Primary Production of Metals: Input of Energy, Water and other Resources (Preliminary Survey)

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Abstract: This document gives information about energy consumption for the primary metal production. The metals considered here are Copper, Aluminium, Magnesium, Titanium, Zirconium, Cobalt and Tungsten. The steps in the hypothetical production of one ton of metal are described with consumption of energy (fuel, electricity. etc.) and material use for each step of the process.

Contents

1. Introduction:

Scarcity of metals could have severe consequences within a few decades. If our collective global behavior does not change, the ongoing growth in global

consumption of metals will cause shortages, aggravate energy scarcity and obstruct the transition towards a sustainable economy.[1]

A number of metals are already scarce, meaning that demand is exceeding supply. The production rate cannot simply be enhanced: more and more energy is required to extract metals from the increasingly lower ore grades at increasingly less favourable locations. Recycling cannot bridge the gap between demand and supply: exponential demand growth requires continuously higher production rates and more intense recycling requires more energy. Scarcity of only one or a few metals doesn't necessarily lead to large problems, because then the metal will eventually be substituted by another metal. However severe problems do arise when dozens of metals become scarce within the same timeframe and this will be the inevitable consequence of increasing global energy scarcity.

The central issue in metals scarcity is the required energy input for the primary production of metals. If energy gets scarce and more expensive, then inevitably so will metals. The present report tries to quantify the required energy input for the different process steps during the primary production of a number of metals. The open literature has some overall numbers available for embedded energy in metals, but since these are aggregate numbers they are less useful to enable assessment of trends. After a decades-long trend of diminishing embedded energy in metals due to technological progress, one might predict a future upward trend of energy input for primary metals production caused by the depletion of higher ore grades and the depletion of the most accessible ore bodies overtaking the effects of technology gains. The present report has gathered data from open literature to specify the input of energy (and other resources like water) for the primary production of a (small) selection of metals.

A lot of work has to be done to get a picture as clear as possible of our predicament, to analyze the data available and to underpin strategies to cope with metals scarcity not only in quality but also in quantity. Report TNO-DV 2010 IN041 ("Main applications and substitution outlook of selected metals") from Grzegorczyk and Diederen (March 2010) looks into the main applications of copper, aluminium, magnesium and titanium to be able to assess substitution possibilities (both ways) and to support assessment of trends. The present report is an exploratory study into available data on

[1]Diederen, A.M., *Metal minerals scarcity: A call for managed austerity and the elements of hope*, TNO, 10.03.2009, published at www.tno.nl, www.hcss.nl and http://europe.theoildrum.com/node/5239

energy consumption (and other input) during the primary production of seven metals: copper, aluminium, magnesium, titanium, zirconium, cobalt and tungsten.

Various processes to produce primary metal with varying degrees of efficiency depending on technology, ore grade, material availability.

2. Copper

Most copper production is based upon sulphide ores containing little copper but quite a lot of iron. New cleaner technologies are now important but older processes present major environmental problems. Complex procedures are used initially to form a type of copper sulphide appropriate for final reduction via a copper oxide. The resulting crude copper is purified using an electrolytic procedure involving plating onto pure copper cathodes.

1. $2Cu_2S + 3O_2 \rightarrow 2Cu_2O + 2SO_2$
2. $2Cu_2O + Cu_2S \rightarrow 6Cu + SO_2$

Notably, the purification step leaves an "anode slime" which contains useful amounts of silver and gold.[2]

2.1 Process of Primary production

Copper metal is produced from various copper minerals found in the crust of earth. Table 1 shows various minerals with associated percentage of copper concentration. The use of sulphuric ores (Cu_2S and $CuFeS_2$) is most common but non-sulphuric ores (e.g. Cu_2O) are also exploited. About 80 % of the primary copper in the world comes from low grade or poor sulphide ores. Chalcopyrite ($CuFeS_2$) is the most consumed mineral in the extraction of copper[3]. Pyro-metallurgical techniques which involve heat and chemicals to concentrate and extract copper from minerals are largely used in industry. In case of lower percentage of copper in the minerals or recycling, hydro-metallurgical techniques based on solutionizing of ore are used in industry.

Calculations for primary copper are given in the following worksheet. Theoretically, copper content in chalcopyrite is (molecular weight of CuFeS2= 183.5), Atomic weight of copper= 63.54, Atomic weight of Sulphur = 32.06 Atomic weight of Iron= 55.84 hence, 183.5 kg of chalcopyrite theoretically gives 63.54 Kg of copper, So 2.88 tons chalcopyrite is required to get 1 ton of copper

Table 1 Mining of Copper[4]

Mineral	Formula	Copper	Crystal	Density,

[2] http://www.webelements.com/copper/
[3] Habashi F, ed. 1997. Handbook of Extractive Metallurgy. WILEY-VCH.
[4] Davenport et al., 2002, Extractive metallurgy of copper, Pergamon

			system	g/cc
Chalcocite	Cu_2S	79.9	orthorhombic	5.5-5.8
Digenite	Cu_9S_5	78.0	Cubic	5.6
Covelite	CuS	66.5	Hexagonal	4.7
Chalcopyrite	$CuFeS_2$	34.6	tetragonal	4.1-4.3
Cuprite	Cu_2O	88.8	cubic	6.15
Tenorite	CuO	79.9	monoclinic	6.4
Malachite	$CuCO_3.Cu(OH)_2$	57.5	monoclinic	4.0
Brochantite	$CuSO_4.3Cu(OH)_2$	56.2	monoclinic	4.0
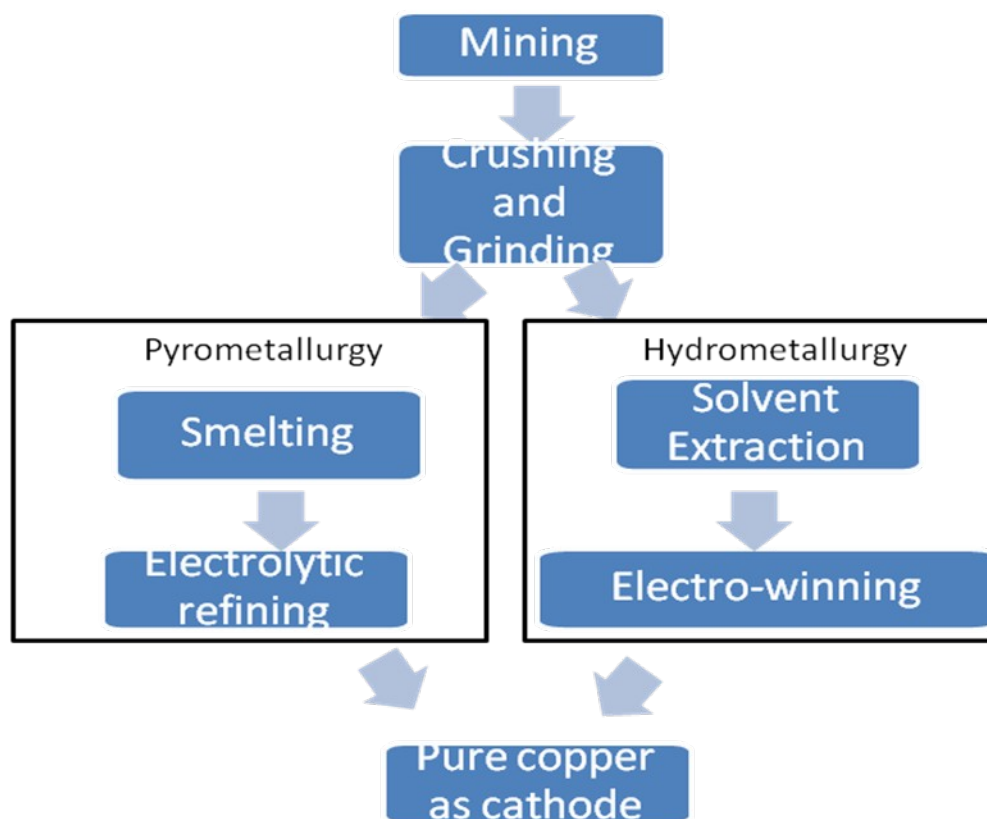
Figure 1 Flow chart of the primary production of copper metal[5]

2.2 Explanation for calculation of copper ore requirement:

The calculation for copper primary metal is done backward with the help of information about ore concentration available in book[6]. For example, to get

[5] (http://www.copper.org/education/production.html)
[6] Gleich Av, ed. 2006. Sustainable Metals Management. Springer

50-70 % of Cu sulphide ore of quantity 1.768 ton, it is required to feed 3.78 ton of 30% Cu Sulphide feed into roasting & smelting. The whole chain of concentration and enrichment of copper ore up to one ton of 99.99 % of copper is done in this fashion.

Figure 2 Calculation of ore requirement for each process to produce one ton of copper metal

Figure 2 shows how the total energy required for the production of 1 ton of copper metal is 133.25 GJ which is slightly higher than references[7] (64-72 GJ/ton). The difference can be put into the calculation of energy of mining n crushing n grinding which are more than what theoretically can make.

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[7]Ashby MF. 2009. Materials and the Environment :Eco-Informed Material Choice. Butterworth-Heinemann.

2.3 Production steps
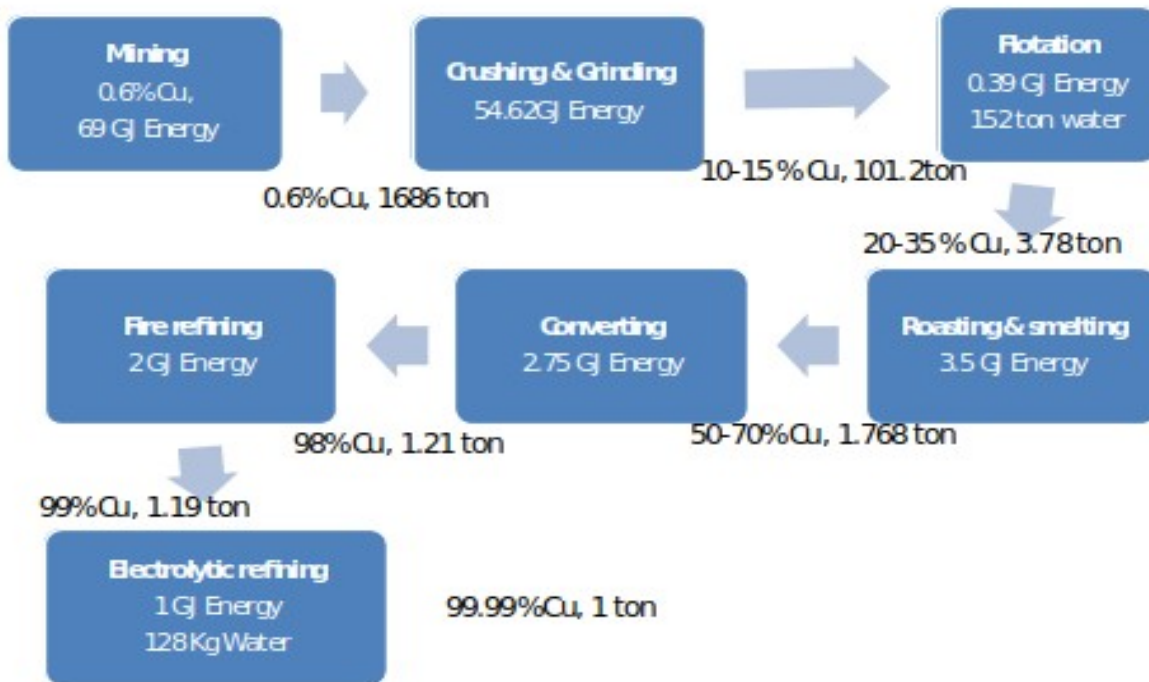
Figure 3 Flow chart for energy and materials consumption for 1 ton copper primary production

	Copper
Mining	69
Concentration*	55
Smelting	3.5
Converting	2.75
Fire refining	2
Electrolytic refining	1
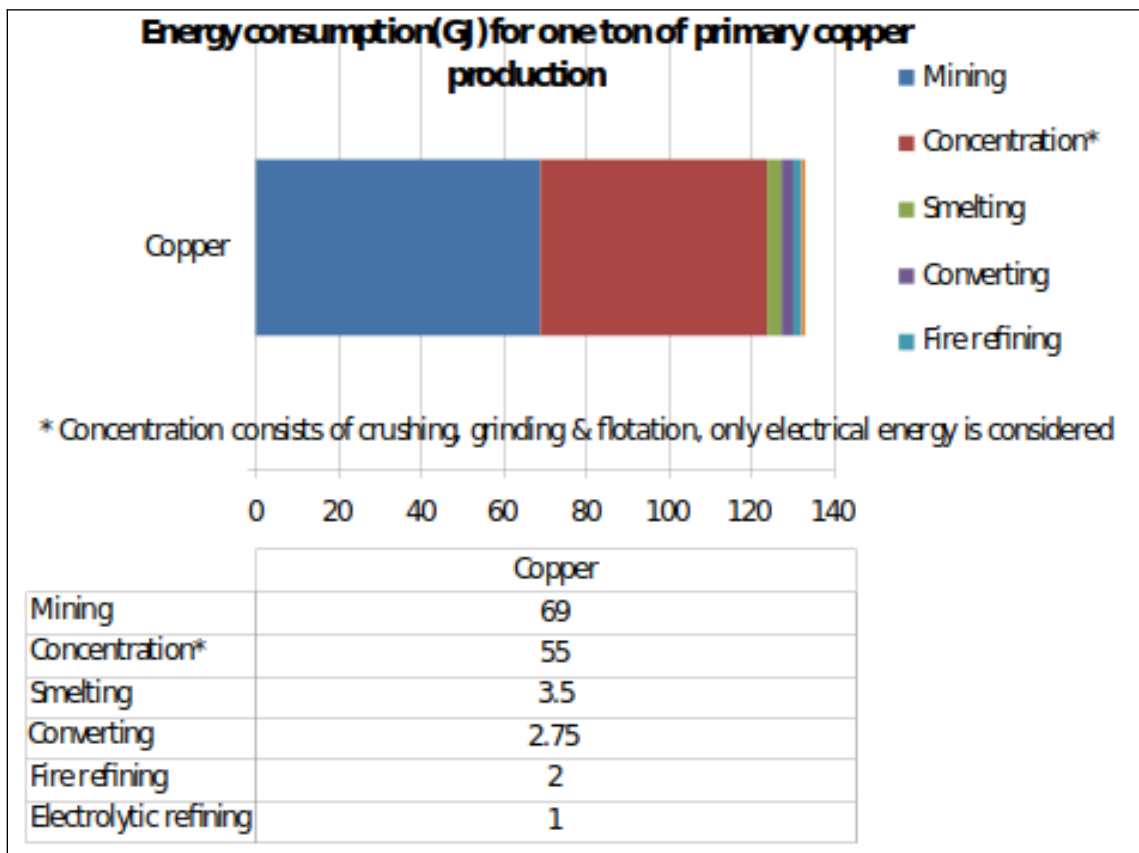
Figure 4 Energy consumption for one ton of copper production

2.3.1 Mining

Mining produces ores with less than 1 percent copper. There are several methods of copper ore mining: Open pit mining, Underground mining, In situ mining and Ocean mining. Few assumptions made in the calculation of energy consumption for mining. The copper sulphide ore is considered to be 0.6% rich. The cost of mining copper ore is taken from cost calculation model available on the website.[8] Energy consumed in the form of electricity, fuel or explosives is generalized in mega joules (MJ).
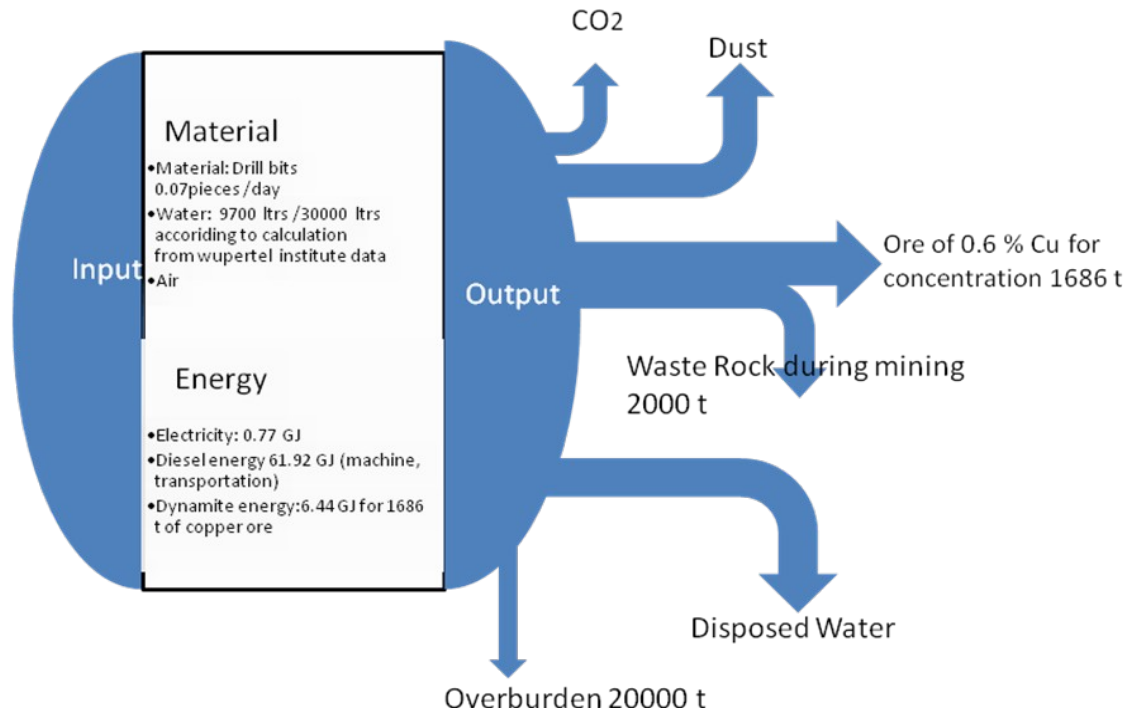
Figure 5 Step 1: Stripping overburden and Mining of copper ore

2.3.2: Crushing, grinding, and flotation purification

Concentration is accomplished at the mine sites by crushing, grinding, and flotation purification, resulting in ore with 15 to 35 percent copper. A continuous process called flotation, which uses water, various flotation chemicals, and compressed air, separates the ore into fractions. Depending upon the chemicals used, some minerals float to the surface and are removed in foam of air bubbles, while others sink and are reprocessed. Pine oils, cresylic acid, and long-chain alcohols are used for the flotation of copper ores. The flotation concentrates are then dewatered by clarification and filtration, resulting in 10 to 15 percent water, 25 percent sulphur, 25 percent iron, and varying quantities of arsenic, antimony, bismuth, cadmium, lead,

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[8] http://costs.infomine.com/costdatacenter/miningcostmodel.aspx

selenium, magnesium, aluminium, cobalt, tin, nickel, tellurium, silver, gold, and palladium.
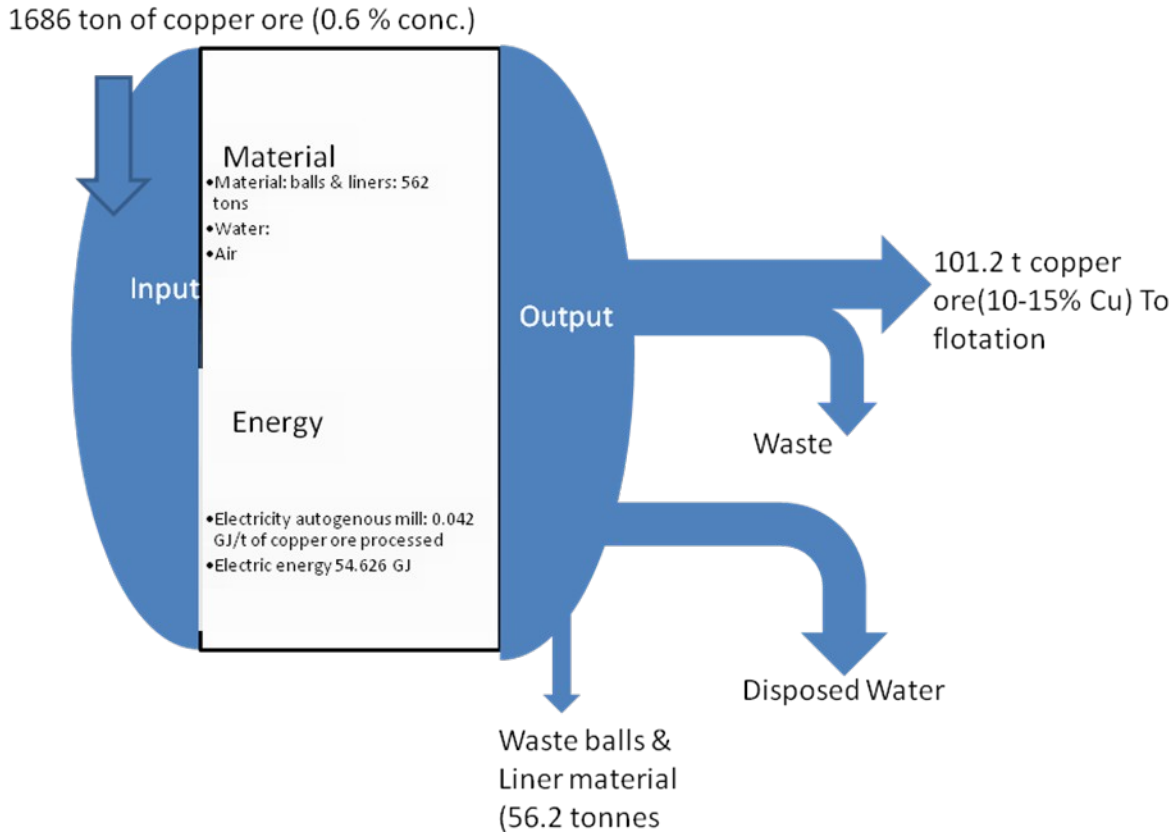
Figure 6 Step 2a: Concentration (Crushing and Grinding)[9]

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[9] *Notes: Crushing and grinding steel balls use from Davenport: for 75% Ore + 25 % steel balls= 100% feed in grinding machine: If we use 1686 tons of copper ore for grinding, then the balls would be 562 tonnes (10% waste for every run, so 56.2 waste)*
Calculation of energy: from Davenport book : 15.12 KWh per ton of copper ore = 54.43 MJ
54.32 MJ X 1686 tons of copper= 91.772 GJ
According to minerals processing book it could be 54.22 GJ
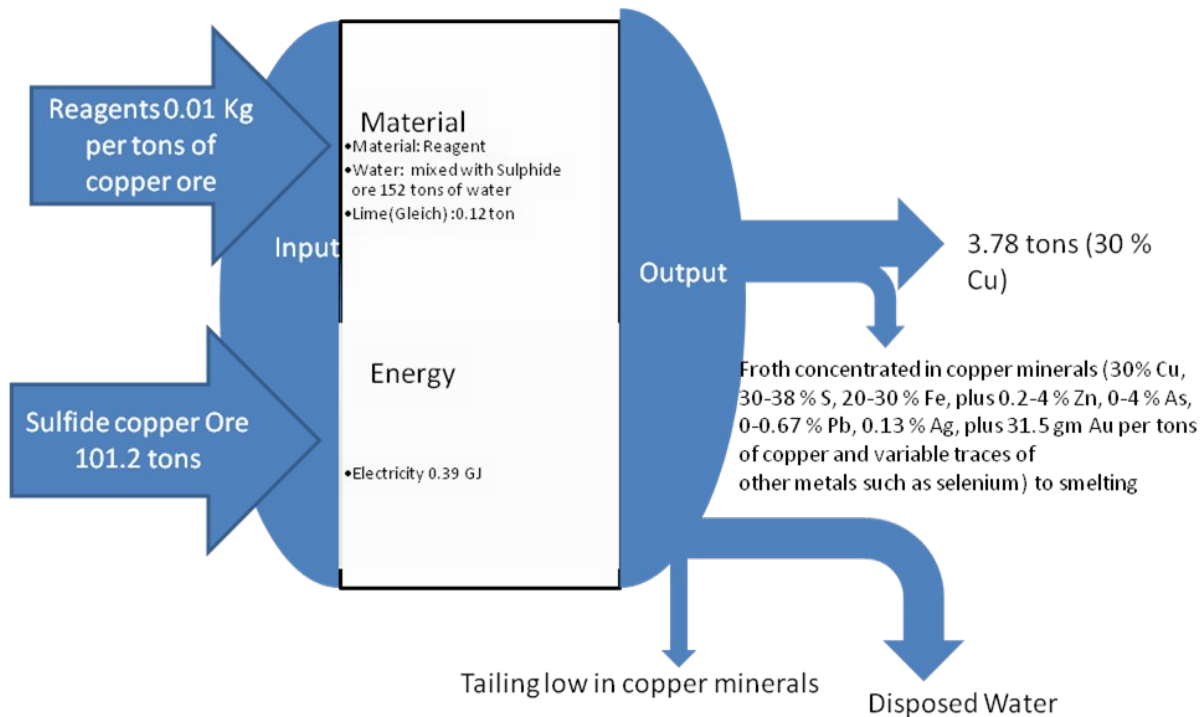
Figure 7 Step 2b: Concentration (Froth flotation)[10]

2.3.3: Roasting and Smelting

Roasting is performed in copper smelters prior to charging reverberatory furnaces. In roasting, charge material of copper concentrate mixed with a siliceous flux (often a low-grade copper ore) is heated in air to about 650°C, eliminating 20 to 50 percent of the sulphur as sulphur dioxide (SO_2). Portions of impurities such as antimony, arsenic, and lead are driven off, and some iron is converted to iron oxide. Roasters are either multiple hearths or fluidized bed; multiple hearth roasters accept moist concentrate, whereas fluidized bed roasters are fed finely ground material. Both roaster types have self-generating energy by the exothermic oxidation of hydrogen sulphide. ($H_2S + O_2$ results into $SO_2 + H_2O$ + Thermal energy.) In the smelting process, either hot Calcine (product of calcination is usually referred to in general as "calcine," regardless of the actual minerals undergoing thermal treatment) from the roaster or raw unroasted concentrate is melted with siliceous flux in a smelting furnace to produce copper matte. The required heat comes from partial oxidation of the sulphide charge and from burning external fuel. Most of the iron and some of the impurities in the charge oxidize with the fluxes to form a slag on top of the molten bath, which is periodically removed and

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[10] *Note: 60 % mass is water in the mixture for flotation: 40% of Ore, **so for 101.2 t of ore, ~152 tons of water is required***

discarded. Copper matte remains in the furnace until tapped. Molten sulphide matte ranges from 50 to 70 % percent copper after smelting.

Dust back to smelter for recycling(0.178t)

Off Gases for recycling to form sulfuric acid, 2812 N.cu.m, containing 10-60% SO_2

Sulfide ore concentrates from froth flotation 3.78t

Input

- Material: Siliceous flux 0.24 t
- Water:
- Air: 2252.10 N.cu.m.
- Oxygen 517.54 kg

- Fuel 3048 MJ
- Natural gas 370.93 MJ
- Electricity 89.02 MJ

Converter slag 0.47 t

Output

- Exothermic reaction leading to melting of products

Heat (1916.49 MJ) and radiation(26.49MJ)

Molten Sulfide matte (50%-70% Cu) to converter (1.768 t)

Molten oxide (e.g. silica) slag 2.08 t

Tailing low in copper minerals

Figure 8 Step 3: Roasting and Smelting[11]

2.3.4: Converting

Converting produces blister copper by eliminating the remaining iron and sulphur present in the matte. Air, or oxygen-rich air, is blown through the molten matte. Iron sulphide is oxidized to form iron oxide (FeO) and SO_2. The process proceeds in two stages: the *slag blowing* stage in the beginning, when most of the slag is formed, and the *copper blowing* phase when most of the sulphur is removed from the system. Blowing and slag skimming

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[11]*Notes : From Gliech book, for 2.14 t of Copper sulfide concentrates, fuel 38 Kg, natural gas 5.4 N.cu.m and electricity 50.4 MJ, Air 1275 Ncu.m, oxygen 293 Kg, converter slag 0.27 t, Siliceous flux 0.14 t*

Hence for 3.78 t of copper sulfide concentrates, fuel 67 Kg(3047.98 MJ), 9.53 N.cu.m. (370.93 MJ), electricity 89.02 MJ, Air 2252.10 Ncu.m, oxygen 517.54 Kg, converter slag 0.48 t, Silica flux 0.24 t

Products: for 2.14 t of copper sulfide concentrates, heat 1085 MJ, radiation 15MJ,

For 3.78 t of copper sulfide concentrates, heat 1916.49 MJ, radiation 26.49 MJ

---for 2.14 t of copper sulfide concentrates, Molten oxide (e.g. silica) slag 1.18 t, offgases 1592 Ncu.m, Dust 0.10 t

for 3.78 t of copper sulfide concentrates, molten oxide slag 2.08 t, off gases 2812 N.cu.m, Dust 0.178 t

continue until an adequate amount of relatively pure Cu_2S, called "white metal" accumulates in the bottom of the converter. A final air blast ("final blow") oxidizes the copper sulphide to SO_2, and blister copper forms, containing 98 to 99 percent coppers. The blister copper is removed from the converter for subsequent refining. The SO_2 produced throughout the operation is vented to pollution control devices.
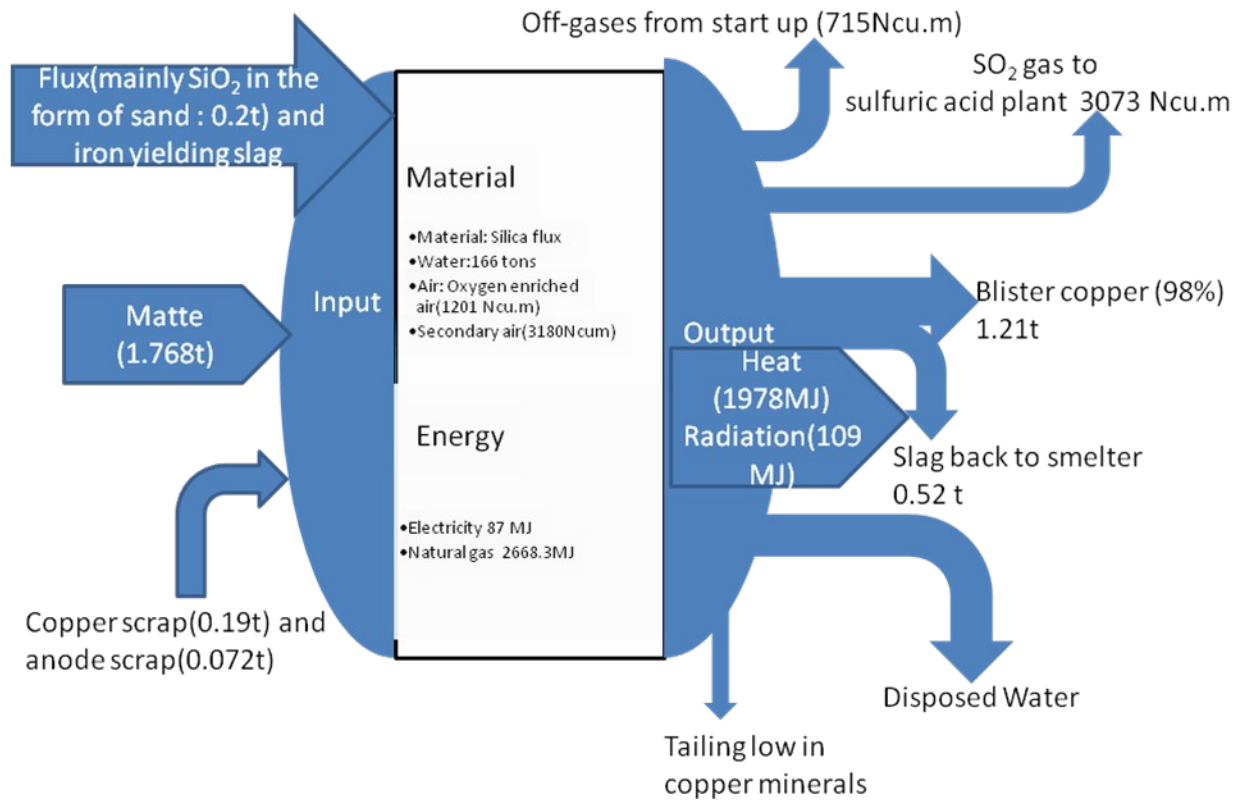
Figure 9 step 4:Converting (autothermal process)[12]

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[12]*Notes: Input in converter process (Gleich book) matte (1.46t), Flux(0.17t), anode slag(0.06t), scrap copper(0.16), air(992Ncu.m), secondary air(2626Ncu.m), natural gas(2203.5MJ), electrical energy(72MJ)*

For 1.768 t of matte, Flux(0.2t), anode slag(0.072t), scrap copper(0.193t), air(1201.27Ncu.m), secondary air(3180Ncu.m), natural gas(2668.3 MJ), electrical energy(87.18MJ)

Output in converter process (Gleich book) : Blister copper(1t), slag(0.43t), off gases(591t), SO2 gas(3073 Ncu.m), heat(1635MJ), radiation(90MJ)

For 1.21 t blister copper : slag(0.52t), off gases(715t), SO2 gas(3718 Ncu.m), heat(1978MJ), radiation(109MJ)

2.3.5: Fire refining

Blister copper is usually mixed with flux and charged into the furnace, which is maintained at 1100°C. Air is blown through the molten mixture to oxidize the copper and any remaining impurities. The impurities are removed as slag. The remaining copper oxide is then subjected to a reducing atmosphere to form purer copper.
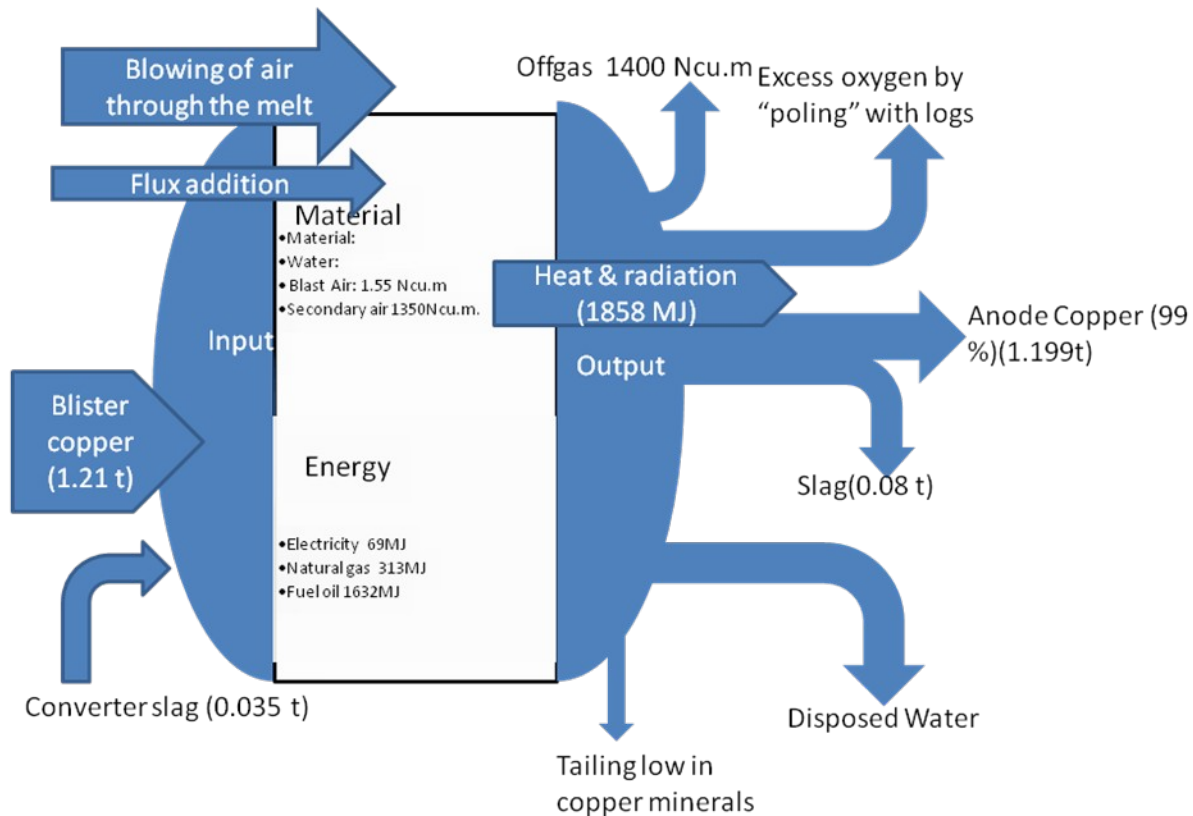
Figure 10 step 5: Fire refining[13]

2.3.6: Electrolytic refining:

The fire-refined copper is then cast into anodes for even further purification by electrolytic refining. Electrolytic refining separates copper from impurities by electrolysis in a solution containing copper sulphate (Cu_2SO_4) and sulphuric acid (H_2SO_4). The copper from impure anode is dissolved and deposited at the cathode which is pure copper sheet. As the copper anode

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[13]*Notes: Input from Gleich Book: Blister copper(1.01 t), converter slag(0.03t), Fuel oil(1362MJ), Scrap copper(0.01t), Blast air(1.3 Ncu.m), secondary air(1127 Ncu.m), natural gas(261.3MJ), electrical energy(57.6MJ)*

For 1.21t blister copper, converter slag(0.035t) Fuel oil(1632MJ), Scrap copper(0.012t), Blast air(1.55 Ncu.m), secondary air(1350 Ncu.m), natural gas(313.04MJ), electrical energy(69MJ)
For 1t anodes, Slag 0.07t, offgas 1168Ncu.m, Radiation+heat 1550MJ
For 1.199t anodes, slag would be 0.083t, Offgas 1400Ncu.m, radiation+heat 1858 MJ

dissolves, metallic impurities precipitate and form sludge. Cathode copper, 99.95 to 99.96 percent pure, is then cast into bars, ingots, or slabs.
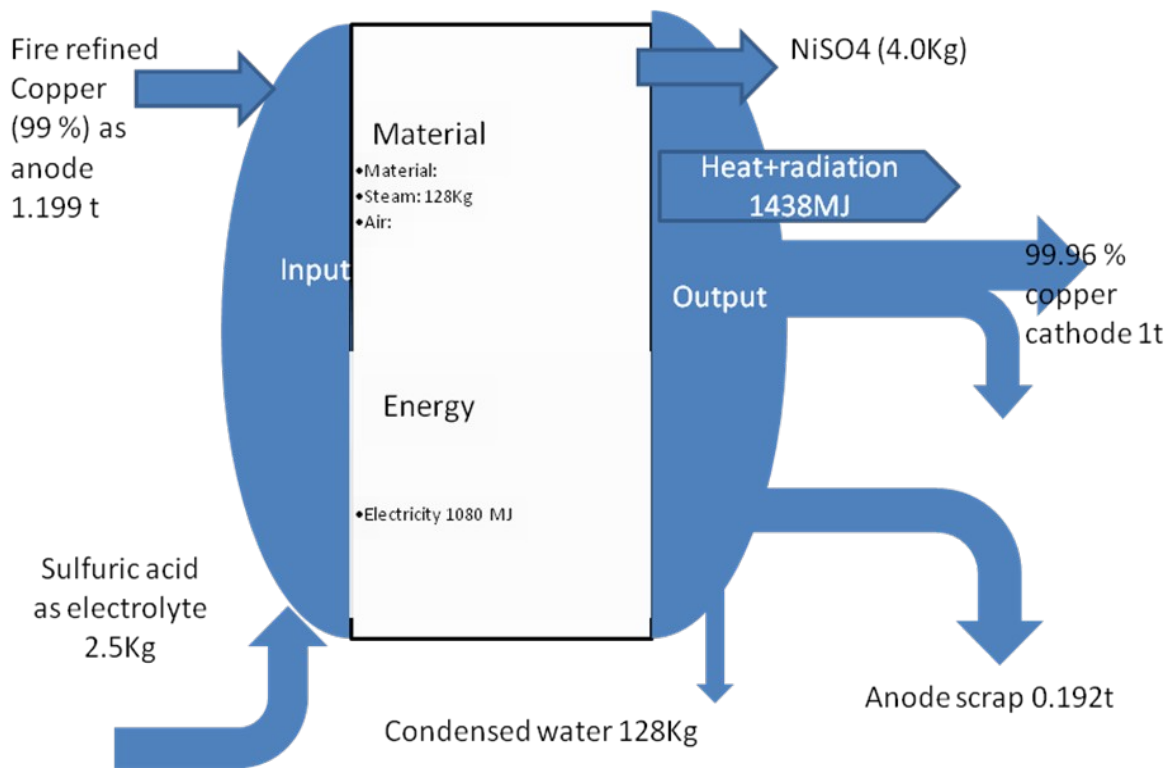
Figure 11 Electrolytic Refining[14]

2.4 Water usage in production of 1 ton of copper:

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[14] One mole of copper = 6.0221415×10^{23} atoms of copper, Each atom releases 2 electrons to ionize, The quantity of electricity required to deposit an amount of metal can be calculated: So Q =
Q = n(e) x F
Q = quantity of electricity in coulombs (C)
n(e) = moles of electrons
F = Faraday constant = 96, 500 C mol^{-1}
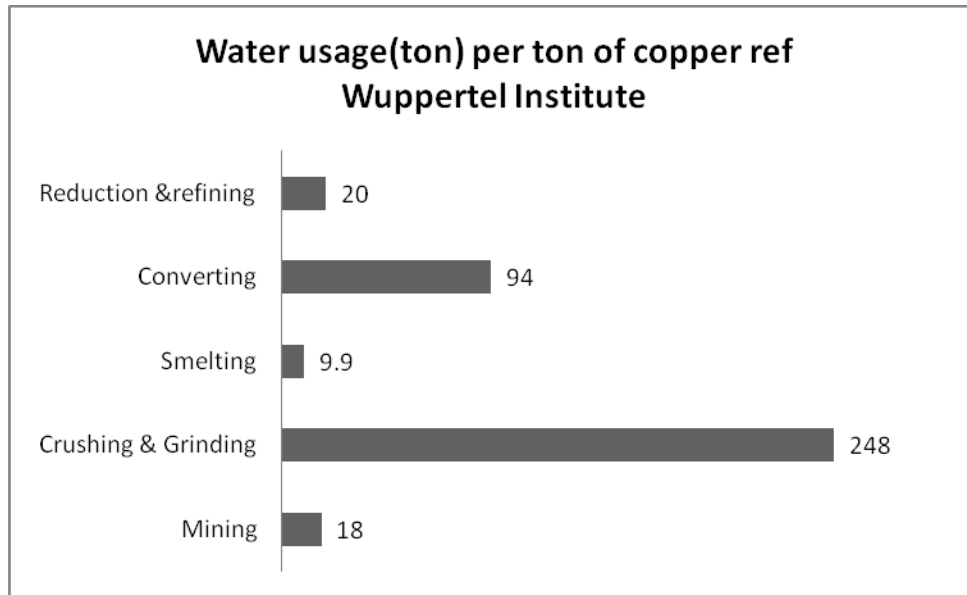
Figure 12 Water usage (ton) per ton of copper[15]

390 ton of water per ton of copper, which shows similarity with the data given in Ashby (Water usage *150 – 450 ton/ton of copper) [16]
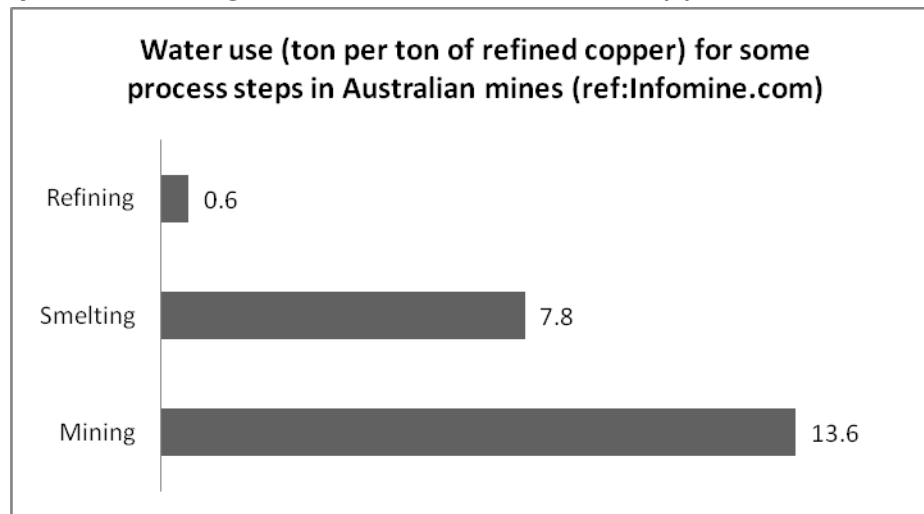
Figure 13 Water usage (ton) for some process steps in Australian mine

Additional water usage according to my calculation: Flotation: 152 tons, Electrolytic refining: 128 tons per ton of copper, Total: 280 Kg According to Ashby, Water usage *150 – 450 l/kg

3. Aluminium

[15] Jacob Sørensen in collaboration with NOAH's Sustainability Group, NOAH, 2005, Ecological rucksack, Friends of the Earth, Denmark

[16]Ashby MF. 2009. Materials and the Environment :Eco-Informed Material Choice. Butterworth-Heinemann.

Fig.4.3 shows simplified flow sheet for the production of aluminium. In brief, bauxite ore are mined from earth and processed to produce alumina which further smelted to produce primary aluminium.
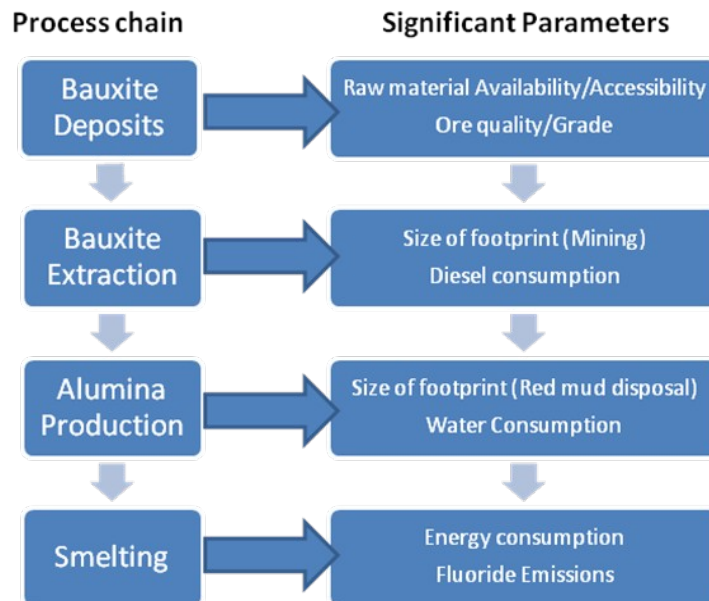
Figure 14 Simplified flow sheet for Primary Aluminium Production[17]

Aluminium from Al_2O_3:
Molecular weight of Al_2O_3 (101.96g)
Atomic weight of aluminium=26.98 g, atomic weight of oxygen=16 g
So 101.96 g Al_2O_3 gives 54 gm of Aluminium
Around 2 tons of Al_2O_3 would theoretically give 1 ton of Aluminium

3.1 Primary production of aluminium

Fig 6-4 shows Materials input per ton of aluminium production. Large amount of electricity needed in the final step of refining as well as to the considerable quantity of fuel oil used in the Bayer process. When focusing attention on wastes and emissions, it can be seen that major emissions are discharged into air. The oxygen in the purified alumina (from the Bayer process) reacts with a carbon anode, made from petroleum coke. The reaction emits 0.65 tonnes of CO_2 per tonne of primary aluminium produced. In addition, primary aluminium plants emitted about 0.02 tonnes of fluorine, per tonne of aluminium, partly as HF and partly as fluoride particulates. This is due to the breakdown of cryolite (an aluminium-sodium fluoride electrolyte used in the process, in which the alumina is dissolved) at the anode. Total airborne emissions from primary aluminium production in the U.S. (3.944 MMT) were, therefore, 2.564 MMT of CO_2, 0.08 MMT of fluorides and about

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[17] US energy requirements for Aluminium Production: Historical perspectives, Theoretical limits, and new opportunities, Choate & Green, US department of energy, Feb 2003

0.17 MMT of other particulates (Al_2O_3). Fluoride emissions, in terms of contained fluorine, can be estimated quite precisely from cryolite and aluminium fluoride consumption.

Figure 15 Flow chart of Aluminium production process[18]

2.1.1 Bauxite Mining

Bauxite is a mixture of aluminium oxide (Al_2O_3), other oxides, such as Fe_2O_3, SiO_2, TiO_2 and water. It is mostly mined by the open pit method; the largest deposits are usually located in tropical regions. After mining, the bauxite ore is crushed, washed and screened to separate clay and useless impurities; it is then dried in a rotary kiln and conveyed to mills to be processed. A typical composition — adapted from (Hall *et al.* 1975) — shows a high content of aluminium oxide, both monohydrate and tri-hydrate.

3.1.2 Alumina Production (Bayer Process)

In the standard Bayer process the hydrate aluminium oxide is transformed into dehydrated alumina (Al_2O_3). Major inputs of the process are bauxite ore (3924 kg), caustic soda (96 kg) and limestone (78 kg). Raw materials are mixed together then conveyed to the digester, where hot steam is added to the mixture. Due to the high pressure and heat of the solution, the available alumina dissolves in the caustic soda forming sodium aluminates ($NaAlO_2$). The purified solution of sodium aluminates, called `green liquor', is further processed to remove suspended solids and other insoluble impurities and, finally, to produce aluminium trihydrate by means of precipitation. The latter is next filtered, washed and calcined to drive off water and produce alumina. The pure alumina is then conveyed to the aluminium production plant, while the remaining liquor solution is processed to recover caustic soda. The residual of this process, called `red mud', is a batch of insoluble metal oxides – mostly iron – which are generally disposed of in ponds. Approximately 2.05 tonnes of red mud are produced for each tonne of pure aluminium.

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[18] Gleich Av, ed. 2006. Sustainable Metals Management. Springer

3.1.3 Aluminium Smelting (Hall-Heroult Process)

Metallic aluminium is produced by electrolytic reduction of alumina in the so called Hall-Heroult process. The reduction plant consists in a series of electrolytic cells made of steel. Each cell is equipped with a consumable carbon cathode and anode made of petroleum coke and pitch. Purified alumina from the Bayer process (approximately 1.96 tonnes per tonne of aluminium) is dissolved in a molten bath constituted of cryolite (Na_3AlF_6), fluorspar (CaF_2) and aluminium fluoride (AlF_3). This bath serves as an electrolyte. When a low-voltage direct current passes through the bath, alumina is reduced to pure metallic aluminium and oxygen. The oxygen combines with carbon from the anode forming CO_2 and CO, and a small amount of fluorine-carbon compounds. Aluminium is then removed from the bottom of the cell and transferred to the casting house. The specific emissions of carbon dioxide have been estimated[19]
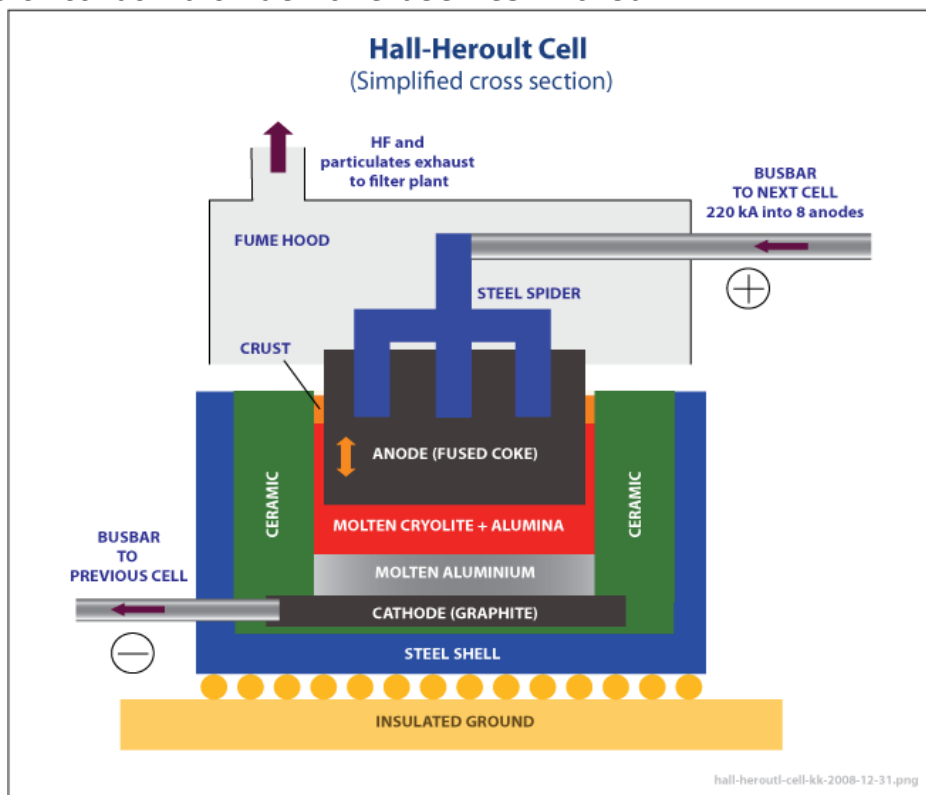
Figure 16 Hall-Herault process for Aluminium Smelting

3.2 Energy consumption

Fig.18 Shows amount of energy consumption in different steps of aluminium production. Table F1 gives the information about material and energy used for the production of one Kg of aluminium. The material and energy is separated for mining, refining, anodizing and electrolysis. Energy input in terms of fuel oil, electricity etc. is given. In the interest of simplicity, this

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[19] Ayres and Ayres 1996, chapter 3 Ayres, R.U., and L.W. Ayres (Eds.), A handbook of industrial ecology, Edward Elgar, 2002

report uses a zero theoretical minimum energy requirement for mining bauxite.

From the references[20], Electrical energy for electrolysis is 10-20 KWh/Kg i.e. 36-72 MJ/kg. From table, energy consumption for aluminium production is 74 GJ/ton, it is slightly lower than that in Ashby (200-240 GJ/ton) as in references subsequent processes like forming and rolling are mentioned which adds total energy consumption.
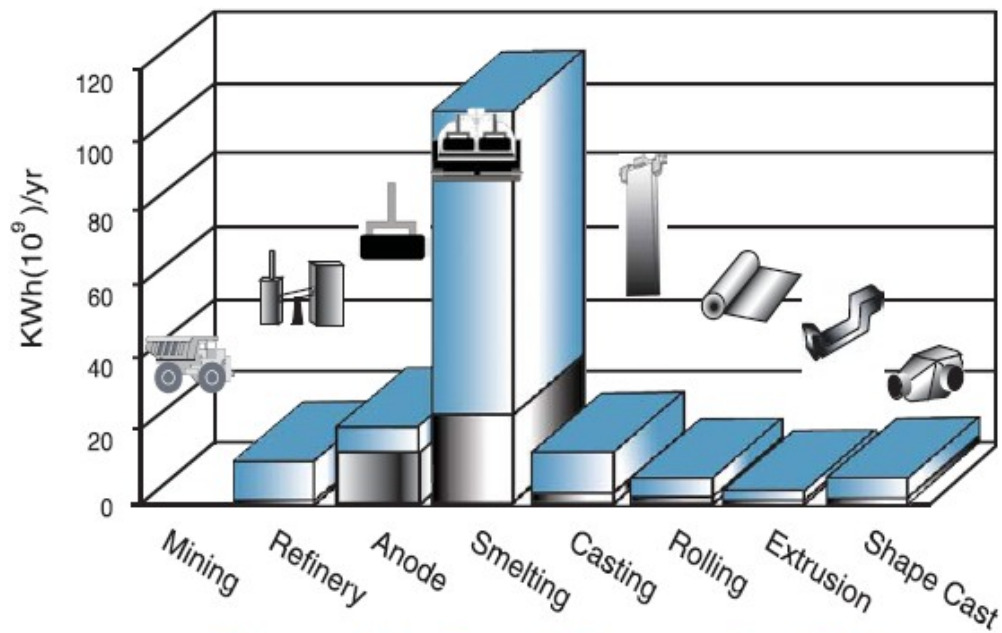
Diagram 3.0 - Energy^{tf} Consumption of U.S. Aluminum Operations

Figure 17 Energy consumption of U.S. Aluminium Operations

The total energy associated with primary aluminium production from bauxite ore was approximately 23.78(45.21^{tf}) kWh/kg of aluminium in 2000. This consisted of: 8.20(14.11^{tf}) kWh/kg aluminium for raw materials and 15.58(31.10^{tf}) kWh/kg aluminium for electrolytic reduction. In MJ/Kg, it turns out to be 85.60 MJ/Kg (i.e. 85.60 GJ/ton). (Ref: US energy requirements for Aluminium Production: Historical perspectives, Theoretical limits, and new opportunities, Choate & Green, US department of energy, Feb 2003).

Andre remark : Diagram 3.0: Mining can be roughly estimated from copper mining: aluminum is "20%" ore grade compared to 0.6% ore grade of copper --> 0.6/20 times 69 GJ/ton is around 2 GJ/ton for aluminum mining.

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[20] http://electrochem.cwru.edu/encycl/art-a01-al-prod.htm
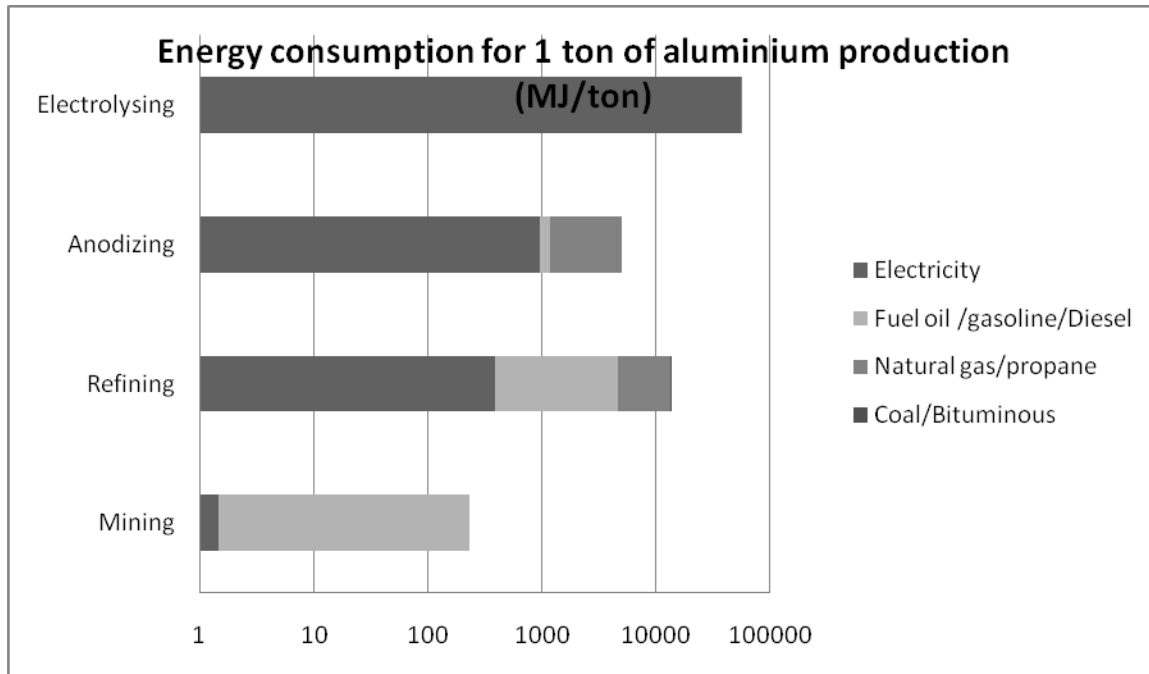
Figure 18 Distribution of energy consumption in Aluminium production
Table 2 Distribution of Energy consumption for Aluminium (MJ energy per ton)

	Mining	Refining	Anodizing	Electrolysis	Total consumption per energy type
Electricity	1.44	392	957	55430	56780.44
Fuel oil/gasoline/Diesel	230.62	4263	219.3	291.87	5004.79
Natural gas /propane		8600	3793	361	12754
Coal/Bituminous		268.9			268.9
Total consumption per process	232.06	13523.9	4969.3	56082.87	**74808.13**

3.3 Water usage in production of 1 ton of aluminium:

According to Ashby, water usage for the production of one ton of aluminium is 125 – 375 l/kg. With reference to Gleich[21], water usage for various sub process for the production of aluminium is given as:

43 Kg for caustic soda which goes to Bayer process for alumina production
15 Kg in Hall-Heroult process for electrolysis to produce aluminium
68 Kg for Sulphuric acid production
75 Kg for Hydrofluoric acid

[21] Gleich Av, ed. 2006. Sustainable Metals Management. Springer

Total: 201 Kg per 1 ton of aluminium which is different than what is given in Ashby (Water usage *). Ashby's number seems more logical.

4. Magnesium:

Table 3 Minerals of Magnesium

Material	Chemical formula
Magnesite	$MgCO_3$
Dolomite	$MgCO_3*CaCO_3$
Bischofite	$MgCl_2*6H_2O$
Carnallite	$MgCl_2*KCl*6H_2O$
Serpentine	$3MgO*2SiO_2*2H_2O$
Sea water	$Mg^{2+}_{(aq)}$

There are two ways to produce Primary Magnesium: Electrochemical method and thermal reduction method.

4.1 Production process

4.1.1 Electrochemical method

Extraction of magnesium from magnesium chloride takes place in two steps:
1. Preparation of magnesium chloride cell feed,
Magnesite ($MgCO_3$) in case of electrochemical method is leached by hydrochloric acid to give $MgCl_2$

$$MgCO_3 + 2 HCl \rightarrow MgCl_2 + CO_2 + H_2O$$
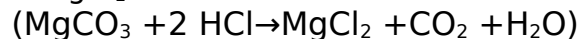
2. Electrolysis
The reduction of $MgCl_2$ is carried out with electric current fed into the electrolyte cells. Electrolysis of hot molten $MgCl_2$ affords magnesium as a liquid which is poured off and chlorine gas.[22]

Cathode: $Mg^{2+}(l) + 2e^- \rightarrow Mg$
anode: $Cl^-(l) \rightarrow \frac{1}{2}Cl_2 (g) + e^-$
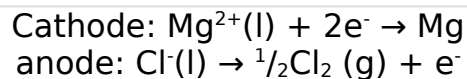
There are massive amounts of magnesium in seawater. This can be recovered as magnesium chloride, $MgCl_2$ through reaction with calcium oxide, CaO.

$CaO + H_2O \rightarrow Ca^{2+} + 2OH^-$
$Mg^{2+} + 2OH^- \rightarrow Mg(OH)_2$
$Mg(OH)_2 + 2HCl \rightarrow MgCl_2 + 2H_2O$
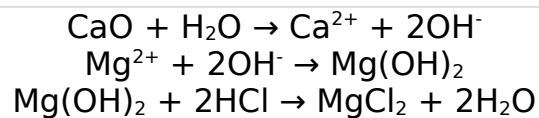
4.1.2 Thermal methods

The reduction is carried out by means of various reducing materials at high temperatures. The thermal reduction method is non electrolytic and involves dolomite, [$MgCa(CO_3)_2$], an important magnesium mineral. This is "calcined" by heating to form calcined dolomite, MgO.CaO,

$$CaCO_3 \cdot MgCO_3 + heat \rightarrow CaO \cdot MgO + 2CO_2$$

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[22] Ref: http://www.webelements.com/magnesium/
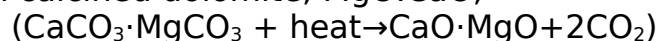
and this reacted with ferrosilicon alloy.

$$2[MgO.CaO] + FeSi \rightarrow 2Mg + Ca_2SiO_4 + Fe$$
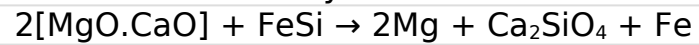
The magnesium may be distilled out from this mixture of products.

Figure 19 Production of Magnesium[23]

[23] Cherubini F, Raugei M, Ulgiati S. 2008. LCA of magnesium production: Technological overview and worldwide estimation of environmental burdens. Resources, Conservation and Recycling 52(8-9): 1093-1100.

4.2 Energy consumption[24]

Table 4 Electrical energy consumption (GJ) for the production of 1 ton of Mg[25]

Process	Mining(GJ)	Ingot production(GJ)	H2 production(GJ)	Total(GJ)
AM(Electrolytic)	0.5	59.32	0.72	60.54
Bolzano(Thermal)	1.28	72.72		74
Magnetherm(Thermal)	1.44	62.3		63.74
Pidgeon(Thermal)	1.41	45.43		46.84

Note: The country has to take into consideration because of the different mixes of primary and secondary energy sources (fuels and electricity) characteristic of each country. For example, the Bolzano process is nowadays only economically viable in those few countries such as Brazil, in which there is a large supply of cheap hydroelectricity for the electric furnaces.

From Habashi, Industrial cell requires energy of 10-20 KWh/kg of Magnesium. That comes out 36-72 MJ/kg or 36-72 GJ/ton.[26]

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[24] Theoretical calculation of ore tonnage requirement for one ton of magnesium:
Atomic weight of Mg: 24.03, Atomic weight of Ca: 40, Atomic weight of C:12, Atomic weight of Oxygen:16
Molecular weight of $[MgCa(CO_3)_2]$ = 24.03+ 40 + 2(12+48))
$$=184.03$$
So 184.03 gm of 100 % Dolomite theoretically gives 24.03 gm of Mg
 So 7.6 tons of 100% Dolomite is theoretical minimum required to get 1 ton of Magnesium metal

[25]Cherubini F, Raugei M, Ulgiati S. 2008. LCA of magnesium production: Technological overview and worldwide estimation of environmental burdens. Resources, Conservation and Recycling 52(8-9): 1093-1100.

[26]Habashi F, ed. 1997. Handbook of Extractive Metallurgy. WILEY-VCH.

Table 5 Comparison between electrolytic and Thermal reduction process
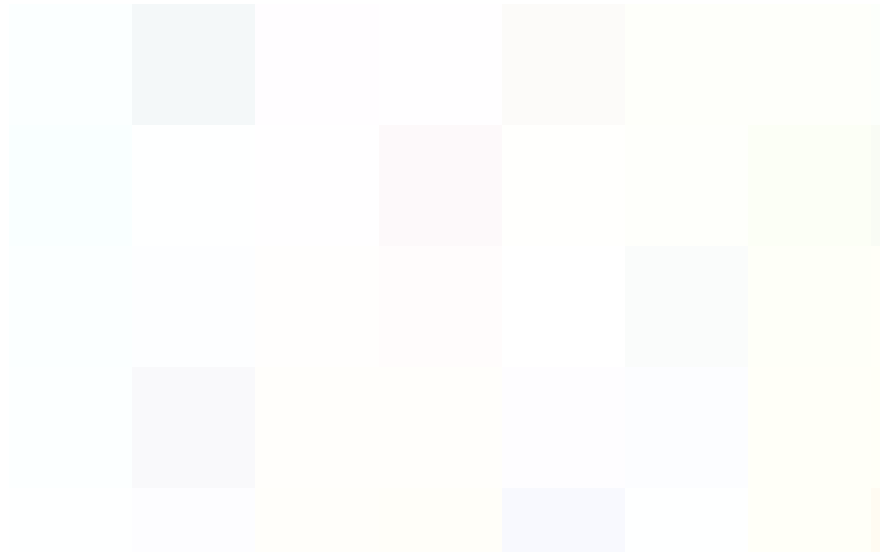
With reference to electrolytic technology, electric energy required would be (64.8-100.8) GJ per ton Mg and in case of thermal reduction technology: 162-288 GJ per ton production of Mg

Embodied energy for Magnesium: 356-394 GJ/ton[27]

4.3 Water usage (tons) in case of per ton of magnesium production

Water requirement (tons) in <u>ingot production</u> of magnesium (tons) for different processes:

AM: 17.63, Bolzano: 5.84, Pidgeon: 40.72, Magnetherm: 4.92

Considering the water material intensities, the Pidgeon, Magnetherm and in part AM processes have high water factors; this means that they should be performed in areas where water supplies are easily accessible and abundant.

Table 6 Material flow accounting per tonne of Mg product[28]

Process (country)	Abiotic MI (tonnes$_{ab}$/tonnes$_{Mg}$)	Water MI (tonnes$_w$/tonnes$_{Mg}$)
AM (Australia)	80.85	156.28
Bolzano (Brazil)	23.57	28.21
Magnetherm (France)	33.35	191.86
Pidgeon (China)	145.27	364.90

For Magnesium: Water usage *500 – 1500 l/kg[29]

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[27]Ashby MF. 2009. Materials and the Environment :Eco-Informed Material Choice. Butterworth-Heinemann.

[28] Cherubini F, Raugei M, Ulgiati S. 2008. LCA of magnesium production: Technological overview and worldwide estimation of environmental burdens. Resources, Conservation and Recycling 52(8-9): 1093-1100.

5. Titanium

Chief source of Titanium: Ilmenite (crystalline iron titanium oxide ($FeTiO_3$)).

5.1 Production

5.1.1 Kroll process:

The Kroll method is used on large scales and involves the action of chlorine and carbon (coke) upon ilmenite ($TiFeO_3$) or rutile (TiO_2). The process essentially consists of high temperature chlorination of rutile (TiO_2) or ilmenite (FeTiO3). The resultant titanium tetrachloride $TiCl_4$, is separated from the iron trichloride $FeCl_3$ in case of Ilmenite, by fractional distillation. Purification of the raw $TiCl_4$ from light and heavy fractions is done in order to remove low and high boiling impurities. The reduction of pure chloride by magnesium at high temperatures is done to produce sponge titanium in specially designed stainless steel reactors. Air is excluded so as to prevent contamination of the product with oxygen or nitrogen.
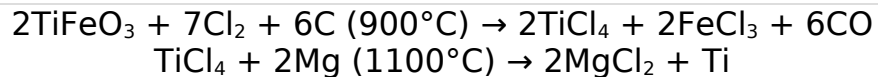
$$2TiFeO_3 + 7Cl_2 + 6C \ (900°C) \rightarrow 2TiCl_4 + 2FeCl_3 + 6CO$$
$$TiCl_4 + 2Mg \ (1100°C) \rightarrow 2MgCl_2 + Ti$$

Excess magnesium and magnesium dichloride is removed from the product by treatment with water and hydrochloric acid to leave a titanium "sponge". This can be melted under a helium or argon atmosphere or in vacuum to allow casting as bars.
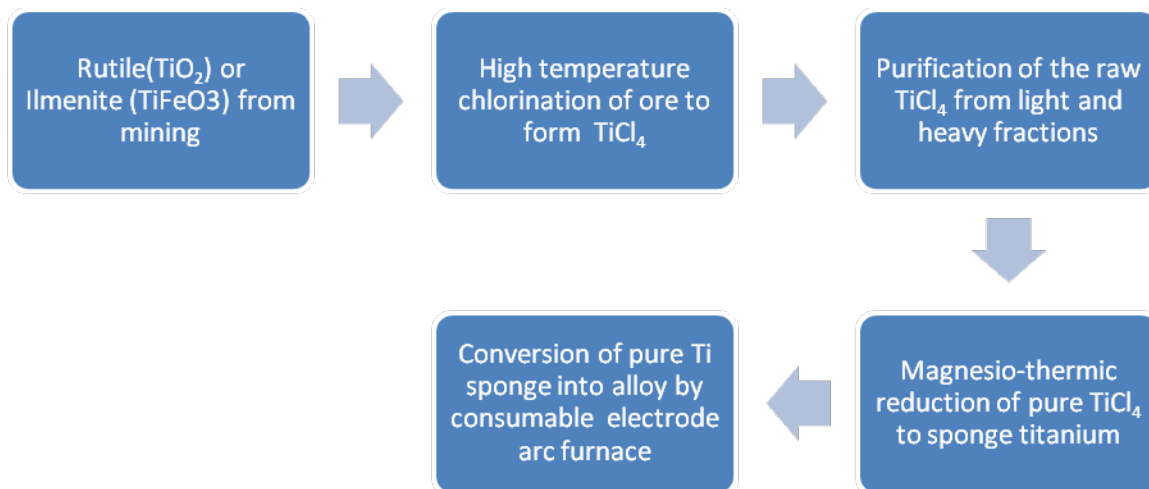
Figure 20 Flow chart of Titanium production process

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[29]Ashby MF. 2009. Materials and the Environment :Eco-Informed Material Choice. Butterworth-Heinemann.

5.1.2 Hunter's process

Alternative to Kroll process, Sodium can be used for reduction of $TiCl_4$ followed by aqueous leaching of the reduced mass.

$TiCl_4 + 4Na \rightarrow 4NaCl + Ti$
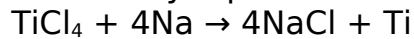
5.1.3 Electrolysis

The third route for titanium sponge production is also based on pure $TiCl_4$ as the starting material and involves fused salt electrolysis of $TiCl_4$ in a mixture of alkali/alkaline earth chlorides.[30]

Table 7 Operating conditions of 30 KA modular, monopolar cell (Defense Metallurgical Research Laboratory)[31]

Cell operating conditions		
Current	:	20–30 kA
Cell voltage	:	4·5–5·5 V
Operating temperature		700–730°C
Bath composition (in wt.%)	:	30% NaCl, 30% KCl
		20% $BaCl_2$, 15% $MgCl_2$
Results		
Average current efficiency	:	70%
Energy consumption (DC)	:	15–17 k Wh/kg
Average metal output per day	:	150 kg

5.2 Energy consumption

Power = 125 KW
Based on above information: Electrical Energy Consumption in the electrolysis: 54 GJ-61.2 GJ/ton of Titanium

Embodied energy for Titanium: 600-740 GJ/ton
(Ashby 2009)

Multiply the temperature (K) with Boltzmann's constant to get theoretical minimum required energy to the reaction to happen

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[30] I. Ya. Vinokurov MIP, G. V. Golov, G. I. Bogachev, L. D. Rozovskii, N. N. Kochetov and N. V. Orininskii. 1976. Production of foamed titanium slag Metallurgist 20(3): 180-182.

[31] Subramanyam RB. 1996. Development of technologies for large scale production of titanium and magnesium metals at the defence metallurgical research laboratory, Hyderabad Bulletin of Materials Science 19(6).

Molecular weight of TiFeO3 is 151.727 gm (Ti atomic weight = 47.88, Oxygen atomic weight = 16, Iron atomic weight = 55.847)
So 151.727 gm of TiFeO3 would give 47.88 gm of Titanium
And 3.169 tons of TiFeO3 would require producing 1 ton of Titanium

Molecular weight of TiCl4 is 189.68
Hence 189.68 of TiCl4 give 47.88 of Ti
4 tons of TiCl4 is required to produce 1 ton of Ti

Voltage or power required for electrolysis
Voltage times current is power: find the conversion between power and energy

Boltzmann's constant: $1.380\,6504(24) \times 10^{-23}$ J/K
        Temperature at which reaction occurs: 900 + 273 = 1073 K
        For equation of Mg and TiCl4,
        Theoretical Energy required for the production: KT
        $= 1.380\,6504 \times 10^{-23}(1173) = 1524.9 \times 10^{-23}$ J
Energy required to happen that reaction $= 1524.74 \times 10^{-23}$ J per mole
        Std. enthalpy of formation of TiCl4 = -804.16 kJ/mol
        From wiki
        TiCl4
Molecular weight = 189.71
        i.e. 189.71 grams per 1 mol of TiCl4
        Atomic weight of titanium: 47.88 g per mol
        Atomic weight of Chlorine: 35.453 g per mol

Theoretically we would get 47.88 g of Ti per mol of titanium chloride and it would cost us 1524.74×10^{-23} J energy
Hence 31.84×10^{-23} J /g of Titanium which seems stupid

5.3 Water usage

According to Ashby, the total water usage for the production of titanium metal is 470 – 1410 l/kg. This can be further separated into water usage for each process. There is large amount of water is required to wash Ilmenite sand to separate titanium rich ore from other (radioactive ores). Every ton of TiO_2 processed through the chlorine method will yield 2.4 tons of solid wastes, 90 kilograms of sulphur dioxide, and 3 kilograms of acidic and trace-metal-tainted effluents[32]. Water usage in the production of titanium slag is

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[32] Jayaraman N. October 24th, 2007. Titanium or Water? Trouble brews in Southern India. CorpWatch.

calculated by Vinokurov[33], 410-600 kg of water per ton of titanium slag input to produce titanium foam slag.

Molecular weight of TiO2= 79.88 g, 47.88 gm of Titanium is theoretically possible
So 1.6 ton of TiO2 would theoretically give 1 ton of titanium

6. Zirconium:

Important minerals of Zirconium: Zircon ($ZrSiO_4$), ZrO_2 (Zirconium dioxide), mostly found as a side product of other mineral recovery operations. As an ore, zircon is recovered from unconsolidated sands in beach deposits.[34]

Despite its ability to be used for many different industrial applications, most of the zirconium produced today is used in water-cooled nuclear reactors. Zirconium has strong corrosion-resistance properties as well as the ability to confine fission fragments and neutrons so that thermal or slow neutrons are not absorbed and wasted, thus improving the efficiency of the nuclear reactor. In fact, about 90 percent of the zirconium produced in 1989 was used in nuclear reactors, either in fuel containers or nuclear product casings.[35]

Molecular weight of Zircon is 183.3 (Zr= 91.22, Si=28.08, O=16)

So 183.3gm of Zircon can give 91.22 gm of Zr

2 tons of Zircon ore is theoretically required to get 1 ton of zirconium

primary metal.

6.1 Extraction Processes[36]

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[33] I. Ya. Vinokurov MIP, G. V. Golov, G. I. Bogachev, L. D. Rozovskii, N. N. Kochetov and N. V. Orininskii. 1976. Production of foamed titanium slag Metallurgist 20(3): 180-182.
Total water consumption per ton, m 3 . . . . 0.41-0.60
100 cm = 1 m, 100 X 100 X 100 cm3 = 1 m3, 1000000 cc= 1 m3, So 0.41-0.6 m3 = 4.1-600000 cc, i.e. 410-600 kg of water per ton of titanium slag input to produce titanium foam slag
[34] Habashi F, ed. 1997. Handbook of Extractive Metallurgy. WILEY-VCH.
[35] http://www.madehow.com/Volume-1/Zirconium.html
[36] Neil Osterwalder CC, Konrad Hungerbühler and Wendelin J. Stark. February, 2006. Energy Consumption During Nanoparticle Production: How Economic is Dry Synthesis? Journal of Nanoparticle Research Volume 8, (Number 1): 1-9.

6.1.1 Opening up of Ore:

Caustic Fusion:

Caustic fusion of Zircon with NaOH at 650°C (or Sodium carbonate at 1000°C) is the usual zircon decomposition process. Water hydrolyzes the sodium zirconate to soluble NAOH and insoluble hydrous zirconia which can be further filtered and dissolved in mineral acid for feeding to hafnium extraction process.

Chlorination: Fluidized-bed carbochlorination of milled zircon sand produces Zirconium chloride ($ZrCl_4$) as a powder

Lime fusion: production of calcium zirconate

Thermal dissociation: Arc plasma produces zirconium oxide

Carbiding: crude zirconium carbonitride ingot and subsequent chlorination

6.1.2 Hafnium separation for nuclear power industry:

Fluride salt crystallization: repeated crystallization of potassium hexafluorozirconate from hot acqueous solution

Methyl isobutyl ketone extraction: extraction of hafnium dihydroxide thiocyanate complex from hydrochloric acid solution by methyl isobutyl ketone

Tributyl phosphate extraction:

Extractive distillation:

Ion exchange for low input-low investment:

6.1.3 Reduction to metal:

Kroll process: Ductile zirconium metal is produced by reduction of pure zirconium tetrachloride with molten magnesium under an inert gas.

6.1.4 Refining

Iodine vapor is reacted with Kroll zirconium sponge or calcium-reduced zirconium metal powder to produce zirconium tetraiodide. The tetraiodide vapor diffuses to a heated filament, usually zirconium wire, where the iodide is thermally dissociated, depositing zirconium and releasing iodine to repeat the cycle.

According to White 1998 [Q299], energy requirement for power plant material zirconium is 161 TJ_{th}/GW_e (?) Van Leeuwen: 1610 GJ/Mg[37]

No of nuclear plant times their power output

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[37]Leeuwen JWSv. October 2007. Nuclear power – the energy balance. (Energy analysis – process data).Ceedata Consultancy.

Nuclear grade zirconium sponges at between \$60 and \$80 a kg, up from \$40 a kg five years ago.[38]

6.2 Energy calculation

Zirconium is available from commercial sources so preparation in the laboratory is not normally required. In industry, reduction of ores with carbon is not a useful option as intractable carbides are produced. As like titanium, the Kroll method is used for zirconium and involves the action of chlorine and carbon upon baddeleyite (ZrO_2). The resultant zirconium tetrachloride, $ZrCl_4$, is separated from the iron trichloride, $FeCl_3$, by fractional distillation. Finally $ZrCl_4$ is reduced to metallic zirconium by reduction with magnesium; Mg. Air is excluded so as to prevent contamination of the product with oxygen or nitrogen.
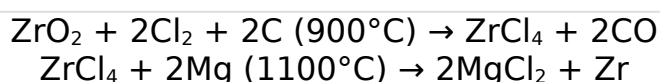
$$ZrO_2 + 2Cl_2 + 2C\ (900°C) \rightarrow ZrCl_4 + 2CO$$
$$ZrCl_4 + 2Mg\ (1100°C) \rightarrow 2MgCl_2 + Zr$$

Excess magnesium and magnesium dichloride is removed from the product by treatment with water and hydrochloric acid to leave a zirconium "sponge". This can be melted under helium by electrical heating.[39]

7. Cobalt

Many ores contain cobalt but not many are of economic importance. These include the sulphides and arsenides linnaeite, Co_3S_4, cobaltite, CoAsS, and smaltite, $CoAs_2$. Industrially, however, it is normally produced as a byproduct from the production of copper, nickel, and lead. In 2003 about 44% of world production of cobalt came from nickel ores.[40]

Table 8 Cobalt production Distribution by process (%)[41]

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[38] World Nuclear Association (http://www.world-nuclear.org/)

[39] http://www.webelements.com/zirconium/accessed on
[40] Cobalt Development Institute <http://www.thecdi.com/about-cobalt>
[41] Kapusta JPT. 2006. Cobalt production and Markets:An Overview. JOM: 33-36.

7.1 Production methods

Five different plants for production of primary cobalt have been described by (Wang 2006). Cobalt's extractive metallurgy from sulfide ores is most frequently linked with that of copper and nickel. The primary cobalt production process is based on the following principles, for example copper ore:

• Treating cobalt minerals within copper or nickel production processing

The first possible separation step is the froth flotation of the ore, in which special surfactants yield in an enrichment of cobalt. The following roasting of the ores can be conducted in a way that the cobalt sulphide is oxidized to the cobalt sulphate, while the copper and the iron are oxidized to the oxide.

• Concentrating cobalt-bearing material through copper or nickel pyro-metallurgical and hydrometallurgical operations

Treatment with sulphuric acid leaves metallic copper as a residue and dissolves out iron, cobalt, and nickel as the sulphates. The leaching with water extracts the sulphate together with the arsenates.

• Purifying cobalt solution/electrolyte by employing separation and purification techniques (e.g., selective precipitation, solvent extraction, and ion exchange)

The residues are further leached with sulphuric acid yielding a solution of copper sulphate. They also present iron nickel and cobalt salts can be precipitated by chlorine or hypo-chloride. If the copper is not produced by leaching and electrowinning but by the pyrometallurgic process, the cobalt can be leached from the slag of the copper smelter.[42] All the above-mentioned processes yield cobalt compounds which are transformed into the cobalt oxide Co_3O_4[43].

• Producing cobalt metal, cobalt powder, or cobalt chemicals in a selected independent process via electrorefining, electrowinning, or reduction precipitation: Cobalt is produced as the hydroxide by precipitation with sodium hypochlorite (NaOCl)

$$2Co^{2+}(aq) + NaOCl(aq) + 4OH^-(aq) + H_2O \rightarrow 2Co(OH)_3(s) + NaCl(aq)$$
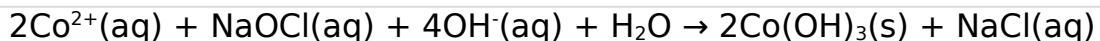
The trihydroxide $Co(OH)_3$ is heated to form the oxide and the reduction to the metal is done either by the aluminothermic reaction or reduction with carbon(as a charcoal) in a blast furnace.[4]

$$2Co(OH)_3 \text{ (heat)} \rightarrow Co_2O_3 + 3H_2O$$
$$2Co_2O_3 + 3C \rightarrow Co + 3CO_2$$
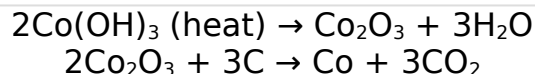
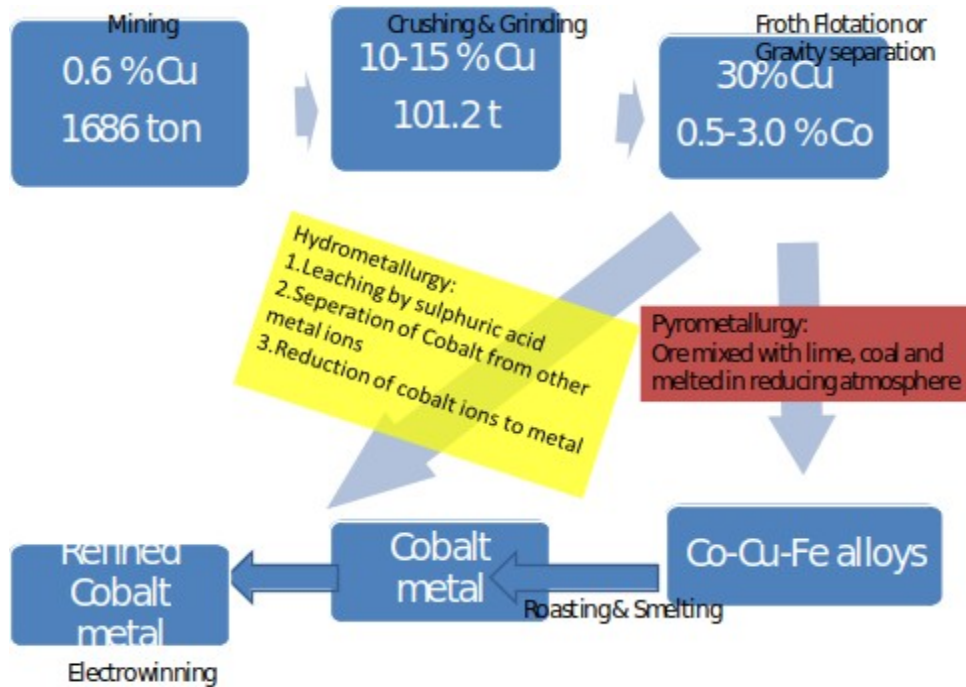[42] http://www.webelements.com/cobalt/
[43] Wikipedia

Figure 21 Steps in Cobalt Production

7.2 Energy consumption in the production of primary cobalt:

Energy consumption for mining and concentration and froth floatation for cobalt is same as a copper. The cobalt mineralization and typical examples are summarized in Table A. Owing to its great similarity to nickel in chemical properties; cobalt tends to follow nickel throughout the various concentrating operations of milling, smelting, and metal separation. Further, since cobalt minerals are commonly associated with ores of nickel, iron, silver, bismuth, copper, manganese, antimony, and zinc, the process includes intensive separation and purification techniques. Pure cobalt oxide or cobalt oxide hydrate can be reduced in hydrogen very readily at temperatures at least as low as 300^0C. The apparent activation energy of the cobalto-cobaltic oxide reduction has been reported to be about 17.8 kcal (74.47 KJ)[44]

Find out percentage of cobalt ore in Copper main ore

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[44] Keely WM. 1965. Differential Thermal Analysis Study of the Reduction of Cobalt Oxide, Iron Oxide, and Copper Oxide. Journal of Chemical and Engineering Data 10(2): 186-188./Kuznetsov, A.N., Shestopavalova, A.A., Kulish, N.F., Zh. Fiz. Khim. 32, 73-8 (1958)

COBALT PRODUCTION PROCESS AND PRINCIPLES

Cobalt's extractive metallurgy from sulfide ores is most frequently linked with that of copper and nickel. The cobalt mineralization and typical examples are summarized in Table A. Owing to its great similarity to nickel in chemical properties, cobalt tends to follow nickel throughout the various concentrating operations of milling, smelting, and metal separation. Further, since cobalt minerals are commonly associated with ores of nickel, iron, silver, bismuth, copper, manganese, antimony, and zinc, the process includes intensive separation and purification techniques. The primary cobalt production process is based on the following principles:

- Treating cobalt minerals within copper or nickel production processing
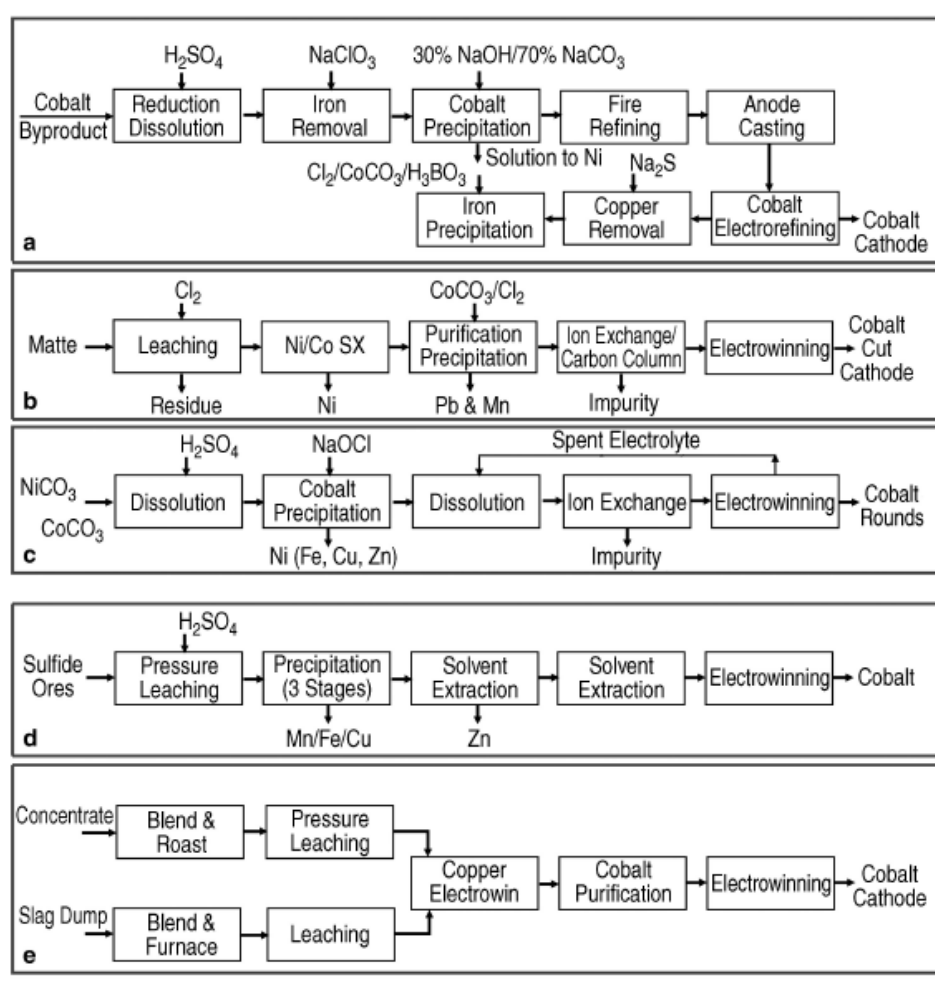- Concentrating cobalt-bearing material through copper or nickel pyrometallurgical

Figure A. Block flow diagrams of five different cobalt plants.

Figure 22 Cobalt production processes and principles[45]

8. Tungsten :

Tungsten occurs only in combined form. The most important tungsten minerals from industry point of view are Scheelite($CaWO_4$) and wolframite(WO_3).[46]

Table 9 Composition of Tungsten Ores

8.1 Production of tungsten:

8.1.1 Ore beneficiation

Most tungsten ores contain less than 1.5% WO_3. Hence it is required to crush and mill the ore depending on the size of the mineralization. After crushing the ore undergoes flotation process to concentrate around 60-70 %.

8.1.2 Pre-treatment of ore concentrates

Hydraulic acid leaching of scheelite concentrates at room temperature is used to reduce phosphorus, arsenic, and sulfur content. Calcination in air (500-600 ^{0}C) is used to oxidize organic flotation agents which could have detrimental effect on subsequent processing.

8.1.3 Hydrometallurgy

Hydrometallurgy is used to produce High purity ammonium paratungstate (APT) which is now the most important raw material for all other tungsten products. Tungsten feeds are digested in sodium hydroxide or sodium carbonate, and the sodium tungstate that results after purification steps is converted to APT after the separation of sodium via liquid ion exchange (LIX). General Flow diagram of hydrometallurgical process for Tungsten is as shown in figure 24.

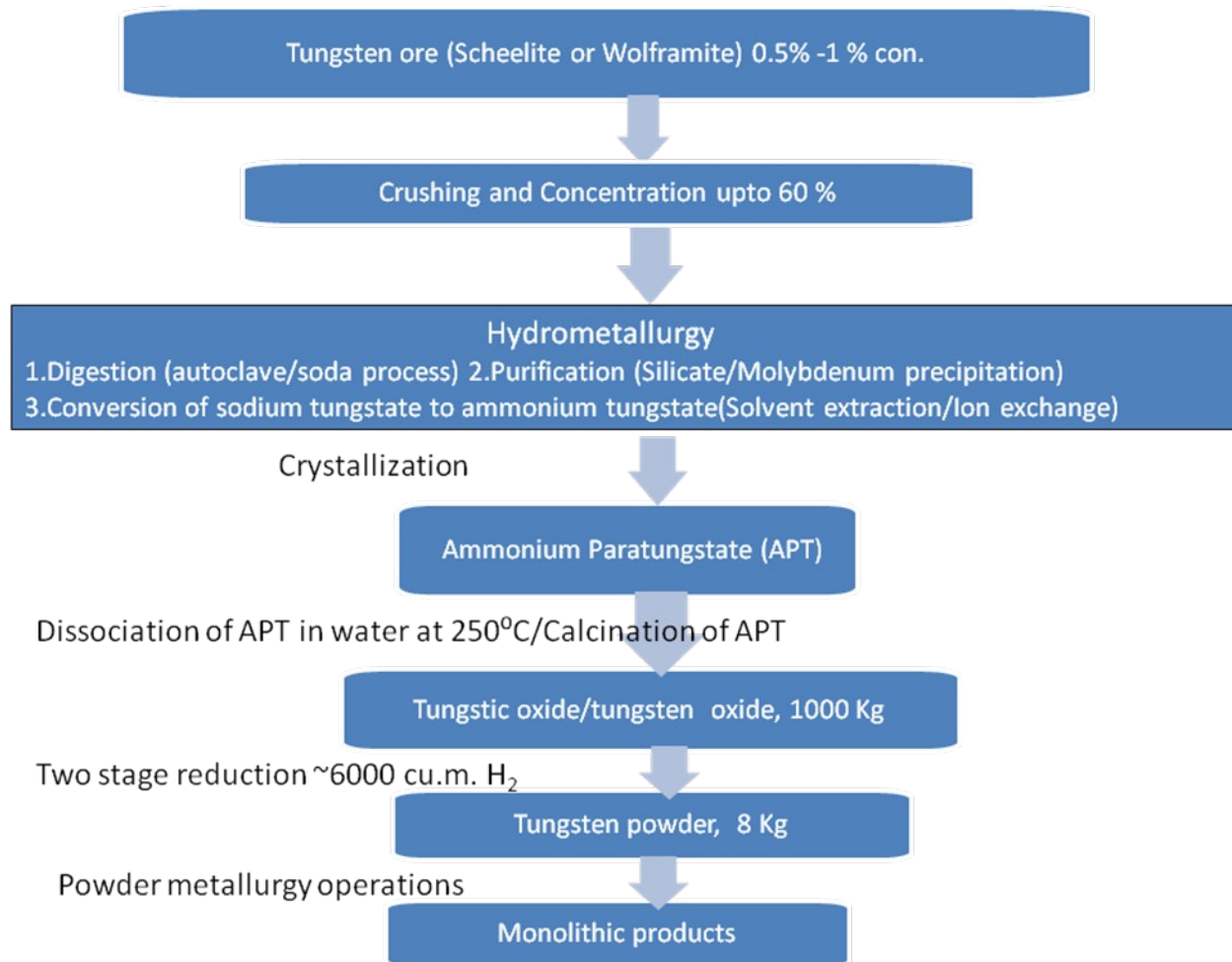[46] Habashi F, ed. 1997. Handbook of Extractive Metallurgy.Vol3 . WILEY-VCH.

Figure 23 Production process for tungsten metal[47],[48]

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[47] Werner Antony B.T. et al., International strategic mineral issues summary report-Tungsten, Washington-U.S. Government Printing office 1998

[48] Habashi F, ed. 1997. Handbook of Extractive Metallurgy.Vol3 . WILEY-VCH.
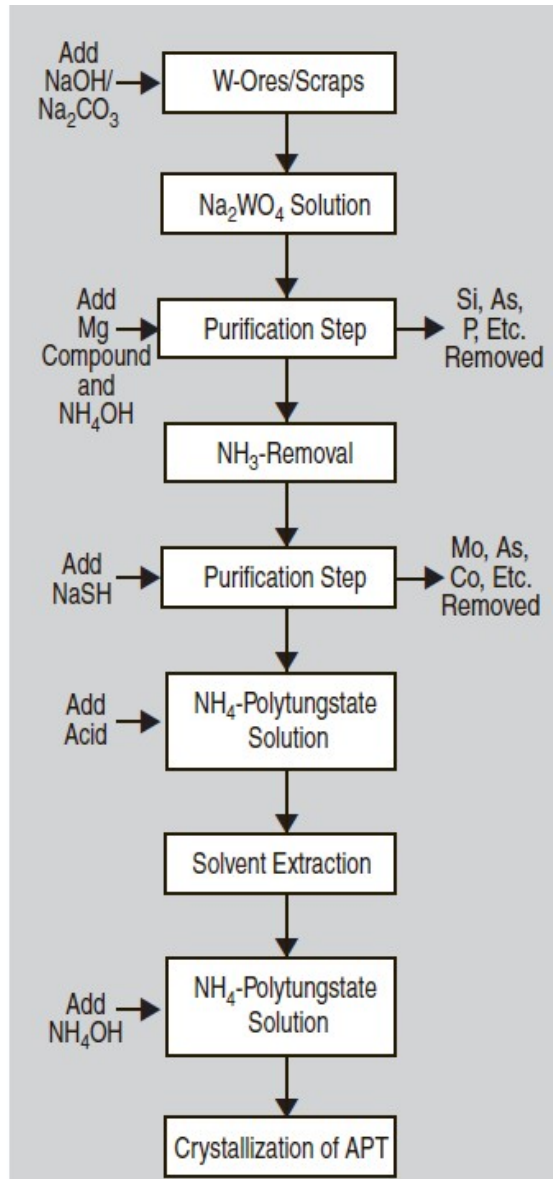
Figure 24 Synthesis of APT from ore[49]

8.2 Energy consumption

Embodied energy for tungsten is 400 MJ/Kg[50]

From data, 1000 Kg of Wolframite ore has 662 Kg WO_3. Molecular weight of WO_3 is 231.85 (W atomic weight =183.85 gm, O atomic weight 16 gm). So

Out of 231.85 kg of WO_3, we get 183.85 kg of W

Then, 662 Kg of WO_3 gives 525 kg of W theoretically

So from above, 1000 kg of Wolframite ore gives 525 kg of tungsten

[49] R.P. Singh gaur, Overview today's technologies tungsten JOM, September 2006, pp. 45-49

[50] Ashby MF. 2009. Materials and the Environment :Eco-Informed Material Choice. Butterworth-Heinemann.

According to USGS survey, tungsten in the form of powder is made from ammonium paratungstate (APT) [51]. A metric ton unit (mtu) of tungsten trioxide (WO_3) contains 7.93 kilograms of tungsten, so 1000 Kg of tungsten trioxide yields ~8 Kg of Tungsten (~125 kg of tungsten trioxide per kg of tungsten). There is no data on production of Tungsten primary metal from US.

9. Conclusion and recommendations

Table 10 summarize the results of the present study. For some metals (like copper) mining takes a relative large share of the total energy consumption for primary production. For other metals (like aluminium) electrolysis is responsible for the largest part of the energy consumption to concentrate the metal, the energy consumed during mining is negligible in comparison.
Water consumption is becoming a much more important issue in the primary production of metals since the associated cost of water consumption can no longer be neglected relative to the total cost. This is being caused by scarcity of water due to falling water tables and depleting aquifers, the need to expand desalination capacity to meet growing water consumption demand and the more stringent rules with regard to cleaning effluents to prevent degradation of the environment.

As mentioned in the introduction, the present report only covers a preliminary study into the consumption of energy and other resources (such as water) during the primary production of metals. Many metals have yet to be covered. Much more data is available in dedicated literature (expensive sources, covering one specific metal at a time) and most knowledge is (not publicly) available at the mining and refining industry.
Most existing infrastructure is only suitable for a certain quality (range) of ore grade. Moreover, the lower ore grades can be accompanied by higher relative amounts of "contaminants" for which the existing process equipment is not suited. Therefore, a follow-on study should also look into the consequences of falling ore grades for necessary changes, expansion or redesign of existing process equipment, besides the consequences for energy, water and ancillary resources (acids, chemicals, etc.) input.

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[51] R.P. Singh gaur, Overview today's technologies tungsten JOM, September 2006, pp. 45-49

Table 10 Summary : Primary Metal production

	Cu	Al	Mg	Ti	Zr	Co	W
Production process	Pyrometallurgy	pyrometallurgy	Pyro/hydrometallurgy	Pyro/hydrometallurgy	Pyro/hydrometallurgy	Pyro/hydrometallurgy	Pyro/hydrometallurgy
Electrical energy/ton	58	56	64-100 (Electrolysis) 162-288 (thermal)	54-61.2 (electrolysis)			
Total energy GJ/ton A:Ashby, L:Leeuwen	67-74[A]	200 – 240[A]	356-394[A]	600-740[A]	1600[L]		
Total energy GJ/ton (calculated)	130						
Water usage ton/ton(Ashby) water consumed during the operation	150 – 450[A]	125 – 375[A]	500-1500[A] $28^{Bolzano\ process} - 365^{Pidgeon\ process}$	470-1410[A]			
Main Mineral Ore	Chalcopyrite $(CuFeS_2)$	Boxite $(Al_2O_3,$ various oxides)	Magnesite $(MgCO_3)$, Dolomite $[MgCa(CO_3)_2]$,	Ilemnite $(TiFeO_3))$	Zircon $(ZiSiO_4)$	Byproduct of Copper mining transformed into cobalt oxide Co_3O_4	Wolframite (WO_3)
Theoretical (100%) tonnage of ore required /ton of metal production	3	2	7.6	$3.17(TiFeO_3)$ $1.6(TiO_2)$	2		2

Practical tonnage of ore required /ton of metal production Ore grades (references)	1686 (0.6% Ore grade)	5.1					175
Check the possibility							
Electrolysis process in the cell			MgCl$_2$ gives Mg + Cl$_2$				

Table 11 Summary of Information about Primary Metal Production

Table 12 Energy Consumption in Electrolysis of Selected Metals

Metal	Electrolytic process	Energy(GJ/ton)
Copper	Refining: Impure copper anode is dissolved in a solution containing copper sulphate (Cu$_2$SO$_4$) and sulphuric acid (H$_2$SO$_4$) and reappears at pure copper cathode sheet At anode Cu -> Cu^{2+} + 2e$^-$; At cathode Cu^{2+} + 2e$^-$ -> Cu	1.08(Gleich) (0.9) (http://electrochem.cwru.edu/encycl/)
Aluminum	Hall-Haroult process: Electrolyte is molten bath constituted of cryolite (Na$_3$AlF$_6$), fluorspar (CaF$_2$) and aluminium fluoride (AlF$_3$) Al$_2$O$_3$ = 2Al^{3+} + 3O^{2-} Cell reaction 2Al$_2$O$_3$ + 3C -> 4Al + 3CO$_2$	55.43 (36-72) (http://electrochem.cwru.edu/encycl/)
Magnesium	Electrolysis of hot molten MgCl$_2$, Cathode: Mg^{2+}(l) + 2e$^-$ → Mg, anode: Cl$^-$(l) → $^1/_2$Cl$_2$ (g) + e$^-$	36-72(Habashi)
Titanium	TiCl$_4$ in the bath of Chlorides	54-61.2(Subramanyam)
Zirconium		
Cobalt	SX-Electrowinning Electrorefining : Impure cobalt anode	
Tungsten		

Put introduction

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Water usage consumed, recycled