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Opinion

Energy, Mining and Metallurgy: Essential Components of Modern Society and Crucial to a Clean Energy Transition

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Opinion

This paper explores the integral roles of energy, mining, and metallurgy in modern society and their pivotal contribution to a clean energy transition. It discusses the established correlation between higher per capita energy consumption and improved human development, underscoring the global need for affordable, clean, and renewable energy. Currently, fossil fuels account for 80-85% of global energy production, while renewables and low-carbon nuclear power contribute approximately 15-20%. Amid ambitious CO_2 reduction targets, electrification of the transportation sector-responsible for roughly 28% of global final energy-is emphasized, highlighting the critical demand for various metals. Recycling processes are demonstrated to require only 5-20% of the energy used in primary production, significantly reducing waste generation. Table 1 provides a detailed comparative analysis of production, recycling routes, energy consumption, and waste generation for key metals, underscoring the strategic, environmental, and economic importance of recycling.

Energy & Metals: From Mining to Metallurgy, the Key Aspect of Recycling of Transition Energy Metals

There exists a well-established relationship between a country's Human Development Index (HDI) and its per capita energy consumption; higher energy consumption is generally associated with greater societal development. Consequently, the global community requires more affordable, clean, and renewable energy. Currently, significant efforts and a major paradigm shift are underway to reduce greenhouse gas emissions (e.g., CO_2, CH_4). These initiatives involve adopting new technologies, optimizing the use of natural resources for energy generation-such as geothermal, wind, and solar-and advancing nuclear energy, a low-carbon yet non-renewable energy source, despite the inherent risks related to nuclear fission, waste storage, and disposal.

Presently, fossil fuels (oil, natural gas, and coal) remain the dominant sources of energy, accounting for approximately 80 to 85% of global energy consumption. In contrast, renewable energy sources and nuclear power contribute roughly 15 to 20% of total energy production. With CO_2 reduction targets currently under active discussion to mitigate the greenhouse effect, one prominent strategy is the electrification of the automotive sector. This is particularly relevant as the transportation sector accounts for about 28% of global final energy consumption. Various technological alternatives are being pursued, including hybrid vehicles (combining internal combustion and electric propulsion) and fully electric vehicles. Additionally, emerging technologies such as hydrogen combustion engines and engines operating on biofuels (ethanol, biodiesel, or methanol) pose significant technological challenges. These alternatives necessitate the incorporation of diverse metals in vehicle manufacturing-such as aluminium, lithium, nickel, and cobalt for batteries, supercapacitors, electrodes, and charging systems; copper for conductive wiring; and rare earth elements for high-intensity magnets. These challenges are further compounded by strategic factors (such as the availability and geographic distribution of these metals), infrastructure constraints (including energy capacity, distribution networks, and charging stations), planned obsolescence of modern vehicles, and evolving opportunities and requirements for recycling and recovering these metals.

Recycling processes offer considerable environmental benefits by reducing the extraction of non-renewable resources, lowering the energy demand for metal production, and decreasing waste generation throughout the entire production chain-from mining and metallurgical processing to metal forming and construction. It is imperative to underscore the significant societal and environmental advantages provided by recycling. Finally, education, public engagement, and the continuous development of new technologies are critical to reducing the demand for non-renewable resources, lowering global energy consumption, and decreasing environmental pollution thereby facilitating a cleaner energy transition. Table #1 illustrates key aspects related to production, recycling, energy consumption, and waste generation for various primary metals in contrast with their recycled counterparts.

Metal	Annual Production (2024)	Primary Production Route	Recycling Route	Energy (Primary Production – KWh/t	Energy (Recycling) KWh/t	Recycling Rate (%)	Remarks
Iron (steel)	1,84 billion of metric tonnes	Blast furnace combined with basic oxygen furnace (BOF) and direct reduction; overall production includes Electric Arc Furnace (EAF) processing	EAF (electric arc furnace)	4,000 to 5,000	500	37%	Recycling one tonne of steel saves approximately 1,400 kg of iron ore, 740 kg of coal, and 120 kg of limestone. Additionally, the production of one tonne of steel generates approximately 2.3-3.5 tonnes of waste from mining and metallurgical processes.
Aluminium	72.8 million tonnes	Bayer process (to extract alumina from bauxite) followed by the Hall-Héroult process (electrolysis to produce aluminium)	Recycling using gas/electric furnaces	14,000 to 16,000	800	~41%	Recycling rates vary by region: approximately 81% in Europe and 57% in the USA. The production of alumina and aluminium generates between 2 to 4 tonnes of waste per tonne of product.
Copper	22.9 million tonnes	Pyrometallurgical processing of sulphide ores (comprising 80-85% of annual production) and hydrometallurgical processing of oxidized ores (15-20%)	Foundry (EAF) and electrolytic refining	5,000 to 8,000	1,000 to 1,500	30-40%	Due to the low concentration of copper in ores, mining and beneficiation processes generate approximately 200-300 tonnes of waste per tonne of refined copper. Mining is the largest contributor to waste generation in this process.
Nickel	3.5 million tonnes	For sulphide ores: pyrometallurgy combined with electrorefining; for lateritic ores: High Pressure Acid Leach (HPAL); submerged arc reduction for ferronickel production	EAF and Hydrometallurgical processing	30,000 to 40,000	3,000 to 4,000	~30% (*)	(*) Estimated. Mining and beneficiation typically generate 50 to 150 tonnes of waste per tonne of refined nickel due to the low ore grade. In ferronickel production, slag generation is also significant.
Silicon Metallic Ferrosilicon	Metallic silicon: Data not separately reported; Ferrosilicon: 4.5 million tonnes	Carbothermic reduction and electric furnace: ferrosilicon	ND	14,000 to 18,000	ND	insignificant	Ferrosilicon production generates approximately 2-3 tonnes of waste (primarily slags) per tonne produced. ND: Not Determined.
Lithium	240,000 (from mine)	Electrolysis of molten salts (LiCl + KCl)	Hydro / Pyro metallurgy	30,000 to 60,000	ND	ND	For lithium extracted from hard rock, approximately 10-20 tonnes of waste (including tailings and residual solids) are generated per tonne of final product. Waste characterization for lithium from brine is different and is typically measured in terms of water residues and residual salts.

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