless steel; added to cast iron; used in ceramics; to make blasting caps; added Te to Pb to improve the strength and hardness of metal and decrease corrosion; for solar cells
Tin (Sn, 50)	As protective coatings and alloys such as soft solder, pewter, bronze, phosphor bronze and steel; Nb–Sn alloy for superconducting magnets
Titanium (Ti, 22)	Used as a white pigment; as a super-hard metal in alloys, aerospace, metallurgy, chemical and desalination plants; and in plastics and paper industries, drilling (oil wells), biomedical food, slag and flux
Tungsten (W, 74)	To make wear-resistant metals
Uranium (U, 92)	As fuel for nuclear fission reactors; in defence to power nuclear submarines and in nuclear weapons
Vanadium (V, 23)	For Ti-, ferrovanadium- and V-steel alloys; minor alloy metal which toughens steel; by adding V to any steel helps remove oxygen and nitrogen, and gives uniform grain size; V_2O_5 is used as a mordant, a material that permanently fixes dyes to fabrics
Zirconium (Zr, 40)	In high-temperature ceramic industries, Hf-free Zr as cladding material; in alloys, chemical industry, refractories (steel and glass works), medicine, tanning and oil industries.

*Compiled from refs 3, 4, 31 and 32.

opportunities. In KABIL, the equity participation among NALCO, HEC and MECL is in the ratio of 40 : 30 : 30 (ref. 27). In this background and taking into consideration the diverse uses of the 33 CMs proposed here (Table 2), it is suggested that GoI may consider constituting a committee, preferably under the aegis of the Geological Survey of India, representing the Ministries/Departments of Steel and Mines, Science and Technology, Earth Sciences, Mining, Commerce, Defence, Atomic Energy, Space, etc. for an in-depth discussion to arrive at a plausible list of CMs that are vital for the economic well-being of the society and security of the nation, by taking into consideration aspects such as geological scarcity, geopolitics, trade policy, vulnerability, industrial needs and other related factors. It may be added that though Th is usually added under the list of CMs in some countries, it is not included in the list here (Tables 1 and 2), because Th resource in the form of the mineral monazite is abundant in the shoreline placer mineral sands of India. However, from monazite, the REEs, especially light REEs can be extracted individually like Nd_2O_3 (9.3–11.6%) and Pr_2O_3 (2.5–3.0%)[28]. Similarly, the apatite veins in Kasipatnam area, Andhra Pradesh, contain ΣLREE of 1–2% (ref. 29). Likewise, HREEs may be extracted from placer garnet (ΣHREE 0.1–0.5%) in the shoreline mineral sand deposits of India[30], as REEs are important CMs having many high-tech industrial uses.

1. Critical minerals. Geoscience Australia; https://www.ga.gov.au resources.
2. Assessment of critical minerals: updated application of screening methodology. Office of the President of the United States. Executive order 13817 pdf, February 2018; https://www.whitehouse.gov
3. Critical minerals in the Federal Register. Interior releases 2018's final list of 35 minerals deemed critical to U.S. National security and economy. Department of the Interior, US Geological Survey, 18 May 2018; apdemas@usgs.gov.
4. Randive, K. and Jawadand, Strategic minerals in India: present status and future challenges. *Miner. Econ.*, 2019, **32**, 337–352.
5. Dhana Raju, R. and Venkat Reddy, D., Metals for electric vehicles: attributes, natural resources and research and development. *Int. J. Earth Sci. Eng.*, 2017, **10**(5), 10.
6. Ngoc Ha, N. *et al.*, Contamination by trace elements at e-waste recycling sites in Bangalore, India. *Chemosphere*, 2009, **76**(1), 9–15; Bibcode:2009Chmsp..76....9H, doi:10.1016/j.chemosphere.2009.02.056, PMID 19345395.
7. Morse, I., Petal to the metal: plants may be future of mining. *Times of India* (Hyderabad edn), 3 March 2020, p. 11.
8. Dhana Raju, R., The prospects for expansion and cost-effective development of mineral resources in the mining and industrial areas of India. *Global J. Earth Sci. Eng.*, 2017, **4**, 1–7.
9. Dhana Raju, R., Comprehensive mineral-exploration/exploitation of ore deposits, with some new techniques, value-addition and creation of wealth from waste. *J. Appl. Geochem.*, 2019, **21**(4), 411–427.
10. Dhana Raju, R., *Indian Uranium Deposits*, Cambridge Scholars Publishing, Newcastle upon Tyne, UK, 2019, p. 535.
11. Dhana Raju, R. and Venkat Reddy, D., Synergizing mineral exploration with mineral-, chemical- and nano-technology for low-cost and high-return exploitation of ore and gangue minerals. *Int. J. Earth Sci. Eng.*, **10**(1), 1–4; World Bank's calculations on generation of waste in India. *Times of India* (Hyderabad edn), 3 March 2020, p. 2.
12. Baldé, C. P. *et al.*, The Global E-waste Monitor 2017, UNU, ITU, ISWA, 2017.
13. World Economic Forum, A new circular vision for electronics: time for a global reboot, January 2019, p. 24; https://www.weforum.org/reports/a-new-circular-vision-for-electronics-time-for-a-global-reboot
14. WEEE CRT and monitor recycling, Executiveblueprints.com, 2 August 2009 (archived from the original on 22 December 2012; retrieved on 8 November 2012).
15. Robinson, B. H., E-waste: an assessment of global production and environmental impacts. *Sci. Total Environ.*, 2009, **408**(2), 183–191; Bibcode:2009ScTEn.408..183R, doi:10.1016/j.scitotenv.2009.09.044, ISSN 0048-9697, PMID 19846207.
16. Lubell, I., Five shocking environmental effects of e-waste; info.mayeralloys.com (retrieved on 8 January 2020).
17. Mukherjee, R., Anticipating ruinations: ecologies of 'make do' and 'left with'. *J. Vis. Culture*, 2017, **16**(3), 287–309; doi:10.1177/1470412917740884.
18. Needhidasan, S., Samuel, M. and Chidambaram, R., Electronic waste- an emerging threat to the environment of urban India. *J. Environ. Health Sci. Eng.*, 2014, **12**(1), 36; doi:10.1186/2052-336X-12-36, PMC 3908467, PMID 24444377.
19. Tarter, A., Environment Programme, UN (UNEP), *Encyclopedia of Crisis Management*, SAGE Publications, Inc, 2013; doi:10.4135/9781452275956.n127, ISBN 978-1-4522-2612-5.
20. United Nations Environment Management Group, United Nations system-wide response to tackling e-waste, 2017; https://unemg.org/images/emgdocs/ewaste/E-Waste-EMG-FINAL.pdf
21. WEEE recycling resources, Simsrecycling.co.uk (archived from the original on 6 January 2015; retrieved on 6 January 2015).
22. Benefits of recycling, hardrawgathering.co.uk (archived from the original on 6 January 2015; retrieved on 6 January 2015).
23. Gabriel, J. C. P., New technologies to recycle electronic waste. *The Conversation*, 30 March 2020; https://theconversation.com
24. Pearce, F., We know the wrong way to deal with e-waste. But what should we do instead? Ensia, 22 August 2018; https://ensia.com>features>e-waste.
25. Finch, S. (ed.), The modular micro-factory extracting value from electronic waste. DisruptionHub; https://disruptionhub.com>recyclin
26. Gupta, V., Biswas, T. and Ganesan, K., Critical non-fuel mineral resources for India's manufacturing sector: a vision for 2030. Council on Energy, Environment and Water, New Delhi; https://www.ceew.in>publications.
27. KABIL set up to ensure supply of critical minerals PIB. 1 August 2019; https://pib.gov.in>print release.
28. Panda, N. K., Rajagopalan, V. and Ravi, G. S., Rare-earth-element geochemistry of placer monazites from Kalingapatnam coast, Srikakulam district, Andhra Pradesh. *J. Geol. Soc. India*, 2003, **62**(4), 429–438.
29. Panda, N. K., Yugandhara Rao, A., Rameshkumar, K., Mohanty, R. and Parihar, P., Anomalous REE concentration in carbonate–phosphate bearing phases from Narasimharajapuram area, Visakhapatnam district, Andhra Pradesh. *Curr. Sci.*, 2015, **109**(5), 860–862.
30. Panda, N. K., Sahoo, P., Rao, A. Y., Rameshkumar, K. and Rai, A. K., Concentration and distribution of rare elements in beach placer garnets of Kalingapatnam coast and their potential for heavy rare earths, Andhra Pradesh, India. *J. Geosci. Res., Spec. Vol.*, 2017, **1**, 131–138.
31. Those who search – find. Brochure of the Atomic Minerals Directorate for Exploration and Research, Department of Atomic Energy, Government of India, 2000, p. 25.
32. Google search on applications of some critical minerals.

ACKNOWLEDGEMENT. I thank three anonymous reviewers for their comments that helped in improving the quality of the revised manuscript.

Received 16 April 2020; revised accepted 11 June 2020

doi: 10.18520/cs/v119/i6/919-925