ELECTRIC VEHICLE (EV) LI-ION BATTERY RAW MATERIALS

An Overview

Abstract

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NYC Fleet

NYC DCAS
Citywide Administrative Services

Electric Vehicle (EV) Li-ion Battery Raw Materials

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Abstract

This report provides a brief overview of the key minerals used in EV Li-ion batteries. It mainly concentrates on lithium, cobalt, nickel, manganese, copper, and aluminum and includes corresponding data regarding of their 2021 supply, reserves, and resources as reported by the US Geological Survey in 2022.

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Section 1: Introduction

According to the United Nations, "*climate change refers to long-term shifts in temperatures and weather patterns.*"

Greenhouse gas (GHG) emissions, mostly carbon dioxide (CO_2) emissions, stay in the atmosphere trapping the sun's heat. This is a natural process that keeps the Earth's surface warm enough for life to exist. However, since the late 1800s, human activities, mainly the burning of fossil fuels like coal, oil, diesel, and gas, have become the primary driver of increases in greenhouse gas concentrations in the atmosphere.

As a result, the Earth is warming up faster than ever before in recorded history, which leads to changes in weather patterns and the disruption of the natural balance. Human beings and all other forms of life on Earth are at risk and unless something is done to mitigate this effect, the Earth will become uninhabitable.

Climate change mitigation involves approaches to reduce and stabilize the levels of heat-trapping greenhouse gases in the atmosphere. One key approach involves the electrification of the transportation sector, which is one of the leading contributors to anthropogenic (caused/produced by human beings) GHG emissions worldwide.

The electrification of the transportation sector has been widely considered critical for the reduction of carbon dioxide (CO_2) emissions.

Currently, transportation vehicles, such as light-duty passenger cars and commercial vehicles (e.g., pick-ups and delivery vans), and heavy-duty trucks, are mainly powered by fossil fuels. These vehicles with internal combustion engines (ICEs) release large quantities of CO_2 and other pollutants (e.g., nitrogen oxides (NOx), carbon monoxide (CO), and hydrocarbons (HC)) into the air (tailpipe emissions) when fossil fuels, such as diesel or gasoline, are burned by their ICEs to power the vehicle.

Full electrification of a vehicle can reduce exhaust/tailgate CO_2 emissions to zero. Plug-in hybrid electric vehicles (PHEVs) operating in all-electric mode, and battery electric vehicles (BEVs), also called all-electric vehicles (EVs), have zero tailgate CO_2 emissions. For this reason, all-electric vehicles are known as zero-emission vehicles.

Furthermore, as electricity becomes greener and generated by sunlight, wind, water and other low-carbon sources in the near future, the life-cycle GHG emissions of EVs will decrease, subsequently lowering the fossil fuel dependency and the environmental impact of road transportation, and making the widespread transition to all-electric vehicles (EVs) a significantly more effective and attractive solution for reduction of global GHG emissions.

Global adaptation of electric light-duty vehicles (LDVs), including passenger cars and light commercial vehicles, is growing rapidly. The electrification of the transportation sector has made striking progress in the LDV sector over the past three years as technology improvements offer longer battery ranges and faster charging sessions. Adoption of PHEVs and BEVs increased significantly in 2021 with 16 million electric cars on the road worldwide, capturing about 9% of the global LDV sales market. [10]

However, when compared to the LDV sector, the electrification of the heavy-duty vehicle (HDV) transport, e.g., trucks and tractor trailers, has moved much slower. This is because the HDV sector requires batteries with much higher power to propel large vehicles with or without loads. In addition, the lifespan of an HDV is much longer than the current lifespan of the EV batteries, which means that HDVs will require more frequent battery replacements during their lifespan.

On August 5, 2021, the U.S. Government announced a new target of 50% electric vehicle sales share by 2030. [11] This was followed by an announcement on December 13, 2021, of an EV charging plan that aimed for the installation of 500,000 chargers across the United States by 2030. [12] In like manner, the European Commission proposed the European Union (EU) fleet-wide CO_2 emission reduction targets for new passenger cars and vans to be 100% zero-emission by 2035. [13]

However, independent of governmental policies and incentives, the EV market is expected to skyrocket within the next 20 years, and according to BloombergNEF (BNEF) consultancy in London, 70% of new passenger-vehicle worldwide sales will be electric by 2040. [14, 15]

As a result, demands for EV batteries, and in turn for battery materials, will also increase, straining even further the supply of raw metals that are key components of EV batteries.

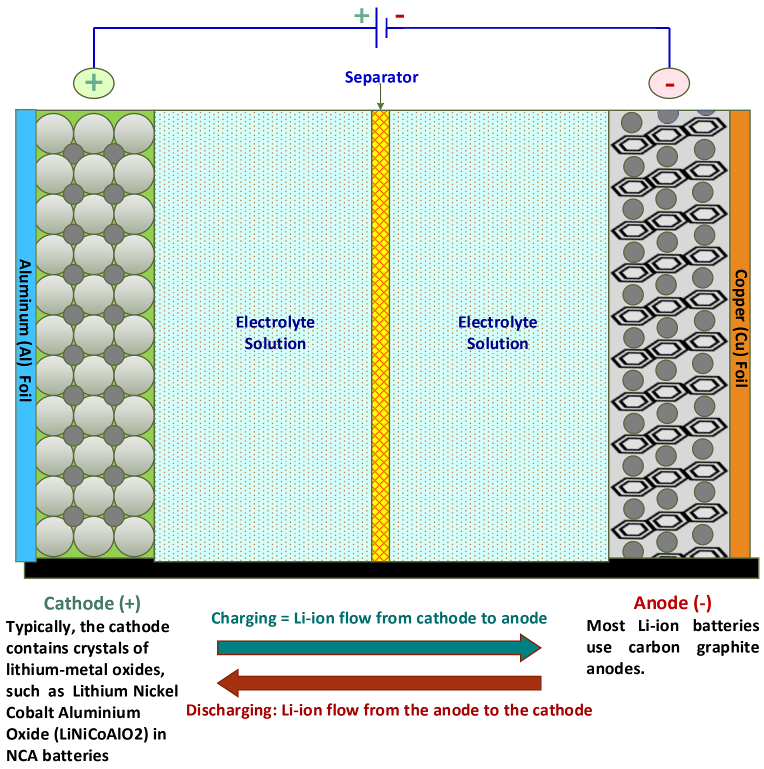
An EV battery, or EV battery pack, consists of several battery modules and contains the Battery Management System (BMS), the cooling system, and other control and protection systems. Battery modules are composed of various battery cells.

Battery Structure

Each battery cell has two electrodes (an anode, a cathode), an electrolyte that provides a medium for the ions to flow between electrodes, and a separator that prevents the electrodes from contacting each other. When the battery is charging, the ions flow from the cathode through the electrolyte and the separator to the anode. When the battery is discharging (powering the EV vehicle), the ions flow in reverse direction, from the anode through the electrolyte and the separator to the cathode, forcing the electrons to go through an outside circuit, creating a current that charges the EV.

Most EVs use lithium-ion (Li-ion) batteries because of their high energy density and thus can have a very high voltage and charge storage per unit mass and unit volume. Commonly, Li-ion batteries use carbon graphite on the anode and some type of Li-ion metal oxide crystals, such as lithium nickel cobalt aluminum oxide ($LiNiCoAlO_2$), on the cathode. Key metals that are used in the Li-ion batteries are lithium, cobalt, nickel, manganese, copper, and aluminum.

Cathodes are the limiting factors that define the performance of EV batteries. Li-ion battery cathodes are composed of a thin layer of micro-scale crystals that contain negative oxygen charged ions (O_2^-) coupled with positive charged lithium (Li^+) and a mix of other metals, i.e., nickel (Ni), manganese (Mn), and cobalt (Co).



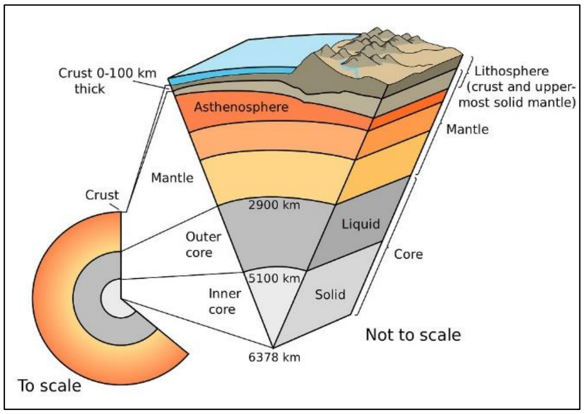
Typically, the cathode contains crystals of lithium-metal oxides, such as Lithium Nickel Cobalt Aluminium Oxide (LiNiCoAlO2) in NCA batteries

Most Li-ion batteries use carbon graphite anodes.

The different types of Li-ion batteries cathodes, positive electrode, are produced using various transition metal oxide crystals, such as lithium cobalt oxide (LCO), lithium manganese oxide (LMO), lithium nickel manganese cobalt oxide (NMC), and lithium nickel cobalt aluminum oxide (NCA). However, battery-grade graphite is almost exclusively used in most Li-ion battery anodes, negative electrode.

The chemistry of the cathodes may differ depending on the metals used in EV batteries. Overall, lithium, cobalt, nickel, and manganese are considered critical materials in the manufacturing of cathode sheet for Li-ion batteries. Graphite that is used in the battery anode is also considered a critical material by the U.S. Geological Survey. These raw materials are non-renewable/finite resources that are concentrated in only a few countries, especially nickel, lithium, cobalt, and graphite. [107]

Earth Layers



USGS: Earth Cross-Section
Source: https://www.usgs.gov/media/images/earth-cross-section

The Earth is composed of four concentric layers: crust, mantle, outer core, and inner core. [73]

The Earth's crust is the outermost layer of the earth, which supports all life on Earth, and accounts for 1% of the Earth's mass. The Earth's crust is divided into an older, thicker continental crust, which makes up about 40% of the surface of the Earth, and a younger, denser oceanic crust beneath the ocean floor. The crust is composed of solid rocks and minerals. [72, 74]

The Earth's mantle is a hot layer of semi-solid rock that lies between Earth's habitable crust and super-heated core. It holds about 84% of the Earth's volume (and about 67% of its mass) and is basically composed of silicate rocks that are rich in iron, magnesium, and calcium. [73, 75]

The Earth's outer core lies between the mantle layer and the inner core. It primarily consists of very hot liquid nickel-iron alloy (NiFe). It can reach temperatures of about 8,132°Farenheit (4,500° Celsius) in the outer surface to about 9,932° Fahrenheit (5,500°Celsius) near the inner core. [76]

The Earth's inner core is the innermost layer at the center of the planet. It is a solid layer mainly composed of about 80% iron and some NiFe alloy. Temperatures in the center of the Earth reach 10,832° Fahrenheit (6,000° Celsius), which is as hot as the surface of the Sun. However, the solid iron layer cannot become liquid because of the immense pressure, about 3.6 million atmospheres (atm), that prevents the iron from melting. The inner core spins faster than the Earth, and it creates the Earth's magnetic field. [76]

The Earth's solid inner core, mostly composed of solid iron, is constantly transferring heat to the Earth's outer core, which is a liquid mixture of nickel and iron. This causes convection currents in outer core's molten metal fluid. As the Earth spins, the molten metals swirl around in eddies, and as the molten metal mass moves around, it acts as an electrical generator producing a flow of electric currents that are hundreds of miles wide. This mechanism produces the Earth's magnetic field (geomagnetic field). The geomagnetic field extends from the inner core out into outer space where it interacts with the solar wind, which is made of destructive charged particles emitted by the sun. These charged particles can strip away the ozone layer that protects the planet from harmful ultraviolet radiation. The geomagnetic field acts as a protective blanket around the planet and prevents the sun's charged particles from reaching the Earth's atmosphere. [77]

Section 2: Battery Raw Materials

Lithium

Lithium (Li) is a soft, silvery metal with atomic number 3. It has the lowest density of all metals and is the lightest of the solid elements. Lithium is highly reactive, especially with water, and flammable. It does not occur freely as a metal in nature, but only in compounds in igneous/pegmatitic rocks and in natural waters, e.g., as salts in mineral springs.

Lithium is not a scarce resource, but global scientists and researchers have raised concerns on how fast lithium resources and production can be scaled-up to meet future planned supplies for the anticipated increased demands for EV Li-ion batteries. [23]

There are two (2) main sources of lithium production, lithium-rich brine bodies and lithium bearing minerals [24]:

Lithium Floating in Oil
Source: Wikipedia- Lithium
https://en.wikipedia.org/wiki/Lithium#/media/File:Lithium_element.jpg

- Lithium-rich brine bodies are found in salt lakes and salars, which are salt dry flats. These brine bodies were formed when lithium and other minerals from surrounding rocks dissolved in prehistoric lake waters that were trapped in a closed basin.

  Salars/salt flats are usually found in deserts where the rate of evaporation is high and the precipitation (e.g., rain, snow, mist, and fog) rate is low. They were formed when the Salt Lake waters naturally evaporated over millions of years, leaving behind solid salt layers/flats with pools of extremely rich lithium-rich brine underneath it. [24]

The Rincon Lithium Project is a high-grade lithium project in the Salar Del Rincon, Argentina
Credit: Argos Minerals
Source: Mining Technology: Rincon Project Argentina

Salinas Grandes, Argentina.
Photo Credit: Shutterstock.
Source: Boston University Global Development Policy Center: Can Escazú Turn Mining Green in the Lithium Triangle? Lofty Promises Meet a Thirsty Industry in the Desert

To extract the lithium, the process involves drilling through the solid salt layer, and then pumping the brine to the surface into a series of manmade ponds, where lithium carbonate (Li_2CO_3) and other salts, e.g., manganese and potassium salts, crystallize via natural evaporation. The mixture is further processed to obtain lithium carbonate, which is used for li-ion batteries, and lithium chloride (LiCl).

The whole process takes 12-18 months and requires large amounts of water. However, this method of extracting lithium is considered low cost and thus, more favorable. About 50% of the global lithium production comes from six primary lithium brine bodies from salars located in the Andes mountains, in a region that passes across Chile, Argentina, and Bolivia. This region is known as the 'Lithium Triangle,' and it is one of the driest places on Earth. Bolivia is not currently producing lithium. [31]

Research is underway to extract lithium from seawaters, which is an almost unlimited resource. However, the extremely low concentration of lithium in seawaters (~0.2 ppm) and the high concentration of competing ions (such as sodium, magnesium, calcium, and potassium ions) are the main challenges that need to be overcome if lithium harvesting from seawaters is to become economically feasible. Scientists are working on developing sieves/membranes that allow smaller lithium ions to pass through while blocking larger ions, e.g., magnesium ion. But this method of selective removal of lithium from seawaters is yet to be demonstrated on a large scale. [25], [26]

- The other source is lithium from lithium bearing minerals from hard magmatic rock deposits formed through the cooling and solidification of lava inside mines. Lithium can be obtained from three minerals/rocks: spodumene, petalite and lepidolite, which are found in pegmatite deposits. Pegmatites are unusually coarse-grained crystalline igneous rocks that are formed during the final stage of magma's crystallization. Spodumene is considered the most important of the three lithium minerals because it has the highest lithium content. [24]

  Spodumene pegmatite deposits are mined using conventional mining techniques, which require substantial amounts of energy. Once the spodumene is extracted, it is concentrated via crushing, grinding, and subsequently subjected to several separation processes that increase the lithium concentration by removing any unwanted materials. The resulting high lithium spodumene concentrate is shipped to processing plants, mostly located in Asia, that extract chemical-grade lithium and convert it to lithium carbonate, lithium chloride, or lithium hydroxide. [24]

In 2021, Lithium mines produced a record global total of about 100,000 metric tons of lithium.
Australia was the world leader by supplying close to 50%, or 55,000 metric tons, of the global lithium production largely from six mine operations, followed by Chile with 26,000 metric tons from brines, China with 14,000 metric tons from brines and mineral operations, and Argentina with 6,200 metric tons from brines. [27]

Most of the Australian lithium is processed by China, making China the world leader in the production of lithium carbonate, which is used in the manufacturing of Li-ion batteries. As a result, China leads the worldwide manufacturing of Li-ion battery. [33]

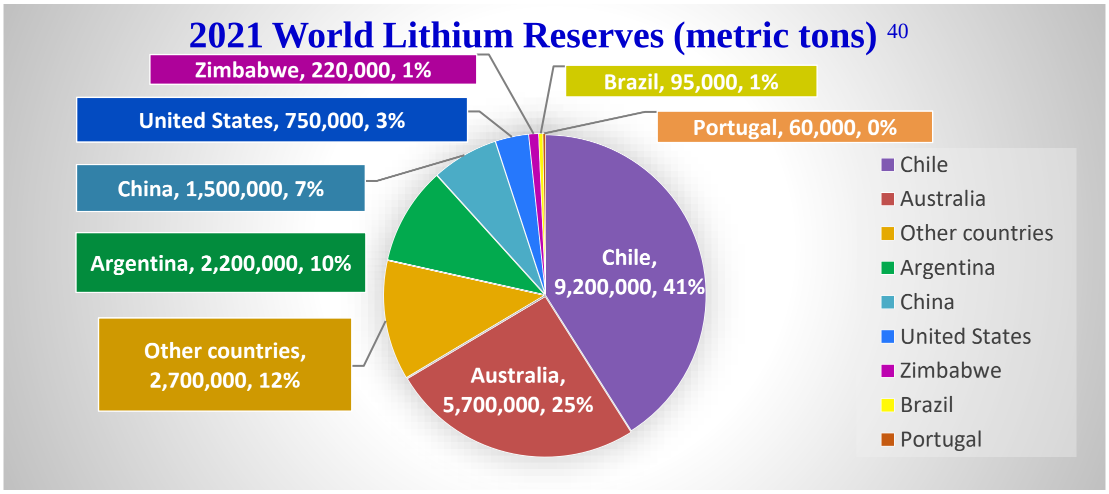
The total amount of global lithium reserves, exploitable deposits that can be economically extracted using existing technologies under current conditions, was estimated to be 22 million metric tons in 2021 with Chile holding 9.2 million metric tons, followed by Australia with 5.7 million metric tons, Argentina with 2.2 million metric tons, and China with 1.5 million metric tons. [28]

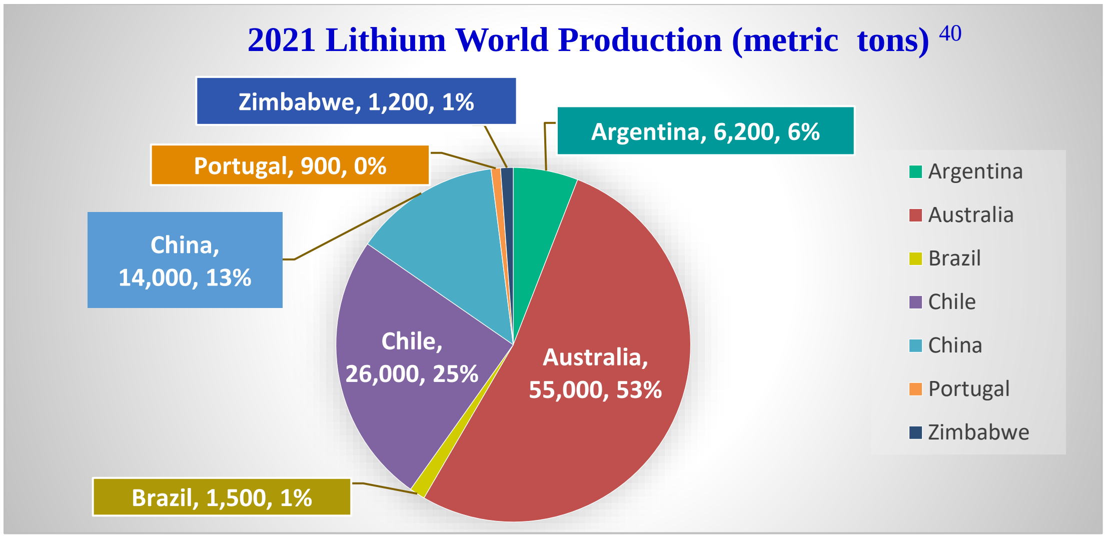
According to the U.S. Geological Survey, Mineral Commodity Summaries, Lithium report published in January 2022, because of continuing exploration, identified lithium resources that remain underground increased to a total of about 89 million metric tons in 2021. The United States alone accounted for 9.1 million metric tons of untapped lithium from continental brines, geothermal brines, pegmatites deposits, and other sources. Bolivia holds the highest amount with 21 million metric tons; Argentina has 19 million metric tons; Chile accounts for 9.8 million metric tons; Australia has 7.3 million metric tons; and China holds 5.1 million tons followed by other countries with lesser amounts of lithium resources. [29]

2021 World Lithium Reserves [40]	
Country	Reserves* (metric tons)
Chile	9,200,000
Australia	5,700,000
Other countries**	2,700,000
Argentina	2,200,000
China	1,500,000
United States	750,000
Zimbabwe	220,000
Brazil	95,000
Portugal	60,000
World total (rounded)	22,000,000

2021 Lithium World Production [40]	
Country	Production* (metric tons)
United States	W
Argentina	6,200
Australia	55,000
Brazil	1,500
Chile	26,000
China	14,000
Portugal	900
Zimbabwe	1,200
Other countries**	—
World total (rounded)	100,000

* Estimated. W Withheld to avoid disclosing company proprietary data. — Zero
** Other countries with reported reserves include Austria, Canada, Congo (Kinshasa), Czechia, Finland, Germany, Mali, Mexico, and Serbia.


2021 World Lithium Reserves (metric tons) [40]


2021 Lithium World Production (metric tons) [40]

As vehicles electrify, the difficulty of how quickly and effectively current lithium production can be scaled up to meet future demands increases. This means that companies producing lithium from hard-rock mining in Australia, and from brine mining in South America would need to invest billions of dollars to increase capacity and to accelerate efforts to bring new mines to the production phase.

Investors are cautious about committing such large sums of money in advance mainly because of concerns that developments in battery technologies may gear the market towards different types of materials and/or technologies, such as sodium-ion batteries and/or fuel cell vehicles. As a result, the lithium rush may not last long enough for the market to recuperate and make profit on investments. It is anticipated that investments in new mining projects will be needed to meet upcoming increases in lithium demands. On average, it takes 16.5 years to carry out a mining project from the concept/discovery phase to the startup/production phase. This length of time could delay the ability of new mine projects to catch up with emerging and rapidly increasing supply demands if companies wait until the supply demands materialized before committing to new mine projects. [38]

Further, scaling up lithium production around the world does come with some technical and environmental challenges. Mining lithium from hard rocks is energy and labor intensive and harvesting lithium from brines requires enormous amount of water.

Current hard rock mining employs traditional mining techniques to dig for mineral ore, crystals, or rocks that contained the desired metal. In the case of lithium, spodumene pegmatite rocks, which are clusters of rocks and crystals that contain lithium, are being mined. Building a mine to extract spodumene pegmatites often impacts local communities and the environment in many ways, including displacing thousands of acres of dirt and rock, disrupting nearby land, contaminating the soil, and polluting and depleting ground water and rivers.

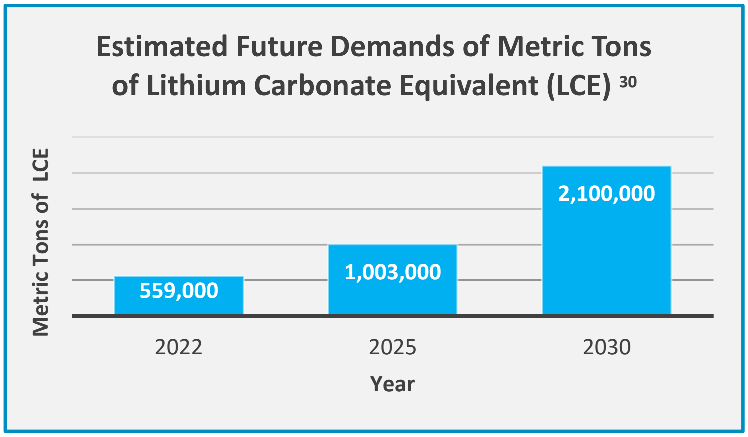
Likewise, harvesting lithium from brines also impacts surrounding localities by consuming enormous amounts of water usually sourced from wells, streams and aquifers that are used by the local people for drinking, farming, and growing crops. The required amount of water to extract a ton of lithium is estimated to be about 500,000 gallons. [31] This is enough water to supply 3,500 people for one year. [32] Most lithium brines are in arid regions, so that water is already a scarce and precious resource.

Major advances in environmentally friendly mining technologies aimed to significantly lower energy and water consumption could help mitigate impacts on water resources and land disruption. An emerging geothermal technology is Direct Lithium Extraction (DLE) that delivers higher yields of battery-grade lithium and uses far less water and geothermal energy, which is thermal energy as hot as 500 degrees Fahrenheit that is trapped in the Earth's crust. [36]

In the United States, the National Renewable Energy Laboratory (NREL) is researching using DLE to extract lithium from underground, untapped brines. NREL's goal is to pump the brine up to the surface, extract the lithium, and pump the cooled water and condensed steam back underground to replenish the geothermal reservoir. The NREL believes that once it is fully developed and implemented, DLE can potentially deliver 10 times the current U.S. demands for lithium from the geothermal area at California's Salton Sea alone. The Salton Sea sits on the seismically active San Andreas Fault, and already there are about a dozen geothermal plans in the area creating electricity from its brine. As part of DLE development, the NREL plans for the DLE to be powered by the electricity from these plants. EnergySource, which operates one of the geothermal plans, has filed two patent applications for lithium extraction techniques and reported that it has demonstrated a small version of the commercial unit. [36]

The use of DLE with untapped geothermal resources is a valuable opportunity to produce lithium carbonate equivalent (LCE) in North America. Still, the challenge is in scaling up to a full production phase and to implement DLE techniques across the U.S. geothermal resources fast enough to meet future U.S. demands for lithium carbonate equivalent (LCE). [37]

Current lithium demands for 2022 are estimated to be 559,000 metric tons of lithium carbonate equivalent (LCE); Lithium demands for 2025 have been forecasted averaging one million metric tons of LCE. However, by 2030, LCE demands are expected to rise to 2.1 million metric tons, or more than double that of 2025. [30]



According to the U.S. Geological Survey, Mineral Commodity Summaries, January 2022 report, the bulk of the world's lithium production in 2021 came from four mineral operations in Australia, two brine operations in Argentina, two brine operations in Chile, and two brine and one mineral operations in China. These accounted for more than 80% of the global lithium production. The rest was supplied by smaller operations in Brazil, the United States, and other countries. [29]

While Australia accounts for about 41% of the worldwide production of Lithium, China accounts for 47% of the worldwide lithium carbonate (which is then purified into materials that are used in Li-ion battery manufacturing, i.e., cathodes and electrolytes) production. This is because in addition to processing the lithium mined domestically, China also processes most of the Australian ore. [29]

Chile, Argentina, and Bolivia, which together composed the "Lithium Triangle," hold more than 75% of the world's supply beneath their salt flats, most of which is untapped. Bolivia alone is estimated to hold about 50% of the world's lithium deposits underneath its Salar of Uyuni, which is the world's largest salt flat extending 4,000 square miles. [31]

Based on the reported global reserves (22 million metric tons of lithium) and resources (89 million metric tons of lithium), there is enough lithium in the Earth's crust to meet all future demands. That said, the lithium supply is destined to be diversified in the upcoming years. Pivotal alliances and joint ventures among technology and exploration companies are taking place to scale up current lithium productions and create new sustainable mines in Australia, South America, China, and the United States, as well as in Africa, Canada, and Europe. [29]

In addition, recycling EV Li-ion batteries can help fortify/strengthen the lithium supply chain. Currently, moderate efforts for recycling of Li-ion batteries are taking place. Worldwide companies are investing in Li-ion battery recycling technologies, but the economics are not as attractive for producing enough recycled battery-grade lithium as they are for harvesting lithium from mining. [23] The US Geological Survey in its Lithium Mineral Commodity Summaries published in January 2022 reports that about 25 companies in the United States and Europe are already planning and/or are considering recycling Li-ion batteries. Investors expect that a profitable market for recycled lithium from EV batteries will emerge as the LDVs and HDVs transition to electrification at the global level. [29]

Lithium-free batteries such as sodium-ion (Na-ion) batteries, which are believed to be safer (although it can still cause fires or explosions if mistreated) and more stable than Li-ion batteries, are another way concerns with the limitations of the lithium supply chain can be addressed. Lithium and sodium are chemically very similar so that both batteries use very similar technologies. One drawback is that Na-ion batteries are heavier than the Li-ion batteries. This is because sodium (atomic weight = 22.990 g/mol) is about three times heavier than lithium (atomic weight = 6.941 g/mol). The main advantage is that sodium is a hundred times more abundant in the Earth's crust than lithium. Thus, it is cheaper and not a scarce resource. However, Na-ion batteries are less powerful (lower energy density) than Li-ion batteries and have a limited number of charge-discharge cycles. China expects to have a Na-ion battery supply chain in place by 2023. [62, 63]

Some experts believe that it will take a while before the Li-ion battery market reaches its maximum demands because these batteries are designed to outlast the vehicles themselves. For example, a 50 kilowatt-hours battery in a Nissan Leaf with ten years of use would lose 20% of its capacity at the most. [14]

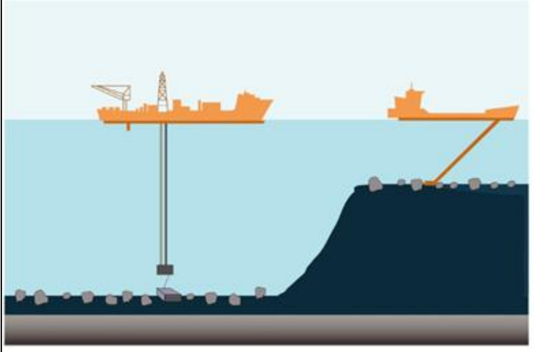
Cobalt

Cobalt (Co) is the chemical element with atomic number 27. It is a blue-gray metal and is used to manufacture cathode active materials for EV Li-ion batteries. It is the most expensive metal in the battery. Nowadays, cobalt can make up to 20% of the cathode material and weight up to 20 kg per each 100 kilowatt-hour(kWh) Li-on battery pack. [42]

Source: Wikipedia- Cobalt
https://en.wikipedia.org/wiki/Cobalt

The composition of the cathode determines the performance of the EV battery. Cobalt-based batteries have high energy density that allows the greatest amount of energy stored for a given volume, which results in lighter batteries with longer EV charge ranges. In addition, cobalt's thermal stability protects the cathode from overheating and catching fire, increasing the safety and reliability of the EV.

Cobalt supply appears to be sufficient in the short term. According to the U.S. Geological Survey, Mineral Commodity Summaries, January 2022, on cobalt, there are 25 million metric tons of world terrestrial cobalt resources, and over 120 million tons of cobalt resources have been identified in polymetallic, metal-rich, nodules and crusts on the seabed of the Atlantic, Indian, and Pacific Oceans. [38]



Schematic illustration of polymetallic nodule extraction by a mining device (left) and ferromanganese concretion extraction by suction dredging (right). In deep-sea polymetallic nodule extraction, the nodules are collected by a mining device and pumped or lifted up to a mining support vessel. The nodules may be separated from the sediment at the seafloor or on board the operational vessel. Shallow water ferromanganese concretions can be extracted by a suction hopper dredger. Figure not to scale

Source: Kaikkonen, Laura & Venesjärvi, Riikka & Nygård, Henrik & Kuikka, Sakari. (2018). Assessing the impacts of seabed mineral extraction in the deep sea and coastal marine environments: Current methods and recommendations for environmental risk assessment. Marine Pollution Bulletin. 135. 1183-1197. 0.1016/j.marpolbul.2018.08.055. https://www.researchgate.net/publication/327419232_Assessing_the_impacts_of_seabed_mineral_extraction_in_the_deep_sea_and_coastal_marine_environments_Current_methods_and_recommendations_for_environmental_risk_assessment

Polymetallic nodules are rounded deposits of iron (Fe) oxyhydroxides and manganese (Mn) oxides that form throughout the ocean floor, especially on underwater plains, abyssal plains, on the deep ocean floor at around 4,000 to 6,500 meters deep. Their growth rate is very slow, millimeters per million years, and they range in size from a few millimeters to tens of centimeters. In addition to iron and manganese, the modules are rich in nickel (Ni), cobalt (Co), copper (Cu), titanium (Ti), and rare earth elements (REEs).

Because of recent concerns with the future supply of these elements, harvesting nodules from the seafloor has become a commercially attractive supply option. During mining, the nodules would be pumped up to the surface into a production vessel for first stage processing and transportation to the distribution or to the manufacturing facility. However, there are serious environmental concerns, such as seabed disturbance and nodule clearance, with nodule mining operations. These concerns need to be resolved to ensure that seabed mining of these modules will not affect the ecosystems. The primary concern is that the nodules are often vehicles for feeders that provide food for nearby species and absence of the nodules can cause food scarcity for many species. [43]

In general, cobalt is mined as a byproduct from mixed nickel and cooper ores. In 2021, the Democratic Republic of Congo (DRC) supplied over 70% of the worldwide mined cobalt production, most of which was exported to China. In turn, China continued to be the world's leading producer of refined cobalt, and its largest consumer with more than 80% of its consumption being used by China's EV battery manufacturers. [40]

Globally, cobalt reserves amount to 7,600,000 metric tons with China holding about 46% of the total reserves with 3,500,000 metric tons, followed by Australia with 1,400,000 metric tons. [40]

However, most of the concerns with the cobalt supply chain do not lie with the current/predicted resources/reserves, but rather the unethical practices associated with cobalt's mining and on the geopolitical control of the supply chain.

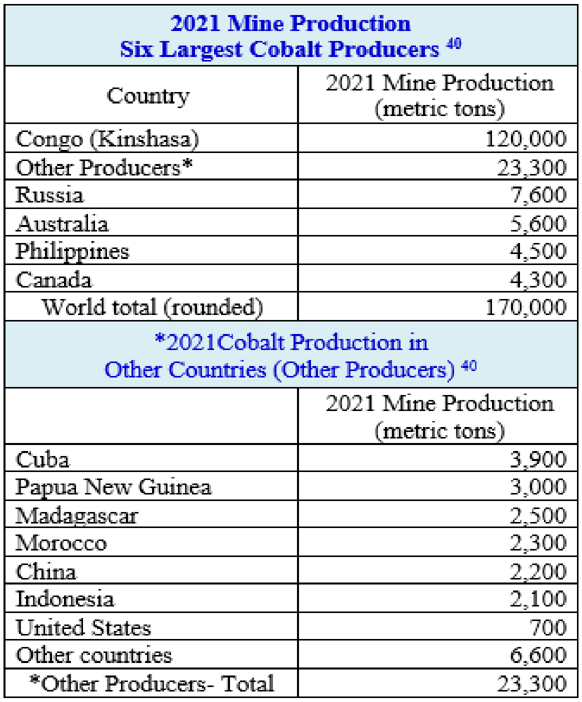
Most of the world's cobalt comes from mines in the Democratic Republic of Congo (DRC), where human-rights activists have raised serious concerns with child labor, some children are as young as six years old, and the unsafe conditions in which the miners work. Cobalt can be toxic if it is not handled properly.

2021 Cobalt Reserves
Five Largest Reserves in the World [40]

Country	2021 Reserves (metric tons)
Congo (Kinshasa)	3,500,000
Australia	1,400,000
Other Countries with Cobalt Reserves*	1,649,000
Indonesia	600,000
Cuba	500,000
World total (rounded)	7,600,000

*2021 Other Countries with Cobalt Reserves [40]

	2021 Reserves (metric tons)
Philippines	260,000
Russia	250,000
Canada	220,000
Madagascar	100,000
China	80,000
United States	69,000
Papua New Guinea	47,000
Morocco	13,000
Other Countries	610,000
Other Reserves- Total	1,649,000

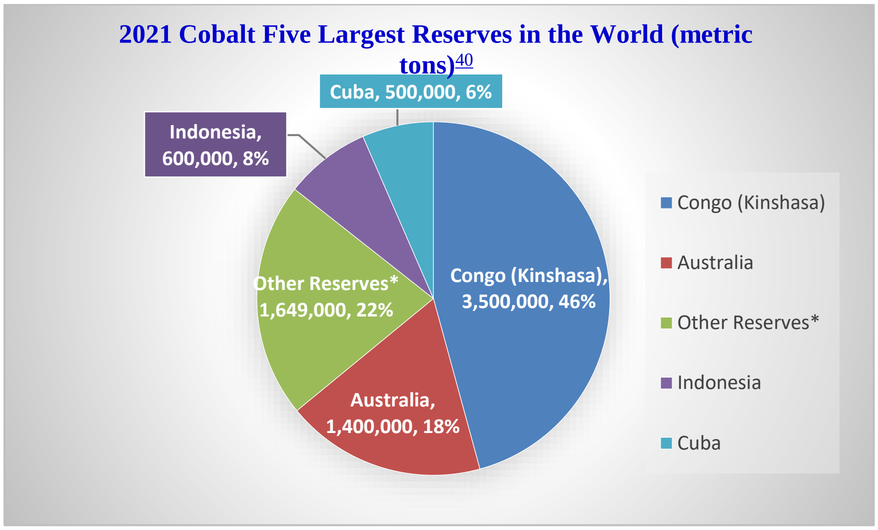


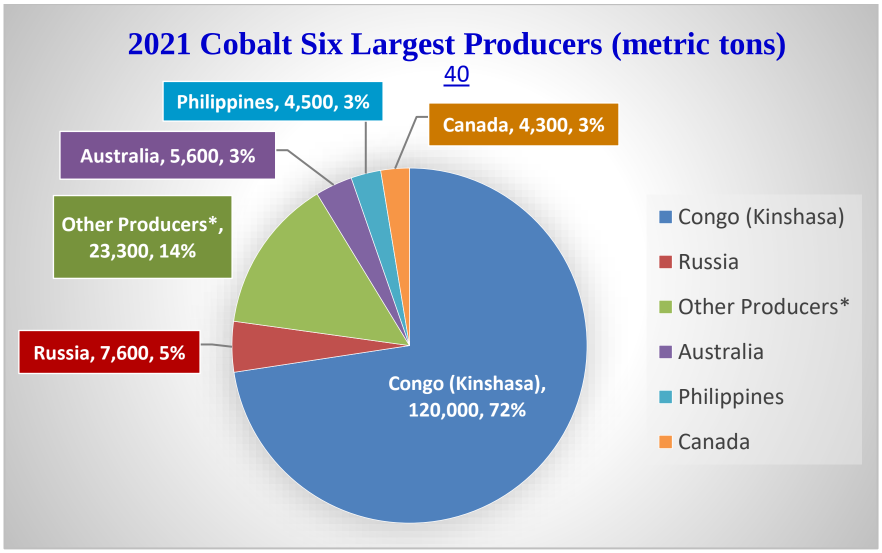
2021 Mine Production
Six Largest Cobalt Producers [40]

Country	2021 Mine Production (metric tons)
Congo (Kinshasa)	120,000
Other Producers*	23,300
Russia	7,600
Australia	5,600
Philippines	4,500
Canada	4,300
World total (rounded)	170,000

*2021Cobalt Production in Other Countries (Other Producers) [40]

	2021 Mine Production (metric tons)
Cuba	3,900
Papua New Guinea	3,000
Madagascar	2,500
Morocco	2,300
China	2,200
Indonesia	2,100
United States	700
Other countries	6,600
*Other Producers- Total	23,300





In 2018, the US Department of Labor- Bureau of International Labor Affairs funded *Combatting Child Labor in the Democratic Republic of the Congo's Cobalt Industry (COTECCO)*, which is a three-year project, from October 2018 to September 2022, to address child labor and improve working conditions in artisanal and small-scale mines in DRC. Artisanal or small-scale miners are miners not employed by a mining company, rather they work independently using their own tools and/or hands. It is estimated that as much as 40,000 mining laborers are poor children working without protective equipment under hazardous conditions in underground tunnels. They make $0.75 to $3.00 a day. In partnership with the government of the DRC, COTECCO aims at supporting efforts to enhance, implement, and enforce laws, policies, and action plans to protect the children and improve working conditions for the laborers at these mines. The project is also working to increase transparency and implement a child labor monitoring system. [44] On July 23, 2021, U.S. Embassy in the Democratic Republic of the Congo announced an increase in U.S. financial assistance to the DRC's mining sector, including COTECCO, for a total of about *"$28 million across ten projects focused on good governance, responsible mineral supply chains, and investment promotion.*" [45]

Currently, Chinese companies, backed by their government, have invested heavily on the DRC's mining and own or have economic interests in 15 of the 19 cobalt mines in the DRC. China's increasing control of the copper, cobalt, and other global resources has raised concerns in Western Countries, including in the United States, regarding the supply chain security for these minerals. [47]

During the Cold War, the United States also had interests in the DRC's natural resources and spent millions of dollars there supporting the military, electricity, and other investments, but as the Cold War ended, and more profoundly after 9/11, the U.S. turned its attention to the Middle East to increase its access to oil. [6]

Around that period, China, who since the 1990s has been interested in increasing its mineral resources from the DRC, was approached by the DRC's president, Joseph Kabila. [6]

President Kabila was reportedly interested in developing the DRC's infrastructure, such as new highways, roads, hospitals, schools, and electricity, but did not have the resources to carry out and accomplish this task. To that end, in 2005, the DRC signed an infrastructure-for-minerals deal with China, where China would build the structures that the DRC needed, and in turn, the DRC would give China access to its minerals, e.g., copper and cobalt. [6]

Today, China holds an oversized hand on the supply chains of critical minerals, including cobalt, creating a concern in the Western World that China now has tremendous leverage because of its control over most of the supply chain for essential resources that are used in electric vehicle batteries, wind turbines, cell phones, computers, and other products. [6] In addition, China has secured access to most of the lithium produced in the mine of Australia.

As a reaction to China's substantial hold on supply chains of critical minerals, the United States is working to devise and implement strategic approaches to build resiliency and secure the supply chain for the critical minerals and metals that the U.S. needs now and in the future.

To address the concerns with the cobalt supply chain, the U.S. is carrying out three main strategic approaches aimed to:

1) Enhance domestic mine cobalt extraction
2) Support mineral extraction from EV battery recycling
3) Increase research and development of cobalt-less batteries

According to the U.S. Geological Survey- Cobalt: Mineral Commodity Summaries 2022, January 2022, the U.S. produced 700 metric tons in 2021. The U.S Geological Survey Summary identified untapped cobalt resources in the United States that are estimated to be about 1 million metric tons. These resources occur mainly in Alaska, California, Idaho, Michigan, Minnesota, Missouri, Montana, Oregon, and Pennsylvania. [40] Moreover, cobalt could be produced as a byproduct from other mineral deposits, e.g., nickel, copper, zinc, and lead. [52] However, enhancing domestic cobalt mining would require the support and funding of the U.S. government.

Recycling of end-of-life EV batteries will play an important role in securing the future cobalt supply chain in the United States. Current technologies for obtaining critical metals via recycling spent EV batteries are not economically feasible, and numerous research and development efforts are being carried out to find better ways to make Li-ion battery recycling more efficient and profitable. But these efforts, like cobalt mining, need support from the federal government to move forward in the United States. [53]

In the United States, the Biden administration has committed billions of dollars to strengthen the U.S. supply chain for EV batteries. And, on June 8, 2021, the administration announced that it has leveraged $17 billion in loan authority to the Department of Energy's (DOE's) Loan Programs office (LPO) (https://www.energy.gov/lpo/loan-programs-office) to issue loan guarantees to projects that will boost domestic EV battery manufacturing and recycling capabilities. [53] Subsequently, on February 11, 2022, the U.S. Department of Energy (DOE) issued two notices of intent that provide approximately $3 billion to fund demonstration projects that would ensure sustainable domestic sources of the critical materials used to make lithium-ion batteries, such as lithium, cobalt, nickel, and graphite. This will help secure the American battery supply chain by supporting viable technologies and capabilities for domestic mining, processing, and recycling of spent EV batteries. [53, 54]

The third approach is targeted at increasing research and development of cobalt-less and cobalt-free batteries. The advantage is two-fold: First, it will lower the cost of Li-ion batteries since cobalt is the most expensive component in Li-ion batteries, and second, it will lessen the dependance of the U.S. battery supply chain on cobalt production, which is mostly controlled by China and the Democratic Republic of Congo (DRC) with the DRC supplying 70% of the world's cobalt. Furthermore, the production of cobalt-free EV batteries will not depend on supply from Chinese investors owning or financing 15 of the 19 cobalt mines in the DRC and controlling over 80% of the cobalt refining industry, which converts raw material into commercial-grade cobalt metal suitable for use in EV batteries. [56]

Numerous efforts are underway to develop cobalt-free batteries with sufficient energy density that deliver acceptable EV range. Cobalt provides good conductivity and structural integrity so that its cathode crystal structure does not easily break up during charging/discharging. Lowering the cobalt content can be done by substituting cobalt with nickel or manganese. However, caution must be exercised when substituting cobalt with nickel because high nickel content can result in unstable interfaces and in turn, poor battery life. [49, 58]

In June 2021, the U.S. Department of Energy's Federal Consortium for Advanced Batteries (FCAB) published the *National Blueprint for Lithium Batteries 2021–2030* to help guide investments to develop a reliable Li-ion battery manufacturing and to "*establish a secure battery materials and technology supply chain"* in the United States. One of the goals outlined in the Blueprint is to eliminate the use of cobalt in EV batteries altogether by 2030. [58]

Some cobalt-free batteries are already in use. For example, the lithium iron phosphate battery (also known as LFP or LiFePO4) is a lithium-ion battery that uses lithium iron phosphate ($LiFePO_4$) as the cathode material. LFP batteries do not overheat or burst into fire. In addition, an LFP battery costs less than a regular Li-ion battery and has a long cycle life, so that it can undergo a high number of charge and discharge cycles before its performance is diminished. [58, 59]

However, there are two main drawbacks for the use of LFP batteries. First, LFP batteries are lower in energy density than the standard Li-ion battery, and thus, they provide shorter driving range. Researchers are conducting studies focusing on increasing the energy density of LFP batteries and are investigating different coating and doping materials/methods to optimize LFP batteries performance. The other drawback of the LFP battery is that its production is currently dominated by Chinese companies, mainly BYD and Contemporary Amperex Technology Limited (CATL). This is because of a licensing agreement that allows Chinese companies to make LFP batteries without paying royalty fees to the patent owners provided that the LFP batteries are produced and used only within China. This licensing agreement was set to expire in 2022 for the United States. [58, 59]

Nevertheless, several car companies, such as Tesla, Ford, and Volkswagen, said that they would offer EVs with LFP batteries. Tesla is already using LFP batteries in its Model 3 and Model Y vehicles that are manufactured in China and plans to expand the use of LFP batteries to all its standard-range entry-level vehicles while it will keep using nickel-cobalt-aluminum (NCA) batteries on its long-range vehicles. [57], [58]

In the U.S., two American-based start-ups that are working on cobalt-free batteries are Sparkz and Texpower, but their cobalt-free battery technologies are yet to be proven/tested in electrical vehicles.

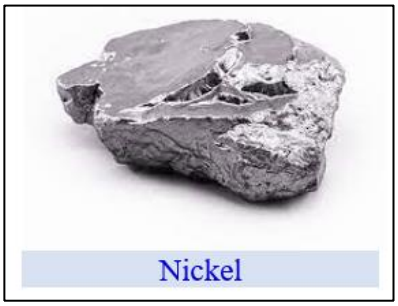
Sparkz was founded in 2019 and is working on replacing the cobalt in the cathode of a Li-ion battery with iron. Its cobalt-free battery is a nickel-iron-aluminum battery called NFA. Sparkz says that its NFA battery has twice the energy density of the LFP battery and costs 30% less. In addition, Sparkz's NFA batteries meet and/or exceed the performance of a typical Li-ion batteries in terms of energy density and life expectancy and are 30% to 40% lower in cost. Sparkz is first targeting light-duty electrical mobility, farm equipment, and medium-to-heavy-duty public vehicles for the introduction of its NFA battery. [57, 60]

Texpower is in Houston, Texas, and it was also founded in 2019. It was co-founded by Arumugan Manthiram, a professor of the University of Texas at Austin. Texpower has patented its cobalt-free lithium Nickel Manganese Aluminum, or NMA, cathode as an alternative to NCA82 (lithium Nickel 82%, cobalt 15%, and aluminum oxide 3%), and to NMC811 cathode (nickel 80%, manganese oxide10%, cobalt 10%). [57, 61]

Texpower says that its NMA cathodes deliver up to 20% higher energy density due to higher Nickel content of about 90%, at a 5-15% lower cost. But obtaining product production consistency from batch to batch is not easy, and Texpower is investigating various solutions and is working with the University of Texas to develop electrolytes that in combination with its NMA cathode and high-energy anode would significantly increase the battery cell's energy density. Texpower tested its cathode materials with multiple cell systems, including liquid, semi-solid and solid electrolyte, with promising results. However, Texpower's NMA has yet to test its technologies in electric vehicles. [57, 61]

Nickel

Nickel is the chemical element atomic number 28. It is a ferromagnetic metal symbolized by the letters Ni. Nickel is highly resistant to rusting and corrosion. It is a hard, tougher than iron, silvery-white metal that is used to coat other metals through the process of plating. Nickel is best known for its use in metal money, e.g., coins. However, its primary use is in the steel industry, which consumes about 70% of the world's nickel production. Nickel is used to make various alloys that are widely utilized in aviation, marine, chemical, electronics, and medical energy industries. There are many finished goods that contain nickel, such as batteries, jet and wind turbines, stainless steel pots and pans, electronic equipment, and pipes. [66, 67, 68]



Source: Freepik
https://www.freepik.com/premium-photo/nickel-is-chemical-element-resulting-from-combination-arsenic-antimony-sulfur_14443480.htm

The battery industry sector accounts for 5% of nickel's world demands. Nickel is utilized in the battery cathode, which is a viscous layer containing micro-scale metal crystals. Most of today's EVs battery cathodes contain a mixture of lithium, nickel, manganese, and cobalt. On average, a nickel-Manganese-Cobalt (NMC) EV Li-ion battery pack (NMC532) may contain 35 kg of nickel or about 50% of the cathode metals by weight.[66, 70]

As the electrification of the transportation sector is anticipated to increase exponentially in upcoming years, worldwide investors and global EV industries are estimating a huge increase in demand for the Li-ion battery metals, including nickel, and have raised serious concerns that the current supply and resources may not be sufficient to meet future demands. [65, 66]

Nickel is the twenty-second most abundant element in the Earth's crust and is the most prevalent element, second to iron, in the Earth's outer core, where it occurs as liquid nickel-iron alloys (NiFe). It is the fifth most common element on Earth overall.

The average concentration of nickel in the Earth's crust is about 80 ppm (0.018%). It is found throughout the world and is currently mined in 25 countries, most of which are in the Asia-pacific region. Identified global land-based mineral resources contain at minimum 300 million metric tons of nickel. Most of the nickel is mined from two types of ore deposits, laterites, also called oxide resources (60%) and magmatic sulfide deposits (40%). [64] In addition to land mining resources, nickel can be extracted from manganese crusts and nodules found on the seafloor, just like lithium. [64] It is estimated that these seafloor deposits contain more than 290 million metric tons of nickel that may become significant resources with future advances in deep-sea mining technologies. [38]

Nickel products are classified into two types depending on their nickel purity: Class 1 nickel products, which contain 99.8% or above nickel, and Class 2 that contain less than 99.8% nickel. Only high purity nickel Class 1 is suitable for battery manufacturing. Both nickel laterites and nickel sulfides can be converted into Class1 nickel.

According to the U.S. Geological Survey, Mineral Commodity Summaries, January 2022 report, in 2021, Indonesia was the largest producer of mined nickel with 1 million metric tons of nickel, followed by The Philippines with 370,000 metric tons, Russia with 250,000 metric tons, New Caledonia with 190,000 million tons, and Australia with 160,000 metric tons. Below are the statistics reported by the U.S. Geological Survey. [64]

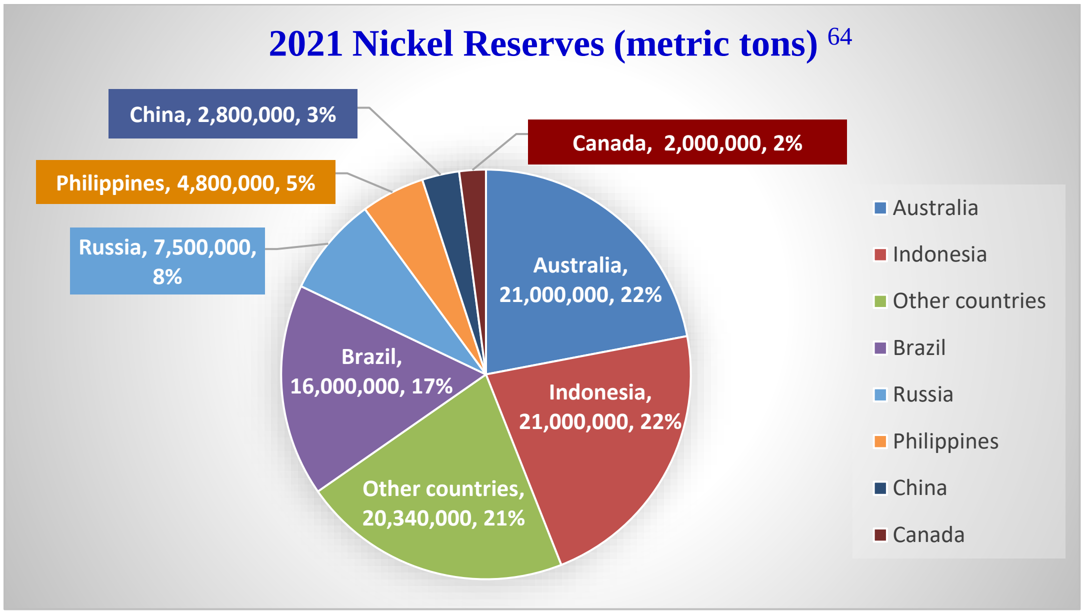
2021 Nickel Reserves (metric tons) [64]

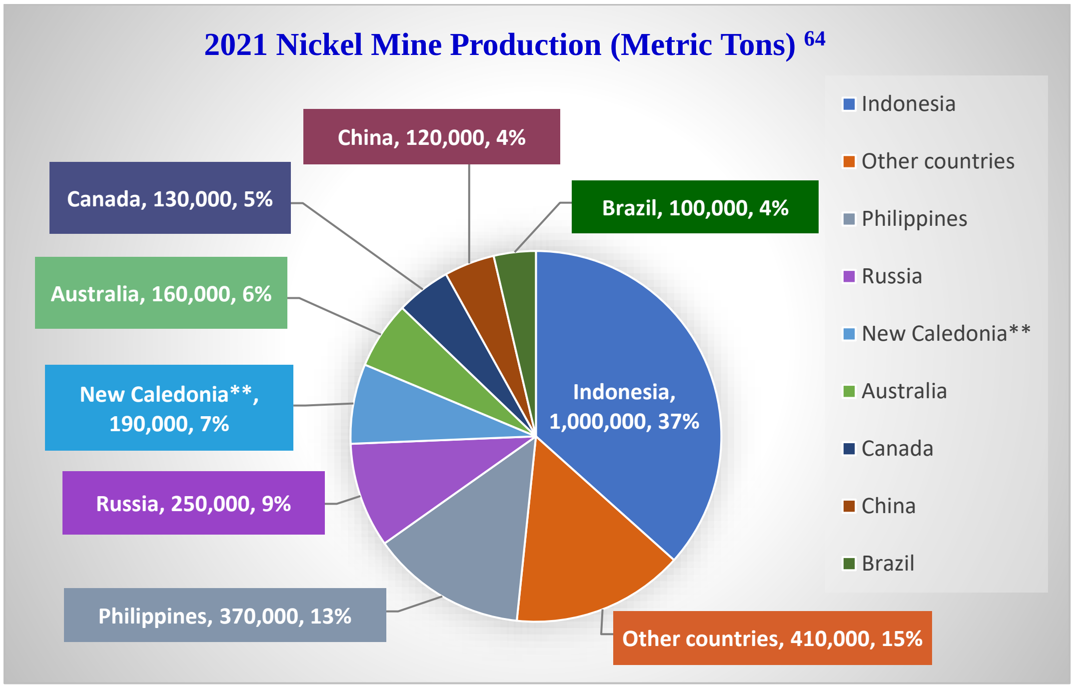
Country	2021 Reserves*
Australia	21,000,000
Indonesia	21,000,000
Other countries	20,340,000
Brazil	16,000,000
Russia	7,500,000
Philippines	4,800,000
China	2,800,000
Canada	2,000,000
World total (rounded)	>95,440,000
United States	340,000

2021 Nickel Mine Production (metric tons) [64]

Country	Production*
Indonesia	1,000,000
Other countries	410,000
Philippines	370,000
Russia	250,000
New Caledonia**	190,000
Australia	160,000
Canada	130,000
China	120,000
Brazil	100,000
World total (rounded)	2,700,000
United States	18,000

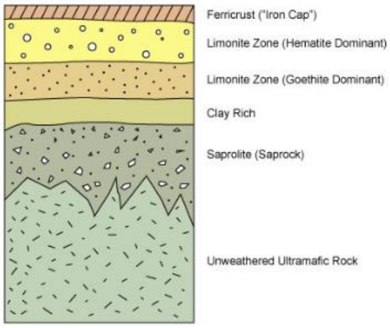
* Estimated. NA Not available. W Withheld to avoid disclosing company proprietary data. — Zero.
** Overseas Territory of France





Nickel sulfide deposits are found in ultramafic (or ultrabasic) rock settings that are rich in iron and magnesium and are found in volcanic and plutonic (plutonic rocks are formed by solidification of a molten magma at great depth) areas that are deep below the Earth's surface. Sulfide ore deposits are primarily found in Russia, Canada, and Australia. Nickel sulfide (NiS) ores can be converted into high-purity Class1 nickel, usually in the form of nickel sulfate ($NiSO_4$), through the process of pyrometallurgy, which uses high temperatures to extract the metal from the ores. [79], [82] Laterites (oxide ores) are reddish rocks that are rich in iron oxide and derived by the weathering of a variety of rocks, specifically ultramafic rocks, in a high temperature and humid climate. Laterites are found near the surface of the Earth, mostly in hot and wet tropical areas. [79] Saprolite and limonite are the two main types of laterites resources. Saprolite ores have higher iron and lower magnesium contents and contain a relatively higher nickel percentage, between 1.8% and 3.0%, than limonite ores, which contain between 0.8% and 1.8% nickel. [38]

Laterite Saprolite is not suitable for Class 1 nickel and is mostly processed through pyrometallurgy to obtain Class 2 nickel, which is comprised of nickel pig iron (NPI) and ferronickel, for the steel industry. Limonite can be converted to Class 2 nickel, and to a lesser extend to Class 1 nickel, through hydrometallurgical processes like 'high-pressure acid leaching' (HPAL), which involve using aqueous metal salt solutions to extract the metal from the ores. [38]

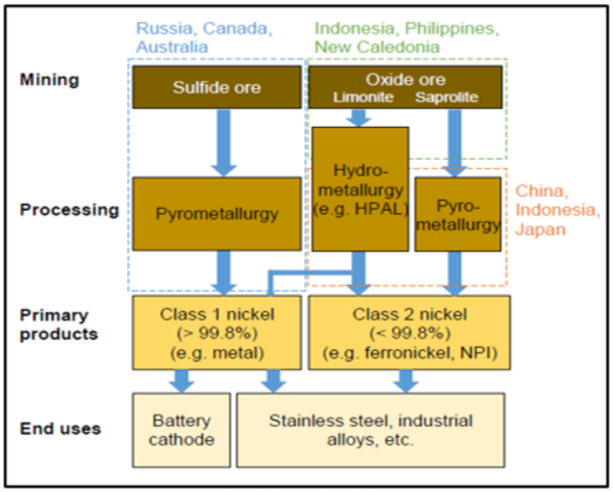


A generalized cross section of nickel laterite deposits

Source: Geology for Investors: Nickel Laterites: The World's Largest Source of Nickel https://www.geologyforinvestors.com/nickel-laterites/

The stainless steel industry, which uses Class 1 and Class 2 nickel, encompasses about 70% of the nickel market, while EV batteries, where only Class 1 nickel can be used, constitute only about 5% of the nickel demands. Further, experts estimate that at most 46% of the nickel produced can be converted to Class 1, battery grade, nickel. [91]

Currently, multibillion-dollar Chinese investors, including Tsingshan- the world's largest nickel producer, are underway in Indonesia to convert nickel laterites into nickel pig iron (NPI) and further into nickel matte, which is considered an artificial/intermediate nickel-iron sulfide product. Nickel Matte can then be refined to produce Class I nickel or battery grade chemicals. However, this effort by Tsingshan at its Indonesian Morowali Industrial Park (IMIP) facility is costly and has come under criticism regarding the higher carbon footprint of its NPI process because it requires a higher energy input than the current production process. In reaction to this, Tsingshan announced plans to build a solar and wind renewable energy base in Indonesia that will supply power for its NPI-nickel production. [84]



Nickel supply chain

Source: International Energy Agency (IEA): The Role of Critical Minerals in Clean Energy Transitions, Revised version March 2022 [38]: https://iea.blob.core.windows.net/assets/ffd2a83b-8c30-4e9d-980a-52b6d9a86fdc/TheRoleofCriticalMineralsinCleanEnergyTransitions.pdf

Nickel does not lose its quality in the recycling process, making it fully recyclable. Recycling of nickel-containing Li-ion battery plays a key role in meeting any future increase in nickel demands. Battery recycling processes to recover valuable metals already exist and must be scaled-up to help meet new demands. Current battery recycling processes use pyrometallurgical or hydro-metallurgical, or a combination of both, to recover critical metals. These processes are energy intensive as spent batteries would undergo smelting at very high temperatures. Battery recycling plants are costly to build and operate, and require complex equipment to handle the toxic emissions produced during the smelting process. Government incentives are driving researchers to develop battery recycling technologies that are cost effective and environmentally friendlier. For example, the U.S. Department of Energy created its first

Li-ion battery recycling R&D center, the ReCell Center, that was launched with a $15 million investment. ReCell is headquartered at the Argonne National Laboratory and Argonne National and includes some 50 researchers based at six national laboratories and universities. Likewise, the United Kingdom's equivalent formed a consortium of researchers headed by the University of Birmingham to work on improving the reuse and recycling of lithium-ion batteries, including EV Li-ion batteries. [85]

In the United States, the White House's 100-day-supply-chain-review-report [49] identified Class 1 nickel as one of three most critical minerals in the production of lithium-ion batteries, along with lithium and cobalt. The report states in reference to critical minerals, "*Among other priorities, the United States should focus on: (1) reducing or eliminating critical or scarce materials needed for EV or stationary storage, including cobalt and nickel; (2) accelerating battery technology advances including next generation lithium ion and lithium metal batteries and solid state design, and (3) developing innovative methods and processes to profitably recover "spent" lithium batteries, reclaim key materials, and re-introduce those materials to the battery supply chain.*" [49] Further, in June 2021, the U.S. Department of Energy (DOE) published its National Blueprint for Lithium Batteries 2021–2030 developed by the Federal Consortium for Advanced Batteries in which nickel and cobalt are targeted to be eliminated in Li-ion batteries by 2030. [58]

The overall nickel supply will remain steady. However, the Class 1 nickel supply chain might face some challenges in the years to come as the demand for electric vehicles increases and industry moves away from using cobalt in the cathode and towards replacing it with nickel. [38]

Manganese

Manganese is a common ferrous metal with atomic number 25 and the chemical symbol Mn. Manganese (Mn) is a hard, brittle, silvery metal that is commonly found in iron ores. It is the twelfth most abundant metal in the Earth's crust. It is roughly 0.1 % of the Earth's crust. Land-based manganese resources are widely geographically distributed, and no individual country is expected to control the manganese supply chain. The United States has not produced manganese ore containing 20% or more since 1970 and has been primarily relying on imports from Gabon (23%), South Africa (19%), Australia (13%), and other countries. There are no domestic reserves. [49, 86, 88]

Manganese
Pure manganese cube and oxidized manganese chips
Source: Wikipedia- Manganese
https://en.wikipedia.org/wiki/Manganese

Manganese is mostly used in the steel industry both as an alloy that converts iron into steel and increases the steel's strength and flexibility, and as a purifying agent in iron-ore refining that helps remove unwanted oxygen and sulfur during the conversion of iron ore into iron. Other uses of manganese include use in animal feed, fertilizers, ceramics, as a catalyst, and in clean energy technologies. [87, 88, 92]

The Mamatwan manganese open pit mine in South Africa
Source: U.S. Geological Survey: Manganese- Professional Paper 1800-L, Cannon et al., 2017
https://pubs.usgs.gov/pp/1802/l/pp1802l.pdf

According to the U.S. Geological Survey (USGS), Mineral Commodity Summaries, January 2022, countries currently leading in the production of manganese are South Africa, Gabon, and Australia. Data from the USGS on the 2021 manganese production/reserves summary is below. [86]:

2021 Manganese Reserves (thousand metric tons) [86]

Country	2021 Reserves
South Africa	640,000
Australia	270,000
Brazil	270,000
Ukraine, concentrate	140,000
Gabon	61,000
China	54,000
India	34,000
Other countries with Manganese Reserves*	23,000
World total (rounded)	1,500,000

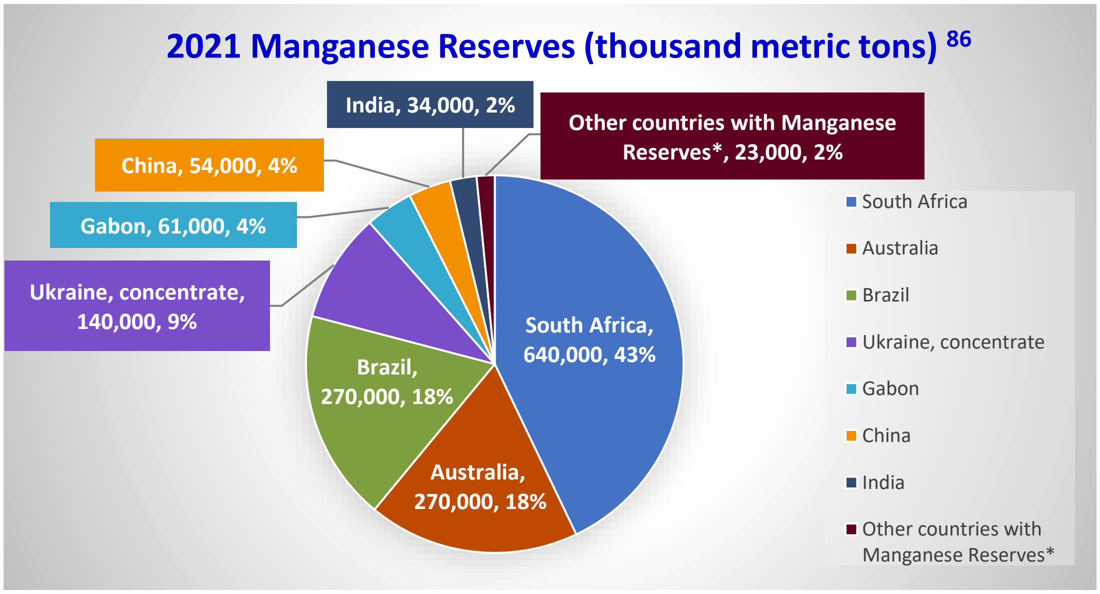
*Other countries with Manganese Reserves	2021 Reserves (metric tons)
Ghana	13,000
Kazakhstan, concentrate	5,000
Mexico	5,000
Burma	NA*
Côte d'Ivoire	NA*
Georgia	NA*
Malaysia	NA*
Vietnam	NA*
United States	---
Other Countries	Small
Total manganese reserves from Ghana, Kazakhstan, and Mexico	23,000

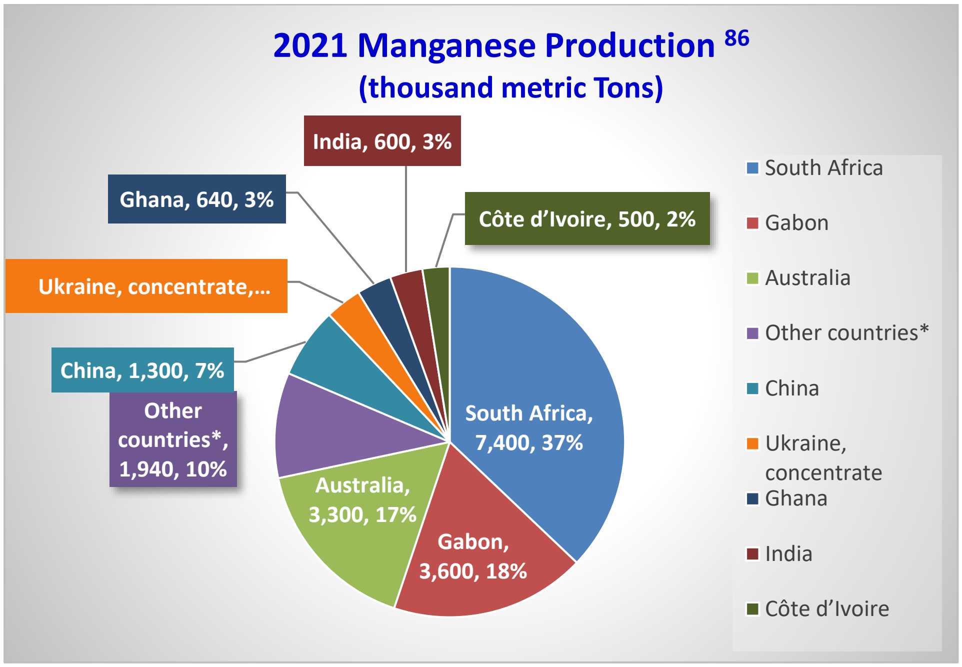
*Estimated. NA Not available. — Zero.

2021 Manganese Production (thousand metric tons) [86]

County	2021 Production
South Africa	7,400
Gabon	3,600
Australia	3,300
Other countries*	1,940
China	1,300
Ukraine, concentrate	670
Ghana	640
India	600
Côte d'Ivoire	500
World total (rounded)	20,000

*2021 Manganese production in other countries	2021 Production (metric Tons)
Brazil	400
Malaysia	360
Other countries	260
Burma	250
Mexico	200
Georgia	190
Kazakhstan, concentrate	160
Vietnam	120
Other countries total	1,940


2021 Manganese Reserves (thousand metric tons) [86]



Manganese is in high demand, and the manganese market is expected to significantly increase due to its applications in the steel industry and in electric vehicle (EV) battery production. In 2021, world reserves accounted for 1.5 billion metric tons of manganese, which is enough to meet global demands for decades to come. [92] In addition to global reserves, identified land deposit resources of manganiferous ores enriched with manganese amount to more than 17 billion metric tons. Thus, global reserves, current resources, and identified land manganese resources are plenty to meet current and foreseeable future global manganese demands. [92]

Seabed manganese deposits represent additional manganese resources. Tens of millions of square kilometers (km^2) of the ocean floor is covered with manganese-rich ferromanganese nodules and crusts. Ferromanganese deposits also contain significant amounts of nickel, cobalt, copper, and possible valuable concentrations of rare-earth elements (REEs). However, no viable technology that is economically sound has been identified for seafloor mining. As a result, no manganese or any other metal has been produced from these deposits. Progress in developing technologies for seabed mining in the deep ocean is mainly hindered by technical issues, economic competitiveness with traditional land mining, and legal issues with the ownership and control of mining resources in international waters. [92] Nevertheless, triggered by the establishment of a legal framework for exploring and mining in international waters and by rising metal prices, numerous studies and development programs are currently underway to find feasible solutions to overcome the technical issues and to develop economically viable technologies for seabed mining. [92] Still, experts believe that if seabed ferromanganese mining is to flourish, it would be because of the more profitable market values of metals present other than manganese, such as cobalt and nickel. In that case, manganese would be mined as a byproduct and not as the main source and/or discarded if its value remains low, and its recovery and recovery processing is deemed not worthwhile. [92]

Manganese is recycled mainly as a component of iron and steel scrap and is recovered together with iron from steel slag. Manganese recycling efficiency from iron and steel scrap, which is defined by the U.S. Geological Survey as "*the amount of scrap recovered and reused relative to the amount available to be recovered and reused*," is at best 53% with a recycling rate of 37%. This represents a huge waste of manganese during the manufacturing process, which is estimated to be about 1.7 times that of recycled manganese. Recycling iron and steel scrap solely for the recovery of manganese is almost non-existent, and the amount of manganese recovered via recycling spent batteries and/or waste generated from battery manufacturing plants is very small. Moreover, metal scrap recovery specifically for the purpose of recovering manganese is insignificant. [86, 92, 93]

Manganese is considered a major battery metal. [38] Numerous studies are underway to increase the manganese content in battery cathode to reduce the amount of cobalt, a much more costly metal, in batteries. [49] For example, a lithiated manganese dioxide (LMD) battery in development that uses 61% of manganese in its mix and only 4% lithium offers higher power output, thermal stability, and improved safety compared to regular lithium-ion batteries. [87] Manganese is abundant, safe, and stable as a lower-cost cathode component, and numerous automakers, including Tesla and Volkswagen, are looking into high-manganese content batteries as a way of lowering battery prices and making electric vehicles more affordable for midstream buyers. [94]

Globally, there is no shortage of manganese, and worldwide total reserves and resources of manganese are ample and enough to see all foreseeable increase in demands. [95]

In the United States, U.S. Geological Survey: Manganese- It Turns Iron Into Steel (and Does So Much More), Factsheet 2014-3087, considers manganese a critical material because it is "*essential and irreplaceable in steelmaking and its global mining industry is dominated by just a few nations.*" [95] However, the White House's 100-day-supply-chain-review-report [49] de-emphasized manganese, as well as graphite, as a material of greatest concern when compared to other U.S. assessments on the basis of its worldwide distribution. [49]

Graphite

Graphite is an allotrope of the chemical element carbon (C). Atomic Carbon is an unstable/ short-lived species that readily converts into numerous molecular structures that are called allotropes. Graphite and diamond are the two best known crystalline carbon allotropes, but they differ in their molecular structure. [97, 100]

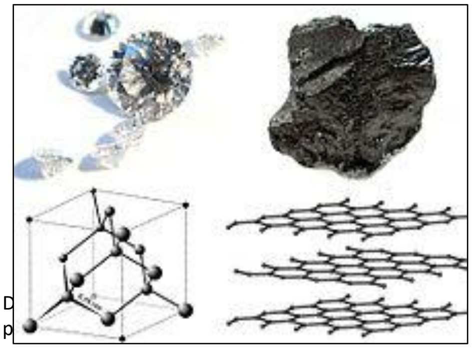
Diamond and graphite are chemically the same, both made up of the element carbon; however, they have entirely different atomic and crystal frameworks.
Source: PetraGems- Difference Between Diamond and Graphite, Sharif Khan, 2021 https://www.petragems.com/blog/difference-between-diamond-and-graphite/

Diamond is formed by the carbon atoms bonding in tetrahedral cubic lattices (diamond cubic). The diamond cubic structure is a strong, rigid three-dimensional structure that results in an infinite network of atoms. This accounts for diamond's hardness, extraordinary strength, and durability, and for making it the hardest naturally occurring substance on Earth. [97, 100]

On the other hand, graphite has a layered chemical structure. The carbon atoms in graphite are arranged in 6-membered, hexagonal rings that are connected to one another at their edges forming horizontal sheets (layers). These sheets are stacked on top of each other and weakly bonded to one another. Each single, two-dimensional atom sheet of graphite is called graphene. While the interaction between atoms on each graphene sheet is strong, the stacked graphene sheets are weakly bonded to each other. This makes graphite a soft, flexible (but not elastic) material as the sheets slip easily past one another under horizontal pressure. [97, 100]

Graphite is chemically inert and the most thermodynamically stable of all allotropes of carbon under standard conditions (temperature of 273.15 K (0 °C, 32 °F) and absolute pressure of 1 atm (101.325 kPa)), while diamond is metastable and slowly converting to graphite at an insignificant rate, such that it would take far more than a billion years to convert one cubic centimeter of diamond to graphite. [97, 100]

Graphite is also an excellent conductor of heat and electricity and is stable over a broad range of temperatures. It is a non-metal mineral and the only non-metal that can conduct electricity. The presence of free, localized electrons that can move freely between the graphene sheets make graphite a good conductor of electricity. Due to its high electrical conductivity, graphite is extensively used in products such as batteries, electrodes, and solar panels. [102, 105]



D
p
structure.
Source: Wikipedia- Allotropes of carbon
https://en.wikipedia.org/wiki/Allotropes_of_carbon

Graphite is present in two main types: Natural and synthetic. [103]

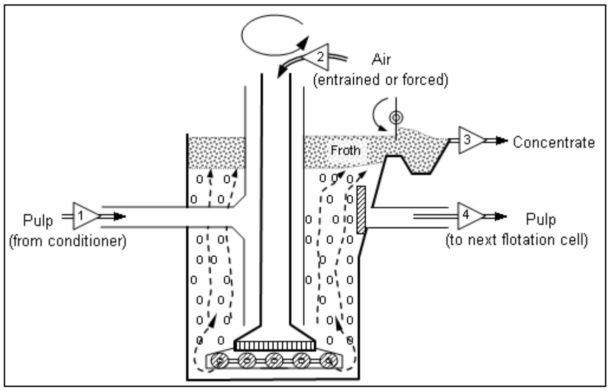
- Natural Graphite occurs in the form of crystalline carbon. It is formed when carbon is subjected to heat and pressure in Earth's crust and in the upper mantle. [101, 103]

- Synthetic graphite is man-made. It is produced by subjecting high-carbon content materials, e.g., petroleum coke and coal-tar pitch, a thick black liquid that results from coal-tar distillation- to high temperatures, 2,500°C to 3,000°C. The resulting synthetic graphite is high quality and can contain over 99% carbon. [101, 103]

Natural Graphite

Natural Graphite is a soft, dark grey mineral composed of graphitic carbon. It mainly forms when carbonaceous sedimentary rocks are subjected to heat and pressure sufficiently high that their compositions and structures are altered. Natural graphite can be found in metamorphic rocks, which are formed when any type of rock is subjected to very high temperatures and pressures deep inside the Earth's crust and undergo structural changes, and in igneous rocks that are formed when hot, molten rock (magma or lava) melts and crystallizes within the Earth's mantle or crust. These subterranean, high temperature fluids (melts) emanating from such hot, highly pressurized sources solidify when they rise to the Earth's surface, creating seams (distinct layers rock in other layers of rock) and veins of mineral ores on or near the surface. [97, 102] Most natural graphite is mined, and graphite deposits contain a significant amount of other mineral. These deposits require considerable processing, such as froth flotation, to extract concentrated graphite. [103]

Froth flotation is commonly used to recover mined graphite. This is a flotation process that selectively separates materials depending on the surface wettability of the particles, hydrophobic (dislike of water) or hydrophilic (affinity to water). During this process the ores are crushed into very fine powder-sized particles and mixed with water forming a pulp. Air bubbles are then introduced to the pulp and a chemical (surfactant) is added to promote the formation of small bubbles and to lower the surface tension of the mixture, providing conditions that help with the attachment of the hydrophobic particles to air bubbles. Graphite, which has high natural hydrophobicity, adheres to the bubbles, and can then be recovered when the bubbles with the graphite particles (froths) rise to the surface of the pulp. [109]



Source: Wikipedia- Froth Flotation
https://commons.wikimedia.org/w/index.php?curid=10542461

There are three main types of natural graphite: [102], [103], [105]

1. High Crystalline graphite- Crystalline vein or lump graphite is rarest and most valuable form of graphite as it is the highest quality form. It used in batteries and other products that require high quality graphite and is currently being produced only in Sri Lanka, where veins of about 3 meters thick and containing from 60% to 95% graphite are mined to depths of up to 650 meters.

2. Amorphous graphite- Microcrystalline graphite that is found as extremely small, crystal-like particles in beds of rocks such as coal, and slate. Although it is not visible to the naked eye, it can be viewed under magnification. Amorphous graphite is the lowest quality and cheapest form of graphite and is used to make low-quality graphite products, e.g., pencils, lubricants, and rubber additives. Amorphous graphite is found in China, Mexico, and the United States.

3. Flake graphite- Natural flake graphite is formed when organic or inorganic carbon is subjected to high temperature and pressure. It can be found in metamorphic rocks that are evenly spread throughout the body of the ore or in concentrated lens-shaped pockets as small plates or flakes (lamella form), or as flattened aggregates that can be separated into scales (scaly form). Natural flake graphite can be found worldwide in numerous places as well-developed crystal platelets of graphite that are equal to or less than 1 centimeter in size.

According to the U.S. Geological Survey (USGS), Mineral Commodity Summaries, January 2022 report, China was the world's leader in the production of natural graphite, accounting for 79%, 820,000 metric tons, of the total world output of 1,000,000 metric tons. It was followed by Brazil with 68,000 metric tons, Mozambique with 30,000 metric tons, Russia with 27,000 metric tons, Madagascar with 22,000 metric tons, Ukraine with 17,000 metric tons, Norway with 13,00 metric tons, and other countries. [96]

Graphite Global Reserves in 2021 (metric Tons) [96]

Countries*	**Reserves (metric tons)**
Turkey	90,000,000
China	73,000,000
Brazil	70,000,000
Madagascar	26,000,000
Mozambique	25,000,000
Tanzania	18,000,000
India	8,000,000
Uzbekistan	7,600,000
Other Countries*	7,200,000
World total (rounded)	324,800,000

*Other Countries with Graphite Reserves (metric tons) [96]

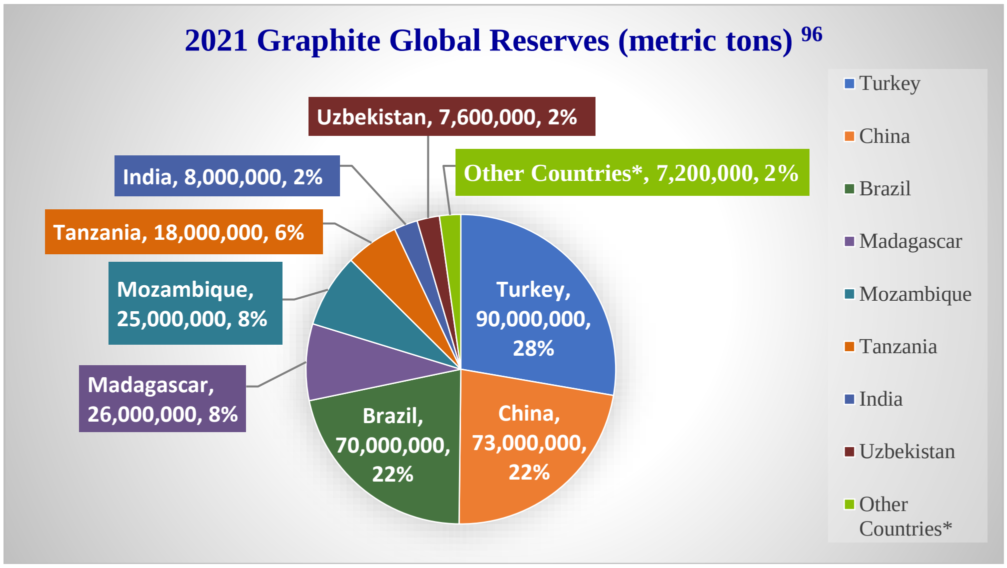
Other Country	**Reserves (metric tons)**
Mexico	3,100,000
Korea, North	2,000,000
Sri Lanka	1,500,000
Norway	600,000
Other countries total=	7,200,000

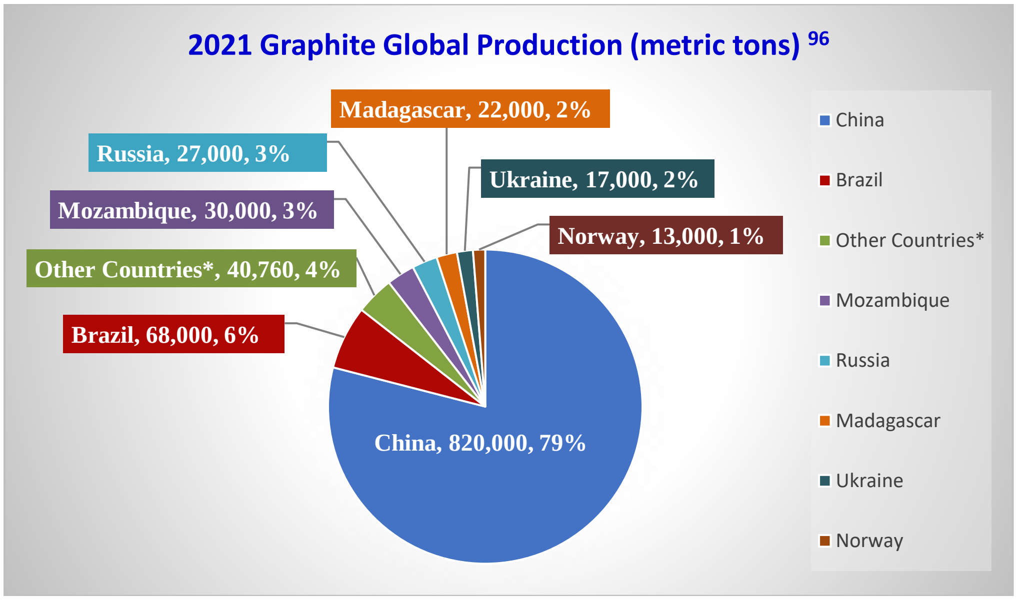
Graphite Global Production (metric tons) [96]

Country	Production (metric tons)
China	820,000
Brazil	68,000
Other Countries*	40,760
Mozambique	30,000
Russia	27,000
Madagascar	22,000
Ukraine	17,000
Norway	13,000
World total (rounded)	1,000,000

*Other Countries with Graphite Production (metric tons) [96]

Other Countries	Production (metric tons)
Korea, North	8,700
Canada	8,600
India	6,500
Vietnam	5,400
Sri Lanka	4,300
Mexico	3,500
Turkey	2,700
Austria	500
Germany	300
Tanzania	150
Uzbekistan	110
Other countries total=	40,760





The USGS report noted that large graphite deposits were being developed in Madagascar, northern Mozambique, Namibia, and south-central Tanzania. The report pointed out that Mozambique has the largest natural graphite mine in a high-grade graphite deposit worldwide, and it is expected to be in operation for the next 50 years. The report also indicated that the world's recoverable graphite resources that can be produced using currently available technology and industry practices, regardless of any economic or accessibility considerations, exceed 800 million tons. [96]

In 2021, China processed most of the world's spherical graphite, also known as battery-grade graphite, that is used as an active material in the anode of Li-ion batteries. Spherical graphite, which is considered modified natural graphite, is manufactured from mined flake graphite that is processed into high purity particles with carbon content greater than 99.5%. This process requires the use of hydrofluoric (HF) acid, a toxic chemical that is harmful to humans and the environment. For this reason, spherical graphite producers are under increased pressure to develop and implement processes to produce battery-grade graphite that are eco-friendly and not harmful to humans. [104]

Different types of Li-ion battery cathodes, positive electrode, are produced using various transition metal oxide crystals, such as lithium cobalt oxide (LCO), lithium manganese oxide (LMO), lithium nickel manganese cobalt oxide (NMC), and lithium nickel cobalt aluminum oxide (NCA). However, battery-grade graphite is almost exclusively used in most Li-ion battery anodes, negative electrode. Graphite accounts for about 50% of the minerals used in the anode of the Li-ion batteries and increases the cell's charge and discharge rates. [104]

Synthetic Graphite

Synthetic graphite, also called artificial graphite, is man-made. It was discovered accidentally in the late 1800s by Edward Goodrich Acheson. Mr. Acheson was trying to manufacture silicon carbide in an electric furnace when he noticed that graphite crystals were formed by an unintended reaction. Highly crystalline synthetic graphite was subsequently produced from certain solid amorphous (unstructured/shapeless) carbons by fine tuning the process and removing the silica altogether. [111]

Synthetic graphite is manufactured by heat treatment (graphitization) of, or chemical vapor deposition of, amorphous hydrocarbon materials. During this process of graphitization, hydrocarbon materials (graphite precursors) are subjected to such high temperatures [above 2100°C (3812°F)] that transform the amorphous (shapeless) structures of the graphite precursors into graphite crystalline structures. It is important to note that graphite is a specific form of carbon that can solely be derived from precursors containing carbon, e.g., petroleum coke from petroleum refining and coal pitch, which is a thick black liquid that remains after the distillation of coal tar. The ultra-high temperatures of the graphitization process also vaporize impurities, such as hydrogen, metals, nitrogen, organic compounds, and sulfur, from the precursors, and as a result, the synthetic graphite produced can be more than 99.9% high purity crystalline graphite. Synthetic graphite can be obtained in particle sizes ranging from 2-µm powders to 2-cm pieces and as flakey in fine powders or irregular grains and needles in coarser products. [105, 111]

The resulting synthetic graphite consists of smaller graphene planes and contains less impurities than natural graphite. However, it has slightly higher porosity, lower density, lower electrical conductivity, and a much higher price than natural flake graphite given that the graphitization process that produces synthetic graphite is high energy intensive. Synthetic graphite also demonstrates a slight decrease (about 10%) in energy density, but it has a better lifetime performance. Thus, there are performance and cost tradeoffs between natural graphite and synthetic graphite. At high volumes, synthetic graphite can cost up to 50% more than natural graphite. Generally, battery anodes use a combination of both materials. [49, 105, 111]

Applications of synthetic graphite concentrate on products that require high-purity graphite, such as: batteries, anticorrosion products, carbon brushes, coatings, conductive fillers, graphite electrodes, electrolytic processes, fuel cell bipolar plates, and nuclear moderator rods. Because of its slightly higher porosity relative to natural graphite, synthetic graphite is not suitable for refractory applications in the steel industry. In North America, synthetic graphite is used in more applications than natural graphite and accounts for a significant share of the graphite market. [49, 105]

The United States has a strong petrochemical refinement and production industry in place and is well positioned as one of the leaders, together with China, Japan, and Germany, in the global supply of synthetic graphite. Further, the U.S. Department of Energy (DOE) is supporting R&D projects to convert high carbon content materials derived from coal, which involve adding coal and coal refuse into battery grade graphite. [49, 112]

Graphite Recycling

Recovered high-end graphite from vehicle battery scraps can substitute for natural graphite. However, most spent vehicle battery recycling processes concentrate on the recovery of cathode materials, e.g., nickel and cobalt, and leave behind reusable anode graphite. This is because recycling processes of spent vehicle batteries are mainly driven by the value of the material recovered, e.g., cobalt, and the recovering graphite from recycled batteries is currently unprofitable when compared to the cost of mining natural graphite. [49]

For graphite to be effectively recovered from recycled batteries, it needs to be regenerated because its surface structure and composition are usually damaged during charging/discharging of the battery. Thus, recycling of graphite requires reconstruction and repair of its structure. There are various methods for graphite recycling/regeneration, such as hydrometallurgical and pyrometallurgical processes. Hydrometallurgical processes utilize organic and inorganic acids to dissolve metal ions (acid-base leaching). The regenerated graphite can then be recovered by floatation or calcination. In pyrometallurgical processes, graphite is subjected to temperatures over 1000°C (1832°F) to repair its structure and gasify residual metals and oxides. However, neither hydrometallurgy (acids, high temperatures) nor pyrometallurgy (very high temperatures) are environmentally friendly or cost-effective methods to recover graphite. [113, 116]

In general, due to the higher costs and drawbacks in the recycling/regenerating processes of spent graphite relative to natural graphite, the recovery of high-end graphite from end-of-life Li-ion EV batteries is currently unprofitable and not practiced. As a result, waste graphite from spent Li-ion battery anodes is usually abandoned or incinerated. This poses a severe threat to the environment and human health as particulate contamination and greenhouse gas emissions occur because of these practices. [113,]

Many technologies are being developed that focus on the elimination of secondary pollution and on positive economic perspectives for the reuse/recycling/regenerating of waste graphite from spent Li-ion batteries. These efforts coupled with legislative back-ups offer an attainable future for graphite recycling and for manufacturing battery products that will not rely on virgin materials. [116]

Copper:

Copper (Cu), atomic number 29 in the periodic table of chemical elements, is a natural reddish-orange transition metal with a bright metallic luster. It is extremely ductile, highly malleable, and a strong conductor of electricity (second only to silver) and heat. Because of these properties, copper is widely used in the form of wires in the electrical industry. Since copper is highly resistant to air, water, and seawater corrosion, it has been commonly used in coins. In the past, American pennies were made almost entirely of copper, although today pennies are typically made of zinc with a copper coating. Other uses of copper include piping, building construction, transportation equipment, industrial machinery, and other industries. [118, 119]

Source: Wikipedia- Copper
https://en.wikipedia.org/wiki/Copper

Because copper readily exists in nature in its useable metallic form, humans started using copper very early in history, the earliest evidence found from circa 8,000 BC. Romans used to get most of their copper from Cyprus and called it *aes cyprium* (metal of Cyprus), later called *cuprum* (Latin). The name copper is derived from *cuprum*. It occurs in nature as native copper and in other minerals such as copper sulfides, and copper carbonates.

Energy systems worldwide are transitioning to clean energy technologies, many of which rely on essential metals, including copper. Copper is a key metal for EV Li-ion batteries. [118], [119] Most of the copper in use today is mined or extracted as copper sulfides from large open pits, and mainly commercially produced by either smelting, where the ore is heated beyond the melting point of the desired element, or by leaching, where the ore is treated with substances that convert the metal into salts while impurities remain unchanged. [118], [119]

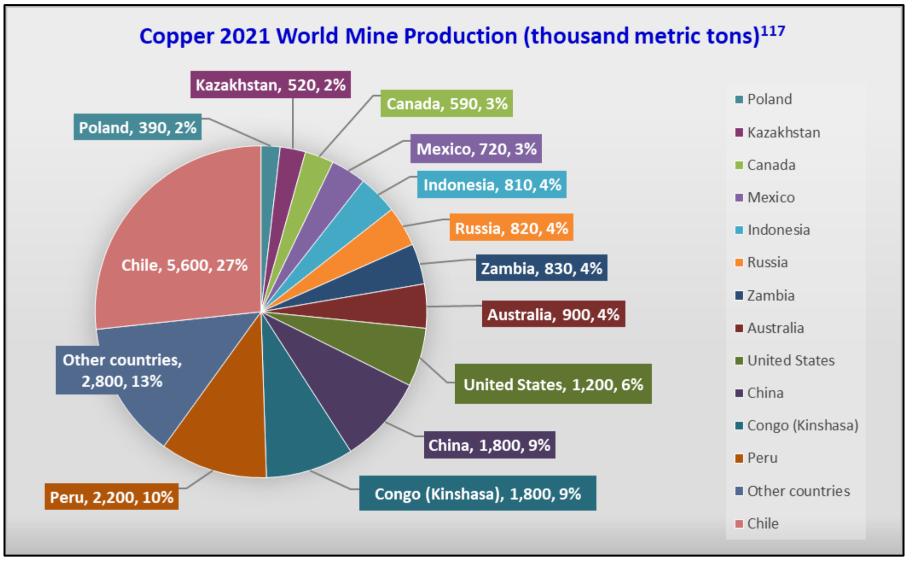
Source: Wikipedia- Cooper- Chuquicamata, in Chile, is one of the world's largest open pit copper mines https://en.wikipedia.org/wiki/Copper

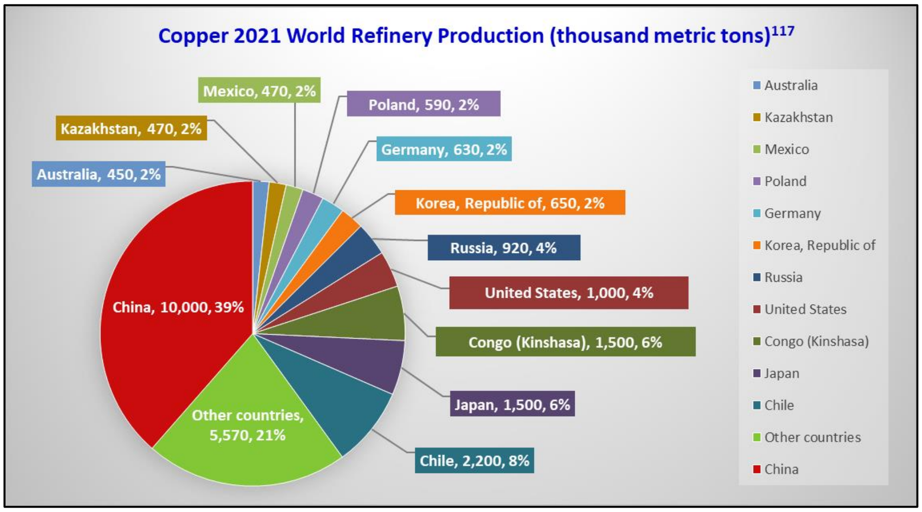
According to the U.S. Geological Survey, Mineral Commodity Summaries, January 2022, Chile was the main mine producer of copper in 2021 with 5,600 metric tons, followed by Peru with 2,800 metric tons, and China and Congo (Kinshasa) both with 1,800 metric tons of copper produced. Refinery production of copper was led by China in 2021 with 10,000 metric tons, followed by Chile with 2,200 metric tons. Chile also holds the largest copper reserves with 200,000 metric tons, followed by Australia with 93,000 metric tons, Peru with 77,000 metric tons and Russia with 62,000 metric tons. The U.S. Geological Survey's data for the mine and refinery copper productions, as well as for the reserves of copper metal for 2021 [117]:

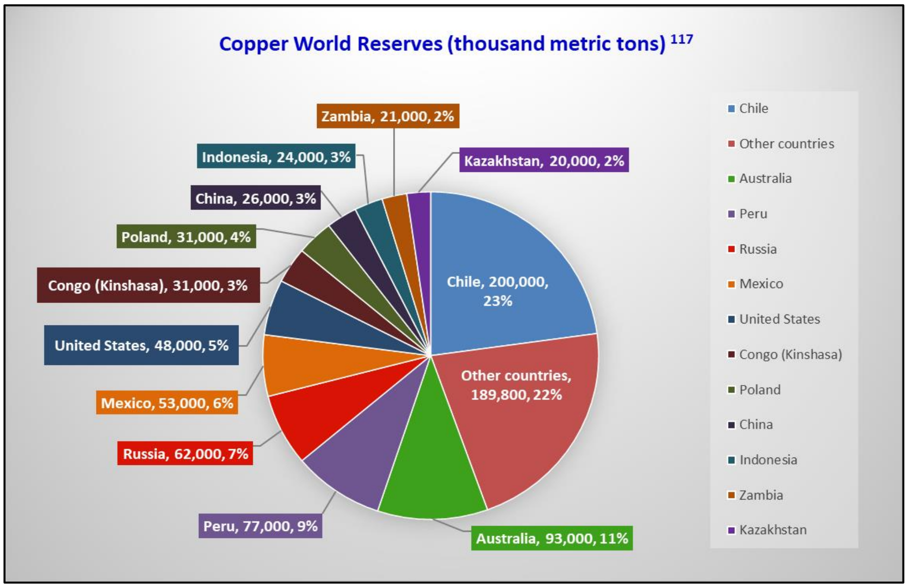
Copper Mine Production in 2021 (thousand metric Tons) [117]	
Country	**Mine Production**
	2021[e]
Poland	390
Kazakhstan	520
Canada	590
Mexico	720
Indonesia	810
Russia	820
Zambia	830
Australia	900
United States	1,200
China	1,800
Congo (Kinshasa)	1,800
Peru	2,200
Other countries	2,800
Chile	5,600
Germany	—
Japan	—
Korea, Republic of	—
World total (rounded)	21,000

Copper Refinery Production in 2021 (thousand metric Tons) [117]	
Country	**Refinery Production**
	2021
Australia	450
Kazakhstan	470
Mexico	470
Poland	590
Germany	630
Korea, Republic of	650
Russia	920
United States	1,000
Congo (Kinshasa)	1,500
Japan	1,500
Chile	2,200
Other countries*	5,570
China	10,000
World total (rounded)	26,000
*Other Countries with Copper Refinery Production (thousand metric tons) [117]	
Indonesia	270
Canada	300
Peru	350
Zambia	350
Other countries (USGS)	4,300
Other countries	5,570

Copper Global Reserves in 2021 (thousand metric Tons) [117]	
Country	**Reserves**[6]
Chile	200,000
Other countries*	189,800
Australia	93,000
Peru	77,000
Russia	62,000
Mexico	53,000
United States	48,000
Congo (Kinshasa)	31,000
Poland	31,000
China	26,000
Indonesia	24,000
Zambia	21,000
Kazakhstan	20,000
Germany	—
Japan	—
Korea, Republic of	—
World total (rounded)	880,000
*Other Countries with Copper Reserves (thousand metric tons)[117]	
Canada	9,800
Other countries (USGS)	180,000
Other Countries	189,800


Copper 2021 World Mine Production (thousand metric tons)[117]


Copper 2021 World Refinery Production (thousand metric tons)[117]


Copper World Reserves (thousand metric tons) [117]

The U.S. Geological Survey, Mineral Commodity Summaries, January 2022 states that as of 2015, identified resources contained 2.1 billion metric tons of copper, and undiscovered resources contained an estimated 3.5 billion metric tons, for a total of 5.6 billion metric tons of copper. [117]

Cooper is a major component of all types of vehicles, in particular electric vehicles. It is one of the main elements used in current and emerging Li-ion batteries. Cooper foils are used on the battery's negative electrode (anode) as a current collector. It is also used in windings and copper rotors used in electric motors, inverters, wiring, busbars and charging infrastructure. The use of copper in vehicles is expected to surge over the coming years as global demands for electric vehicles increase and the development and introduction of new technologies, e.g., energy independent vehicles (EIV) that are powered by renewable energy from copper-powered solar photovoltaic panels. Copper is one of the most used and reused metals of our times.[49, 123, 125]

COPPER USED BY VEHICLE TYPE [123]

TYPE OF VEHICLE	POUNDS OF COPPER
Internal Combustion Engine (ICE)	51
Hybrid electric vehicle (HEV)	88
Plug-in hybrid electric vehicle (PHEV)	132
Battery electric vehicle (BEV)	183
Hybrid electric bus (Ebus HEV)	196
Battery-powered electric bus (Ebus BEV)	494 - 814

Copper Recycling

Copper is 100% recyclable, and it is one of the few materials that can be recycled repeatedly without losing the quality of the material. The quality of recycled copper is as good as that of newly mined copper, so that recycled copper and mined copper can be exchanged with each other without any significant difference. [124]

In volume, copper is the third most recycled metal after iron and aluminum. Because of its high recycling rate, almost 80% of copper that has been mine-produced throughout history is still in use. Experts believe that some pennies in use today contain copper from the time of Egyptian pharaohs. [126, 127]

Today, around 8.7 million tons of copper per year come from the recycling of old/post-consumer scrap and from new scrap generated during production and manufacturing processes. [124]

According to the U.S. Geological Survey, Mineral Commodity Summaries, January 2022, copper recovered from scrap contributed about 32% of the U.S. copper supply. [117]

Good quality used copper can be recycled by simply melting the metal and checking for impurities before casting. If the copper has been contaminated, it may be necessary to remelt it and cast it into an anode form to be refined electronically. [125]

Recycling of copper offers considerable benefits to the environment. It requires 80-90% less energy than its mine production. As a result, there is a significant reduction in CO_2 emissions when copper is recycled rather than mined. In addition, the recycling of complex copper scrap, e.g., electronic waste, also drives the recovery of other metals, such as gold, silver, nickel, tin, lead and zinc. [124, 126]

Bearing in mind the copper mine resources and reserves, and the fact that copper is 100% recyclable, experts believe that there is enough copper in the world to meet current EV demands. [128]

However, a study published by S&P Global, The Future of Copper: Will the Looming Supply Gap Short-circuit the Energy Transition?, projected that global demand for copper will nearly double over the next decade, from 25 million metric tons today to about 50 million metric tons by 2035, and will continue to increase to 53 million metric tons by 2050, which exceeds the amount of copper consumed in the world between 1900 and 2021. These projections are based on the amount of copper that will be required by emerging EV, wind, solar, batteries and other technologies that have been identified as critical in achieving net-zero goal by 2050. The study found that the new mines, which take 16 years on average to develop and become productive, and expansion of current mine production would not be able to keep up with the increasing copper demands. [129]

According to MINING.COM, *"(there) simply aren't enough copper mines being built or expanded to provide all the copper needed to produce the 27 million EVs that S&P Global has forecast to be sold annually by 2030*." Further, while increased recycling rates and reuse of spent batteries will play an important role in meeting future copper demands, it will not be enough to close the forecasted gap in the copper supply chain. [131]

S&P Global Market Intelligence says in reference to meeting the overall copper supply outlook for the years ahead: "*Technology and innovation will both be critical in meeting this challenge, as will partnership between governments, producers and end-users*." [130]

The White House- 100-day-supply-chain-review-report identifies copper as one of the main elements used in Li-ion batteries. It does not consider copper as one of the critical elements but as an element that requires monitoring to understand potential risks and opportunities for U.S. economic development. [49]

Aluminum

Aluminum (AL) is the chemical element with atomic number 13 on the periodic table. It is a light metal with a silvery white color. Aluminum is the most abundant metallic element, and the third most abundant of all elements behind oxygen and silicon, in Earth's crust. However, aluminum is highly reactive, and because of its chemical activity, it does not exist in its natural/metallic form in nature. It readily reacts with oxygen and water to form hydroxides and powdery oxides. Aluminum compounds can be found in most rocks, vegetation, and animals at different concentrations. [133, 134]

Aluminum
Source: Wikipedia- Aluminum
https://en.wikipedia.org/wiki/Aluminium

Because aluminum in pure state is ductile and highly malleable, it can be firmly pressed into fine thin sheets (aluminum foils) and drawn into wires. Further, aluminum is an excellent conductor, with about 60% of the thermal and electrical conductivities of copper. Aluminum has a melting point of 660 °C (1,220 °F) and a density of 2.7 grams/cm^3. [133, 134]

Aluminum exists in the Earth's crust embedded within rocky lumps of ore. Bauxite is the world's main ore source of pure aluminum. Bauxite is a sedimentary rock, which originates from mineral (e.g., sand) and organic (e.g., dead plants, and animal skeletons) sediments that accumulate and become compacted into rock over thousands of years. It is formed from a reddish clay material called laterite soil that is commonly found in tropical or subtropical regions. Bauxite is reddish-brown, white, or tan and is usually strip-mined because it is commonly found near the surface of terrain. Bauxite is primarily composed of aluminum oxide compounds (alumina), silica, iron oxides and titanium dioxide. Alumina is used to produced aluminum. [136, 137, 138]

Mineral: Bauxite Mineral Origin: Les Baux, France
Source: U.S. Geological Survey- Bauxite and Alumina Statistics and Information
https://www.usgs.gov/centers/national-minerals-information-center/bauxite-and-alumina-statistics-and-information

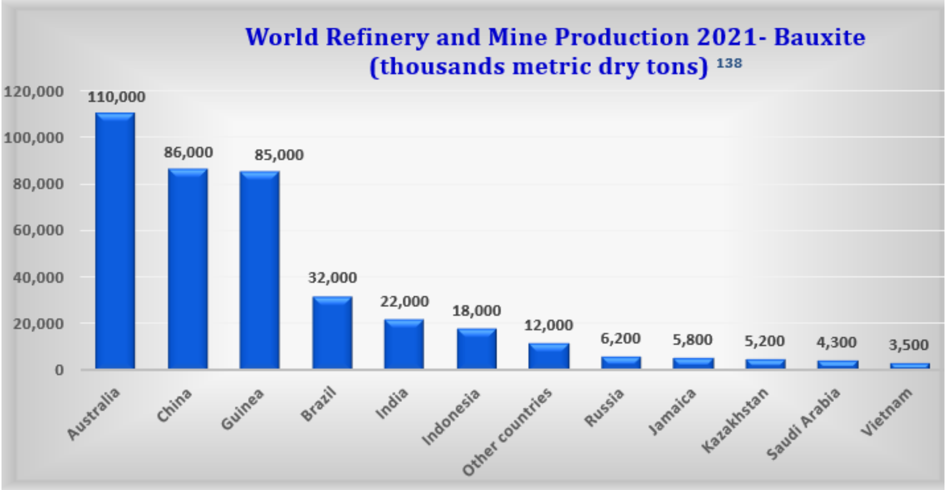
The extraction of aluminum from bauxite is a two-process production. The first is the Bayer Process (1886), which is a wet chemical caustic leach process through which bauxite is converted to alumina (Al_2O_3). The

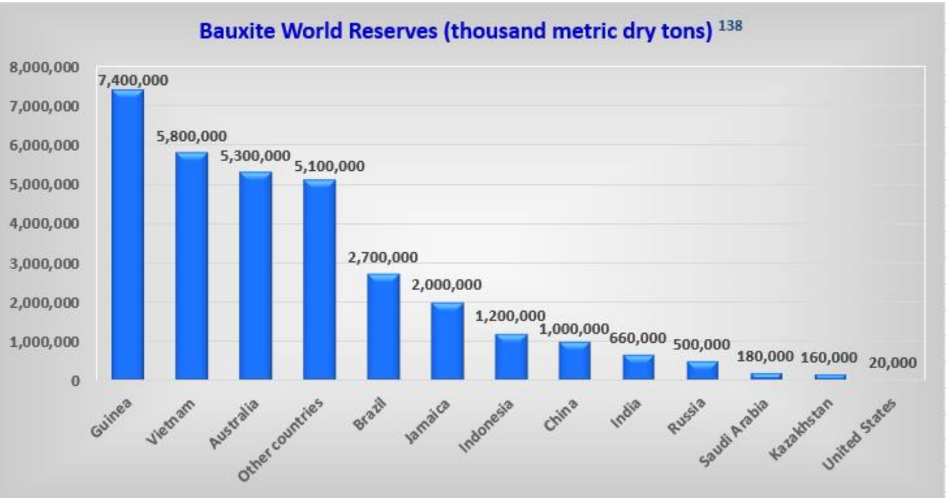
second is the Hall–Héroult Process (1889) that refines the alumina into aluminum metal via electrolytic reduction of alumina in a molten bath of natural or synthetic cryolite (Na_3AlF_6). [138]
Approximately 85% of world bauxite production is used to manufacture alumina. During the strip-mining process, bauxite is broken up and transported to an alumina refinery. In general, 4 tons of dried bauxite is required to produce 2 tons of alumina, which, in turn, produces 1 ton of aluminum.

According to the U.S. Geological Survey, Mineral Commodity Summaries, January 2022, in 2021, the leaders in bauxite production included Australia, China, Guinea, Brazil, and India. The world's bauxite reserves are mainly held by Guinea, Vietnam, and Australia. Bauxite resources are estimated to be between 55 billion and 75 billion tons, distributed in Africa (32%), Oceania (23%), South America and the Caribbean (21%), Asia (18%), and elsewhere (6%). [136, 138]

Country	**World Refinery and Mine Production Bauxite (thousands dry metric tons)** [138]		**World Bauxite reserves (thousand dry metric tons)** [138]
	2021^e		
United States	W		20,000
Australia	110,000		5,300,000
Brazil	32,000		2,700,000
Canada	—		—
China	86,000		1,000,000
Germany	—		—
Guinea	85,000		7,400,000
India	22,000		660,000
Indonesia	18,000		1,200,000
Ireland	—		—
Jamaica	5,800		2,000,000
Kazakhstan	5,200		160,000
Russia	6,200		500,000
Saudi Arabia	4,300		180,000
Spain	—		—
Ukraine	—		—
United Arab Emirates	—		—
Vietnam	3,500		5,800,000
Other countries	12,000		5,100,000
World total (rounded)	390,000		32,000,000

^{e} Estimated. W Withheld to avoid disclosing company proprietary data. — Zero





Aluminum oxide (Al_2O_3) is commonly called alumina and is mainly extracted from bauxite to be refined into aluminum. Alumina also occurs freely in nature as the mineral corundum, which is a hard, tough, and stable mineral that is best known for its gem varieties, primarily ruby and sapphire. Although Ruby and Sapphire are scientifically the same mineral, they differ in color. Ruby is the red variety due to its chromium content, and sapphire is the variety that exhibits other colors, with the most popular and valued color of sapphire being blue. [141], [142]

Corundum
Source: Wikipedia- Corundum
https://en.wikipedia.org/wiki/Corundum

The Bayer process is the principal and most economically sound means of producing alumina from bauxite. It involves dissolving the bauxite ore in sodium hydroxide (caustic soda), NaOH, at a high temperature (150 to 200°C/302 to 392°F) and pressure. At these temperatures, the aluminum oxide in the bauxite ore is in the form of aluminate ($Na(Al(OH)_4)$). Other than alumina and silica, the other components of bauxite do not dissolve. The aluminum compounds are then extracted by filtering/washing away the undissolved impurities/waste (red muds or sands). Finally, hydrated alumina is crystallized and calcinated (dried in a rotary kiln) to produce solid alumina. [143], [144]

Red mud near Stade (Germany)
Source: Wikipedia- Red Mud
https://en.wikipedia.org/wiki/Red_mud

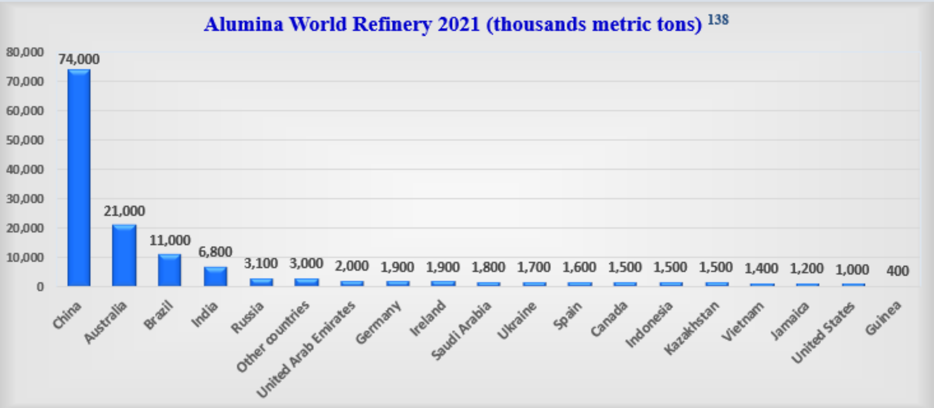
The process of refining bauxite into alumina generates a significant amount of red mud (bauxite residue), which is rich in calcium and sodium hydroxide and contains significant amounts of iron, aluminum, calcium, and sodium, depending on the composition of the ore and processing conditions. Red mud is extremely acoustic and is a source of pollution. Red mud waste is usually kept in large impoundments (reservoirs) that are lined with clay or synthetic liners. Scientists and refiners are seeking uses for red mud wastes, but the United States does not currently approve any uses due to the danger it poses to the environment. [143], [144]

The U.S. Geological Survey, Mineral Commodity Summaries, January 2022 reported that during 2021, China was the leading producer of alumina with approximately 74 million metric tons, followed by Australia with 21 million metric tons, Brazil with 11 million metric tons, and India with 6.8 million metric tons. [139]

Alumina Worldwide Refinery and Mine Production (thousands dry metric tons) [139]

Country	2021^e
China	74,000
Australia	21,000
Brazil	11,000
India	6,800
Russia	3,100
Other countries	3,000
United Arab Emirates	2,000
Germany	1,900
Ireland	1,900
Saudi Arabia	1,800
Ukraine	1,700
Spain	1,600
Canada	1,500
Indonesia	1,500
Kazakhstan	1,500
Vietnam	1,400
Jamaica	1,200
United States	1,000
Guinea	400
World total (rounded)	140,000

[e] Estimated.

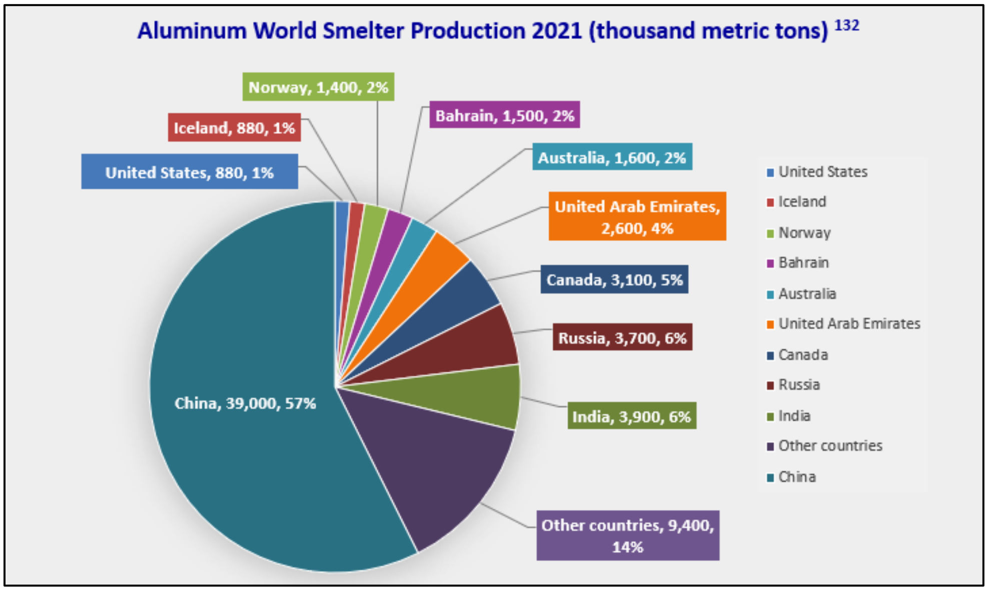

Alumina World Refinery 2021 (thousands metric tons) [138]

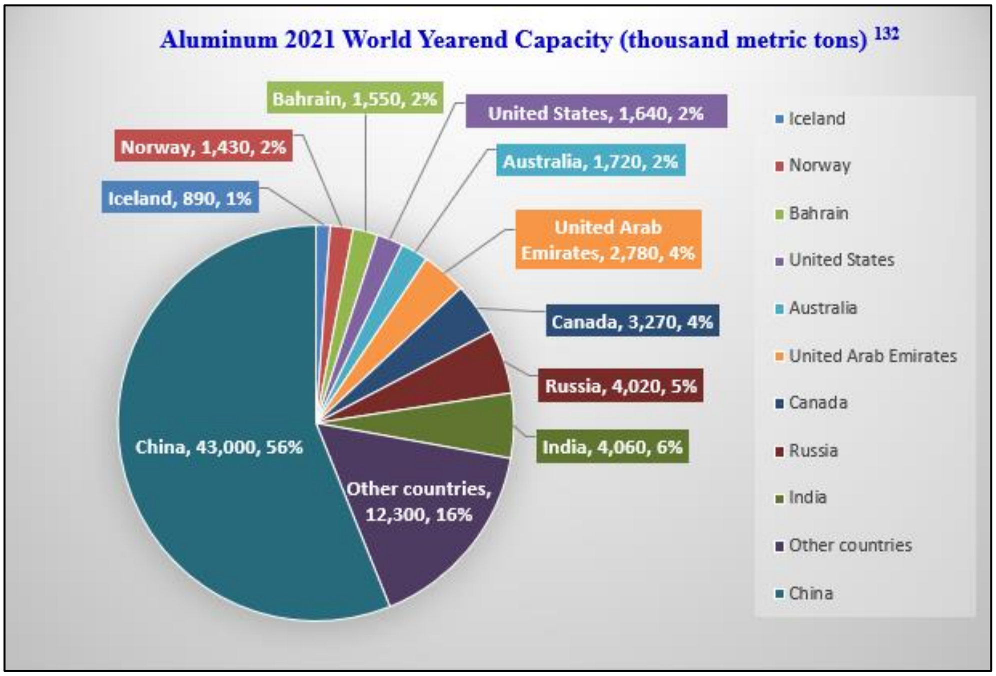
Once alumina is extracted from the bauxite ore, it is then refined into aluminum via aluminum smelting, usually through the Hall-Héroult process. This is an electrochemical process that uses large amounts of electric power to dissolve the alumina in molten cryolite (Na_3AlF_6) bath at around 950 °C (1,750 °F). The process works by dissolving the aluminum oxide (alumina) in cryolite (Na_3AlF_6,) to lower its melting point and then passing an electric current through the mixture to reduce the oxide. It separates aluminum metal as a precipitate from the chemical solution. Liquid aluminum is denser than the molten cryolite and sinks to the bottom of the bath, where it is collected periodically. The Hall-Héroult process produces 99.5–99.8% pure aluminum. [145]

About 90% of the alumina is used to produce aluminum metal. According to the U.S. Geological Survey, Mineral Commodity Summaries, January 2022, China was the world's aluminum production leader in 2021 with 39 million metric tons, which captured 57% of the market. China was followed by India with 3.900 million metric tons, Russia with 3,700 million metric tons, Canada with 3,100 metric tons, and other producers. Yearend aluminum capacity is also led by China with 43 million metric tons. [132]

Aluminum Worldwide Smelter Production (Thousand Metric tons) [132]	
Country	**2021^e**
China	39,000
Other countries	9,400
India	3,900
Russia	3,700
Canada	3,100
United Arab Emirates	2,600
Australia	1,600
Bahrain	1,500
Norway	1,400
United States	880
Iceland	880
World total (rounded)	68,000

Aluminum Worldwide Yearend Capacity (Thousand Metric Tons) [132]	
Country	**2021^e**
China	43,000
Other countries	12,300
India	4,060
Russia	4,020
Canada	3,270
United Arab Emirates	2,780
Australia	1,720
United States	1,640
Bahrain	1,550
Norway	1,430
Iceland	890
World total (rounded)	77,000





According to the International Energy Agency (IEA), aluminum production is responsible for about 3% of the world's 9.4 gigaton (Gt) of direct industrial CO_2 emissions in 2021. Increased global production of aluminum has caused a steady rise in CO_2 emissions in the aluminum sector over the past decade. Alumina refining and the electrical consumption of the aluminum smelters are the two main sources of greenhouse emissions, accounting for over 90% of the direct CO_2 emissions released in aluminum production. Development of new energy efficient and near zero emission technologies and their deployment in the aluminum production sector are crucial for the aluminum industry to meet the mid- and long-term climate emission targets and to get on track with the Net Zero Scenario, which targets a decline in emissions intensity of 3.5% annually until 2030. Numerous studies and research efforts are underway regarding the use of alternative energy sources, such as bioenergy and hydrogen for high-temperature processes or near zero-emission electricity for lower-temperature heat processes, and the use of inert anodes which release oxygen as they decay, instead of carbon anodes that release CO_2 during the smelting process. However, commercialization and adoption of these new technologies will be critical in the next few years for the aluminum production industry to get back on track in time to meet the Net Zero Scenario. [146]

Aluminum Recycling

Aluminum scrap can be recycled again and again. Its recycling process does not require electrolysis, and it involves re-melting the scrap, which uses only 5% of the energy required to produce aluminium from raw ore and releases less greenhouse gases. Most aluminum scrap comes from beverage containers, and about 75% of the aluminum ever produced is still in use today. In the United States, about 36% of the aluminum in use comes from recycled old aluminum scrap. [146], [147]

To achieve the decarbonation of the aluminum sector and reduce carbon emissions, the aluminum industry must turn away from conventional fuels and replace the use of fossil fuels with environmentally friendly production technologies. [146]

Section 3: End-of-Life EV Li-ion Battery Recycling and Reuse

As demands for electric vehicles increase globally, experts are concerned with what happens to the battery packs of EVs when they are used up. The number EV batteries from light and heavy-duty BEV and PHEV reaching end-of-life has been estimated to be: [146]

- 1.2 million by 2030
- 14 million by 2040
- 50 million by 2050

The International Council for Clean Transportation (ICCT) published the report "Scaling Up Reuse And Recycling Of Electric Vehicle Batteries: Assessing Challenges And Policy Approaches" in February 2023 where it estimated that reusing 50% of the end-of-life vehicle batteries for stationary energy storage could provide a capacity of 96 GWh in 2030, 3,000 GWh in 2040, and 12,000 GWh by 2050. If the remaining 50% of the end-of-life vehicle batteries are recycled, the combined annual mining demand for lithium, cobalt, nickel, and manganese could be reduced by 3% in 2030, 11% in 2040, and 28% in 2050. [146]

year	End-of-Life BEVs/PHEVs (millions)	Estimated % reduced combined annual mining demand of Li, Co, Ni, and Mg if 50% of the EOL EV batteries are recycled	Estimated annual energy storage if 50% of the EOL EV batteries are reused
2030	1.2	3%	96 GWh
2040	14	11%	3000 GWh
2050	50	28%	120,000 GWh

Effective reuse measures to extend the use of spent EV batteries and recycle initiatives to reclaim their critical metal components need to be adopted to diminish environmental burdens associated with the production and disposal of EV batteries and to reduce mining demands for EV metals. [146]

Reuse of End-Of-Life EV Batteries

In most cases, EV batteries reach their end-of-life (EOL) and become unsuitable for powering EVs when their capacity falls below 70% to 80% of their initial value, which is after roughly eight to ten years of use. That said, these spent EV batteries may be used as stationary energy storage units for less energy-demanding applications. [146]

Second-life applications extend the useful life of spent EV batteries by repurposing them for lower energy-scale applications, such as: [146]

- Small energy-scale applications:
    - Battery storage for residential settings
    - Storage systems at electric vehicle charging stations, or street lighting
- Medium energy-scale applications:
    - Energy supply storage for industrial sites
    - Power traction batteries for maritime applications
- Large energy-scale applications:
    - As grid-scale storage, where end-of-life EV batteries are reused as energy storage units to store electricity and deliver it back to the grid at peak times

EV Battery reuse processing includes five main steps. These are battery collection, battery transport, battery inspection, sorting and regrouping, and battery second-life placement. [146]

Battery collection is the first step in the EV battery reuse process. This step confronts two main challenges in that many jurisdictions lack traceability mechanisms to ensure that the EV batteries are collected once the vehicles reach end-of-life, and lack regulations that clearly define who is responsible for the disposal of the spent batteries, e.g., vehicle or battery manufacturers. In addition, parties collecting the spent EV batteries must take safety measures and exercise proper handling during the battery removal. [146]

Battery transport to a reuse center for second-life application processing must follow the international and domestic safety standards defined by several organizations, such as the United Nations, the Institute of Electrical and Electronics Engineers (IEEE), and the U.S. Department of Transportation. The transportation of EV batteries faces several challenges, including complex licensing processes, costly safety measures, and long distances traveled to the reuse centers. [146, 147]

Battery inspection affronts the absence of readily available information regarding battery design, chemistry, state of health, and usage history that is needed to determine the battery's suitability for a second-life application. [146]

Sorting and regrouping of battery cells, modules, and packs that passed the safety and state of health tests refers to the process of regrouping them according to their performance, e.g., internal resistance and thermal behavior. This is a necessary step to avoid any adverse impact to the performance of the second-life battery. [146]

Battery second-life placement requires adopting control strategies to stabilize power output and limit overheating or discharging events. Inconsistencies in electrochemical behavior of individual cells or modules may be reduced by designing/implementing equalization strategies. Further, fault-diagnosis algorithms must be developed and implemented to readily detect events, such as internal short circuits in second-life batteries. [146,]

Increasing the EV battery reuse market will involve resolving the different technical challenges of battery reuse, as well as ensuring that the reused EV battery is less expensive than using a new battery. [146]

Recycling of End-Of-Life EV Batteries

Recycling of spent EV batteries can be pursued before or after the spent battery is reused. The main objective is to recover the high value metals, such as cobalt, copper, nickel, and iron. In general, the recycling process includes battery collection, transportation, inspection, disassembly, and recycling. The collection and transportation processes for battery recycling are similar to the aforementioned methods for battery reuse. For the battery inspection step, information on the battery's chemistry and design is needed to effectively assign it to an appropriate recycling plant. Battery disassembly entails taking apart the battery packs, modules, and cells. It requires knowledge of the battery's geometry and architecture, and it is mostly done manually. Disassembled batteries are then thermally treated to remove impurities and shredded for recycling.[146]

There are two current pathways for battery recycling, pyrometallurgy (melting) and hydrometallurgy, which can be used combined or separately.

The pyrometallurgical process is an energy-intensive mature technology as it takes place at high temperatures where the shredded battery components are incinerated/melted, resulting in a mass/slag of the plastics, metals, and glues. Valuable metals, e.g., cobalt, copper, nickel, and iron, can then be recovered using various techniques, such as precipitation, solvent extraction, ion exchange and electrolytic extraction. However, other materials, including lithium and aluminum, remain in the slag, which is usually sold as concrete additive. [146, 149]

Hydrometallurgy is a mature technology that involves submerging battery materials in pools of acid and then further refining to extract the metals. It is environmentally friendlier than pyrometallurgy. Battery metals recovered through hydrometallurgy include aluminum, cobalt, copper, lithium, manganese, and nickel. Hydrometallurgy requires water treatments to prevent acid contamination. [147]

Direct recycling, or cathode-to-cathode recycling, of EV batteries is a new method that does not use pyrometallurgy or hydrometallurgy processes. In theory, direct recycling preserves the cathode structure, the most valuable part of the EV battery, so it may be reused. This method has only been demonstrated at a pilot level and is still under development. [146, 149]

Section 4: The White House 100-Day Supply Chain Review Report

- A Brief Overview: Review of Large Capacity Batteries -

In the United States, the Biden administration has implemented initiatives to counter China's leading position in battery production and to ensure that the U.S. will have the critical materials it needs. U.S. government officials are diligently working to localize supply chains within the U.S. and to boost the United States relations with the Democratic Republic of the Congo in order to increase access to essential resources, e.g., cobalt. [6, 47]

Moreover, on February 24, 2021, the Biden administration introduced Executive Order 14017, "America's Supply Chains" which directed the Administration to immediately conduct "a 100-day review and strategy development process to address vulnerabilities in the supply chains of four key product categories". The four key product categories are [47, 50] :

1) Semiconductor manufacturing and advanced packaging
2) Large capacity batteries, such as those for electric vehicles
3) Critical minerals and materials
4) Pharmaceuticals and advanced pharmaceutical ingredients

Findings of the 100-day review of America's supply chain were published by the White House in June 2021 in the report "Building Resilient Supply Chains, Revitalizing American Manufacturing, and Fostering Broad-Based Growth." [47] The report revealed significant vulnerabilities in both domestic and international supply chains and put forward recommendations to strengthen the United States' competitive edge and supply chain resilience on all four product categories. [47]

Regarding the large capacity batteries category, the report highlights that the U.S. government needs to work with private industries and provide incentives across all five stages of the high-capacity battery supply chain [47]:

1) Raw material
2) Production material refinement and processing
3) Battery material manufacturing and cell fabrication
4) Battery pack and end use product manufacturing
5) Battery end-of-life and recycling.

Most importantly, the report emphasizes that the United States must take action to secure reliable and sustainable supplies of critical minerals and metals–particularly Class I nickel, lithium, and cobalt–to ensure resilience across U.S. manufacturing and to close gaps that can undermine efforts to secure the supply chain in a manner consistent with America's labor-related, environmental, and equity principles. [47, 49]

The report identifies raw critical material productions as primary upstream supply chain vulnerabilities, and the U.S. government needs to implement measures to increase economically viable and responsible domestic extractions of these materials while enforcing strong labor standards, critical modern environmental standards, and cultural protections. [47, 49]

Increasing recycling end-of-life batteries to recover critical materials is another domestic source option that can help reduce new mining needs. 47, 49 However, current technologies for recycling batteries are not effective or economically profitable. As a result, it is cheaper to mine some critical materials, including lithium, than to source them from battery recycling. [14]

Battery recycling can become a major supplementary source for the supply of critical materials. If recycling is to take hold today, cobalt recovery from end-of-life batteries would be the driver due to it being the most expensive material in batteries, and as such, would make the cost of recycling batteries competitive with critical mineral mining sources.

Most batteries are first shredded into powdery mixtures to be recycled. These mixtures are then either melted at very high temperatures in a smelter (pyrometallurgy) or dissolved in an acid (hydrometallurgy). During the final step of the recycling processes, the metals are precipitated from the resulting solutions and recovered. These processes are neither energy efficient nor cost effective.

The U.S. Department of Energy's (DOE) Vehicle Technologies Office's (VTO) launched ReCell, its advanced battery recycling R&D center, which in collaboration with battery recycling experts from three national laboratories and three universities focuses on the development of cost-effective, environmentally sound processes aimed at recovering, regenerating, and recycling lithium-ion battery components without changing their chemical structure. To that end, ReCell is looking at 'Direct Cathode Recycling' that retains the valuable crystal structure of the cathode, instead of separating the cathode into its constituents. Direct Cathode Recycling is expected to be a more environmentally sound battery recycling process, and less costly since it uses significantly less energy than pyrometallurgy or hydrometallurgy. [39]

Regarding the securing of the supply chains for large capacity batteries and minerals and materials product categories, the 100-day review of America's supply chain report delivered recommendations that urge the U.S. Federal Government and the private sector to collaborate in undertaking efforts to strengthen raw critical material supply, enhance domestic materials processing capacity, expand domestic battery production, and support EV adoption. [49]

Abbreviations and Acronyms

Abbreviation/Acronyms	Description
Al_2O_3	Aluminum Oxide (Alumina)
BEV	Battery electric vehicle
BMS	Battery Management System
BNEF	BloombergNEF
CATL	Contemporary Amperex Technology Limited
CO_2	Carbon Dioxide
CO2	Carbon Monoxide
COTECCO	Combatting Child Labor in the Democratic Republic of the Congo's Cobalt Industry
DLE	Direct Lithium Extraction
DOE	Department of Energy
DRC	Democratic Republic of Congo
EIV	Energy Independent Vehicles
EV	All-electric vehicle
GHG	Greenhouse gas
HC	Hydrocarbon
HDV	Heavy-duty vehicle
ICEs	Internal combustion engines
IEA	International Energy Agency
IMIP	Indonesian Morowali Industrial Park
LCE	Lithium Carbonate Equivalent
LCO	Lithium Cobalt Oxide
LDV	Light-duty vehicles
LFP or LiFePO4	Lithium Iron Phosphate Battery
$Li2CO_3$	Lithium Carbonate
LiCl	Lithium Chloride
Li-ion	Lithium-ion
$LiNiCoAlO_2$	Lithium Nickel Cobalt Aluminum Oxide
LMD	Lithiated Manganese Dioxide
LMO	Lithium Manganese Oxide
LPO	Loan Programs Office
Na_3AlF_6	Sodium Aluminum Hexafluoride (cryolite)
Na-ion	Sodium-ion
NaAl(OH)4	Sodium Tetrahydroxoaluminate (Aluminate)
NaOH	Sodium Hydroxide
NCA	Lithium Nickel Cobalt Aluminum Oxide
NCA82 cathode	Nickel 82%, Cobalt 15%, and Aluminum Oxide 3% cathode
NFA	Nickel-iron-aluminum Battery

Abbreviations and Acronyms (Continuation)

Abbreviation/Acronyms	Description
NiFe	Nickel-iron Alloy
NiS	Nickel Sulfide
NiSO4	Nickel Sulfate
NMA	Lithium Nickel Manganese Aluminum
NMC	Lithium Nickel Manganese Cobalt Oxide
NMC811 cathode	Nickel 80%, Manganese Oxide 10%, Cobalt 10% cathode
NOx	Nitrogen Oxides
NPI	Nickel Pig Iron
NREL	National Renewable Energy Laboratory
PHEV	Plug-in hybrid electric vehicles
REEs	Rare-Earth Elements
USGS	U.S. Geological Survey

References and links

1. FORBES: Can Metals Supply Keep Up With Electric Vehicle Demand? July 24, 2019 article
https://www.forbes.com/sites/woodmackenzie/2019/07/24/can-metals-supply-keep-up-with-electric-vehicle-demand/?sh=65572b906c9b

2. Nature Communications: Impact of transport electrification on critical metal sustainability with a focus on the heavy-duty segment, Hao et al., 2019
https://www.nature.com/articles/s41467-019-13400-1.pdf

3. Boomberg: How Much Lithium Will the World Need? It Depends Who You Ask, February 8, 2022 article
https://www.bloomberg.com/news/articles/2022-02-09/lithium-s-feast-or-famine-future-keeps-ev-makers-guessing

4. Battery University: BU-308: Availability of Lithium, article
https://batteryuniversity.com/article/bu-308-availability-of-lithium

5. S&P Global Market Intelligence: EV Impact: Battery disruptors are jolting metal supply chains, 9/21/2021
https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/ev-impact-battery-disruptors-are-jolting-metal-supply-chains-66518783

6. New York Times: The Global Race to Mining the Metal of the Future, Podcast on March 18, 2022
https://www.nytimes.com/2022/03/18/podcasts/the-daily/cobalt-climate-change.html?rref=vanity

7. Grepow: What is the NMC 811 Battery? What are its features? Webpage and video link
https://www.grepow.com/blog/what-is-the-nmc-811-battery-what-are-its-features-battery-monday/

8. Science Direct- Elsevier: Securing Platinum-Group Metals for Transport Low-Carbon Transition, Hao et al., 2019
https://www.sciencedirect.com/science/article/pii/S2590332219300181

9. IOPscience- Environmental Research Letters: The role of transport electrification in global climate change mitigation scenarios, Runsen Zhang and Shinichiro Fujimori, February 19, 2020
https://iopscience.iop.org/article/10.1088/1748-9326/ab6658/pdf

10. International Energy Agency (IEA)- Electric cars fend off supply challenges to more than double global sales, Leonardo Paoli and Timur Gull, January 30 2022
https://www.iea.org/commentaries/electric-cars-fend-off-supply-challenges-to-more-than-double-global-sales

11. White House- FACT SHEET: President Biden Announces Steps to Drive American Leadership Forward on Clean Cars and Trucks, August 5, 2021
https://www.whitehouse.gov/briefing-room/statements-releases/2021/08/05/fact-sheet-president-biden-announces-steps-to-drive-american-leadership-forward-on-clean-cars-and-trucks/

12. White House- FACT SHEET: The Biden-Harris Electric Vehicle Charging Action Plan, December 13, 2021
https://www.whitehouse.gov/briefing-room/statements-releases/2021/12/13/fact-sheet-the-biden-harris-electric-vehicle-charging-action-plan/

13. European Commission- Climate Action: CO_2 emission performance standards for cars and vans
https://ec.europa.eu/clima/eu-action/european-green-deal/delivering-european-green-deal/co2-emission-performance-standards-cars-and-vans_en

14. Nature: Electric cars and batteries: how will the world produce enough?, Davide Castelvecchi, August 17, 2021
https://www.nature.com/articles/d41586-021-02222-1

15. BloombergNEF (BNEF): Electric Vehicle Outlook 2021
https://about.bnef.com/electric-vehicle-outlook/

16. University of Washington-Clean Energy Institute: Lithium-Ion Battery, Webpage
https://www.cei.washington.edu/education/science-of-solar/battery-technology/

17. Bloomberg Green: The Hidden Science Making Batteries Better, Cheaper and Everywhere, Rathi et al., April 27, 2021
https://www.bloomberg.com/graphics/2021-inside-lithium-ion-batteries/

18. You Tube: How a Lithium Ion Battery Actually Works // Photorealistic // 16 Month Project
https://www.youtube.com/watch?v=4-1psMHSpKs

19. You Tube- Learn Engineering: Lithium-ion battery, How does it work?
https://www.youtube.com/watch?v=VxMM4g2Sk8U

20. You Tube-BASF: Lithium-ion batteries: How do they work?
https://www.youtube.com/watch?v=VXy-IoRykWk

21. You Tube-Mechanical Engineering- Battery-Lithium ion: Lithium-ion Battery Chemistries | SKILL-LYNC
https://www.youtube.com/watch?v=vr1tuBWnI6Y

22. National Renewable Energy Laboratory (NREL)- Clean Energy manufacturing Analysis Center (CEMAC): Supply Chain of Raw Materials Used in The Manufacturing of Light-Duty Vehicle Lithium-Ion Batteries
https://www.nrel.gov/docs/fy19osti/73374.pdf

23. Physics Today: Fears of a lithium supply crunch may be overblown, Physics Today 74, 5, 20 (2021)
https://physicstoday.scitation.org/doi/10.1063/PT.3.4745

24. Orocobre Limited: Lithium Supply, webpage
https://www.orocobre.com/the-markets/lithium-supply/

25. Chemistry World: Salt Lakes Worth their Lithium, May 2014
https://www.chemistryworld.com/news/salt-lakes-worth-their-lithium/7351.article

26. Energy and Environmental Science: Continuous electrical pumping membrane process for seawater lithium mining, Li et al., 2021
https://pubs.rsc.org/en/content/articlepdf/2021/ee/d1ee00354b

27. Statista- Chemicals & Resources- Mining, Metals, & Minerals: Major countries in worldwide lithium mine production in 2021
https://www.statista.com/statistics/268789/countries-with-the-largest-production-output-of-lithium/

28. Statista- Chemical & Resources- Mining, Metals, & Minerals: Countries with the largest lithium reserves worldwide as of 2021
https://www.statista.com/statistics/268790/countries-with-the-largest-lithium-reserves-worldwide/

29. US Geological Survey- Lithium Data Sheet - Mineral Commodity Summaries 2022, January 2022
https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-lithium.pdf

30. Statista- Chemical & Resources- Mining, Metals, & Minerals: Mineral Commodity Summaries 2022 – Lithium:
https://www.statista.com/statistics/452025/projected-total-demand-for-lithium-globally/

31. Harvard International Review: The Lithium Triangle: Where Chile, Argentina, and Bolivia Meet, January 16, 2020
https://hir.harvard.edu/lithium-triangle/

32. Dialogo Chino: Explainer: the opportunities and challenges of the lithium industry, Sophie Bauer, December 2, 2020
https://dialogochino.net/en/extractive-industries/38662-explainer-the-opportunities-and-challenges-of-the-lithium-industry/

33. Energy Monitor- Sector>Transport: Booming EV sales challenge critical mineral supply chains, Isabeau van Halm and Cathy Mullan, February 14, 2022
https://www.energymonitor.ai/sectors/transport/booming-ev-sales-challenge-mineral-supply-chains

34. International Energy Agency (IEA): Net Zero by 2050- A Roadmap for the Global Energy Sector, October 2021
https://iea.blob.core.windows.net/assets/deebef5d-0c34-4539-9d0c-10b13d840027/NetZeroby2050-ARoadmapfortheGlobalEnergySector_CORR.pdf

35. GreenBiz: Lithium mining is booming — here's how to manage its impact, Robin Bolton, August 11, 2021
https://www.greenbiz.com/article/lithium-mining-booming-heres-how-manage-its-impact

36. National Renewable Energy Laboratory (NREL): Using Direct Lithium Extraction To Secure U.S. Supplies, July 21, 2021
https://www.nrel.gov/news/program/2021/using-direct-lithium-extraction-to-secure-us-supplies.html

37. Los Angeles Times: Lithium will fuel the clean energy boom. This company may have a breakthrough, Sammy Roth, October 14, 2022
https://www.latimes.com/environment/story/2019-10-14/california-lithium-geothermal-salton-sea

38. International Energy Agency (IEA): The Role of Critical Minerals in Clean Energy Transitions, Revised version March 2022
https://iea.blob.core.windows.net/assets/ffd2a83b-8c30-4e9d-980a-52b6d9a86fdc/TheRoleofCriticalMineralsinCleanEnergyTransitions.pdf

39. U.S. Department of Energy's (DOE) Vehicle Technologies Office's (VTO) first advanced battery recycling R&D center: ReCell Program
https://recellcenter.org/

40. US Geological Survey- Cobalt: Mineral Commodity Summaries 2022, January 2022
https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-cobalt.pdf

41. New York Time- Podcast: The Global Race to Mine the Metal of the Future
https://www.nytimes.com/2022/03/18/podcasts/the-daily/cobalt-climate-change.html?rref=vanity

42. US Department of Energy (DOE)- Office of Energy Efficiency and Renewable Energy, Vehicle Technologies Office: Reducing Reliance on Cobalt for Lithium-ion Batteries, April 6, 2021
https://www.energy.gov/eere/vehicles/articles/reducing-reliance-cobalt-lithium-ion-batteries

43. Managing Impacts of the Deep Sea Resource Exploitation (MIDAS): Polymetallic Nodules
https://www.eu-midas.net/science/nodules

44. US Department of Labor- Bureau of International Labor Affairs: Combatting Child Labor in the Democratic Republic of the Congo’s Cobalt Industry (COTECCO), Project Duration: October 2018-September 2022
https://www.dol.gov/agencies/ilab/combatting-child-labor-democratic-republic-congos-cobalt-industry-cotecco

45. U.S. Embassy in the Democratic Republic of the Congo: Ambassador Hammer Announces Expanded Programs, Stresses Good Governance in Meeting with Vice-Minister of Mines
https://cd.usembassy.gov/ambassador-hammer-announces-expanded-programs-stresses-good-governance-in-meeting-with-vice-minister-of-mines/

46. Science Direct- Elsevier: Identifying supply risks by mapping the cobalt supply chain, van den Brick et al., January 2020
https://reader.elsevier.com/reader/sd/pii/S0921344920300653?token=EA3B4660874CA5FAAB5A122D721A131CB43D96A6710A748AF45F628C2807A89E579E1AD430780CA6C9BD6E070D1BC8CC&originRegion=us-east-1&originCreation=20220504191026

47. The New York Times: Chinese Company Removed as Operator of Cobalt Mine in Congo, Feb. 28, 2022
https://www.nytimes.com/2022/02/28/world/congo-cobalt-mining-china.html

48. Mining: What China’s increasing control over cobalt resources in the DRC means for the West – report, January 17, 2022
https://www.mining.com/what-chinas-increasing-control-over-cobalt-resources-in-the-drc-means-for-the-west-report/

49. The White House- 100-day-supply-chain-review-report: Building Resilient Supply Chains, Revitalizing American Manufacturing, And Fostering Broad-Based Growth- 100-Day Reviews under Executive Order 14017, June 2021
https://www.whitehouse.gov/wp-content/uploads/2021/06/100-day-supply-chain-review-report.pdf

50. The White House-This document has been published in the Federal Register: America's Supply Chains- Executive Order 14017 of February 24, 2021
https://www.govinfo.gov/content/pkg/FR-2021-03-01/pdf/2021-04280.pdf

51. U.S. Geological Survey- ScienceBase-Catalog: Cobalt Deposits in the United States
https://www.sciencebase.gov/catalog/item/5ad623f2e4b0e2c2dd23f09e

52. U.S. Geological Survey- ScienceBase-Catalog- Identification Information: Cobalt Deposits in the United States
https://www.sciencebase.gov/catalog/file/get/5ad623f2e4b0e2c2dd23f09e?f=__disk__fa%2F91%2F2e%2Ffa912e76ca78eafa07c7819e13af478af4e81c51&transform=1&allowOpen=true#Identification%20Information

53. The White House: FACT SHEET: Biden-Harris Administration Announces Supply Chain Disruptions Task Force to Address Short-Term Supply Chain Discontinuities, June 8, 2021
https://www.whitehouse.gov/briefing-room/statements-releases/2021/06/08/fact-sheet-biden-harris-administration-announces-supply-chain-disruptions-task-force-to-address-short-term-supply-chain-discontinuities/

54. U.S. Department of Energy (DOE)- Biden Administration, DOE to Invest $3 Billion to Strengthen U.S. Supply Chain for Advanced Batteries for Vehicles and Energy Storage, February 11, 2022
https://www.energy.gov/articles/biden-administration-doe-invest-3-billion-strengthen-us-supply-chain-advanced-batteries

55. U.S. Department of Energy- Title XVIII
https://www.energy.gov/lpo/title-xvii

56. GlobalEdge- Global Business Knowledge: Congo's Cobalt Controversy, Cade Ahlijian, April 20, 2022
https://globaledge.msu.edu/blog/post/57136/congos-cobalt-controversy

57. CNBC: Here's why battery manufacturers like Samsung and Panasonic and car makers like Tesla are embracing cobalt-free batteries, Magdalena Petrova, November 17, 2022
https://www.cnbc.com/2021/11/17/samsung-panasonic-and-tesla-embracing-cobalt-free-batteries-.html

58. U.S. Department of Energy- Federal Consortium for Advanced Batteries: National Blueprint for Lithium Batteries 2021–2030, June 2021
https://www.energy.gov/sites/default/files/2021-06/FCAB%20National%20Blueprint%20Lithium%20Batteries%200621_0.pdf

59. Wikipedia: Lithium Iron Phosphate Battery
https://en.wikipedia.org/wiki/Lithium_iron_phosphate_battery

60. Sparkz: Innovative Technology- Zero Cobalt Lithium-Ion Battery
https://sparkz.energy/

61. TexPower: EV Technologies- Cobalt-Free High-Energy Cathode
https://texpowerev.com/ev-technologies/

62. Reuters: China's CATL unveils sodium-ion battery - a first for a major car battery maker. July 29, 2021
https://www.reuters.com/technology/chinas-top-ev-battery-maker-catl-touts-new-sodium-ion-batteries-2021-07-29/

63. ScienceDirect: Sodium-ion Battery
https://www.sciencedirect.com/topics/materials-science/sodium-ion-battery

64. U.S. Geological Survey, Mineral Commodity Summaries- Nickel, January 2022
https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-nickel.pdf

65. Reuters: Enough nickel, lithium for 14 mln EVs in 2023 – Nick Carey, European climate group, May 3, 2022
https://www.reuters.com/business/autos-transportation/enough-nickel-lithium-14-mln-evs-2023-european-climate-group-2022-05-02/#:~:text=May%203%20(Reuters)%20%2D%20Data,(T%26E)%20said%20on%20Tuesday.

66. S&P Global- Commodity Insight: Electric vehicles and the nickel supply conundrum: Opportunities and challenges ahead, Leah Chen and Scott Yarham, December 31, 2022
https://www.spglobal.com/commodityinsights/en/market-insights/blogs/metals/123121-nickel-supply-electric-vehicle-demand

67. Encyclopedia Britannica: Nickel
https://www.britannica.com/print/article/414313

68. Nickel Institute: Is there enough nickel? Reserves, resources and recycling, January 6, 2020
https://nickelinstitute.org/en/blog/2020/january/reserves-resources-and-recycling-is-there-enough-nickel/

69. PMF IAS: Earth's Layers: Crust, Mantle & Core, Seismic Discontinuities, December 13, 2019
https://www.pmfias.com/earths-layers-crust-mantle-core/

70. Nature: Electric Cars: The Battery Challenge, Davide Castelvecchi, August 19, 2021
https://media.nature.com/original/magazine-assets/d41586-021-02222-1/d41586-021-02222-1.pdf

71. United States Department of The Interior-Geological Survey Professional Paper 205-A: Relative Abundance of Nickel in The Earth's Crust, Roger Clark Wells, 1943
https://pubs.usgs.gov/pp/0205a/report.pdf

72. Nickel Institute: The Life of Ni
https://nickelinstitute.org/media/1190/thelifeofni.pdf

73. U.S. Geological Survey- Inside The earth
https://pubs.usgs.gov/gip/dynamic/inside.html

74. National Geographic- Earth's Crust
https://education.nationalgeographic.org/resource/crust

75. National Geographic: Earth's Mantle
https://education.nationalgeographic.org/resource/mantle

76. National Geographic: Earth's Core
https://education.nationalgeographic.org/resource/core

77. National Aeronautics and Space Administration (NASA): Earth's Magnetosphere: Protecting Our Planet from Harmful Space Energy, August 3, 2021
https://climate.nasa.gov/news/3105/earths-magnetosphere-protecting-our-planet-from-harmful-space-energy/

78. Research Gate: A Detailed Assessment of Global Nickel Resource Trends and Endowments, Gavin Mudd and Simon Jowitt, August 2014
A Detailed Assessment of Global Nickel Resource Trends and Endowments

79. U.S. Geological Survey: Nickel Statistics and Information
https://www.usgs.gov/centers/national-minerals-information-center/nickel-statistics-and-information

80. McKinsey and Company-The future of nickel A class act, November 2017
https://www.mckinsey.com/~/media/McKinsey/Industries/Metals%20and%20Mining/Our%20Insights/The%20future%20of%20nickel%20A%20class%20act/The%20future%20of%20nickel%20A%20class%20act.ashx

81. Fitch Solutions / Metals / Global /: Battery Grade Nickel: Assessing Global Supply Bottlenecks And Opportunities, December 30, 2021
https://www.fitchsolutions.com/metals/battery-grade-nickel-assessing-global-supply-bottlenecks-and-opportunities-30-12-2021#:~:text=At%20present%2C%20global%20production%20of,(54%25%20of%20global).

82. Argus: Class 1 Ni shortfall complicates nickel supply chain, Raghav Jain, April 29, 2022
https://www.argusmedia.com/en/news/2326899-class-1-ni-shortfall-complicates-nickel-supply-chain

83. Geology for Investors: Nickel Laterites: The World's Largest Source of Nickel, Greg Ashcroft, October 17, 2019
https://www.geologyforinvestors.com/nickel-laterites/

84. Sherritt International Corporation: Does Matte Matter? Is nickel pig iron the answer to EV battery demand? 2021
https://s2.q4cdn.com/343762060/files/doc_downloads/2021/Does-Matte-Matter-Sept-2021.pdf

85. American Chemical Society- Chemical & Engineering News (C&EN): It's time to get serious about recycling lithium-ion batteries, Mitch Jacoby, July 14, 2019
https://cen.acs.org/materials/energy-storage/time-serious-recycling-lithium/97/i28

86. U.S. Geological Survey, Mineral Commodity Summaries, Manganese, January 2022
https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-manganese.pdf

87. Mining.com: Manganese – the third electric vehicle metal no one is talking about, March 24, 20217
https://www.mining.com/web/manganese-the-third-electric-vehicle-metal-no-one-is-talking-about-it-heres-how-to-take-advantage/

88. Wikipedia: Manganese
https://en.wikipedia.org/wiki/Manganese

89. Argonne National Laboratory: Researchers eye manganese as key to safer, cheaper lithium-ion batteries, Christina Nunez, June 4, 2020
https://www.anl.gov/article/researchers-eye-manganese-as-key-to-safer-cheaper-lithiumion-batteries

90. INN- Investing News: Manganese: Why This Critical Steel, Battery and EV Metal Should Be on Your Radar, May 11, 2021
https://investingnews.com/innspired/manganes-critical-steel-battery-ev-metal/

91. McKinsey and Company: How clean can the nickel industry become?, Marcelo Azevedo et al., September 11, 2020
https://www.mckinsey.com/industries/metals-and-mining/our-insights/how-clean-can-the-nickel-industry-become

92. U.S. Geological Survey: Manganese- Professional Paper 1802-L, Cannon et al., 2017
https://pubs.usgs.gov/pp/1802/l/pp1802l.pdf

93. U.S. Geological Survey: Manganese Recycling in the United States in 1998, 2001
https://pubs.usgs.gov/of/2001/of01-304/of01-304.pdf

94. Institute of Electrical and Electronics Engineers (IEEE)- IEEE Spectrum: Manganese Could Be the Secret Behind Truly Mass-Market EVs Wanted: Abundant transition metal to electrify the automobile for the global mainstream, Lawrence Ulrich, April 25, 2022
https://spectrum.ieee.org/manganese-ev-batteries

95. U.S. Geological Survey: Manganese- USGS Mineral Resources Program: It Turns Iron into Steel (and Does So Much More), Fact Sheet 2014-3087, August 2014
https://pubs.usgs.gov/fs/2014/3087/pdf/fs2014-3087.pdf

96. U.S. Geological Survey, Mineral Commodity Summaries, January 2022- Graphite (Natural)
https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-graphite.pdf

97. Wikipedia: Graphite
https://en.wikipedia.org/wiki/Graphite#:~:text=Graphite%20(%2F%CB%88%C9%A1r%C3%A6,of%20carbon%20under%20standard%20conditions.

98. Wikipedia: Carbon
https://en.wikipedia.org/wiki/Carbon#Allotropes

99. Wikipedia: Allotropy
https://en.wikipedia.org/wiki/Allotropy

100. Wikipedia: Allotropes of Carbon
https://en.wikipedia.org/wiki/Allotropes_of_carbon

101. Geology.com: Graphite- A mineral with extreme properties and many uses, Hobart M. King,
https://geology.com/minerals/graphite.shtml

102. Engineering Choice: What Is Graphite?- Definition, Types, And Uses, Jignesh Sabhadiya, August 29, 2020
https://www.engineeringchoice.com/graphite/#:~:text=What%20are%20the%20types%20of,well%2Dsuited%20for%20certain%20applications.

103. AZO Materials: Graphite (C) - Classifications, Properties & Applications, Miriam Doerr Martin Frommherz / Shutterstock, September 10, 2002
https://www.azom.com/article.aspx?ArticleID=1630

104. EcoGraf: Graphite
https://www.ecograf.com.au/graphite/#:~:text=Spherical%20graphite%20(SpG)%2C%20also,as%20a%20battery%20anode%20material.

105. U.S. Geological Survey: Graphite- Professional Paper 1802-J, Robinson et al., 2017
https://pubs.usgs.gov/pp/1802/j/pp1802j.pdf

106. U.S. Geological Survey: What are "technically recoverable" oil and gas resources?
https://www.usgs.gov/faqs/what-are-technically-recoverable-oil-and-gas-resources

107. U.S. Geological Survey: U.S. Geological Survey releases 2022 list of Critical Minerals, February 22, 2022
https://www.usgs.gov/news/national-news-release/us-geological-survey-releases-2022-list-critical-minerals

108. Electronicsnotes: Li-ion Lithium Ion Batteries
https://www.electronics-notes.com/articles/electronic_components/battery-technology/li-ion-lithium-ion-technology.php

109. Aip.citation: Floatability study of graphite ore from southeast Sulawesi (Indonesia), Florena et al., February 24, 2021
https://aip.scitation.org/doi/pdf/10.1063/1.4941888

110. Wikipedia: Froth Flotation
https://en.wikipedia.org/wiki/Froth_flotation

111. Asbury Carbons- Introduction to Synthetic Carbon, Albert V. Tamashausky, 2006
https://asbury.com/media/1225/syntheticgraphiteparti.pdf

112. U.S. Department of Energy- Office of Fossil Energy and Carbon Management: Funding Opportunity Announcement 2405, Advanced Coal Waste Processing: Production of Coal-Enhanced Filaments or Resins for Advanced Manufacturing and Research and Development of Coal-Derived Graphite, October 5, 2021
https://www.energy.gov/fecm/articles/funding-opportunity-announcement-2405-advanced-coal-waste-processing-production-coal

113. Science Direct- Elsevier: Efficient recovery and regeneration of waste graphite through microwave stripping from spent batteries anode for high-performance lithium-ion batteries, Yuwen et al., December 2, 2021
https://www.sciencedirect.com/science/article/pii/S0959652621043626

114. AZO Materials: An Overview of Recycling Graphite from Lithium-Ion Batteries, Ibtisam Abbasi, Nov 19, 2021
https://www.azom.com/news.aspx?newsID=57403

115. AZO Materials: Boosting the Environmentally Sustainable Recycling of Spent Graphite from Lithium-Ion Batteries, Ibtisam Abbasi, Nov 7 2021
https://www.azom.com/news.aspx?newsID=57215

116. ACS Sustainable Chemistry and Engineering: Environmental Impacts of Graphite Recycling from Spent Lithium-Ion Batteries Based on Life Cycle Assessment, ACS Sustainable Chem. Eng. 2021, 9, 14488−14501
https://pubs.acs.org/doi/pdf/10.1021/acssuschemeng.1c04938

117. U.S. Geological Survey, Mineral Commodity Summaries, January 2022- Copper
https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-copper.pdf

118. Encyclopedia Britannica: Copper, published on March 13, 2022
https://www.britannica.com/science/copper

119. Wikipedia: Copper
https://en.wikipedia.org/wiki/Copper
120. National Library of Medicine- National Center of Biotechnology Information: Element- Copper
https://pubchem.ncbi.nlm.nih.gov/element/Copper

121. Los Alamos National Laboratory- Chemistry Division: Periodic Table of Element, Cooper
https://periodic.lanl.gov/29.shtml

122. JLAB- Science Education: The Element Copper
https://education.jlab.org/itselemental/ele029.html

123. International Copper Association (ICA)-Copperalliance.org: The Electric Vehicle Market and Copper Demand- Research Conducted by: IDTechEx, June 2017
https://copperalliance.org/wp-content/uploads/2017/06/2017.06-E-Mobility-Factsheet-1.pdf

124. International Copper Association (ICA)-Copperalliance.org: Copper Recycling, ICA-RecyclingBrief-202201-A4-R2.pdf, January 2022
https://copperalliance.org/wp-content/uploads/2022/02/ICA-RecyclingBrief-202201-A4-R2.pdf

125. Copper Alliance Development, Inc.- Copper Alliance: Copper - the World's Most Reusable Resource
https://www.copper.org/environment/lifecycle/g_recycl.html

126. CJD E-Recycling: Copper Recycling Guide, June 5, 2020
https://www.cjdecycling.com/copper-recycling-guide/#prettyPhoto

127. Wikipedia: Copper
https://en.wikipedia.org/wiki/Copper#Recycling

128. Router: Copper's Role in Growing Electric Vehicle Production, May 5, 2021
https://www.reuters.com/article/sponsored/copper-electric-vehicle
129. S&P Global: The Future of Copper: Will the looming supply gap short-circuit the energy transition? July 2022
https://cdn.ihsmarkit.com/www/pdf/0722/The-Future-of-Copper_Full-Report_14July2022.pdf

130. S&P Global: Looming Copper Supply Shortfalls Present a Challenge to Achieving Net-Zero 2050 Goals, S&P Global Study Finds
https://press.spglobal.com/2022-07-14-Looming-Copper-Supply-Shortfalls-Present-a-Challenge-to-Achieving-Net-Zero-2050-Goals,-S-P-Global-Study-Finds

131. Mining.com: The Top 10 EV battery manufacturers in 2022, October 5, 2022
https://www.mining.com/web/the-top-10-ev-battery-manufacturers-in-2022/

132. U.S. Geological Survey, Mineral Commodity Summaries, January 2022- Aluminum
https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-aluminum.pdf

133. Wikipedia: Aluminum
https://en.wikipedia.org/wiki/Aluminium

134. Encyclopedia Britannica: Aluminum- chemical element
https://www.britannica.com/science/aluminum

135. Boyd: Everything You Need to Know About: Aluminum
https://blog.boydmetals.com/everything-you-need-to-know-about-aluminum

136. The Aluminum Association: Bauxite 101
https://www.aluminum.org/bauxite-101

137. Wikipedia: Bauxite
https://en.wikipedia.org/wiki/Bauxite

138. U.S. Geological Survey: Bauxite and Alumina Statistics and Information
https://www.usgs.gov/centers/national-minerals-information-center/bauxite-and-alumina-statistics-and-information

139. U.S. Geological Survey (USGS)_Mineral Commodity Survey 2022-bauxite-alumina
https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-bauxite-alumina.pdf

140. U.S. Geological Survey (USGS)_Mineral Commodity Survey 2022- Aluminum
https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-aluminum.pdf

141. Wikipedia- Corundum
https://en.wikipedia.org/wiki/Corundum

142. Mineral.net- The Mineral Corundum
https://www.minerals.net/mineral/corundum.aspx

143. US Environmental Protection Administration (EPA)- TENORM: Bauxite and Alumina Production Wastes
https://www.epa.gov/radiation/tenorm-bauxite-and-alumina-production-wastes#:~:text=Bauxite%20ore%20is%20dissolved%20in,furnace)%20to%20produce%20solid%20alumina.

144. Wikipedia: Bayer Process
https://en.wikipedia.org/wiki/Bayer_process

145. Wikipedia: Hall–Héroult process
https://en.wikipedia.org/wiki/Hall%E2%80%93H%C3%A9roult_process

146. The International Council on Clean Transportation (ICCT)- Scaling Up Reuse and Recycling Of Electric Vehicle Batteries: Assessing Challenges and Policy Approaches, Alexander Tankou, Georg Bieker, Dale Hall, February 2023
https://theicct.org/wp-content/uploads/2023/02/recycling-electric-vehicle-batteries-feb-23.pdf

147. McKinsey and Company- Battery recycling takes the driver's seat, March 2023
https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/battery-recycling-takes-the-drivers-seat

148. Car and Driver- Everything You Need to Know about EV Battery Disposal, John Voelcker, June 10, 2023
https://www.caranddriver.com/features/a44022888/electric-car-battery-recycling/

149. Advanced Energy- Electric Vehicle Battery Reuse and Recycling, Shawn Allred- November 17, 2021
https://www.advancedenergy.org/2021/11/16/electric-vehicle-battery-reuse-and-recycling/