Materials Production;
energy used and carbon emitted

T. G. Gutowski

2.83/2.813
Readings

2. Ellingham Diagrams
3. Thermodynamics of Separation (Materials Separation and Recycling, Ch 4 Gutowski 2011)
4. Scale/Improvements (Gutowski, Sahni, Allwood, Ashby and Worrell, 2013)
Outline

1. Exploration and Mining
2. Smelting (liquid metal)
   - Iron (Fe)
   - Aluminum (Al)
   - Copper (Cu)
   - Gold (Au)
3. Liquid metal to sheet
4. Efficiency improvements
5. Prices, saturation and new materials
World Energy and Carbon

IEA 2010
The Role of Materials in Manufacturing

Final Energy

Rest of Industry 31%
Chemicals 14%
Other Materials 5%
Plastics 15%
Total Industry 120 EJ

Steel 20%
Cement 7%
Paper 6%
Aluminum 2%

Carbon Dioxide

Rest of Industry 29%
Chemicals 12%
Other Materials 4%
Plastics 6%
Aluminum 3%
Paper 4%
Total Industry 10.6 GtCO₂

Steel 24%
Cement 18%
What’s in the crust

**FIGURE 2.1** The average concentration of the elements in the earth’s crust, as parts-per-million (ppm) and as wt %. The top eight elements account for 98.5% of the total.
Diverse Sources of Uranium

Figure 5.15 The distribution of uranium in the earth's crust among the major geological reservoirs, plotted on a log-log plot (Source: Deffeyes\textsuperscript{16})
Figure 5.19 The metal contents of the largest known deposits of the geochemically scarce metals versus the crustal abundance of the elements (Source: Skinner$^{23}$)

What's at the mine
“McKelvey Box”
Exergy Analysis gives us the minimum work for Mat’l Prod

Geo-physical processes

Concentrated ore

Mining & concentrating

Pure ore

Materials production

Pure metal/mineral

Other inputs

Other inputs

Other inputs

Exergy Scale

Crustal composition
See Thermodynamics of Separation

Separate slides, and “Materials Separation and Recycling”, TG Ch 4
For Ideal Mixtures

\[ B_{\text{mixture}} = \sum N_i b_i + RT_0 \sum N_i \ln x_i \]

\[ B'_{\text{mixture}} = (N_1 - 1)b_1 + \sum_{2} N_i b_i + RT_0 (N_1 - 1)\ln x_1 + RT_0 \sum_{2} N_i \ln x_i \]

\[ W_{\text{min}} = -RT_0 \ln x_1 \]
“Separation”

\[ w_{\text{min}} = -T_0 R \sum_{i=1}^{n} x_i \ln x_i \]
“Extraction”

\[ W_{\text{min}}^{(N_1)} = -T_0 R \left( N_1 \ln x + N_2 \ln(1-x) \right) \]

\[ W_{\text{min}}^{(N_1-1)} = -T_0 R \left( (N_1-1) \ln x + N_2 \ln(1-x) \right) \]

\[ \omega_{\text{min, 1}} = T_0 R \left( \ln \frac{1}{x_1} \right) \]
Extraction from the crust: \(Fe_2O_3\)

Extracting \(Fe_2O_3\) from \(x = 1.3 \times 10^{-3}\) (crust) to \(x = 1\)

\[
e_x^o = T_o R \ln \frac{1}{1.3 \times 10^{-3}}
\]

\[
e_x^o = 298.2 K \times 8.314 \frac{J}{molK} \times \ln \frac{1}{1.3 \times 10^{-3}} = 16.5 \frac{kJ}{mol}
\]

Note: \(R = k N_{avo}\) (Boltzmann’s constant X Avogadro’s number)
Extraction from the crust: Gold

Extracting Au from \( x = 1.36 \times 10^{-9} \) (crust) to \( x = 1 \)

\[
e^o_x = T_o R \ln \frac{1}{1.36 \times 10^{-9}}
\]

\[
e^o_x = 298.2K \times 8.314 \frac{J}{molK} \times \ln \frac{1}{1.36 \times 10^{-9}} = 50.6 \frac{kJ}{mol}
\]

Szargut’s Table updated by Rivero & Garfias Energy (2006); was 50.5
“Sherwood Plot”

FIGURE 1 The Sherwood plot: Selling prices of materials correlate with their degree of dilution in the initial matrix from which they are being separated. Note that the horizontal axis shows increasing dilution, or decreasing concentration, in the initial matrix. SOURCE: National Research Council (1987).
Figure 3.7 The relationship between metal prices and typical ore grades
Cost Scaling for Metals

\[ k_v m_p c_v > k_c m_p, \text{ or } k_v > k_c/c_v \]

where

\( k_v \) is the market value of the target material ($ per kg of target material),
\( m_p \) is the total mass of ore processed (kg of ore),
\( c_v \) is the concentration of the target material in the ore (kg of target material per kg of ore), and
\( k_c \) is the cost of processing the ore ($ per kg of ore).
energy requirements for mining and milling, possible future trends

underground ~ 1000/g (MJ/t metal)

open pit ~ 400/g (MJ/t metal)

Chapman and Roberts p 113 & 116

Figure 7.9 The variation of the ger of mining and milling ($F_{mm}$) with ore grade ($g$)

Figure 7.11 A possible sequence of sources of copper and their energy requirements (Source: Skinner)
Importance of Dilution
<table>
<thead>
<tr>
<th>Compound</th>
<th>Formula</th>
<th>Mass Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silica</td>
<td>SiO₂</td>
<td>59.71%</td>
</tr>
<tr>
<td>Alumina</td>
<td>Al₂O₃</td>
<td>15.41%</td>
</tr>
<tr>
<td>Lime</td>
<td>CaO</td>
<td>4.90%</td>
</tr>
<tr>
<td>Magnesia</td>
<td>MgO</td>
<td>4.36%</td>
</tr>
<tr>
<td>Sodium oxide</td>
<td>Na₂O</td>
<td>3.55%</td>
</tr>
<tr>
<td>Iron(II) oxide</td>
<td>FeO</td>
<td>3.52%</td>
</tr>
<tr>
<td>Potassium oxide</td>
<td>K₂O</td>
<td>2.80%</td>
</tr>
<tr>
<td>Iron (III) oxide</td>
<td>Fe₂O₃</td>
<td>2.63%</td>
</tr>
<tr>
<td>Water</td>
<td>H₂O</td>
<td>1.52%</td>
</tr>
<tr>
<td>Titanium dioxide</td>
<td>TiO₂</td>
<td>0.60%</td>
</tr>
<tr>
<td>Phosphorus pentoxide</td>
<td>P₂O₅</td>
<td>0.22%</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>99.22%</td>
</tr>
</tbody>
</table>

Density ≈ 2.70g/cm³
$CO_2$ from Materials Production

• Reduction of oxides with carbon
  
  \[
  2Fe_2O_3 + 3C \rightarrow 4Fe + 3CO_2
  \]
  
  \[
  2Al_2O_3 + 3C \rightarrow 4Al + 3CO_2
  \]

• Calcination of limestone in cement production

  \[
  CaCO_3 + \text{heat} \rightarrow CaO + CO_2
  \]
Ellingham Diagram

\[ \Delta G = \Delta H - T\Delta S \]
However, most CO2 comes from fuel use
Smelting (Liquid Metal)

1. Iron - carbon reduction
2. Aluminum - electrolytic process
3. Copper - sulfide ores & recycling
4. Gold - the effects of dilution

refs Ayres 2006 and Mudd 2007
Iron: Important oxide ores

Hematite: $\text{Fe}_2\text{O}_3$

Magnetite: $\text{Fe}_3\text{O}_4$

Taconite

Blast Furnace

Iron Blast Furnace

Materials required:

1. Iron Ore
2. Carbon (coke is used both as fuel and reducing agent).
3. Hot air (hot enough to ensure combustion of the fuel).
4. Flux (removes earthy matter – turns into slag)
5. Slag (combination of calcium carbonate, silica, alumina and other impurities).

Source: http://www.yourdictionary.com/images/ahd/jpg/A4blfurn.jpg
Reactions taking place in the furnace:

• \(2 \text{C} + \text{O}_2 \rightarrow 2 \text{CO}\) (1300 °C)

• \(\text{CaO} + \text{SiO}_2 \rightarrow \text{CaSiO}_3\) (1200 °C)

• \(\text{FeO} + \text{CO} \rightarrow \text{Fe} + \text{CO}_2\) (800 °C - 1000 °C)

• \(\text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2\) (800 °C - 1000 °C)

• \(\text{CO}_2 + \text{C} \rightarrow 2 \text{CO}\) (800 °C)

• \(\text{Fe}_3\text{O}_4 + \text{CO} \rightarrow 3 \text{FeO} + \text{CO}_2\) (600 °C)

• \(3 \text{Fe}_2\text{O}_3 + \text{CO} \rightarrow 2 \text{Fe}_3\text{O}_4 + \text{CO}_2\) (450 °C)
Steel Exergy (US)

Figure 8: Exergy flows (mJ) in the production of 1 Mt steel (simplified processes, typical material mixes)

Ayres, Ayres and Masini, 2006
Steel Summary (US)

Figure 9: Steel unit mass and exergy flows

Material composition & processes are exemplary only
Wastes are pretreatment & pre-reprocessing
Process water included for chemical reactions only
Cooling water not included; overburden not included
Wastes include depleted air and water vapor

1 MT STEEL
FROM ORE [53% Fe]
& SCRAP [93% Fe]

Utilities Inputs

Material Inputs

Mass 7.261 MT
Embodied Exergy 18.757 gJ

Wastes & Losses

Air 3.797 MT (0.195 gJ)
Iron ore 1.648 MT (0.695 gJ)
Coking coal 0.377 MT (13.648 gJ)
Limestone 0.545 MT (0.029 gJ)
Fluorspar 0.333 MT (0.116 gJ)

Utilities Inputs

Exergy 5.157 gJ

Products & Byproducts

Mass (inc. byproducts) 1.386 MT
Embodied Exergy 8.686 gJ

Steel: 1.000 MT (6.750 gJ)
Byproducts

Slags: 0.334 MT (0.441 gJ)
Combustible offgas: 0.024 MT (0.914 gJ)
Coal tar, oil 0.015 MT (0.564 gJ)
Ferrous sulfate 0.012 MT (0.014 J)

Ayres, Ayres and Masini, 2006
Aluminum

It is the most abundant metal (7% of the earth’s crust) but one of the more energy intensive metals to refine

Aluminum occurrence:

Bauxite: $\text{Al}_2\text{O}_3 \cdot 2\text{H}_2\text{O}$

Cryolite: $\text{Na}_3\text{AlF}_6$

+ many silicates such as clay: $\text{H}_2\text{Al}_2(\text{SiO}_4)_2 \cdot \text{H}_2\text{O}$

Aluminum Production:


   A. **Extraction**: dissolve oxides with hot solution of NaOH.

   \[
   \text{Al(OH)₃} + \text{Na}^+ + \text{OH}^- \rightarrow \text{Al(OH)}₄^- + \text{Na}^+ 
   \]

   B. **Precipitation**: reverse of above, but controlling crystal formation.

   \[
   \text{Al(OH)}₄^- + \text{Na}^+ \rightarrow \text{Al(OH)}₃ + \text{Na}^+ + \text{OH}^- 
   \]

   C. **Calcination**: water is driven off Al(OH)₃ to form alumina (aluminum oxide).

   \[
   \text{Al(OH)}₃ \rightarrow \text{Al}_2\text{O}_3 + 3 \text{H}_2\text{O} 
   \]

Source: [http://www.world-aluminium.org](http://www.world-aluminium.org)

A. $\text{Al}_2\text{O}_3$ is dissolved in molten cryolite ($\text{Na}_3\text{AlF}_6$)

B. As the current passes through this mixture, (4-5 volts, 50,000-280,000 amperes) aluminum ions reduce to molten aluminum at the cathode, and oxygen is produce at the anode reacting with carbon to produce $\text{CO}_2$.

$$2 \text{Al}_2\text{O}_3 + 3 \text{C} \rightarrow 4 \text{Al} + 3 \text{CO}_2$$
Aluminum Exergy (US)

Ayers, Ayres and Masini, 2006
Aluminum Summary (US)

Ayres, Ayres and Masini, 2006
Main Ore Types for Copper

globally 90% sulfides, 10% oxides

$\text{Cu}_2\text{S}$: Chalcocite

$\text{Cu}_2\text{O}$: Cuprite

$\text{CuFeS}_2$: Chalcopyrite

(50% of Copper Production)

$\text{Cu}_2\text{CO}_3 (\text{OH})_2$: Malachite

Open-Pit Copper Mine, Utah

Source: http://encarta.msn.com/media_461533479_761561391_-1_1/Open-Pit_Copper_Mine_Utah.html
Chuquicamata, Chile
drilling rig in underground mine in the Głogow area of Poland

Copper concentrations in this area are about 2%.
Figure 5.1 The range of copper ore grades mined in the USA for three selected years (Source: Phillips and Edwards)
Historical Costs for Copper

Copper—U.S. Ingot and Electrolytic Copper Prices at Refinery, 1870–1997

Tilton, 2003
Głogow* Copper Smelter

*pronounced Gwogov
Copper Smelting Process

1) Copper Ore (~ 1%) → Concentrate (~20 to 35%)
   - milling, flotation, separation

2) Roasting and Smelting

\[
\begin{align*}
\text{CuFeS}_2 & \quad \rightarrow \quad \text{Cu}_2\text{S} \quad \text{(matte)} \quad \rightarrow \quad \text{Cu} \quad \text{(blister)} \\
& \quad \rightarrow \quad 2\text{FeOSiO}_2 \quad \text{(slag)} \\
& \quad \quad \quad \text{0.34 -1% Cu} \\
& \quad \rightarrow \quad \text{Cu} \quad \text{(blister)} \quad \sim 98\% \text{ Cu}
\end{align*}
\]
Copper Smelting Process

3) Roasting and Smelting

\[ 2\text{FeS} + 3\text{O}_2 \rightarrow 2\text{FeO} + 2\text{SO}_2 \]
\[ x\text{FeO} + y\text{SiO}_2 \rightarrow (\text{FeO})_x \cdot (\text{SiO}_2)_y \quad \text{- slag} \]
\[ 2\text{Cu}_2\text{S} + 3\text{O}_2 \rightarrow 2\text{Cu}_2\text{O} + 2\text{SO}_2 \]
\[ \text{Cu}_2\text{S} + 2\text{Cu}_2\text{O} \rightarrow 6\text{Cu} + \text{SO}_2 \quad \text{(blister copper ~98%)} \]

4) Electrolytic Refining (99.99%)

- sulfuric acid electrolyte
- anode mud (1:100) contains (Cu, Ag, As, Se, Bi, ..Au, Te…)
electro-refining of copper

Cu(s) ↔ Cu^{2+}(aq) + 2e^{-}

<table>
<thead>
<tr>
<th></th>
<th>Cu</th>
<th>Ag</th>
<th>Au</th>
<th>Se</th>
<th>Te</th>
<th>As</th>
<th>Sb</th>
<th>Bi</th>
<th>Fe</th>
<th>Ni</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>20</td>
<td>5</td>
<td>0.5</td>
<td>5</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>3</td>
<td>0.25</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Anode slime analysis (%) see Greadel et al (2002)
Figure 1  The metal wheel showing metal linkages in natural resource processing, illustrating the capacity of available metallurgical processes to deal with impurities in their (primary or secondary) feed. The sectors or wedges of the circle represent the metallurgy of the carrier metal. The bold radial lines divide metallurgical recovery into three main areas, namely sulfide metallurgy, oxide metallurgy, and a mixture of sulfide and oxide metallurgy, whereas the lighter radial lines separate the metallurgy of individual commodity metals. Coelements are economically and technologically valuable minor elements or impurities found in ores of carrier or commodity metals (Verhoef et al. 2003).
Copper Summary (US)

Figure 13: Primary copper mass and exergy flows

- Material composition & processes are exemplary only
- Wastes are pretreatment & pre-reprocessing
- Process water included for chemical reactions only
- Cooling water not included, overburden not included
- Wastes include depleted air and water vapor

1 MT PRIMARY COPPER PRODUCTION
- 73% from sulfide ores, 0.63% Cu
- 27% from oxide ores, 0.58% Cu

Mass (inc. byproducts) 1.67 MT
Embodied exergy 3.22 gJ

Utilities Inputs

Material Inputs
- Mass 204 MT
- Embodied exergy 67.8 gJ

Wastes & Losses
- Waste mass 202 MT
- Waste embodied exergy 21.1 gJ
- Waste heat exergy 90.9 gJ

Products & Byproducts
- Product copper 1 MT 2.11 gJ
- Potential byproduct sulfuric acid 0.687 MT 1.11 gJ

Ayres, Ayres and Masini, 2006
Copper Mass Flows (US)

Ayres, Ayres and Masini, 2006
Copper Exergy (US)

Figure 12: Exergy flows (mI) in the production of 1 Mt copper (simplified processes, typical material mixes)

Ayres, Ayres and Masini, 2006
Tailings pond at Głogow, Poland about 7 km across
Estimated concentration of tailings ~ 0.2%, these tailings will be mined in the future
Gold Production

Placer Gold

Open Pit Nevada

Metal Slimes from Cu Production
Open Pit Mining

Open Pit Mine in Nevada

Ore grades (ppm) Vs Time

Ref Gavin Mudd 2007
Open Pit Process

- Milling (grinding)
- Froth floatation
- Sodium Cyanide leaching
  \[
  4 \text{Au} + 8 \text{NaCN} + \text{O}_2 + 2 \text{H}_2\text{O} \rightarrow 4 \text{Na[Au(CN)\textsubscript{2}]} + 4 \text{NaOH}
  \]
- Precipitation
  \[
  2 \text{Au(CN)} + \text{Zn} = 2\text{Au} + \text{Zn(CN)}\textsubscript{4}^{-2}
  \]
- Extraction (Carbon in Pulp)
Cerro Vanguardia Gold and Silver Mine, Argentina
Energy Consumption Intensity and the Sustainability of Gold Mining

- Central & South America - (5.77, 1,076)
- Africa
- Asia-Pacific
- Australia
- Canada
- Central & South America
- United States

Energy Consumption per Gold Produced (GJ/kg Au) vs. Gold Grade (g/t Au)
Water
Figure 5 – Cyanide Consumption in Gold Production
Figure 6 – Greenhouse Gas Emissions per Gold Produced
Summary

<table>
<thead>
<tr>
<th>Metal</th>
<th>Element</th>
<th>Ref. Compound</th>
<th>Common Ore</th>
<th>$e_x^0$ MJ/kg</th>
<th>(-T_oR ln $x_{ref}$) as % of total</th>
<th>ΣLHV “embodied energy”</th>
<th>Apparent efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron</td>
<td>Fe</td>
<td>Fe₂O₃</td>
<td>Fe₂O₃</td>
<td>6.7</td>
<td>4%</td>
<td>~22MJ/kg</td>
<td>30%</td>
</tr>
<tr>
<td>Alu</td>
<td>A1</td>
<td>Al₂SiO₅</td>
<td>Bauxite, silicates</td>
<td>29.5</td>
<td>2%</td>
<td>~200 MJ/kg</td>
<td>15%</td>
</tr>
<tr>
<td>Copper</td>
<td>Cu</td>
<td>CuC₀₃</td>
<td>Sulfides carbonates</td>
<td>2.1</td>
<td>23%</td>
<td>~70 MJ/kg</td>
<td>3%</td>
</tr>
<tr>
<td>Zinc</td>
<td>Zn</td>
<td>ZnC₀₃</td>
<td>Sulfides carbonates</td>
<td>5.2</td>
<td>8.5%</td>
<td>~72MJ/kg</td>
<td>7%</td>
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<tr>
<td>Gold</td>
<td>Au</td>
<td>Au</td>
<td>Au</td>
<td>0.27</td>
<td>100%</td>
<td>~70GJ/kg</td>
<td>0.0004%</td>
</tr>
</tbody>
</table>
Liquid Metal to sheet stock
Material Flow Diagrams

Allwood, Cullen & Milford ES&T, 2010
Energy intensity of downstream processes

### Table 3
Steel process summary table.

<table>
<thead>
<tr>
<th>Process</th>
<th>Yield (%)</th>
<th>Primary energy GJ/t output</th>
<th>Emissions t CO₂/t output</th>
<th>Process</th>
<th>Yield (%)</th>
<th>Primary energy GJ/t output</th>
<th>Emissions t CO₂/t output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sintering</td>
<td>82</td>
<td>1.6</td>
<td>0.27</td>
<td>Fabrication</td>
<td>99</td>
<td>0.30</td>
<td>0.02</td>
</tr>
<tr>
<td>Coking</td>
<td>100</td>
<td>3.2</td>
<td>0.30</td>
<td>Pickling</td>
<td>95</td>
<td>0.75</td>
<td>0.04</td>
</tr>
<tr>
<td>Ironmaking</td>
<td>99</td>
<td>12</td>
<td>0.50</td>
<td>Cold rolling</td>
<td>99</td>
<td>0.9</td>
<td>0.05</td>
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<tr>
<td>Steelmaking</td>
<td>88</td>
<td>-0.3</td>
<td>0.10</td>
<td>Galvanising</td>
<td>91</td>
<td>1.5</td>
<td>0.09</td>
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<tr>
<td>Refining</td>
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<td>0.02</td>
<td>Slitting</td>
<td>98</td>
<td>0.1</td>
<td>0.01</td>
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<td>Casting</td>
<td>97</td>
<td>0.1</td>
<td>0.01</td>
<td>Blanking</td>
<td>90</td>
<td>0.3</td>
<td>0.02</td>
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<tr>
<td>Hot rolling</td>
<td>95–97</td>
<td>2.2–2.4</td>
<td>0.17–0.19</td>
<td>Stamping</td>
<td>68</td>
<td>1.2</td>
<td>0.07</td>
</tr>
</tbody>
</table>

### Table 4
Aluminium process summary table.

<table>
<thead>
<tr>
<th>Process</th>
<th>Yield (%)</th>
<th>Primary energy GJ/t output</th>
<th>Emissions t CO₂/t output</th>
<th>Process</th>
<th>Yield (%)</th>
<th>Primary energy GJ/t output</th>
<th>Emissions t CO₂/t output</th>
</tr>
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<tbody>
<tr>
<td>Bauxite extraction</td>
<td>86</td>
<td>0.1</td>
<td>0.01</td>
<td>De-reeling and lubrication</td>
<td>100</td>
<td>1.1</td>
<td>0.06</td>
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<td>Alumina production</td>
<td>37</td>
<td>15</td>
<td>0.77</td>
<td>Cupping</td>
<td>85</td>
<td>1.6</td>
<td>0.09</td>
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<tr>
<td>Anode manufacture</td>
<td>98</td>
<td>4</td>
<td>0.62</td>
<td>Body making and trimming</td>
<td>98</td>
<td>11</td>
<td>0.61</td>
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<tr>
<td>Smelting</td>
<td>53</td>
<td>132</td>
<td>6.78</td>
<td>Casting</td>
<td>88</td>
<td>7.5</td>
<td>0.40</td>
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<tr>
<td>Ingot casting</td>
<td>93</td>
<td>1.4</td>
<td>0.13</td>
<td>Homogenising</td>
<td>99</td>
<td>1.4</td>
<td>0.07</td>
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<tr>
<td>Remelting</td>
<td>92</td>
<td>4.7</td>
<td>0.27</td>
<td>Edge cropping</td>
<td>92</td>
<td>0.1</td>
<td>0.01</td>
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<tr>
<td>Sawing</td>
<td>84–96</td>
<td>0.0–0.5</td>
<td>0.00–0.03</td>
<td>Solution heat treatment</td>
<td>99</td>
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<td>0.28</td>
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<td>Scalloping</td>
<td>87–95</td>
<td>0.1–0.3</td>
<td>0.01</td>
<td>Levelling</td>
<td>99</td>
<td>0.3</td>
<td>0.02</td>
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<tr>
<td>Preheating</td>
<td>99–100</td>
<td>0.2–4.6</td>
<td>0.01–0.25</td>
<td>Stretching</td>
<td>99</td>
<td>0.2</td>
<td>0.01</td>
</tr>
<tr>
<td>Hot rolling</td>
<td>89–92</td>
<td>1.4–2.3</td>
<td>0.08–0.12</td>
<td>Precipitation heat treatment</td>
<td>99</td>
<td>1.0</td>
<td>0.06</td>
</tr>
<tr>
<td>Cold rolling</td>
<td>95</td>
<td>1.3</td>
<td>0.08</td>
<td>Testing</td>
<td>100</td>
<td>0.0–1.0</td>
<td>0.00–0.05</td>
</tr>
<tr>
<td>Annealing</td>
<td>100</td>
<td>1.2</td>
<td>0.07</td>
<td>Machining</td>
<td>29–55</td>
<td>1.1–3.2</td>
<td>0.05–0.16</td>
</tr>
<tr>
<td>Slitting</td>
<td>96</td>
<td>0.1</td>
<td>0.00</td>
<td>Inspection</td>
<td>100</td>
<td>0.0</td>
<td>0.00</td>
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<tr>
<td>Blanking</td>
<td>90</td>
<td>0.3</td>
<td>0.02</td>
<td>Packing</td>
<td>100</td>
<td>0.0</td>
<td>0.00</td>
</tr>
<tr>
<td>Stamping</td>
<td>72</td>
<td>1.2</td>
<td>0.07</td>
<td>Releasing</td>
<td>100</td>
<td>0.5</td>
<td>0.03</td>
</tr>
</tbody>
</table>
Down stream yield losses and embodied energy

Fig. 3. Cumulative energy against cumulative yield – normalised steel.
And CO2

Fig. 5. Cumulative CO₂ against cumulative yield – normalised steel.
Steel dominates

(Ashby, 2011)
World Steel Production 1900-2010

*World Steel Association*

*The New Industrial Revolution*

Figure 5: China’s steel production since 1900, set against Germany, US, Japan and the UK

Notes: World output in million tonnes shown in brackets.

*Peter Marsh, 2012*
Data taken from Ashby 2009
Aluminum Smelting

Energy Intensity (Wh/g)

Production, 1000's tonnes

y = 175.59x^{0.139}
R^2 = 0.98567

Aluminum Smelting 75%
Bauxite Mining 0%
Alumina Refining 13%
Anode Production 10%
Primary Casting 2%
Trends in energy intensity

Aluminum: Hall-Heroult Process

IEA
Material Prices

Figures from Ashby 2009
Apparent Saturation in Steel Stocks

![Graph showing iron stocks versus GDP](image)

**FIGURE 3.** Per capita iron stocks in use versus per capita GDP PPP (1990 international dollars). Iron stock data are based on medium lifetime assumptions, except for Japan, where lower lifetime estimates were applied. The thick gray-green line is a fitted logistic growth curve used to estimate the contemporary iron stocks in other countries.

*Muller 2001*
88
2 orders of mag.

4 to 5 orders of mag.

Ashby 2009