The Future of Mining

Unlocking Sustainable, Secure Minerals and Metals Supply Chains

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The Future of Mining

- The Urgency of Now
- Technical & Structural Challenges
- Reimagining Mining – Our Opportunity
- The Mine of the Future – Our Core Principles
- Case Studies
- Mining Ecosystem Redevelopment:
  - People
  - Systems & Processes
  - Science, Technology & Innovation
- Closing - Vision

The Urgency of Now

- Growing demand for minerals for the economy: energy, healthcare, defense, advanced technology, …
- Supply chain vulnerabilities + dependence on China
- Legacy issues: industry practices and environmental issues have eroded public trust
- Knowledge & workforce gaps in mining
- Lack of appreciation for the role mining plays in modern life
- Lack of awareness that modern mining will employ new technologies and sustainable practices to protect the environment and communities

All the Metals We Mined in 2022

The world produced almost **2.8 billion tonnes** of metal in 2022.

METALS VS ORES

ORES
are naturally occurring rocks that contain metals or metal compounds.

METALS
are the valuable parts of ores that can be extracted and sold.

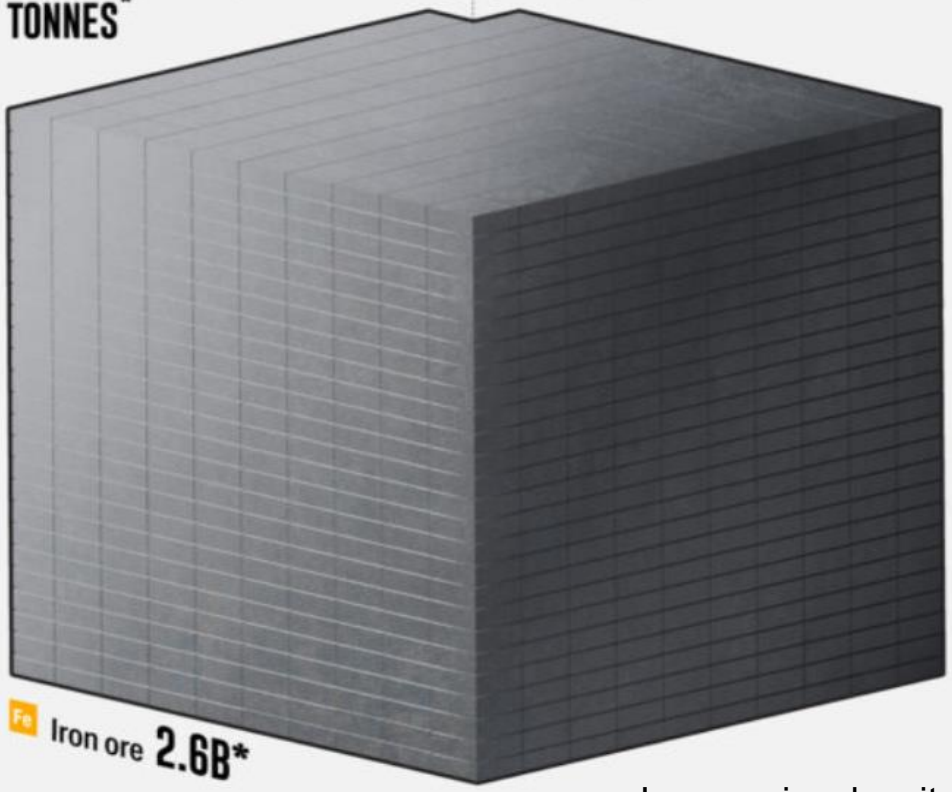
LARGEST END-USE

- Steelmaking
- Construction
- Chemicals
- Energy/Batteries
- Alloying Agents
- Magnets
- Electronics
- Others

IRON ORE

2,600,000,000 TONNES*

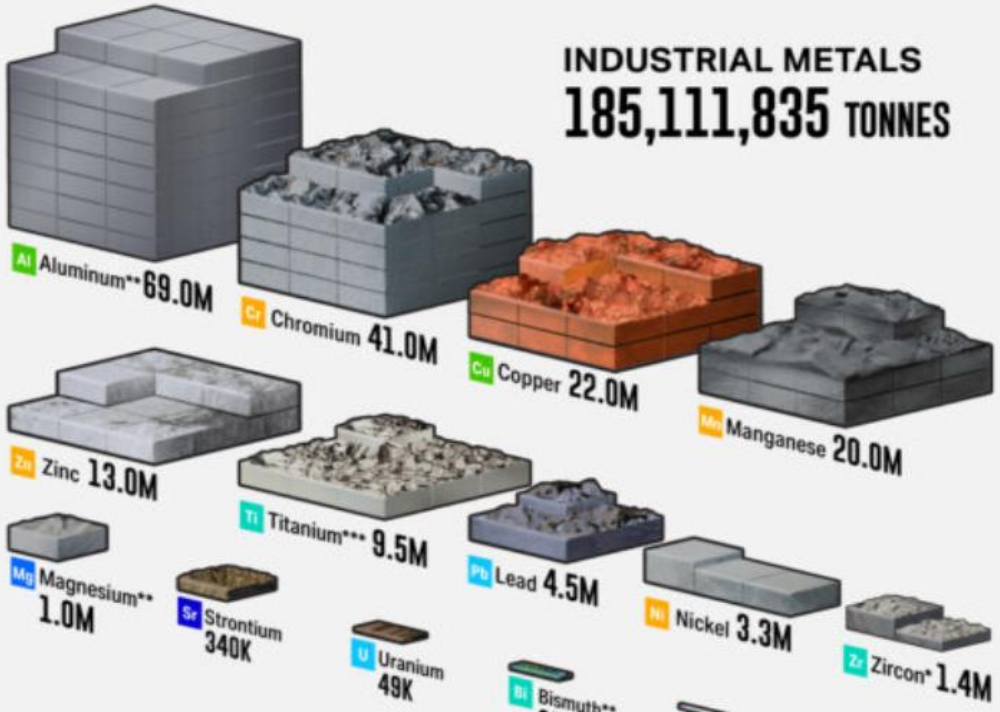
= 1,000,000 tonnes



Fe Iron ore 2.6B*

INDUSTRIAL METALS

185,111,835 TONNES



TECHNOLOGY AND PRECIOUS METALS

1,500,008 TONNES

*Usable ore: 2,600,000,000 tonnes; Iron content: 1,600,000,000 tonnes.

** Smelter/refinery production.

*** Represents titanium mineral concentrate production.

Source: USGS Mineral Commodity Summaries (2023)

ELEMENTS

ELEMENTS.VISUALCAPITALIST.COM

Image: visualcapitalist

Mining in the Future: Meeting Urgent Needs

Critical materials are essential to the technologies we rely on every day

- National Security
- Advanced Technologies
- Energy
- Healthcare
- Transportation

Copper Production – Global Demand Growth

Demand for copper to dramatically outstrip supply within decade

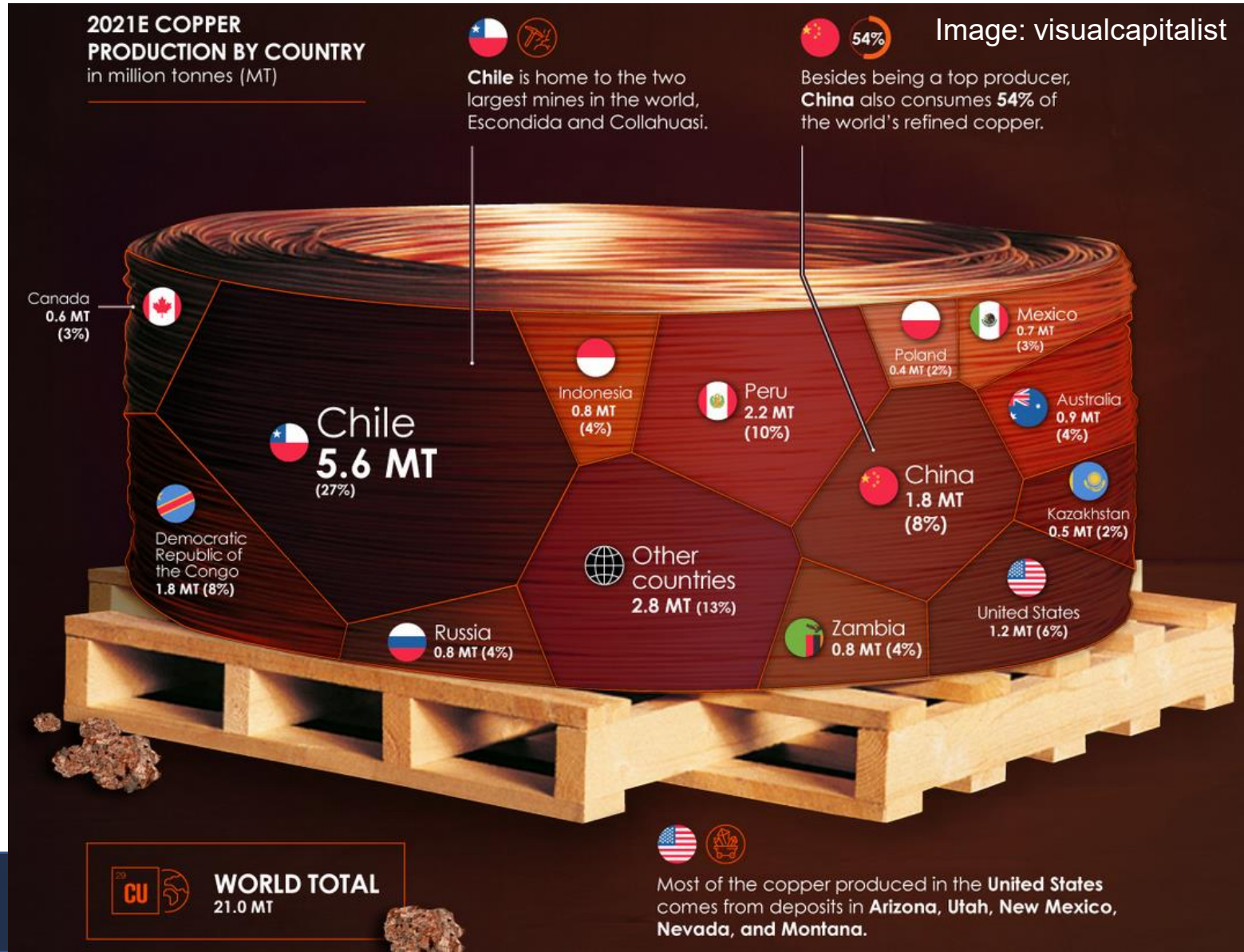
International Energy Agency says it is 'time to sound alarm' over future shortages of metal needed for low-carbon transition

Miners need to invest over $100 billion to meet copper demand

Cecilia Jamasmie | March 31, 2022 | 4:44 am Intelligence Markets News Suppliers & Equipment Top Companies Africa Asia Australia Canada Latin America Copper

The world needs eight projects the size Escondida in Chile, the world's largest copper mine, in the next eight years. (*Image of Escondida courtesy of BHP.*)

Copper industry needs to invest >$100B to build mines able to close annual supply deficit of 4.7 million tons by 2030.




Artwork: Dillon Marsh
Palabora Mine, ZA
~4 million tons of Cu


EV market requires
~2 million tons of Cu/yr

Lithium

Supply for energy storage, mobility, electrification

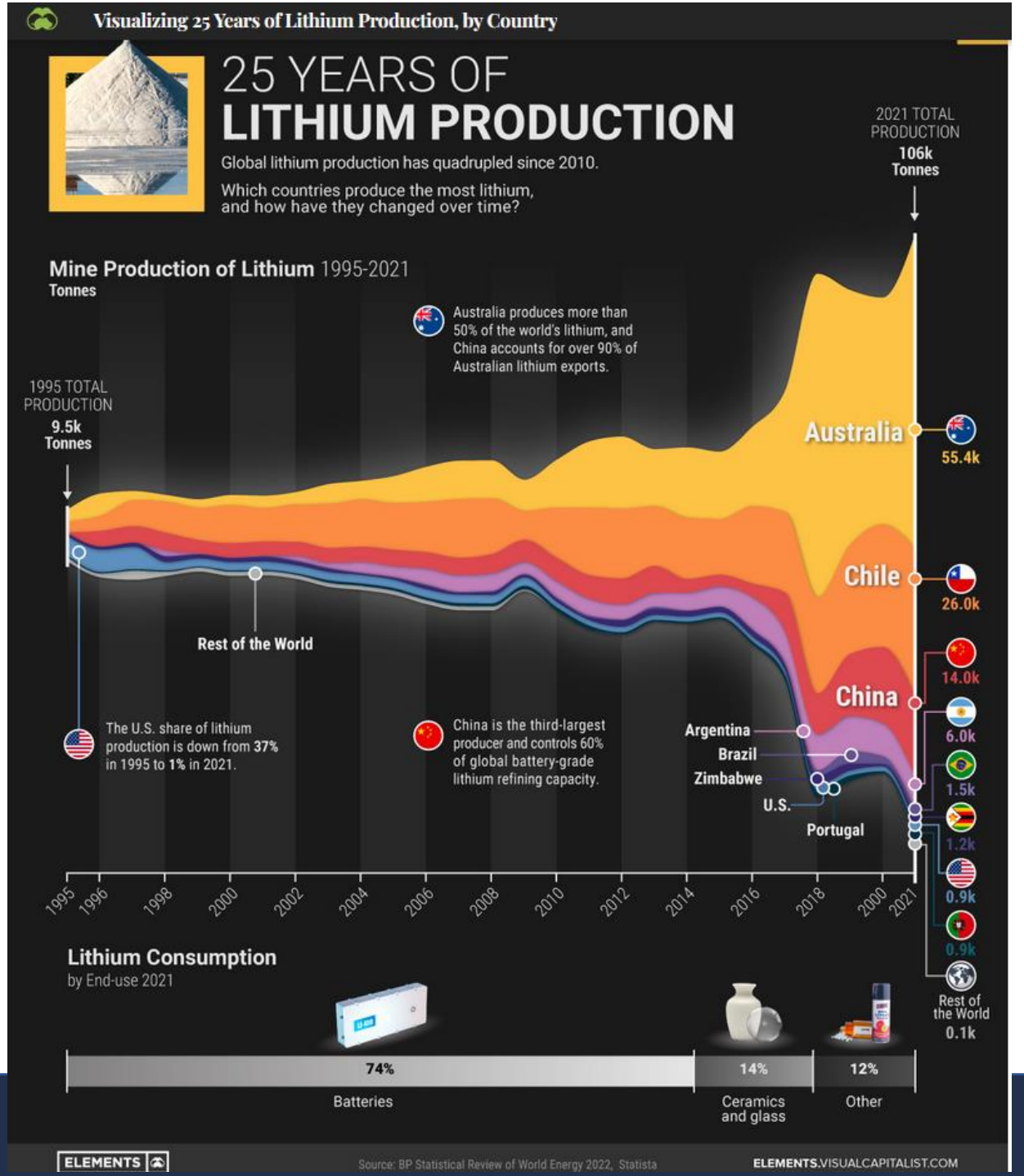


Image: visualcapitalist

The Mine of the Future – Our Core Principles

- Resource efficient, profitable, and net-positive for environment and communities
- Interdisciplinary effort across science, engineering, and social sciences
- Sustainable and circular: total mining, waste to value
- Transformative technologies: digital, robotics, AI/ML leverage, sensor-directed, brine extraction, etc.
- People-centered: socioeconomic, historical, and cultural understanding


Tailings dam failure, Brumadinho, Brazil - 2019

Restoring Public Trust

Mining: Legacy of negative environmental impacts.

The Mine of the Future must restore public trust through sustainable and community-centered practices.

The Mine of the Future will employ new technologies that:

- Use and recycle mine wastes into new products
- Improve safety
- Minimize the impact of mining on the environment
- Visibly deliver positive benefits to communities, society and the economy.

Technical & Structural Challenges

- Critical minerals: Each mineral is its own unique challenge; U.S. lists represent 55+ different challenges
- Diverse supply options needed: new mines, imports, byproducts, mine wastes processing, recycling, new materials
- Technological innovation required across the entire value chain
- Barriers: permitting complexity, small opaque markets, limited domestic processing capacity, long timelines

Reinventing Mining – Our Opportunity

Mines' thesis: ***Reimagine the entire minerals and materials value chain***

- Research, development and innovation
- Talent development
- Policy leadership
- Academic, industry, government and philanthropic partnerships

Edgar Mine - Experimental Station

The World looks to Mines for the Future of Mining

Edgar Mine at Colorado School of Mines

Mines educational and research expertise span the full mining and minerals lifecycle

- Exploration
- Extraction
- Production & Co-Production
- Processing
- Tailings
- Mine Closure & Reclamation
- Water Management
- Recycling
- Community Engagement
- Minerals Workforce
- Mineral Economics
- Public Policy & Geopolitics
- National Security

Case Study: Turning Risk into Resource – Mine Tailings

- Innovation in tailings and waste processing
- Example: transforming mine waste into value-added products with secondary extraction of critical materials

Mine Tailings

Mine Tailing Storage

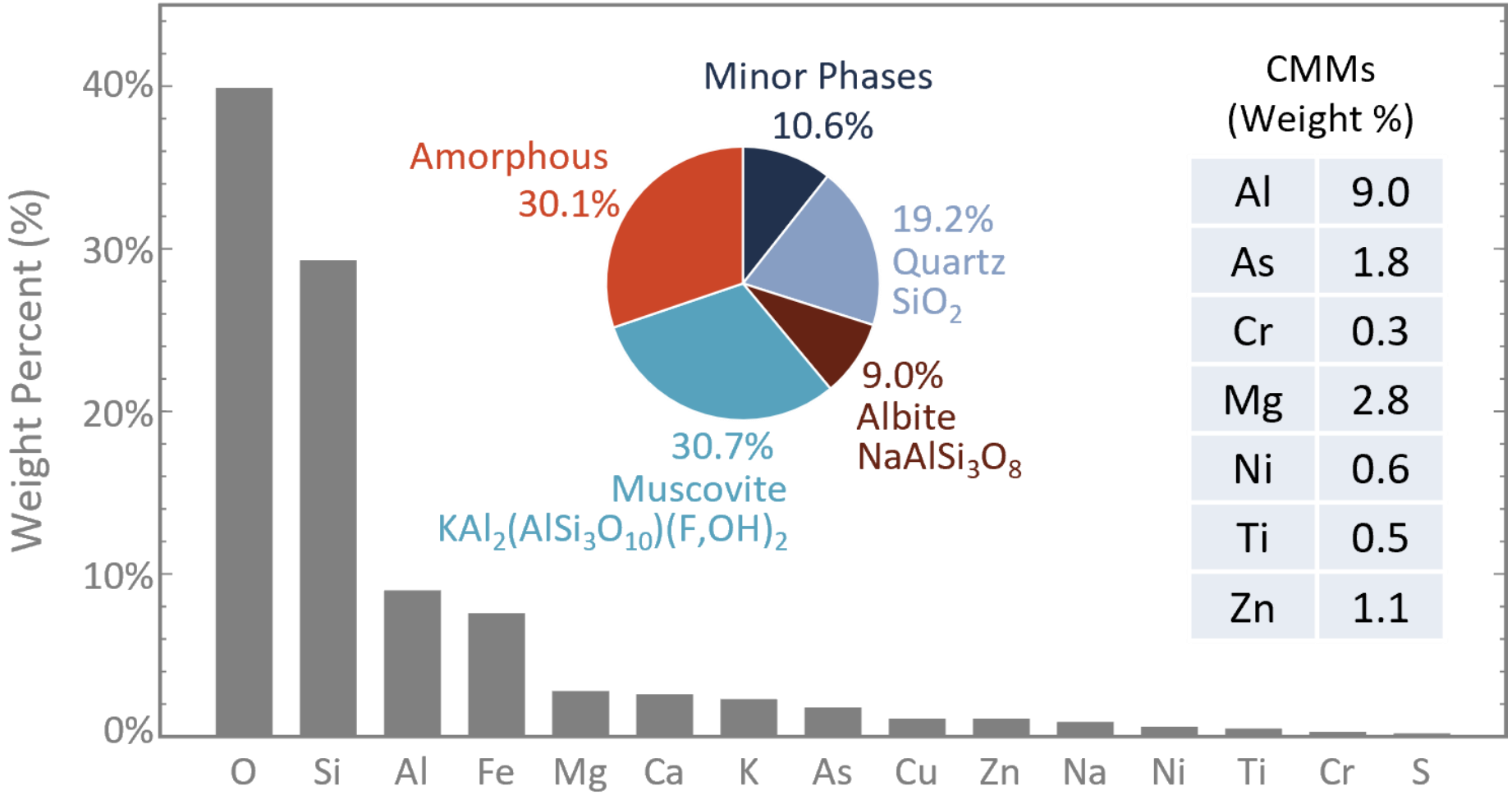
Mine Tailings Dam Failures and Hazards

Sino-Metals tailings dam failure in Zambia, Feb 2025

Dust from tailing piles

Contamination of rivers, soil

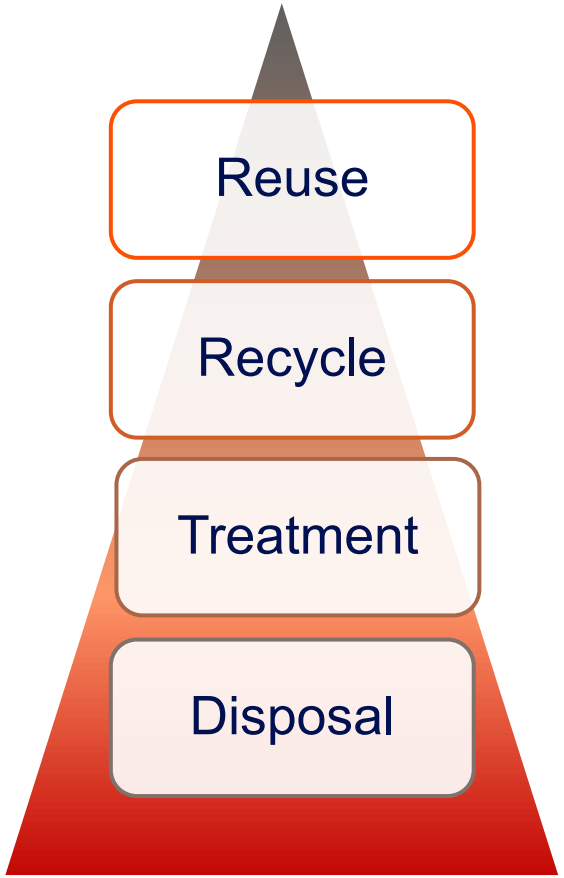
Tailing Characterization – More CMM Value Available



CMMs (Weight %)

Al	9.0
As	1.8
Cr	0.3
Mg	2.8
Ni	0.6
Ti	0.5
Zn	1.1

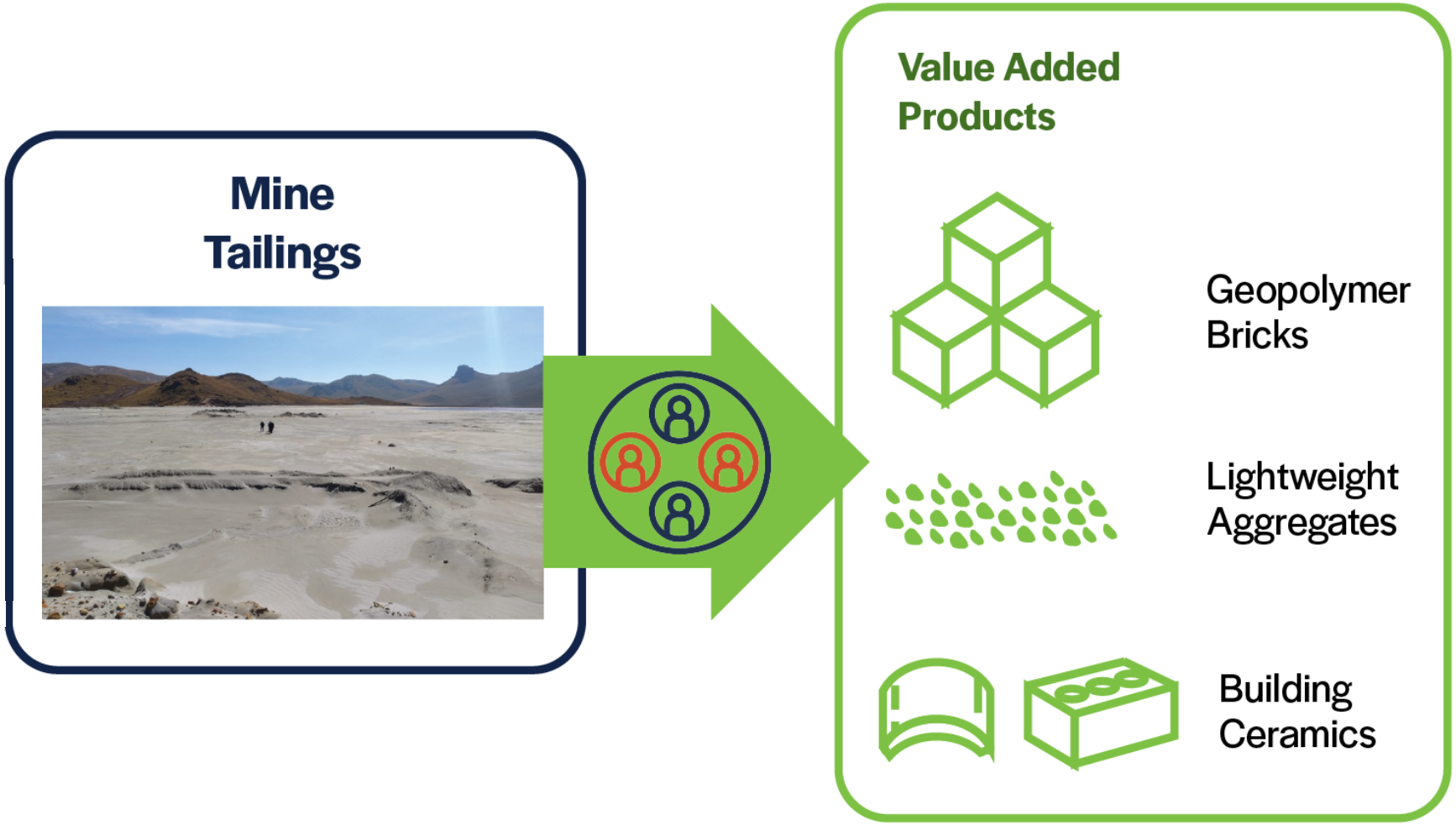
Reuse of Mine Tailings



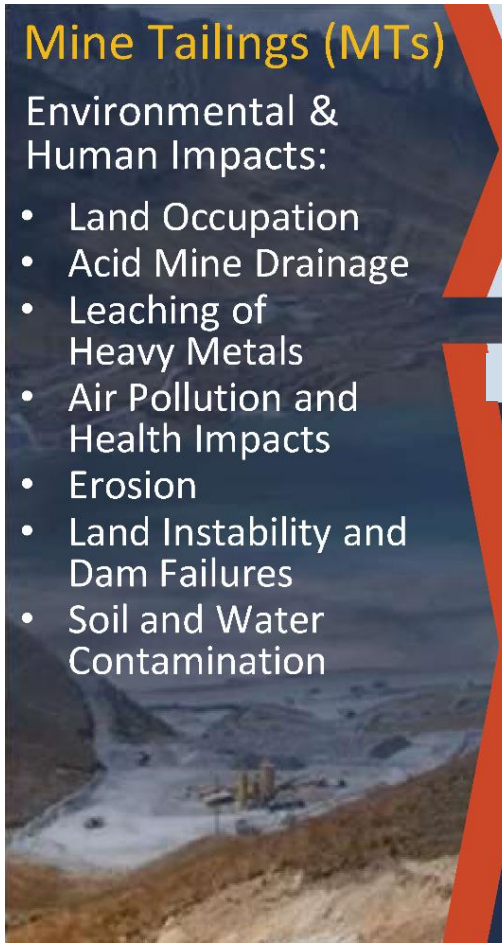
Waste Hierarchy

Reuse Benefits

Reuse of Mine Tailings



Reuse of Mine Tailings



Mine Tailings (MTs)

Environmental & Human Impacts:

- Land Occupation
- Acid Mine Drainage
- Leaching of Heavy Metals
- Air Pollution and Health Impacts
- Erosion
- Land Instability and Dam Failures
- Soil and Water Contamination

Community Engagement

Sustainability Assessment

Value Added Products

Geopolymer Bricks

Lightweight Aggregates

Ceramic Tiles

Overview

Motivation	Reuse of CMM MTs	Circular Economy	Community Benefits
Goals	Value-added Products	Sustainable, durable, economical products	Continuous process with TRL 4
Objectives	Develop production processes	Meet target performance metrices	Optimization of processes
Tasks	Collection & Pre-treatment of MTs	Geopolymer brick extrusion	Pelletization of LWA	Machine Learning
	Ceramics production	Life Cycle Assessment	Techno-Economic Analysis	Community Engagement

Ecosystem Redevelopment – People

People: ***Rebuild technical workforce and accelerate capacity development***

- The talent gap and need for modern mining education
- Training students in tech, policy, sustainability, and engagement
- Role in shaping the next generation
- Consistent community engagement to help change perceptions and bolster workforce

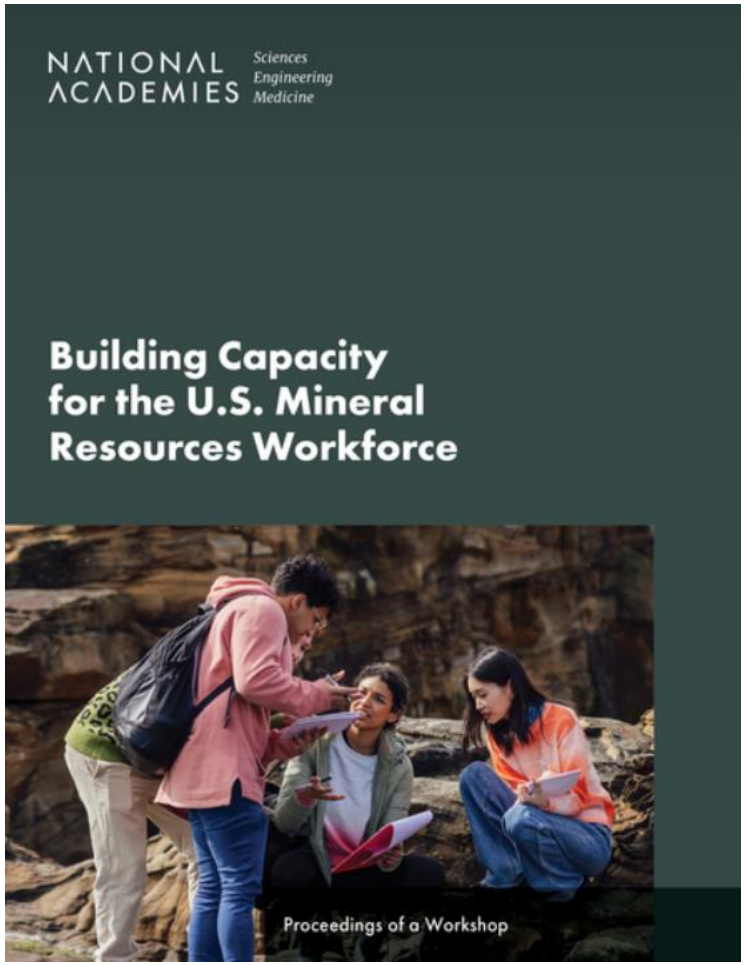
U.S. Mining Workforce

Meeting the needs of the economy and energy requires more mining – and mining innovation

- Half of the current U.S. mining workforce (~221,000 workers) will be eligible for retirement by 2030
- U.S. conferred 327 mining and mineral engineering degrees in 2020
- 2023-4: 590 enrollments in U.S. undergrad programs, 126 graduates
- Industry demand: 400-600 per year
- Number of U.S. mining & mineral engineering schools: 15

U.S. Competitiveness

- Address workforce gaps to rebuild global competitiveness in mining, minerals and metals processing.
- Invest in R&D (public & private)
- Credibly establish positive industry image, enhance recruitment
- Global McKinsey study of people aged 15 to 30 years: 70% *“definitely wouldn’t”* or *“probably wouldn’t”* work in mining



https://doi.org/10.17226/27733

Mining Schools Act

- Bipartisan Legislation re-introduced in the Senate and House in April of 2025
  - S. 1130—Introduced by Sen. John Barrasso (R-WY) and Sen. John Hickenlooper (D-CO)
  - H.R. 2457—Introduced by Rep. Burgess Owens (R-UT) and Rep. Jim Costa (D-CA)

- Objective: Increase the number of trained mining professionals
  - Establish a grant program for mining schools to receive funding to recruit students and carry out studies, research projects, or demonstration projects related to the production of minerals
  - Establish the Mining Professional Development Advisory Board to evaluate applications and recommend recipients to the Secretary of Energy

- Authorization: $10 million for 8 years.

Ecosystem Redevelopment – Systems & Processes

- Technology innovation with Systems integration
- Digital transformation and automation
- Domestic infrastructure capacity development
  - Expand mining operations base
  - Processing facilities commissioning & expansion
  - Advance transportation and logistics
  - Energy systems delivery (including SMRs)
  - R&D and demonstration hubs

Ecosystem Redevelopment – Science & Technology

- Accelerate discovery, foundational science, and engineering for scale
- Promote cross-sector technology transfer
- Increase innovation pace and market opportunities for processes and products involving critical minerals and materials
- Advance technology entrepreneurship and investment
- Drive market opportunities and supply chain growth with innovation, efficiency and lower total lifecycle cost

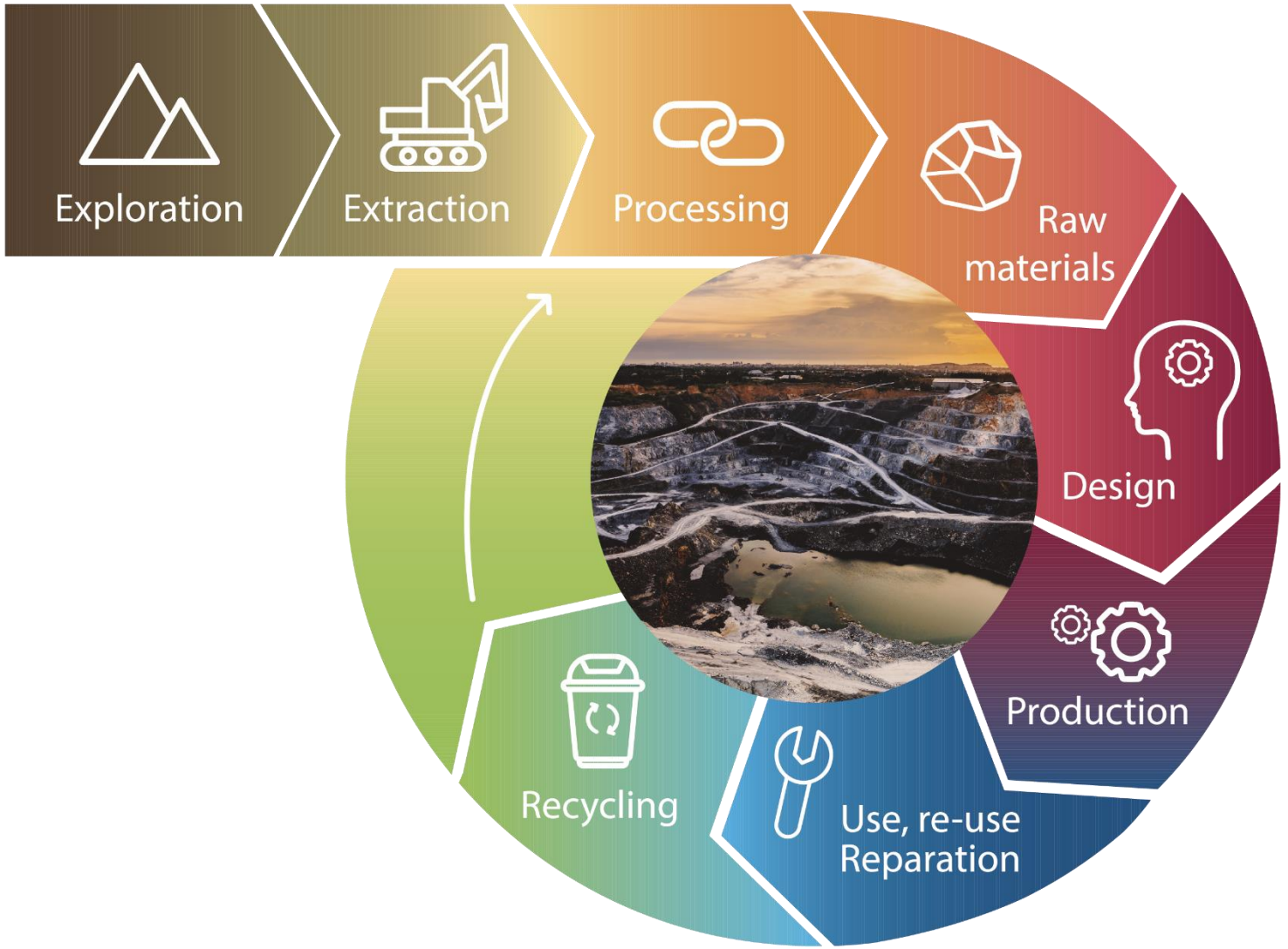


Image: Idea.es

The Mine of the Future

The Mine of the Future is a vision that integrates advanced technologies, automation, data analytics, and sustainable mining practices to increase productivity, improve safety, minimize environmental impact, and optimize resource utilization.

Low Carbon to Net Zero

Minimal Footprint & Water Use

Max Rate Recycling

Automated/AI Leveraged

Minimal Tailings

In Situ Recovery

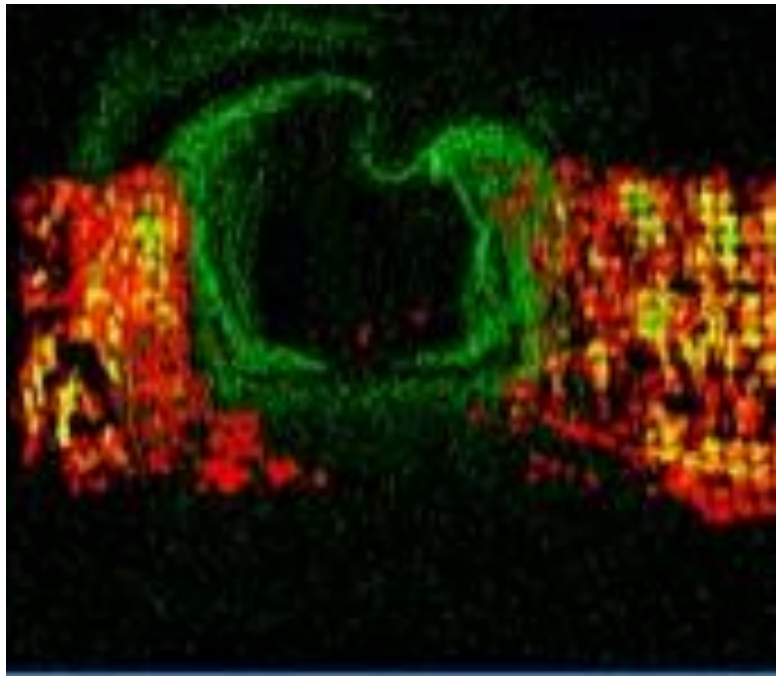
Affordable, Safe, Clean, & Sustainable

Community & Environment Centered

Efficiency and Safety Through Digitalization and Automation

The mine of the future is a fully integrated digital mine:

- AI/machine learning/robotics for exploration, mining and processing
- Continuous & Selective Directed Mining
- Improved operations and productivity through communications and data management
- Safer, more efficient mining and maintenance practices through automation
- Deep underground-first autonomous design, operations with reduced surface impacts



Design for Sustainability

- Community-centered innovation with co-developed solutions
- Integrated Water + Energy Systems
- Zero-Waste, Zero-Emission Mining
- Tailings management and total use
- Innovation in processing and extraction
- Design for minesite remediation

Vision

A new era of mining: Safe, sustainable, data-driven, attractive and human-centered

Call to action: Partnership, Research, Innovation

Thank You!

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