Energy Use in Metal Production

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Energy is consumed at all stages in the production of primary metals – mining, beneficiation and chemical extraction – directly in the processes and indirectly through the production of inputs (such as electricity and reagents) used in the processes. The sum of the direct and indirect energies of the individual stages along the value-adding chain is the embodied energy of the metal. The embodied energy of the common metals varies widely, from typically around 20 MJ per kilogram for lead and steel to over 200 MJ per kilogram for aluminium (Figure 1.) The chemical transformation stages (leaching, smelting, electrowinning, etc) contribute the largest component and mining the least.

The main factors determining the embodied energy content of primary metals are:

- the stability of the minerals from which the metal is produced (determined by the ΔG of formation);
- the ore grade, since the lower the grade, the more ore that has to be mined and processed per unit of metal produced;
- the degree of beneficiation required, particularly grinding to achieve liberation since this is the most energy intensive operation in beneficiation; and
- the overall recovery, since losses along the value-adding chain require more ore to be mined per unit of metal produced.

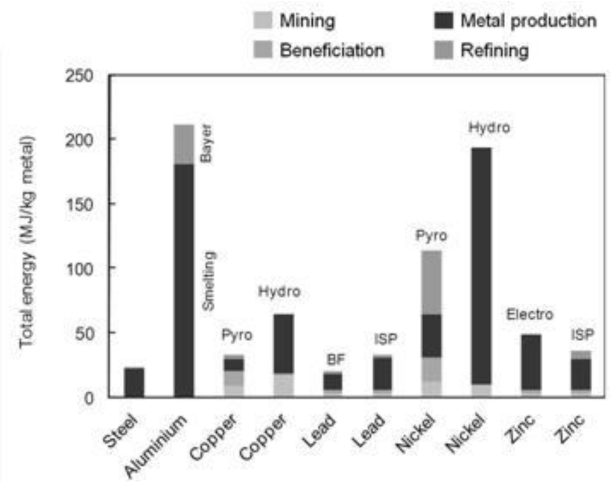

Figure 1: The embodied energy of common metals (Norgate and Rankin, 2000, 2001, 2002a, 2002b).

Globally, of all the metals, steel production contributes the greatest quantity of greenhouse gases (Table 1), about 7% of global CO_2 produced from fossil fuels. This is because, although steel has a low embodied energy content it is produced in the largest quantity (about one billion tonnes per year). The annual production of aluminium is much lower than that of steel (about 38 million tonnes per year) but it is far more energy intensive and aluminium production is responsible for around 3% of global CO_2.

The quantity of greenhouse gases produced follows closely the trends in embodied energy (Table 1) though for those metals which require a high component of electrical energy, such as aluminium and magnesium, the source of electrical energy (coal, hydro, nuclear, etc) has a major impact on the quantities of greenhouse gases produced. For example, the embodied energy in aluminium produced using electricity that is coal-based, natural gas-based and nuclear energy-based is approximately 22.4, 13.3 and 9.9 kg CO_2-e/kg Al, respectively.

The energy required to recycle metals is a relatively small fraction of the energy required to produce metals from their ores since energy is required largely only for melting and not chemical transformation (Table 2). However, when the energy required for collection and separation of scrap is included, the embodied energy of recycled metals increases as the fraction of scrap collected increases since transportation and separation costs progressively increase.

Table 1: Global CO_2 production for primary production of metals (Note: electrical energy is assumed to be black coal based at 35% efficiency).

Metal		% of total global metal production	Global annual production (Mt)	Embodied Energy (GJ per tonne)	Tonnes CO_2 per tonne metal	Global annual energy consumption (GJ)	Global annual CO_2 (tonnes)	% Global greenhouse gas production*
Copper	pyro	80	15.6	33.0	3.25	6.13×10^{8}	6.0×10^{7}	0.21
	hydro	20		64.5	6.16			
Nickel	pyro	60	1.66	113.5	11.45	2.42×10^{8}	2.2×10^{7}	0.08
	hydro	40		193.8	16.08			
Lead	BF	89	3.55	19.6	2.07	7.5×10^{7}	7.8×10^{6}	0.03
	ISP	11		32.5	3.18			
Zinc	electrolytic	90	10.5	48.4	4.61	4.95×10^{8}	4.7×10^{7}	0.16
	ISP	10		35.8	3.34			
Aluminium		100	38	211.5	21.81	8.0×10^{9}	8.3×10^{8}	2.9
Steel	BF/BOF	70	924	22.7	2.19	2.1×10^{10}	2.0×10^{9}	7.0
Cement			2 600	5.6	~0.9	1.46×10^{10}	2.3×10^{9}	8.1

*Global annual production of CO_2 from fossil fuel sources = 28 962 Mt (IEA, 2009)

Table 2: Energy for recycling metals after collection and sorting.

Commodity		Embodied energy (GJ/tonne)		Embodied energy (as % that of primary production)		
		Secondary Production*	Primary production	Calculated	Commonly quoted values (various sources)	
Plastic						30
Paper						60
Glass						70
Aluminium	alloy	17.5	212	8.3	**Al**	5 – 10
	cans	10.1		4.8		
Copper	no. 1 scrap	4.4	33	13.3	**Cu**	15
	no. 2 scrap	20.1		60.9		
	low-grade scrap	49.3		149		
Steel	billets	9.7	23	42.7	**Steel**	20 – 40
Lead – soft	batteries	9.4	20	47.0	**Pb**	35
Lead – hard	batteries	11.2		56.0		
Nickel	alloy scrap	12.9	114	11.3	**Ni**	10
Zinc	new scrap	3.8	48	7.9	**Zn**	25 – 40
	slab	22.0		45.5		

*Kusik and Kenahan (1978)

Technology plays an important role in reducing the embodied energy content of metals and greenhouse gas production and there has been progressive improvement over many decades. However, without step changes in technology, incremental improvements in energy efficiency become increasingly difficult to achieve. For example, the energy required for smelting aluminium in a modern smelter is around 13.5 kWh per kg Al which is about twice the theoretical amount required. However, this is approaching the limits of incremental improvements to the Hall Heroult cell and further reductions in energy will require radically new technologies. Some examples of step change high temperature technologies include the top gas recycling blast furnace, heat recovery from slag, and thin strip casting.

However there is a limit to the energy reduction possible because of thermodynamic constraints, most importantly, the stability of the compound from which the metal is produced. There is a thermodynamic limit below which it is not possible to go. Present technology is far removed from that limit. For example, the theoretical limit for making steel from hematite is around 7 GJ per tonne Fe but modern iron and steelmaking practice requires around 20 GJ per tonne. Hence there remains much scope for further technical developments, particularly in removing energy intensive steps from existing processes, such as coke making and sinter making in steel production and carbon electrode production in aluminium production, or developing radically new processes with fewer steps and less materials handling; for example, the TIRO™ process for producing titanium (Doblin and Wellwood, 2008).

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