

Mining, the Future



In another EarthDate, we talk about how mining provides the materials to build the modern world. But new technology is changing that world. We're building huge new data centers for AI; batteries to power EVs, and stabilize the power grid; and enormous volumes of solar panels and wind turbines.

All these will require a lot more mining. And all mining impacts the environment. So engineers are working to make the process cleaner and safer. Mine tailings – the waste rock – are today kept in huge ponds, which can spill catastrophically. New techniques dry them out for safer storage, or to use as construction materials, and recycle the water. And more mines are capturing, treating and reusing water throughout their processes.

Many mines are working to reduce emissions at the site, switching diesel equipment and trucks for electric motors, requiring more electricity. More advanced automation makes mines more efficient. More advanced exploration uses less energy and disturbs less land to find new resources.

New technologies extract lithium directly from hot, deep brines. And use electricity, instead of high heat or strong acids, to separate metals from mining waste.

Meanwhile, improved recycling programs recover more copper, lithium and other metals from old electronics, batteries and scrap, to help reduce the need for new mines. And we talk about that, on another EarthDate.

I'm Scott Tinker.

A fully electric mining haul truck capable of carrying up to 372 tons illustrates how mining operations are evolving to meet growing material demand with new technologies.

Credit: U.S. Department of Agriculture
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Background: Mining, the Future

Synopsis: Demand for minerals is rising as new technologies reshape energy, transportation, and digital infrastructure. Mining is evolving through new practices and technologies that aim to reduce impacts while supplying the materials modern systems depend on.

A Growing Need for Minerals

- Modern technologies depend on large and diverse quantities of metals mined from Earth. As societies expand digital infrastructure, electrify transportation, and build new energy systems, demand for these materials is rising rapidly.
- Supplying that demand presents the challenge of increasing production while limiting impacts on land, water, energy use, and nearby communities.

Metals Behind Modern Technologies

- Phones, computers, electric vehicles, solar panels, and wind turbines all rely on specialized metals, often in greater quantities or combinations than earlier technologies.
 - A Tesla Model S contains roughly as much lithium as 10,000 cell phones.
 - Electric vehicle batteries require large amounts of copper, graphite, cobalt, and nickel, totaling more than six times the mass of metals used in a conventional combustion engine.
 - A solar panel installation, measuring one square kilometer, can contain nearly eleven tons of silver.
 - Cobalt and nickel increase battery energy density, while neodymium strengthens magnetic components of wind turbines.

- Iridium and platinum improve the performance of fuel cells.
- Copper’s high conductivity makes it essential across nearly all electronic systems.
- These examples illustrate how modern technologies depend on not a single source, but on a broad suite of mined minerals, each serving a specific role.
- As efforts to produce energy and reduce emissions of carbon dioxide and other pollutants, the volume of minerals required for these systems grows as well.
- Those materials must come from the Earth, carrying their own environmental and societal impacts alongside their benefits.

Shrinking the Mining Footprint

- Understanding the challenges of mining shows where innovation is needed, and several new approaches are emerging to improve how minerals are extracted and processed.
- Not every improvement is suitable for every mineral deposit or mining setting, and the effectiveness of new approaches depends on local geology, water availability, infrastructure, and economics.

Electric cars need more than six times the mass of metals compared to conventional cars. Numbers represent the kilograms of each material per vehicle

	Copper	Lithium	Nickel	Manganese	Cobalt	Graphite	Zinc	Rare Earths	Others
Electric car	53.2	8.9	39.9	24.5	13.3	66.3	0.1	0.5	0.31
Conventional Car	22.3	0	0	11.2	0	0	0.1	0	0.3

Credit: IEA (2021), Minerals used in electric cars compared to conventional cars, IEA, Paris <https://www.iea.org/data-and-statistics/charts/minerals-used-in-electric-cars-compared-to-conventional-cars>, Licence: CC BY 4.0

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All energy technologies require copper, but solar and wind require more minerals than fossil fuel sources. Numbers represent the kilograms of material needed for each Megawatt of energy produced.

	Copper	Nickel	Manganese	Cobalt	Chromium	Molybdenum	Zinc	Rare Earths	Silicon	Others
Offshore Wind	8000	240	790	0	525	109	5500	239	0	6
Onshore Wind	2900	404	780	0	470	99	5500	14	0	0
Solar PV	2822	1.3	0	0	0	0	30	0	3948	32
Nuclear	1473	1297	148	0	2190	71	0	0.5	0	94
Coal	1150	721	4.6	202	308	66	0	0	0	34
Natural Gas	1100	16	0	1.8	48.3	0	0	0	0	0

Credit: Data from IEA (2021), Minerals used in clean energy technologies compared to other power generation sources, IEA, Paris <https://www.iea.org/data-and-statistics/charts/minerals-used-in-clean-energy-technologies-compared-to-other-power-generation-sources>, Licence: CC BY 4.0

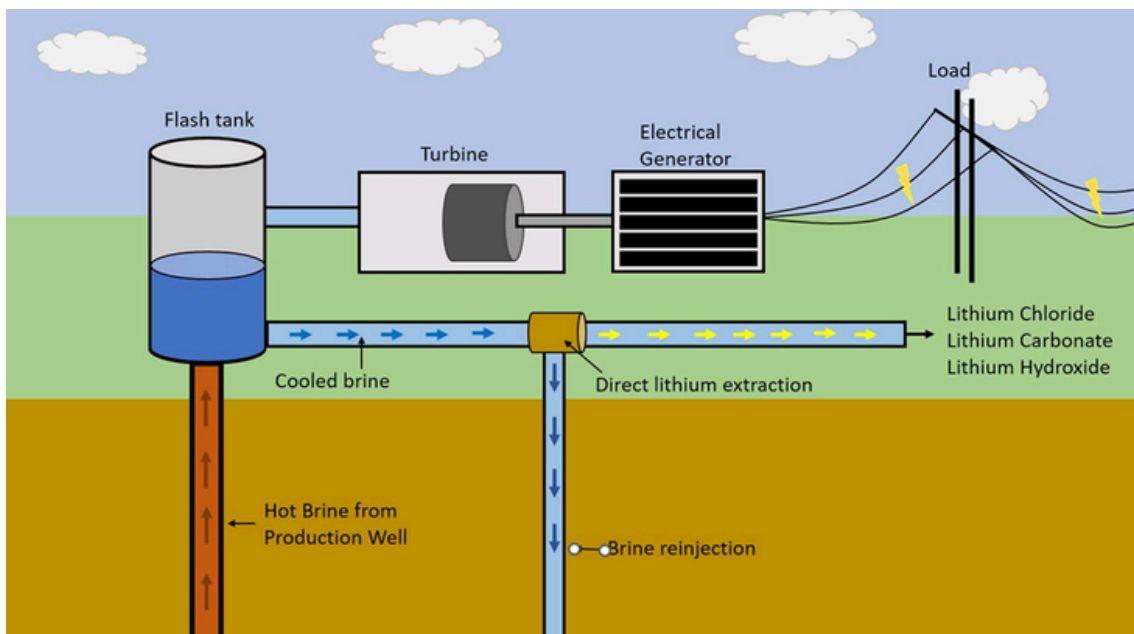
- Reducing energy use and emissions at mine sites:
 - Mines are adopting electrified equipment, battery-powered haul trucks, and solar and wind energy systems to replace diesel generators.
 - Automation and digital sensors help optimize operations, lowering energy waste and reducing overall emissions from extraction and transport.
 - These tools are especially important as demand for “green-technology metals” grows and industry works to shrink its footprint.
- Improving tailings and waste management:
 - Instead of storing tailings as large, wet ponds, some mines are now using dry-stack tailings, removing water so the material can be stored more safely and with less risk of catastrophic spills.
 - Waste material is increasingly treated as a secondary resource. Some mines extract additional copper, rare earths, or metals from tailings that were once discarded. (See [EarthDate Episode 451](#), Rare Earth Recovery) .
- Reusing or repurposing waste rock for things like backfilling tunnels or construction materials, reduces the total footprint of a mine.
- Better mine-site design and water management:
 - Mines are designed to close the water loop by capturing process water, treating it, and cycling it back through the operation instead of constantly drawing new freshwater.
 - Reducing freshwater withdrawals helps protect rivers, lakes and aquifers, especially in arid regions where mining competes with agriculture and communities for limited water.
 - Groundwater monitoring wells and real-time sensors detect leaks early, protecting surrounding ecosystems from contamination and helping stabilize water tables throughout the mining life cycle.
- Stronger planning, transparency, and community engagement:
 - Many mining companies now map resources across a project’s entire life cycle, from exploration to closure, updating plans as data improves.

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- International frameworks encourage companies to engage local communities, guarantee safer conditions, and improve benefit-sharing for people living near mining regions.
- Transparent sourcing helps manufacturers ensure minerals come from sites that meet environmental and social standards.
- Advancing a circular economy for metals:
 - Recycling programs recover copper, aluminum, lithium, cobalt, and rare earths from old electronics, batteries, and manufacturing scrap. These programs help to reduce pressure on new mining.
 - Improved product design allows materials to be disassembled more easily, so metals can be recovered instead of lost in landfills.
 - Rapid advances in refining allow recycled materials to reach nearly the same purity as mined metals.
- Many of these approaches are still in early development or pilot-scale testing, and their broader use will depend on technical performance, site conditions, and long-term reliability.
 - AI-guided exploration uses machine learning to analyze vast geologic datasets and pinpoint richer ore bodies with fewer exploratory drill sites, reducing land disturbance and waste rock.
 - Direct lithium extraction from geothermal brines removes lithium from hot underground fluids using filters or membranes, avoiding evaporation ponds and lowering water use.
 - Electro-extraction systems recover metals from low-grade ore or mine waste using electricity instead of high heat or strong acids, producing fewer emissions and less chemical waste.
 - Carbon-absorbing tailings take advantage of natural reactions between ultramafic rock and CO₂, allowing some mine waste to trap carbon and potentially offset part of a mine's footprint.
 - Hydrogen-powered or electric haul trucks aim to replace diesel engines in heavy equipment, reducing emissions in some of the most energy-intensive parts of mining operations.

New Technologies in Mining

- While these improvements make mining more responsible today, researchers and engineers are also developing new technologies that could reshape how minerals are discovered, extracted and refined in the future.



In geothermal brine extraction, underground hot water carries dissolved lithium to the surface, where filters capture the metal and the fluid is sent back below.

Credit: By LazerRocDoc - Own work, CC BY-SA 4.0, <https://commons.wikimedia.org/w/index.php?curid=130607170>

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- Autonomous and precision mining uses drones, robots, and real-time sensors to map ore bodies more accurately and remove only targeted material, minimizing disturbance to surrounding rock layers.

Mining Future

- All the varied mining methods allow us to reach the minerals modern technologies rely on, and processing turns those ores into metals we use every day. Each step, however, comes with costs to land, water, energy, and sometimes nearby communities, creating a growing dilemma as demand for these materials grows.
- Scientists and engineers are responding with better mining practices, improved water and waste management, and new technologies that reduce impacts and recover more metals with fewer resources.
- Even with these advances, meeting future demand will also depend on recovering valuable metals already embedded in cities, infrastructure, and discarded products.

References: Mining, the Future

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