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Hard-to-abate metals: the case of steel and aluminium

MSE-433 Towards Sustainable Materials

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Learning objectives

- What is the economy and impact of metals
- How to recycle metals and what are the main challenges
- What are the challenges for steel and Al to achieve a circular economy

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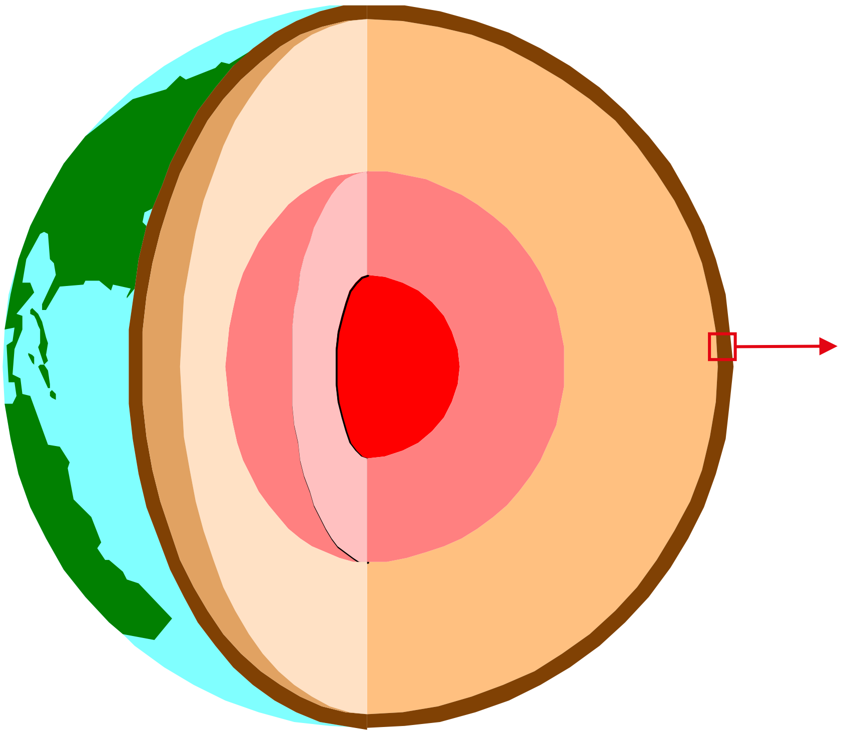
Outline

1. The economics and impact of metals
2. Strategies to reduce the energy intensity of primary Fe and Al
3. Recycling metals and the case of Al beverage cans
4. A model of future energy demand
5. Summary

Earth crust composition



46.46 %	Oxygen
26.61 %	Silicon
8.07 %	Aluminium
5.06 %	Iron
3.64 %	Calcium
2.83 %	Natrium
2.58 %	Potassium
2.07 %	Magnesium
0.62 %	Titanium
0.14 %	Hydrogen
0.12 %	Phosphor
0.09 %	Carbon
0.09 %	Manganese
0.06 %	Sulfur
0.0001 %	Copper

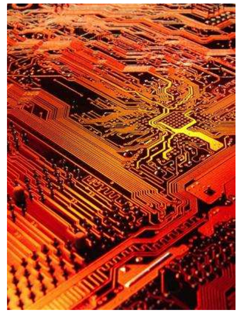
Metal production and demand

- Metal ores are extracted from mines and treated to obtain pure metals, which represents ~ 8% of the global energy consumption and fossil-fuel related CO_2 emissions.
- Rising needs: as populations in emerging economies adopt similar technologies and lifestyles as currently used in OECD countries, global metal needs over the 21st century will be 3 to 9 times larger than all the metals currently used in the world.
- Challenges with primary metals:
  - High energy costs related to extraction and conversion
  - Environmental and social impacts associated with mining
  - Limited resource, location-dependence

Main families and applications

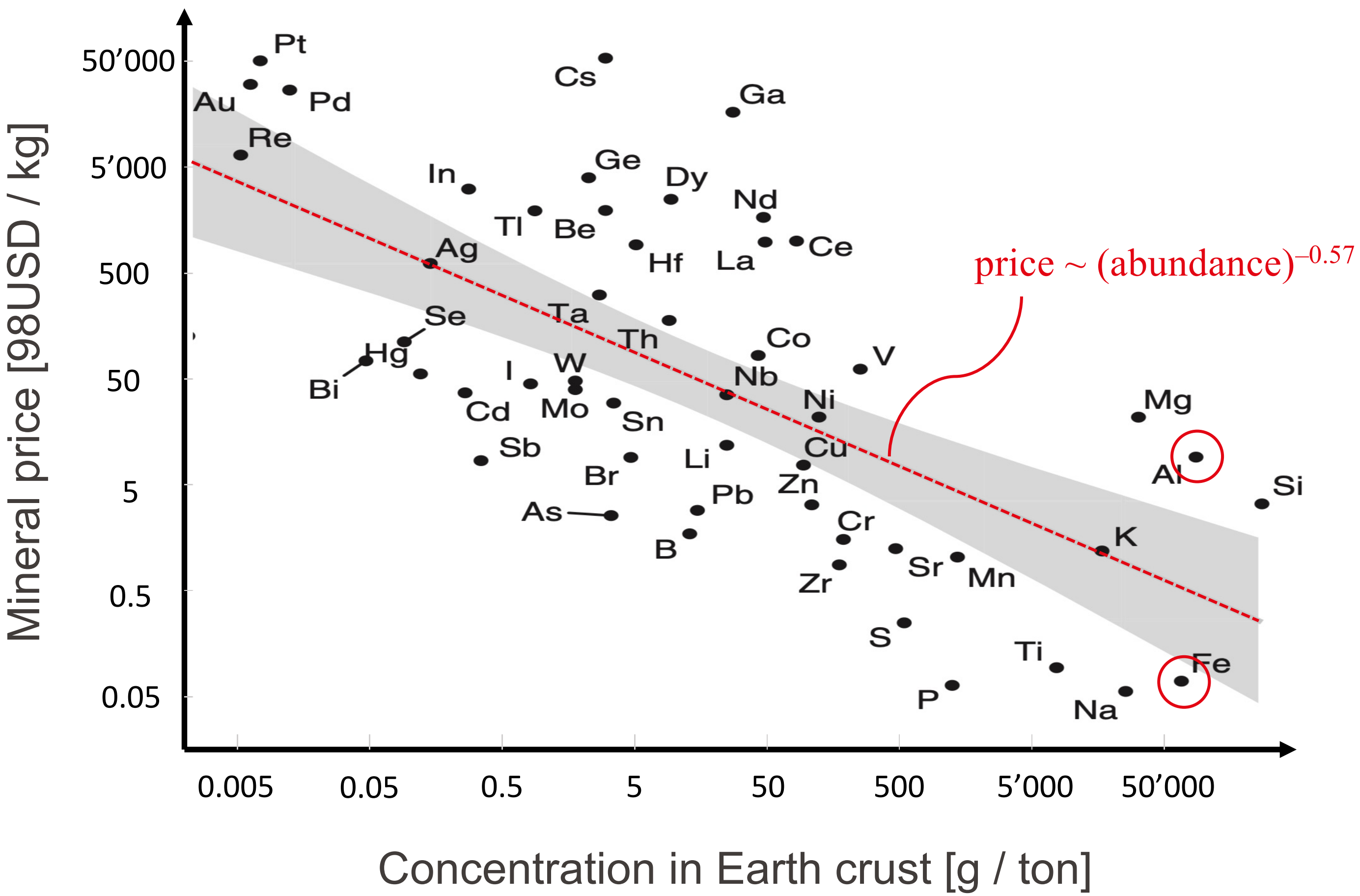
- Fe-based alloys → high strength for structural alloys
  (~ 20 MJ/kg)

- Al-based alloys → low density for transportation
  (~ 100 MJ/kg)



- Cu-based alloys → conductivity for functional components
  (~ 40 MJ/kg)

Metal prices vs abundance



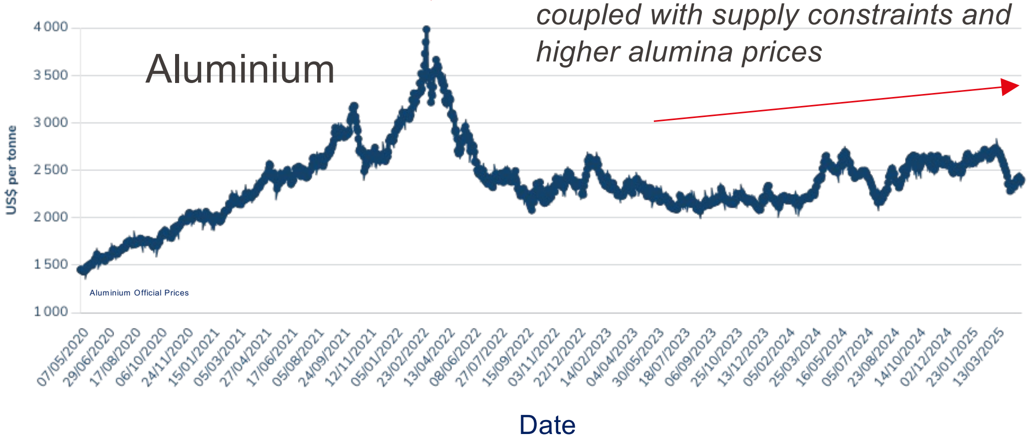
Watson & Eggert, Journal of Industrial Ecology 25, 890 (2020)

Metal prices 05.2020–05.2025 (*London Metal Exchange*)

COVID-19 disruption of supply chains, rising energy costs, and a surge in demand

Al prices increase due to increased demand (automotive and construction), coupled with supply constraints and higher alumina prices

Steel prices decrease due to weak demand, an oversupply of steel, and reduced costs for raw materials like iron ore.



https://www.lme.com/en/Metals

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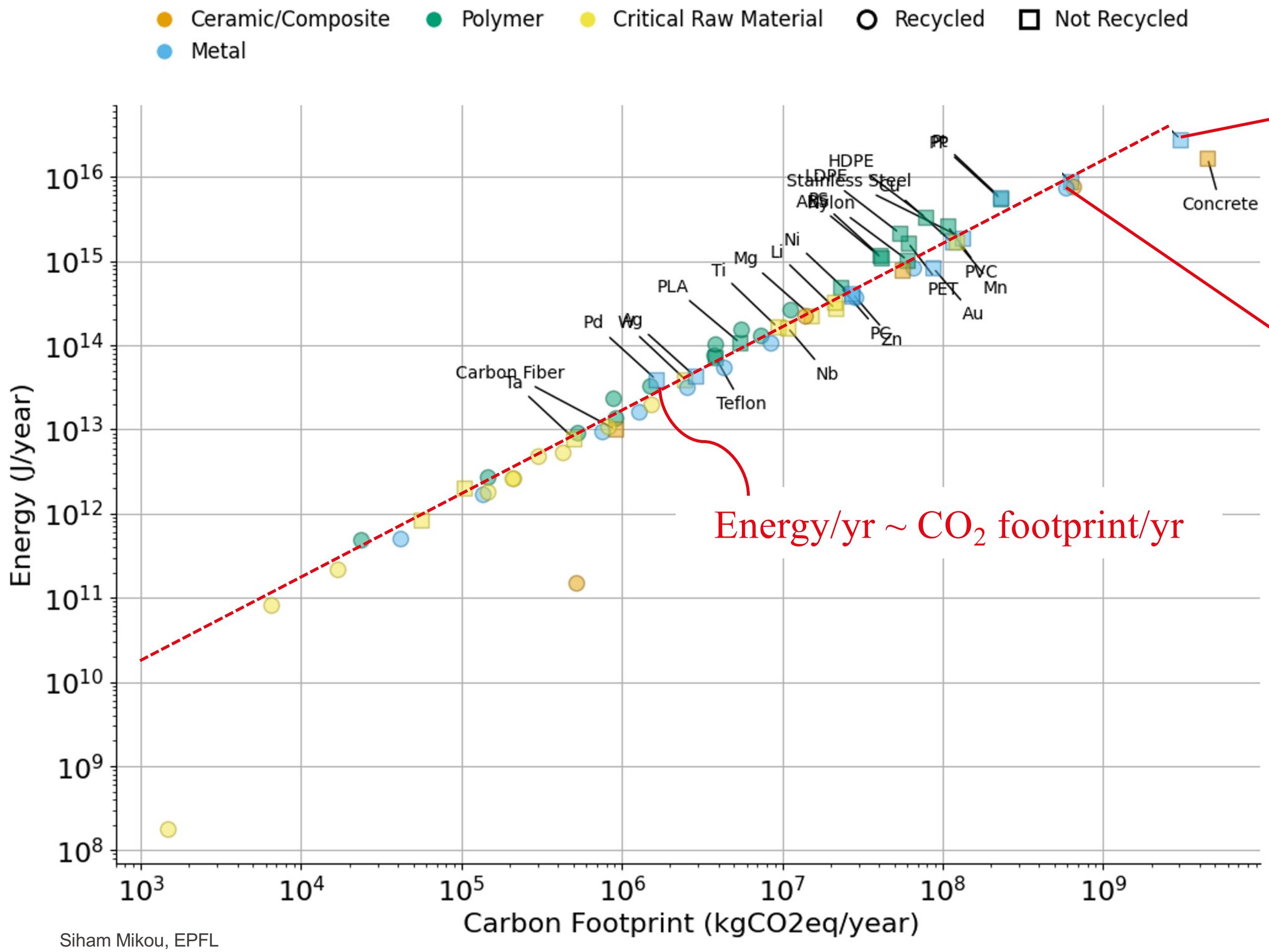
Yearly energy demand and CO_2e emissions



Fe: 30 PJ/yr

Production 3 billion tons/year
(94% of all metals)
~ 3 billion tons CO_2eq/year
(7% of all emissions)
Total resources 230 billion tons

Al: 9 PJ/yr

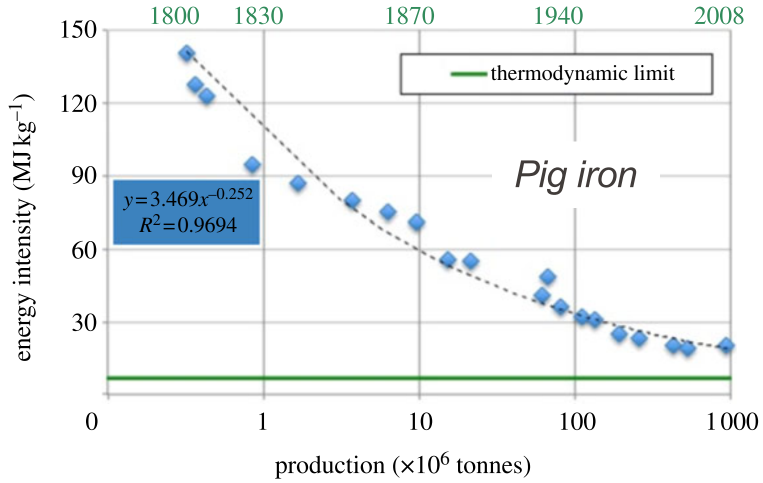
Production 63 million tons/year
1.1 billion tons of CO_2eq/year
(2% of all emissions)
Total resources 55 billion tons

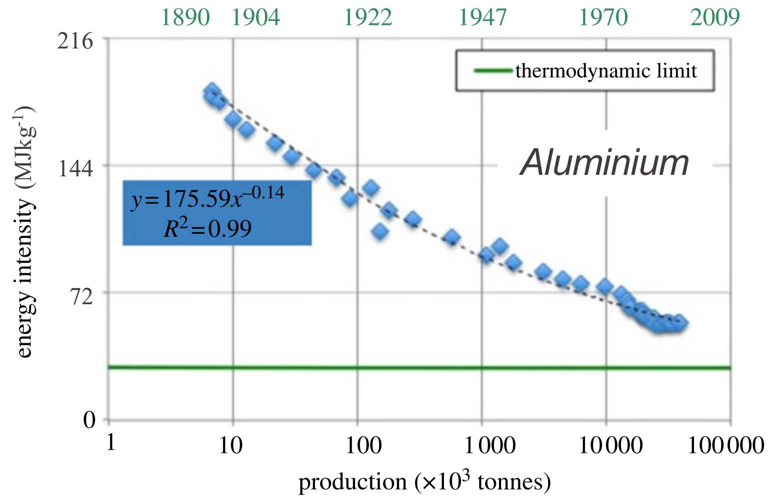
CE strategies imply that the total energy demand for materials be reduced by 75%

Siham Mikou, EPFL
Watari et al., Global Environmental Change 69, 102284 (2021)
US geological Survey Database
https://www.weforum.org/stories/2021/10/all-tonnes-metals-ores-mined-in-one-year/

Energy intensity of primary iron and aluminium

- The energy intensity for pig iron correspond to the coke used in blast furnaces
- The energy intensity for aluminium corresponds to the electricity used in the smelting (Hall–Héroult process)
- Massive improvements of the energy intensity during the last 200 years (1.0–1.5% / year)
- Future improvements slow down towards the thermodynamic limit (Gibbs free energy of formation for the ores Fe_2O_3, 6.7 MJ kg^{-1}, and Al_2O_3, 29.5 MJ kg^{-1})

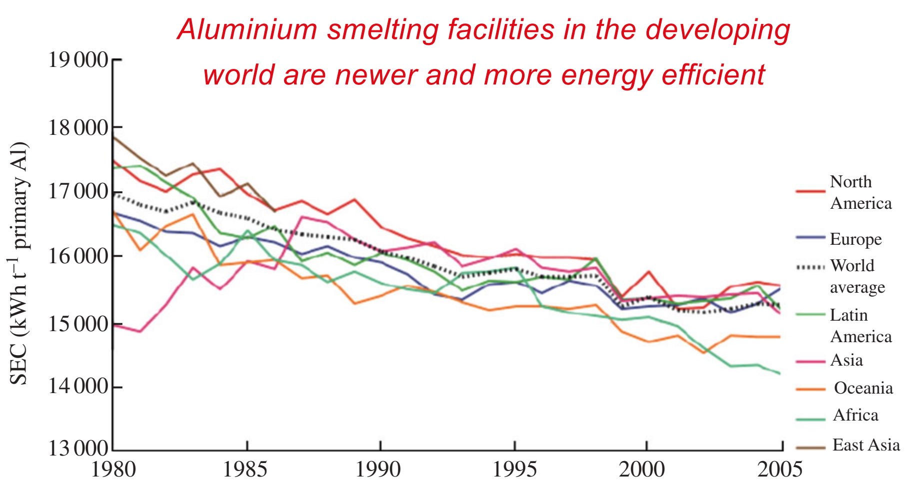




Ashby, *Materials and the environment: eco-informed material choice*, 2nd Ed. Oxford, UK: Butterworth-Heinemann (2012)
Gutowski et al., Phil Trans R Soc A371, 20120003 (2013)

Strategies to reduce primary energy demand

- Move the world average down to the best available technology, with an overall energy reduction of about 18%
  - e.g., worldwide implementation of by-product gas recovery from steel production, retrofitting of aluminium smelters
  - Slow because of financial constraints due to large capital investment
- Move further towards the thermodynamic limit with an overall energy reduction of about 19%
  - e.g., direct smelting of iron ore using coal, inert anodes for aluminium
- Overall, both strategies would enable ~ 37% energy savings … when CE strategies require more than 75%!



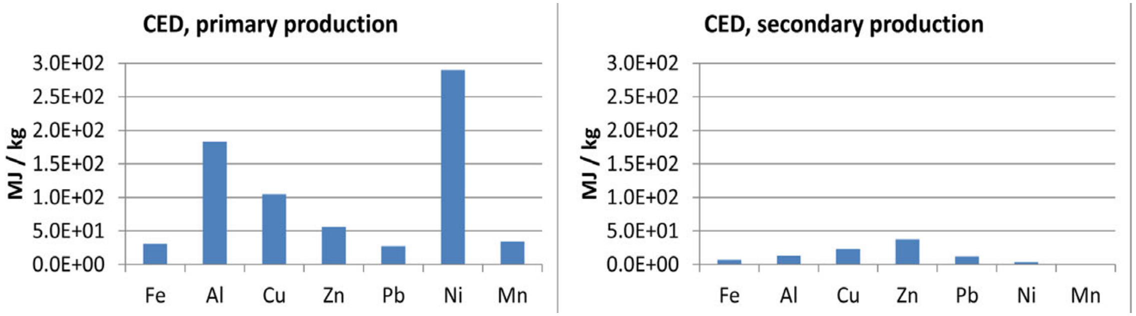
SEC: specific energy consumption

International Energy Agency, Energy technology transitions for industry: strategies for next industrial revolution. Cedex, France: IEA (2009)
Gutowski et al., Phil Trans R Soc A371, 20120003 (2013)

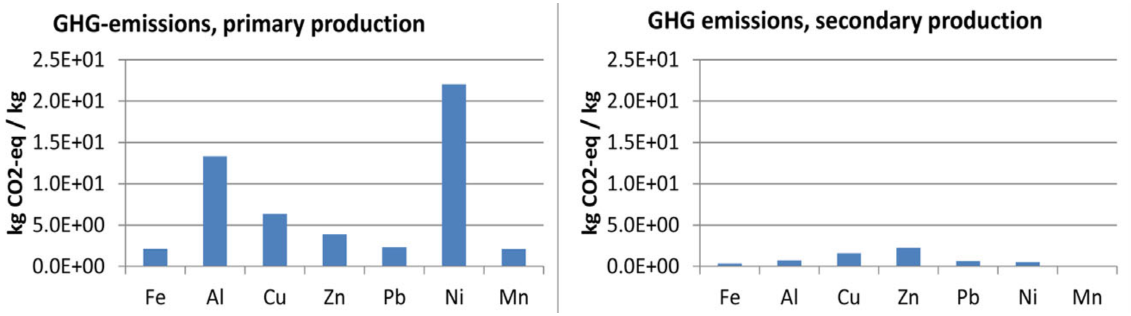
Why recycle metals

- Metals in use contain a large (and increasing) recycled fraction:
  - ~ 70% (cans) to 85% (cars) for steel
  - ~ 70% (cars and cans) for Al
  - ~ 30% for Cu
- The global aggregate EOL recycling rates of metals is high (71%), but the addition to stock keeps the degree of circularity much lower at 36%.
- Recycling of metals saves energy and CO_2 emissions:
  - 70% for steel
  - 95% for Al
  - 85% for Cu
- A major issue are the serious constraints on the quantity of secondary materials that can be captured and processed, especially for emerging countries that are building their infrastructure

Cumulative Energy Demand (CED, 2010)



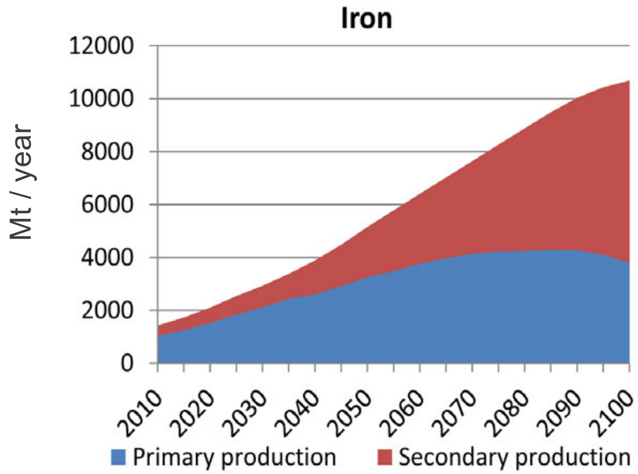
CO_2eq (2010)

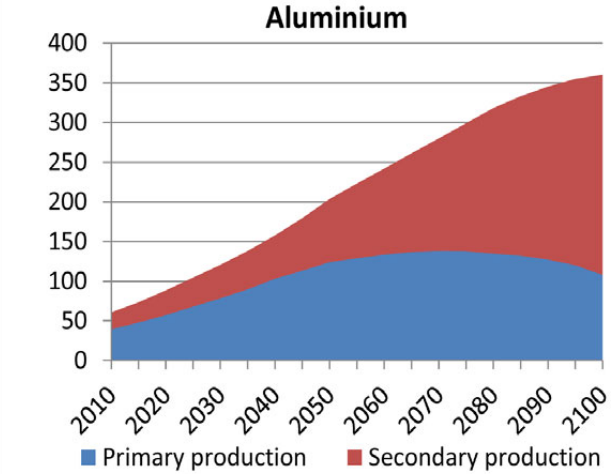


Eckelman M.J., Resources, Conservation and Recycling 54, 256 (2010)
Haas et al., Journal of Industrial Ecology 19, 765 (2015)
Van der Voet et al., Journal of Industrial Ecology, 23, 141 (2018)

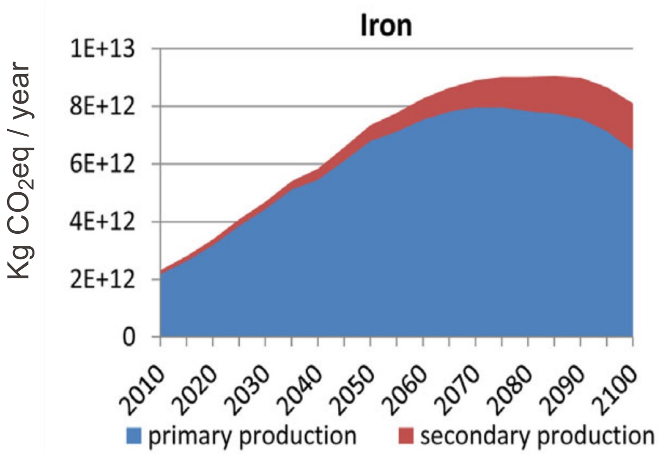
Why recycle metals

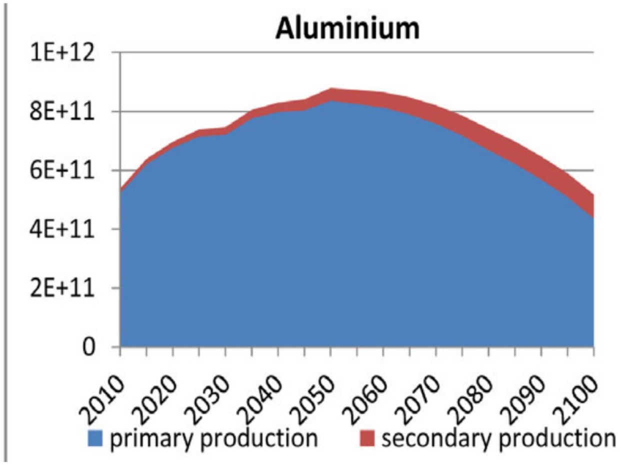
Primary and secondary supply of iron and aluminium under a CE scenario





Greenhouse gas emissions of iron and aluminium under a CE scenario





Van der Voet et al., Journal of Industrial Ecology, 23, 141 (2018)

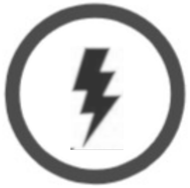
The four recycling routes for metals

Pyrometallurgy

energy intensive smelting

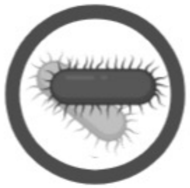
Hydrometallurgy

treatment with strong acids



Electrometallurgy

energy intensive electrolysis



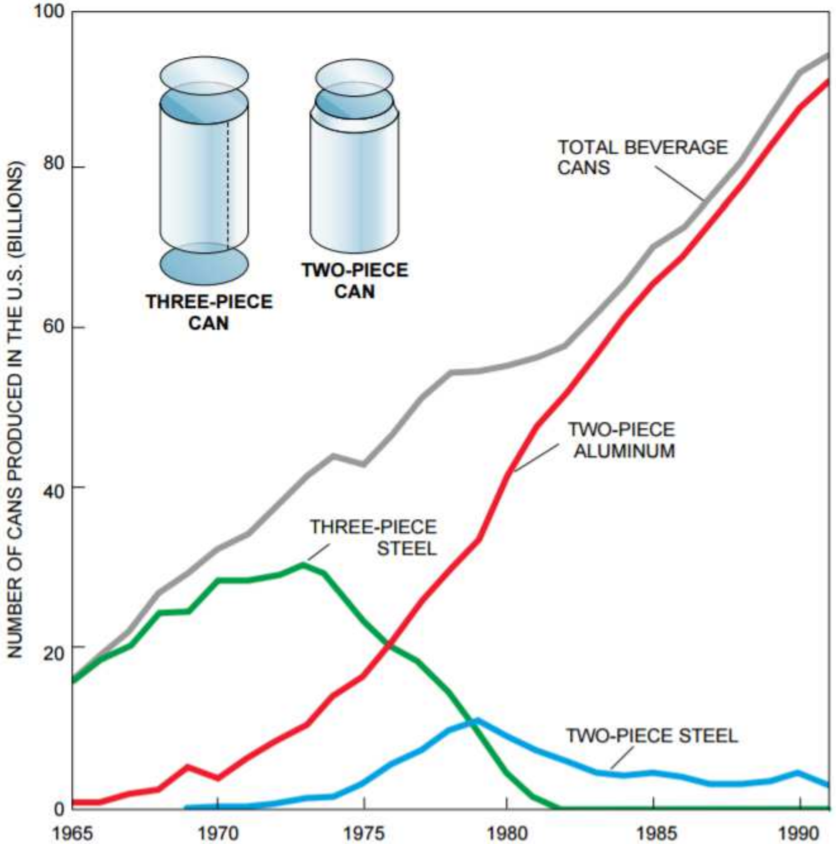
Biohydrometallurgy

costly harnessing natural biogeochemical cycles

- Pyrometallurgy
  - The most common process, cost-effective but energy-intensive and harmful to the environment. Waste is grinded and separated by magnetic and electrostatic properties. Materials are molten, the liquid separates into layer and the metal-containing fraction is further refined.
- Hydrometallurgy
  - Less environmentally intensive method to extract metal than pyrometallurgy. Can also target metals specifically to separate them into high-purity products. Waste is grinded and physically separated, and then treated with a lixiviant (strong acids). The leach liquor is refined by electrowinning.
- Electrometallurgy
  - Energy and cost intensive process that uses electrolysis to produce metals from solutions, including molten salt solutions (electrowinning), or to purify metals by electrochemical dissolution and deposition (electrorefining).
- Biohydrometallurgy
  - A sustainable but slow and costly recycling method to recover metals from e.g., e-waste. Waste is grinded and iron and sulfide oxidizing microorganisms free protons from iron or sulphur, which attack and convert the metals to dissolved ions. The ions are refined through chemical reactions and electrowinning.

https://delftia.wordpress.ncsu.edu/delftia-and-e-waste-literature-findings/

Recycling of Al beverage cans



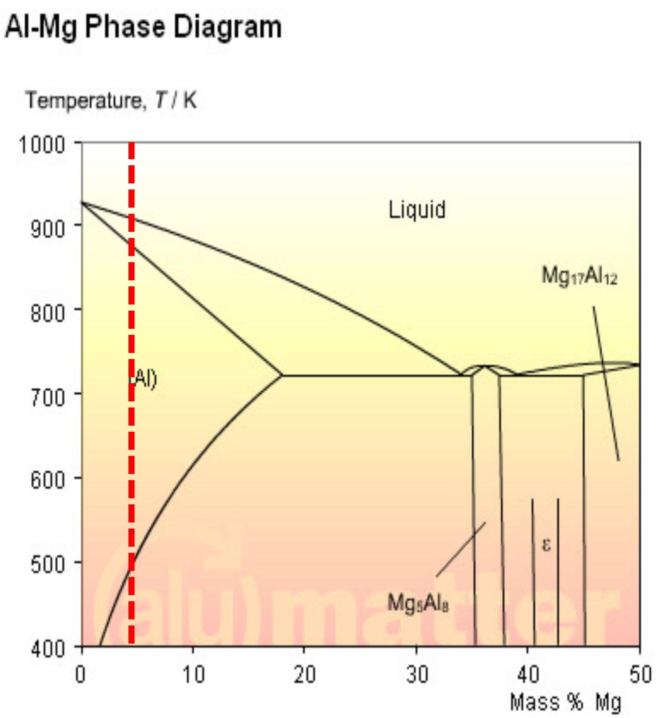
3104 - AlMn1Mg1Cu ; deep-drawing ; ~10g

5182 – AlMg4.5 ; strength ; ~2g

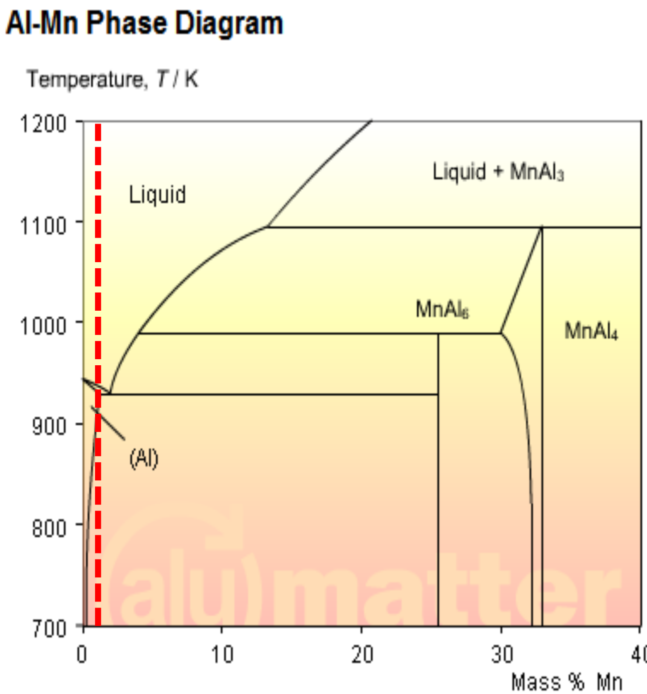
Thickness ~ 100µm

Recycling of Al beverage cans

Approach #1: Management of melting points



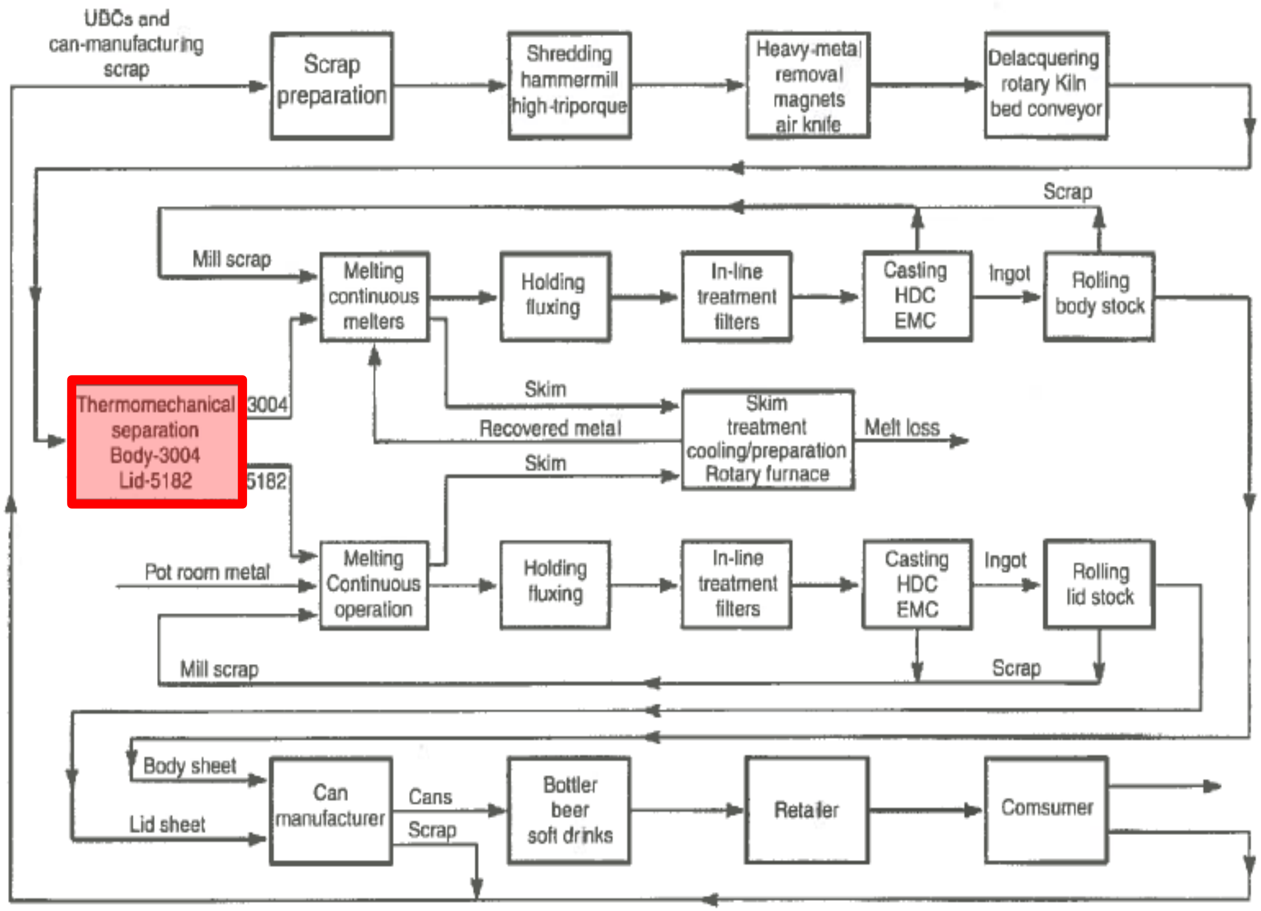
AA5182 : Al-4.5Mg
solidus 577°C, liquidus 638°C



AA3104 : Al-1Mn-1Mg
solidus 638°C, liquidus 657°C

Recycling of Al beverage cans

Approach #1: Management of melting points



UBC: used beverage cans
HDC: horizontal drill chill
EMC: Electromagnetic casting

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Recycling of Al beverage cans

Approach #2: Management of alloying elements

Body 3104 - AlMn1Mg1Cu ~ 10g
End 5182 - AlMg4.5 ~ 2g
} resulting mix alloy ≡ AlMg1.6Mn0.8

- An alloy having a target Mg content of 1% (T = 1)
- Scrap with 1.6% Mg (S = 1.6)
- Primary metal with 0.1% Mg (P = 0.1)

→ e = (T-P)/(S-T) = 0.9/0.6 = 1.5

→ Fraction of primary metal = 100/(T+e) = 100/(1+1.5) = 40%

The proportions would be significantly less favorable to recycle scrap if more highly alloyed scrap were to be used. For example if scrap has S = 4.5% Mg and target metal has T = 1%, then only 20% scrap can be recycled.

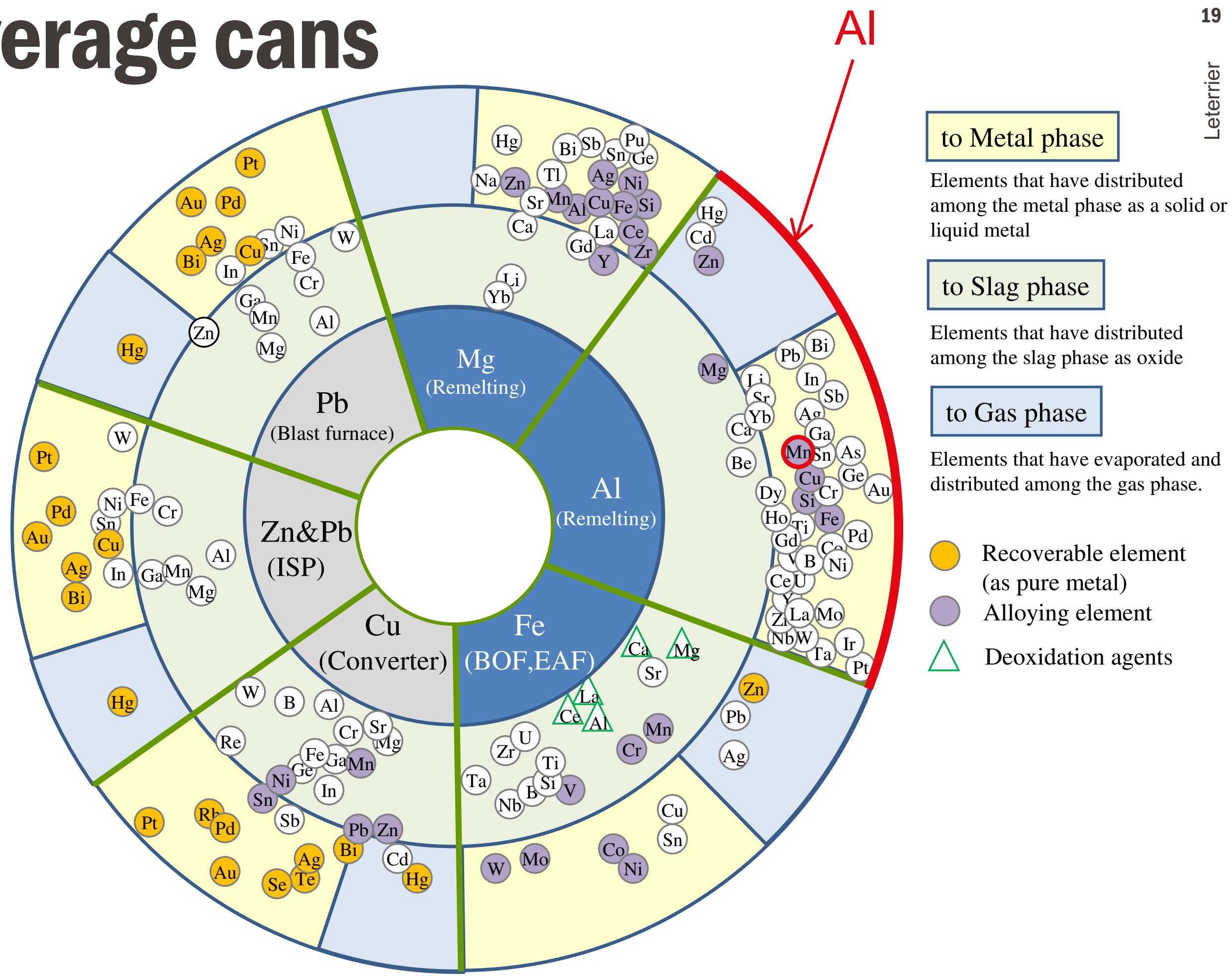
Recycling of Al beverage cans

Approach #2: Management of alloying elements

Thermodynamic limitations!

Manganese (Mn), for example, used in the 3000 series of aluminium alloys, is retained in the metal phase during remelting, producing a melt that would be unsuitable for reuse in any other Al-based system.

Unless the 3000 series alloys were separated prior to remelting, the resulting metal would be unsuitable for 95% of all aluminium applications.



Element radar chart for the recycling of Fe, Cu, Zn, Pb, Al and Mg into the metal phase (BOF, basic oxygen furnace; EAF, electric arc furnace; ISP, imperial smelting process)

Hiraki et al, Sci. Technol. Adv. Mater. 12 035003 (2011)
Reck and Graedel Science 337, 690 (2012)

Recycling of Al from cars (~ 200 kg of aluminium alloys)

… the complication comes from the large diversity of alloys

Alloy composition of automotive aluminium

Alloy type	Code	Notation	Share/%
Casting alloys (78%)	A359	AlSi9Cu3	48
	A356	AlSi7Mg	20
	A361	AlSi10Mg	12
	–	AlSi12Cu	9
	A413	AlSi12	7
	A332	AlSi12CuNiMg	4
Wrought alloys (22%) including extrusions, forgings and rolled products	AA6060	AlMgSi0.5	35
	AA6082	AlMgSi1	11
	AA3003	AlMn1	10
	AA5182	AlMg4.5Mn0.4	9
	AA5754	AlMg3	14
	AA6016	AlSi1.2Mg0.4*	15
	AA7020	AlZn5.4Mg1	6

* It was AlSi1.2Mn0.4 in Ref.[12]

- Casting alloys contain a maximum of 20% alloying elements (mainly Si, Mg, and Cu) and the silicon content is more than 5%.
- Wrought alloys contain a maximum of 10% alloying elements (Mn, Mg, Si, Cu, Zn) and less than 1% silicon.
- It is thus very difficult to make wrought alloys out of cast alloys, but it is possible to make cast alloys out of wrought alloys.

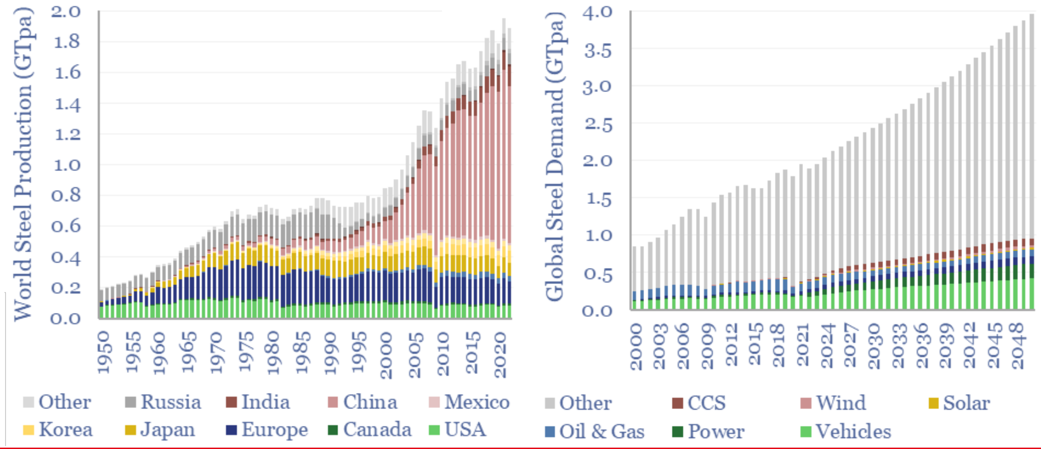
Energy demand model

- Total demand (mass) of a material $Q_T = Q_p + Q_s$ (primary + secondary)
- Total energy demand $E_T = Q_p e_p + Q_s e_s = Q_T\left[(1-r)e_p + re_s\right] = Q_T\bar{e} = Q_T e_p(1-m)$ where
  - e_p and e_s are the primary and secondary energy intensities
  - $r = Q_s/Q_T$ is the recycled fraction
  - $m = r\left(1 - e_s/e_p\right)$ represents potential energy savings … the goal is to achieve m = 0.75
- Also $r = f(1+i)^{-n}$ where
  - $f = Q_s/Q_{waste}$ is the recycling efficiency (E_F in the MCI calculation), with Q_{waste} being the actual amount of waste
  - n is the average lifetime of the material in products
  - i is the annual growth rate of the material

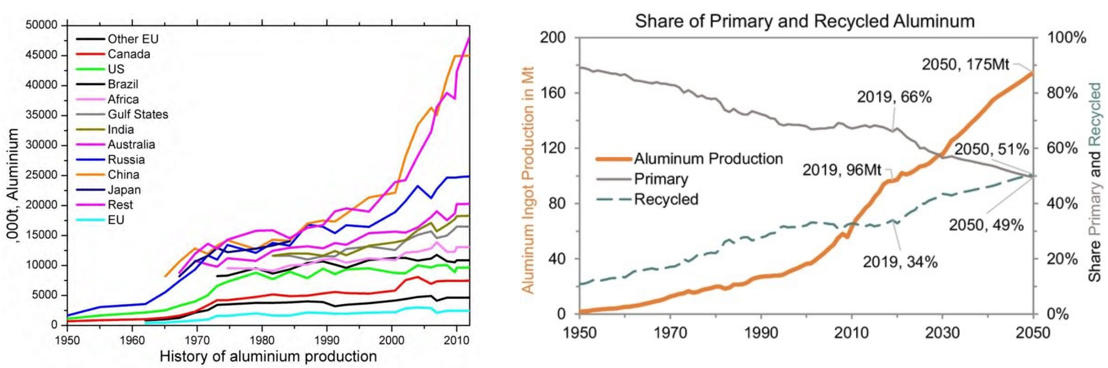
Gutowski et al., Phil Trans R Soc A371, 20120003 (2013)

Energy demand model

Steel



Al



Material	Steel	Al
Input data (years 2005-2006)		
n [years]	19	15
$i_{2005–2050}$ [%]	2.62	2.60
Q_T [Mt]	1250	55
e_p [MJ/kg]	25	93
e_s [MJ/kg]	9	6
r [%]	37	30
f [%]	56	49
m [%]	23.7	28.1
Predicted data for year 2050		
Q_T [Mt]	4003	175
e_p [MJ/kg]	13	56
e_s [MJ/kg]	5	3
r [%]	55	61
f [%]	90	90
m [%]	33.9	58.0

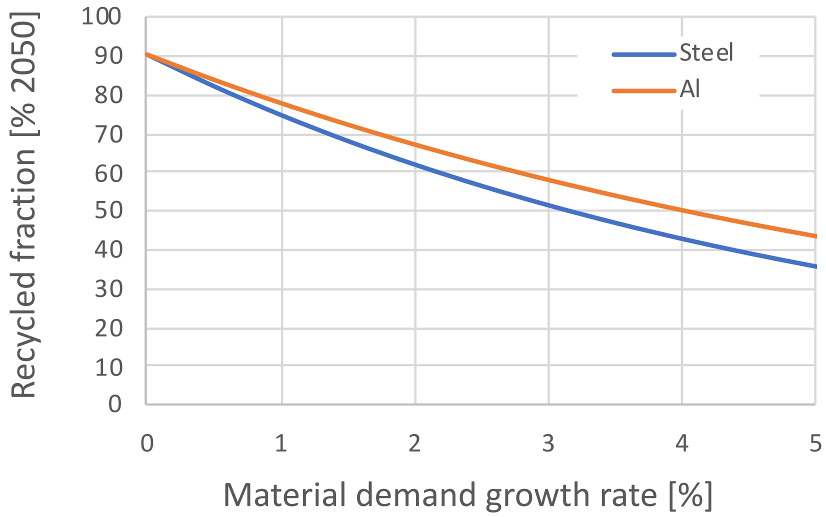
Far from 75%!

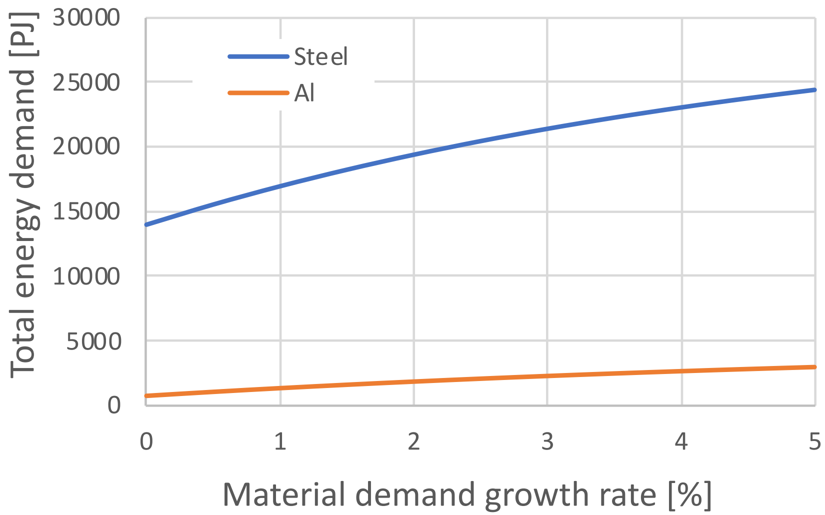
https://thundersaidenergy.com/downloads/global-steel-supply-demand-model/
http://www.alueurope.eu/2012
source: International Aluminium Institute

Energy demand model

- The higher the future increase of the demand, and the longer the product lifetime, the lower the possible recycled fraction, and the higher the total energy demand
- Alternatives to metals based on environmental and cost optimizations are very difficult to identify and will not help much
- The priority should be given to '*material efficiency*', i.e., reduce the consumption of metals, which would require new thinking about how we use materials:
  - Effort in the North in favor of the South
  - Extend lifetime and share

The situation in 2050





Summary (1/2)

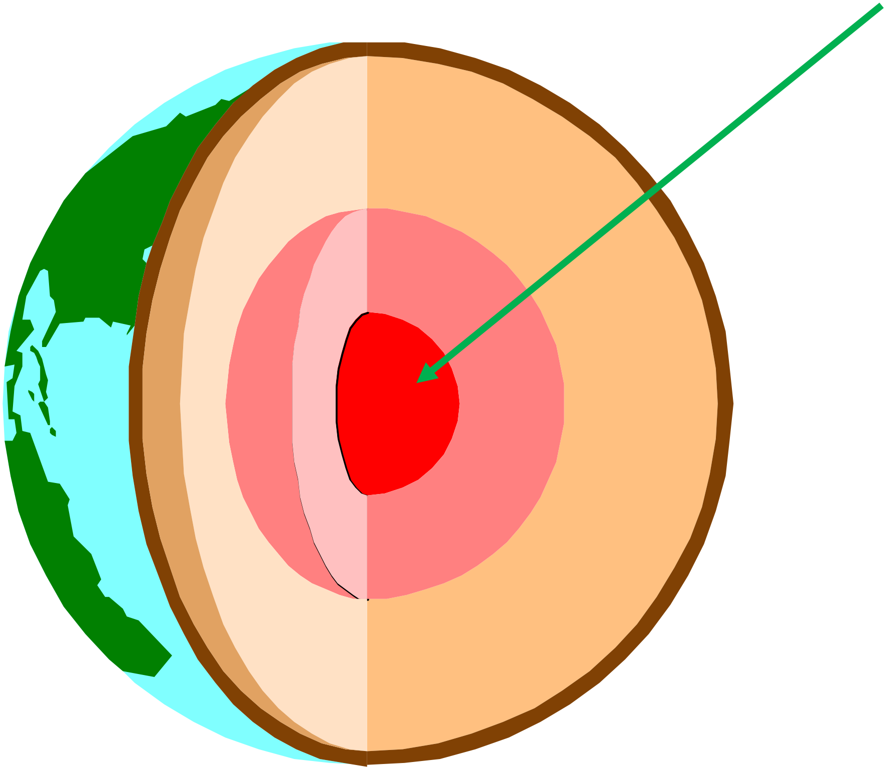
- Metal production represents ~ 8% of the global energy consumption and fossil-fuel related CO_2 emissions
- The most abundant and energy intensive metals are steel (30 PJ/yr) and aluminium (9 PJ/yr)
- Strategies to reduce the energy demand for primary steel and Al are limited by thermodynamic limits and would enable ~ 37% energy savings … when CE strategies require more than 75%!
- Steel and Al are recycled via pyrometallurgy, electrometallurgy or (bio)hydrometallurgy and contain an increasing recycled fraction (Al 70%, steel 70-85%), which saves energy and greenhouse gases emissions (Al 95%, Steel 70%)

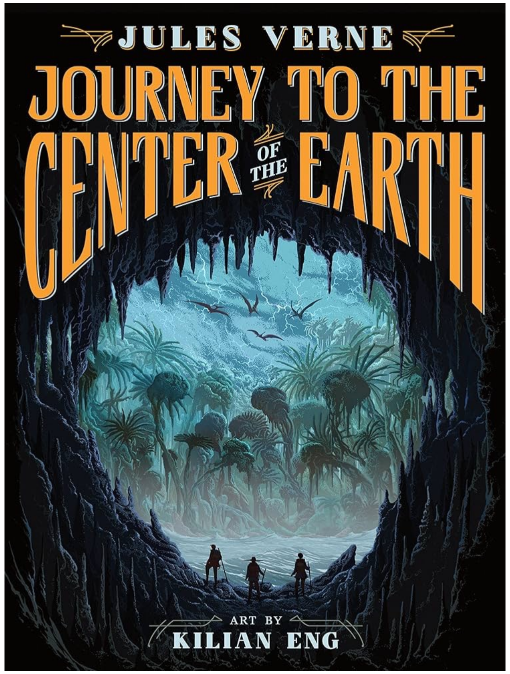
Summary (2/2)

- Metals are infinitely recyclable in principle, but in practice, recycling is often inefficient or essentially nonexistent because of limits imposed by social behavior, product design, recycling technologies, and the thermodynamics of separation.
- A model shows that the reduction in energy demand in 2050 for these 2 metals is far from the 75% target due to increasing demand, especially in developing countries. Alternative materials are yet to be identified, so the most effective alternative is to reduce demand in developed countries.

Summary

Mass of the Earth core (Fe & Ni) 1.7 x 10^{24} kilograms





An illustration from the novel "Journey to the Center of the Earth" by Jules Verne painted by Édouard Riou