1. Materials

Materials extraction in the world in 2013 was estimated at 84.4 billion (10^9) metric tons (45.8% industrial and construction materials, 26.8% biomass, 17.2% fossil fuels, and 10.2% metals, excluding unused portion), or 11.8 metric tons per capita per year [1].

In the United States during 2013, materials consumption, excluding fuels, was estimated at 3.78 billion (10^9) metric tons per year [2], corresponding to 11.9 metric tons per capita per year.

1.1. Metals

Aluminum

Aluminum production from bauxite via alumina is one of the most-energy intensive processes in industry. According to a United Nations report based on 1979 data, the energy profile of aluminum is:

	Energy consumption		**Energy type**		
	MJ/kg	**Fraction**	**Electricity**	**Gas**	**Other**
Mining	2.3	0.6%	6%	40%	54%
Alumina	44.5	17.1%	12%	80%	7.5%
Smelting	193.6	68.6%	85%	3%	12%
Fabrication	38.6	13.7%	38%	51%	11%
Total	279.0	100%			

Source: [3]

Technologies have evolved (see [4] page 125), leading to greater energy efficiency. Compilation of multiple data sets for primary production (excluding the fabrication stage) yields an embodied energy in aluminum of 210 ± 10 MJ/kg [4, p. 471].

The carbon footprint for primary production is 12 kg of CO_2/kg whereas the water usage varies from 495 to 1,490 L/kg [4, p. 471].

Recycling aluminum demands much less energy, only 26 MJ/kg for cast aluminum and 26.7 MJ/kg for wrought aluminum [5]. Its carbon footprint is 2.1 kg CO_2/kg (in average). The estimated recycled fraction in 2012 ranged between 41% and 45% [4, p. 471].

Copper and its alloys

According to a United Nations report using 1975 data, the energy profile of copper is:

	Energy consumption		Energy type			
	MJ/kg	fraction	Electricity	Gas	Oil	Other
Mining	25.1	19.2%	42%	1%	35%	22%
Concentrating ore	49.1	37.7%	73%	6%	1%	20%
Smelting	44.3	34.0%	11%	48%	24%	17%
Refining	9.5	7.2%	43%	15%	39%	2%
Melting & Casting	2.3	1.7%				
Total	130.3	100%				

Source: [3]

Technologies have evolved, leading other sources to provide lower numbers:

Metal	Embodied Energy (MJ/kg)	Carbon Footprint (kg CO_2/kg)	Water Usage (L/kg)
Copper - pure			
Primary	57 – 63	3.7	293 – 324
Recycled (40 to 45%)	12.9 – 14.3	1.07	
Copper alloys			
Primary	56 – 62	3.7	268 – 297
Recycled (40 to 45%)	12 – 15	0.83	
Brass			
Primary	52 – 60	3.7	310 – 340
Recycled (41 to 45%)	12 – 15	1.06	
Bronze			
Primary	58.2 – 64.9	3.7	280 – 314
Recycled (41 to 45%)	13.2 -14.7	1.1	

Source: [4, page 477] and accompanying CES EduPack software

Iron & Steel

The amount of energy consumed in steel production varies widely based on the process used and on the mix of scrap metal with iron ore in the feed material. The Basic Oxygen Furnace (BOF) consumes 23.2 MJ/kg while the Electric Arc Furnace (EAF) consumes 9.3 MJ/kg [6]. The theoretical thermodynamic limit is 7.6 MJ/kg [3].

In the United States, the energy consumed for the production of steel is about 19 MJ/kg from iron ore [3] and 10 MJ/kg from scrap metal [3].

Almost 40% of the world's steel production is made from scrap [7]. Recycling 1 kg of steel saves 1.1 kg of iron ore, 0.63 kg of coal, 0.055 kg of limestone, 0.642 kWh of electricity, 0.287 L of oil, 10.9 thousand BTUs of energy, and 2.3 L of landfill [7].

Metal	**Embodied Energy**	**Carbon Footprint**	**Water Usage**
	(MJ/kg)	(kg CO_2/kg)	(L/kg)
Cast iron			
Primary	16 – 20	1.5	13 – 39
Recycled (40 to 45%)	10 – 11	0.52	
Casting energy	10 – 11	0.79	
Low-carbon steel			
Primary	25 – 28	1.8	23 – 69
Recycled (40 to 44%)	6.6 – 8.0	0.44	
Low-alloy steel			
Primary	31 – 34	2.0	37 – 111
Recycled (40 to 44%)	7.7 – 9.5	0.52	
Stainless steel			
Primary	81 – 88	5.0	112 – 336
Recycled (35 to 40%)	11 – 13	0.73	

Sources: [4, pages 463, 465, 467, 469]

Lead

Production of lead from ore (galena, PbS) requires 27 MJ/kg, 175 to 525 liters of water per kg and generates 2.0 kg of CO_2 per kg, while production of lead from recycled sources (mostly discarded automobile batteries) consumes 7.5 MJ/kg and generates 0.45 kg of CO_2/kg. The single largest use of lead (70% of total production) is as electrodes in lead-acid batteries [4, p. 479].

Magnesium

Production of magnesium causes the following environmental impacts:

Metal	**Embodied Energy** (MJ/kg)	**Carbon Footprint** (kg CO_2/kg)	**Water Usage** (L/kg)
Magnesium			
Primary	300 – 331	36.5	932 – 1030
Recycled (37 to 41%)	46 – 51	5.5	
Magnesium alloys			
Primary	300 – 330	36	500 – 1,500
Recycled (36 to 41%)	23 – 26	2.9	

Source: [4, page 473] and accompanying CES EduPack software

Nickel

Production of nickel causes the following environmental impacts:

Metal	Embodied Energy (MJ/kg)	Carbon Footprint (kg CO_2/kg)	Water Usage (L/kg)
Nickel-chromium alloys			
Primary	173 – 190	11.5	564 – 620
Recycled (29 to 32%)	30 – 36	2.0	
Nickel-based super alloys			
Primary	221 – 244	11.6	134 – 484
Recycled (22 to 26%)	33.8 – 37.5	2.14	

Source: [4, pages 483, 485]

Together with chromium and other elements, nickel is a component of stainless steel.

Specialty and precious Metals

Metal	Embodied Energy (MJ/kg)	Carbon Footprint (kg CO_2/kg)	Water Usage (L/kg)
Gold			
Primary	240,000 – 265,000	26,500	126,000 – 378,000
Recycled (42%)	650 – 719	43	
Iridium			
Primary	43,000 – 47,600	2,900	186,000 -206,000
Recycled (0.7%)	2,000 – 2,210	165	
Palladium			
Primary	149,000 – 165,000	8,500	186,000 – 206,000
Recycled (3%)	5,140 – 5,680	426	
Platinum			
Primary	257,000 – 284,000	14,750	186,000 – 206,000
Recycled (3%)	7,760 – 8,570	642	
Rhodium			
Primary	531,000 – 587,000	30,450	186,000 – 206,000
Recycled (0.7%)	13,500 – 14,900	1,120	
Silver			
Primary	1,400 – 1,550	100	1,150 – 3,460
Recycled (66%)	140 – 170	9.3	
Titanium alloys			
Primary	650 – 720	46.5	470 – 1,410
Recycled (23%)	78 – 96	5.2	

Source: [4, pages 127, 474, 487, 488] and accompanying CES EduPack software

Zinc

Production of zinc causes the following environmental impacts:

Metal	Embodied Energy (MJ/kg)	Carbon Footprint (kg CO_2/kg)	Water Usage (L/kg)
Zinc			
Primary	43.9 – 48.5	3.3	327 – 361
Recycled (21 to 24%)	10.6 – 11.8	0.88	
Zinc die-casting alloys			
Primary	57 – 63	4.1	160 – 521
Recycled (21 to 25%)	10 – 12	0.67	

Source: [4, page 481]

1.2. Plastics and rubber

Except for biodegradable plastics, plastics are made from so-called feedstocks derived from crude oil refining and natural gas processing. The rule of thumb is that half the fossil fuel goes into the plastic itself while the remaining half is combusted to provide the energy during manufacture. Thus, it takes about 2 kg of fossil fuel to produce 1kg of plastics. Since petroleum holds in average 43 MJ/kg, it takes approximately 86 MJ to produce 1 kg of plastics, and, with about 3 hydrogen atoms for every carbon atom in the fuel consumed in production (molar mass of 15 grams per mole), the CO_2 emission (with molar mass of 44 grams per mole) is 44/15 = 2.9 kg of CO2 for every a kg of plastics produced. *Note*: The amount of 6kg of CO_2 emitted per kg of plastic mentioned by Time for Change [8] is inaccurate.

Actual amounts vary with the type of plastics, as the table below indicates.

Polymers and Elastomers	Acronym	Embodied Energy (MJ/kg)	Greenhouse gas Emission (kg CO_2/kg)	Water Usage (L/kg)
Acrylonitrile butadiene styrene	ABS	90 – 99	3.6 – 4.0	250 – 277
Recycling		42 – 51	2.5 – 3.1	
Epoxy		127 – 140	6.8 – 7.5	107 – 322
Ethylene-vinyl-acetate	EVA	75 – 83	2.0 – 2.2	100 – 289
Recycling		42 – 52	2,5 – 3.1	
High-density polyethylene	HDPE	100 – 111	3.43 – 3.79	166 – 183
Recycling		26.2	0.90 – 0.99	
Phenolics		75 – 83	3.4 – 3.8	94 – 282
Polyamides (Nylons)	PA	116 – 129	7.6 – 8.3	250 – 280
Recycling		38 – 47	2.3 – 2.8	
Polycarbonate	PC	103 – 114	5.7 – 6.3	142 – 425
Recycling		38 – 47	2.3 – 2.8	

Polychloroprene	CR	61 – 68	1.6 – 1.8	126 – 378
Polyester		68 – 75	2.8 – 3.2	100 - 264
Polyethylene Recycling	PE	77 – 85 45 – 55	2.6 – 2.9 2.7 – 3.0	38 – 114
Polyethylene terephthalate (PET) Recycling	PET	81 – 89 35 – 43	3.7 – 4.1 2.1 – 2.6	14.7 – 44.2
Polyhydroxyalkanoate Recycling	PHA	81 – 90 35 – 43	4.1 – 4.6 2.1 – 2.6	100 – 300
Polylactide Recycling	PLA	49 – 54 33 – 40	3.4 – 3.8 2.0 – 2.4	100 – 300
Polypropylene Recycling	PP	75 – 83 45 – 55	2.9 – 3.2 2.0 – 2.2	189 – 209
Polystyrene Recycling	PS	92 – 102 43 – 52	3.6 – 4.0 2.6 – 3.1	108 – 323
Polyurethane Recycling	PU/PUR	82.7 – 91.5 28.1 -31.1	3.52 – 3.89 1.2 – 1.32	93.5 – 103
Polyvinyl chloride Recycling	PVC	56 – 62 32 – 40	2.4 – 2.6 1.9 – 2.4	77 – 85
Rubber – natural	NR	64 – 71	2.0 – 2.2	(15 – 20) x 10^3
Rubber – butyl rubber	BR	112 – 124	6.3 – 6.9	63.8 – 191
Styrene		110 – 122	3.95 – 4.37	385 - 426

Source: [4, Chapter 15] and accompanying CES EduPack software

Recycling 1 kg of plastics saves 5.774 kWh of electricity, 2.604 L of oil, 98 thousand BTUs of energy, and 0.022 m^3 of landfill [7].

1.3. Paper and cardboard

There can grow 16 to 20 mature trees on 1 acre (40 to 59 trees per hectare) [9].

A cord of wood is 8ft x 4 ft x 4ft = 128 ft^3 and, if air dried and consisting of hardwoods weighs about 2 short tons (1,800 kg), about 15-20% of which is still water. One cord of wood makes 1,000 to 2,000 lbs of paper, depending on the process [10].

The production of 1 metric ton of paper requires 17 trees, in average, with the following spread: 24 trees for 1 ton of uncoated virgin (non-recycled) printing and office paper but only 12 trees for 1 ton of 100% virgin (non-recycled) newsprint, 15.36 trees for 1 ton of higher-end magazine paper (for glossy magazines), and 7.68 trees for 1 ton of lower-end magazine paper (most catalogs) [11].

The production of 1 metric ton of paper consumes 51,500 MJ of energy, 25 m^3 of water, 680 gallons (2.57 m^3) of oil and generates 1,150 kg of CO_2 [4, 11, 12].

A "pallet" of copier paper (20-lb. sheet weight) contains 40 cartons and weighs 1 metric ton. It contains 440 reams, whereas 1 ream of paper contains 500 sheets and weighs 5 lbs = 2.27 kg. Therefore [11],

- 1 carton (10 reams) of 100% virgin copier paper uses 0.6 trees;
- 1 tree makes 16.67 reams of copy paper or 8,333 sheets;
- 1 ream (500 sheets) uses 6% of a tree;
- 1 ton of coated, higher-end virgin magazine paper (used for high-end magazines) uses 15.36 trees;
- 1 ton of coated, lower-end virgin magazine paper (used for newsmagazines and most catalogs) uses 7.68 trees.

In the USA, paper and cardboard recovery reached 66.8% in 2015. Of this, 33.4% went to produce corrugated cardboard, 11.8% non-corrugated cardboard (boxboard), 8.6% tissue, and 0.8% newsprint. Net exports accounted for 39.8%. Also, 36% of the fibers used to make new paper come from recycled sources [13].

1.4. Chemicals

In the United States, the chemical industry consumes an average of 6,935 BTUs per lb of product [14]. This energy intensity, however, depends widely on the nature of the chemical, as the table below illustrates.

Because different production paths consume different amounts of energy, the energy used in the production of a chemical depends on its feedstock. Chemicals obtained from the cracking and distillation of petroleum or inorganic sources are called raw materials. Thus, the total energy consumed in the production of a chemical is the sum of the energy inputs for itself and all its predecessors (each with the corresponding mass ratio deduced from the stoichiometric ratio), starting from the raw material. *Example*: The energy consumed in producing 1 lb of Ethylene Glycol from Ethylene Oxide (with mass ratio 0.710:1) from Ethylene as raw material (with mass ratio 0.637:1) is:

$$E = 2{,}045 + 0.710 \times (1{,}711 + 0.637 \times 8{,}107) = 6{,}923 \text{ BTU/lb.}$$

To such number may be added the energy necessary for the intermediate production of the required hydrogen and chlorine.

Chemical	**Energy Consumption** BTU/lb unless otherwise noted	**When made from**	**Mass ratio**
Acetic Acid (vinegar)	2,552 [15]	---	---
Acetone	7,850		
Acrylonitrile	956	Propylene	0.793:1
Ammonia	12,150	---	---
Ammonium	323	Ammonia	0.944:1
Ammonium Nitrate	341	Nitric Acid	0.787:1

Ammonium Phosphate	323		
Ammonium Sulfate	4,000	Ammonia	0.258:1
Benzene	1,255	Petroleum	---
Bisphenol A (BPA)	6 MJ/kg [16]	---	---
1,3-Butadiene	95	By-product of ethylene	
Carbon Black	3,703MJ/ton [17]	---	---
Chlorine	4,800	Sodium Chloride	1.648:1
Cumene (Isopropylbenzene)	696	Benzene	0.650:1
Cyclohexane	1,743	Benzene	0.928:1
Ethyl Benzene	1,404	Benzene	0.736:1
Ethylene	8,107	Petroleum	---
Ethylene Dichloride	3,410	Ethylene	0.283:1
Ethylene Glycol	2,045	Ethylene Oxide	0.710:1
Ethylene Oxide	1,711	Ethylene	0.637:1
Formaldehyde	150 kWh/ton [17]		
Hydrochloric Acid	1.2MJ/kg [17]		
Hydrogen	1.8 GJ/ton	---	---
Isopropyl Alcohol	4,693	Propylene	0.700:1
Methanol	38.4 GJ/ton		
Methyl Ter-Butyl Ether (MTBE)	1,871 [18]	---	---
Nitric Acid	267	Ammonia	0.270:1
Oxygen	1.8 GJ/ton [18]		
Phenol & Acetone together	7,850	Cumene	0.790:1
Phosphoric Acid	4,300	Sulfuric Acid	1.001:1
Polyethylene (PE)	1,178	Ethylene	1.000:1
Polypropylene	514	Propylene	1.000:1
Polystyrene	2,264	Styrene	1.000:1
Poly Vinyl Chloride (PVC)	1,246	Ethylene Dichloride	
Propylene	1,351	Petroleum	---
Propylene Glycol	2,045	Propylene Oxide	0.763:1
Propylene Oxide	2,557	Propylene	0.725:1
Sodium Carbonate	3,393		
Sodium Chloride	negligible	Sea Salt	---
Sodium Hydroxide	3,765	Sodium Chloride	1.461:1
Sodium Silicate	5,344 MJ/ton [19]		
Sulfuric Acid	1,047	---	---
Styrene	16,891	Ethyl Benzene	1.019:1
Styrene Butadiene (synthetic rubber)	2,271	1,3-Butadiene & Styrene	1.000:1
Terephthalic Acid	1,779	Xylene	
Titanium Dioxide	24.8 GJ/ton [19]		
Toluene	1,025	Petroleum	---
Urea	843	Ammonia	0.567:1
Xylene	1,025		

Source: [14] based on 1997 data, unless otherwise noted

1.5. Shaping of materials

Energy is not only spent in producing the material but also in shaping it into its desired form.

Primary shaping processes

Material	Shaping process	Energy use (MJ/kg)	Carbon emission (kg of $CO_{2,eq}$/kg)
Metals[1]	Casting	8-12	0.4-0.6
	Rough, foil, rolling	3-5	0.15-0.25
	Extrusion, foil rolling	10-20	0.5-1.0
	Wire drawing	20-40	1.0-2.0
	Metal powder forming	20-30	1-1.5
	Vapor phase methods	40-60	2-3
Polymers	Extrusion	3.1-5.4	0.16-0.27
	Molding	11-27	0.55-1.4
Ceramic	Ceramic powder form	20-30	1-1.5
Glasses	Glass molding	2-4	0.1-0.2
Composites	Compression molding	11-16	1.6-0.5
	Spray-/Lay up	14-18	0.7-0.9
	Filament winding	2.7-4.0	0.14-0.2
	Autoclave molding	100-300	5-15

Source: [4, page 133] [1] For variations across metals, see [4].

Secondary processes

Process type	Variant	Energy use (MJ)	Carbon emission (kg of $CO_{2,eq}$)
Machining (per kg removed)	Heavy	0.8-2.5 MJ	0.06-0.17 kg
	Finishing (light)	6-10 MJ	0.4-0.7 kg
	Grinding	25-35 MJ	1.8-2.5 kg
	Water jet, EDM, Laser	500-5000 MJ	35-350 kg
Welding (per m welded)	Gas welding	1-2.8 MJ	0.055-0.15 kg
	Electric welding	1.7-3.5 MJ	0.12-0.25 kg
Fasteners (per fastener)	Fasteners, small	0.02-0.04 MJ	0.0015-0.003 kg
	Fasteners, large	0.05-0.1 MJ	0.0037-0.0074 kg
Adhesives (per m^2)	Adhesives, cold	7-14 MJ	1.3-2.8 kg
	Adhesives, heat-curing	18-40 MJ	3.2-7.0 kg
Painting (per m^2)	Painting	50-60 MJ	0.63-0.095 kg
	Baked coating	60-70 MJ	09-1.3 kg
	Powder coatings	67-86 MJ	3.7-4.6 kg
Plating (per m^2)	Electroplating	80-100 MJ	4.4-5.3 kg

Source: [4, page 135]

Polymer shaping

Polymer		Molding		Extrusion	
		Energy use (MJ/kg)	CO_2 footprint (kg/kg)	Energy use (MJ/kg)	CO_2 footprint (kg/kg)
Acrylonitrile Butadiene Styrene (ABS)		18-20	1.4-1.5	5.8-6.4	0.44-0.48
Polyamides (Nylons, PA)		21-23	1.55-1.7	5.9-6.5	0.44-0.49
Polypropylene(PP)		20.4-22.6	1.5-1.7	5.9-6.5	0.44-0.49
Polyethylene (PE)		22.7-25.1	1.7-1.9	6.0-6.6	0.45-0.49
Polycarbonate (PC)		17.6-19.5	1.3-1.5	5.8-6.4	0.43-0.48
Polyethylene Terephthalate (PET)		18.7-20.6	1.4-1.55	5.8-6.4	0.44-0.48
Polyvinylchloride (PVC)		13.9-15.4	1.05-1.16	5.6-6.3	0.42-0.47
Polystyrene (PS)		16.5-18.3	1.24-1.37	5.7-6.4	0.43-0.48
Polyhydroxyalkanoates (PHA, PHB)		16.6-18.4	1.25-1.38	5.8-6.4	0.43-0.48
Polylactide (PLA)		15.4-17	1.15-1.27	5.7-6.3	0.43-0.47
Epoxies		21-23	1.7-1.85		
Polyester		26-28	2.1-2.3		
Phenolics		26-29	2.1-2.3		
Rubber	Natural	15-17	1.2-1.4		
	Butyl	14-16	1.2-1.4		
Ethylene-Vinyl-Acetate (EVA)		13.8-15.2	1.1-1.2	5.4-6.0	0.43-0.48
Polychloroprene (Neoprene, CR)		17.2-18.5	1.37-1.5		

Source: [4, pages 492-525]

1.6. Miscellaneous materials

Material		Primary production		
		Embodied energy (MJ/kg)	Greenhouse gas emission (kg CO_2/kg)	Water usage (L/kg)
Automotive	Anti-freeze	76	---	---
	Engine oil	60.2	---	---
	Other fluids	52	---	---
Carbon fiber		450 – 500	33 - 36	360 – 1,367
Ceramics	Alumina	49.5 – 54.7	2.67 – 2.95	29.4 – 88.1
	Glass	10 - 11	0.7 – 0.8	14 – 20.5
	Pyrex glass	27 - 30	1.6 – 1.8	26 – 37.5
Construction	Brick	2.2 – 3.5	0.2 – 0.23	2.8 – 8.4
	Concrete	1.0 – 1.3	0.09 – 0.12	1.7 – 5.1

	Sand	1.0	---	---
	Stone	0.4 – 0.6	0.03 – 0.04	1.7 – 5.1
Cotton		44 – 48	2.4 – 2.7	7,400 – 8,200
Fiberglass (GFRP)		107 - 118	7.47 – 8.26	105 - 309
Foams	Rigid polymer	96 - 107	3.7 – 4.1	299 – 865
	Flexible polymer	104 - 114	4.3 – 4.7	181 - 544
Straw bale		0.1 – 0.3	-1.1 - -0.9	0
Woods	Bamboo			
	Hardwood	9.8 – 10.9	0.8 – 0.94	500 – 750
	Plywood	13 - 16	0.78 – 0.87	500 – 1,000
	Softwood	8.8 – 9.7	0.36 – 0.40	500 -750
Wool		51 – 56	3.2 – 3.5	(1.6 – 1.8) x 10^5

Sources: [4 Chapter 15, 5]

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