Sustainable Steel?

Christina Chang
Harvard Energy Journal Club
2/14/2019

Year 2005

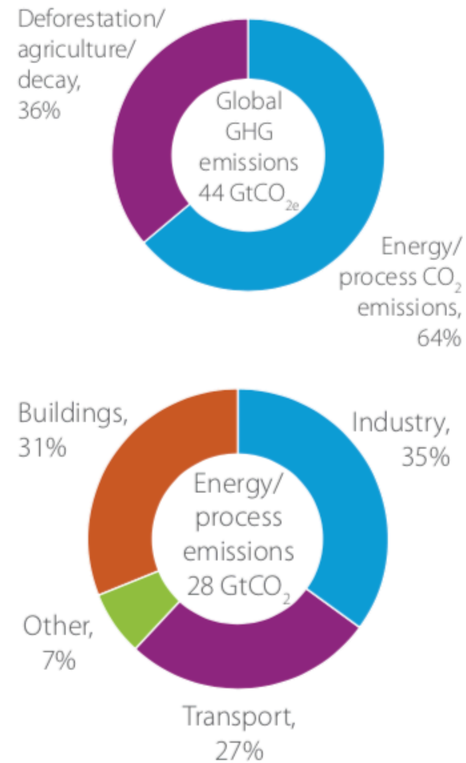
The scale of the materials challenge

Definitive anthropogenic CO_2 emissions contribute significantly to total CO_2 emissions

Industry is greatest single sector for CO_2e

Just 5 materials account for 55% of industrial emissions

Figure 2.1—Pie charts showing the sources of global CO_2 emissions



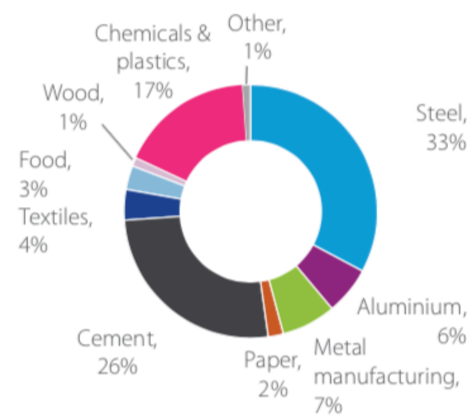
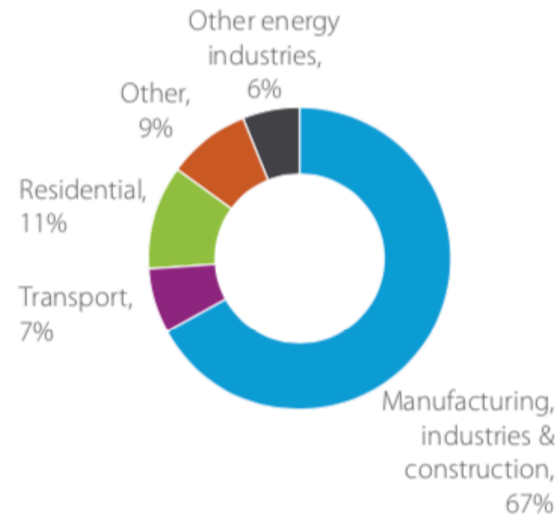


Figure 2.4—Sources of Chinese CO_2 emissions

A more detailed breakdown (China) confirms that stock production is largest CO_2e source

China's CO_2e profile



Manufacturing, industries, & construction breakdown

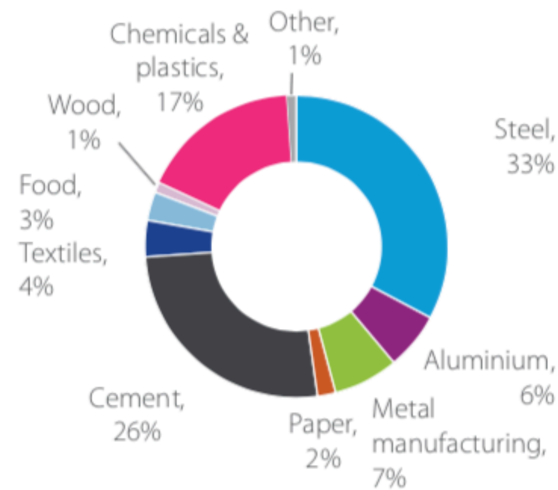


Figure 2.4—**Sources of Chinese CO_2 emissions**

5 Materials – Breakdown of Production, Energy Intensity, and Carbon Intensity

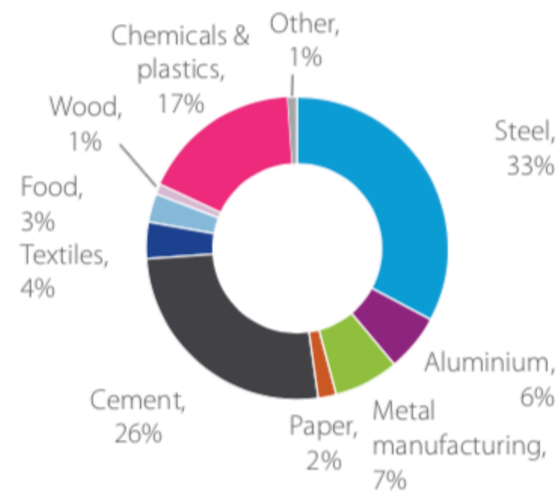


Figure 2.4—**Sources of Chinese CO_2 emissions**

Material	Global annual production (Mt)	Energy intensity (GJ/t)	Carbon intensity ($t\,CO_2/t$)
Cement	2,800	5	1
Steel	1,400	35	3
Plastic	230	80	3
Paper	390	20	1
Aluminium	70	170	10

What do we use these materials for?

Conversion device switching + renewable electricity would aid in decarbonizing industry

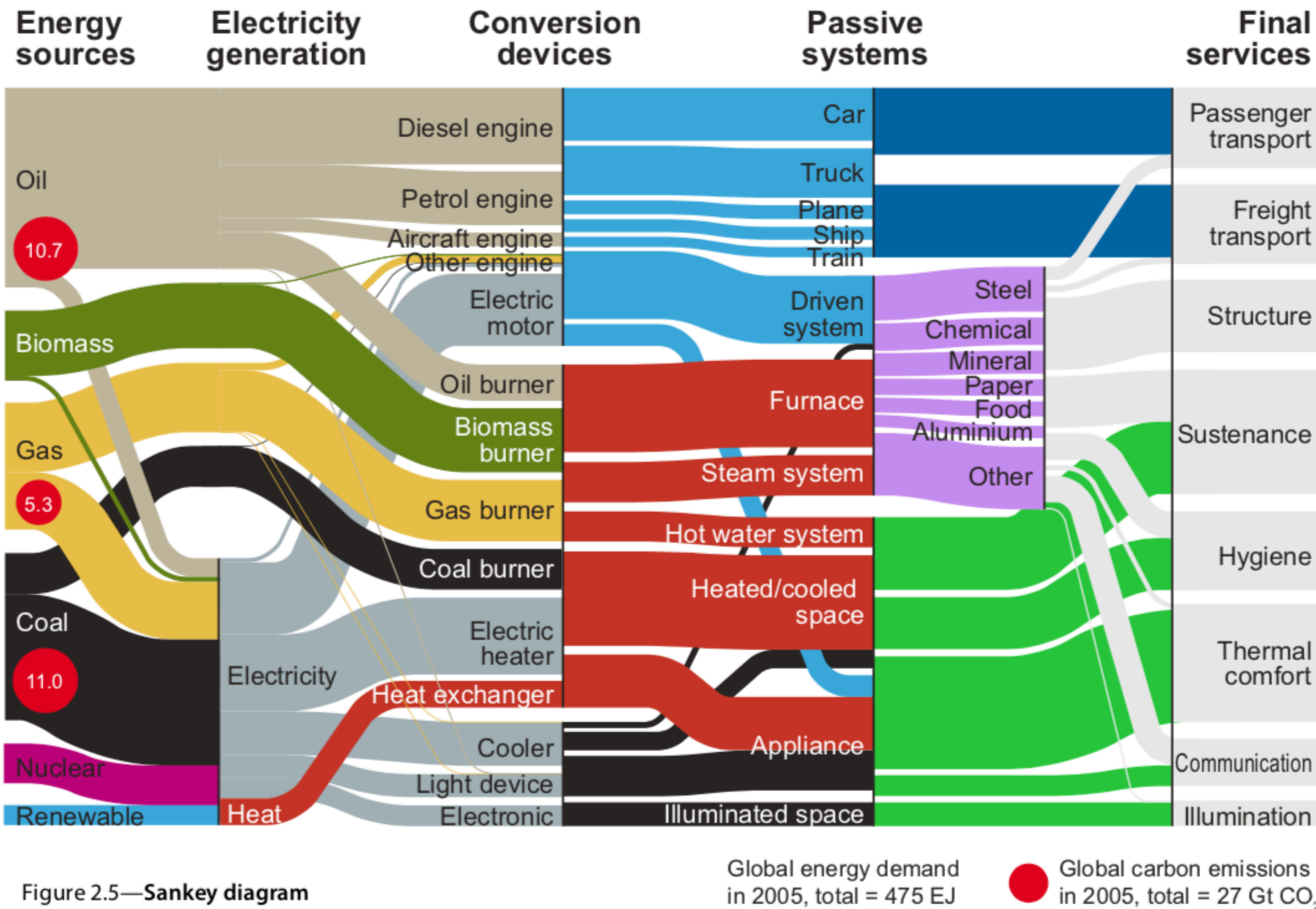
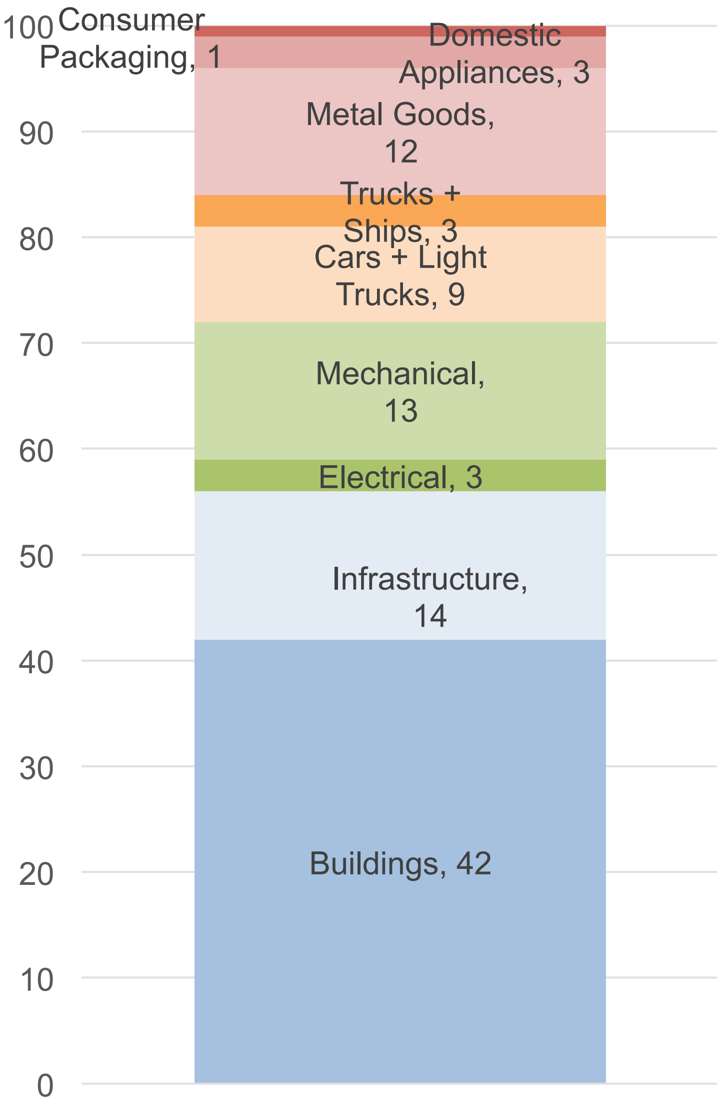
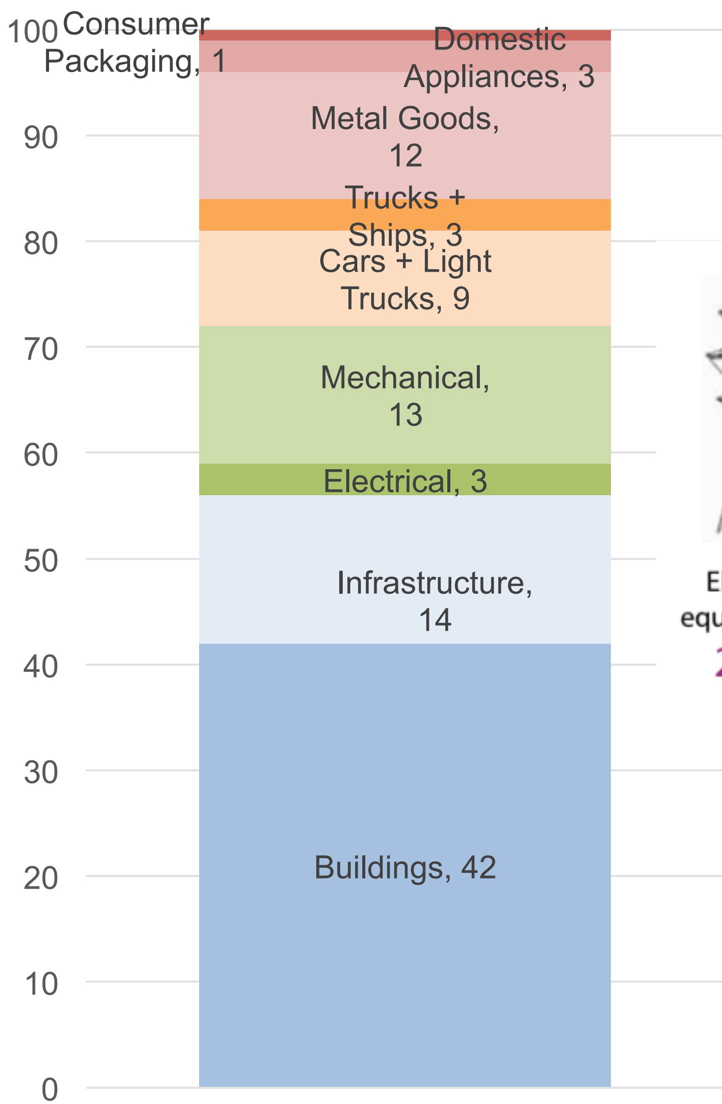


Figure 2.5—**Sankey diagram of global energy use**[18]

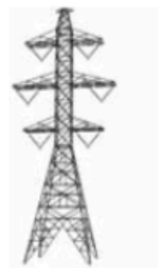
Our uses of steel



Our uses of steel



Industrial equipment



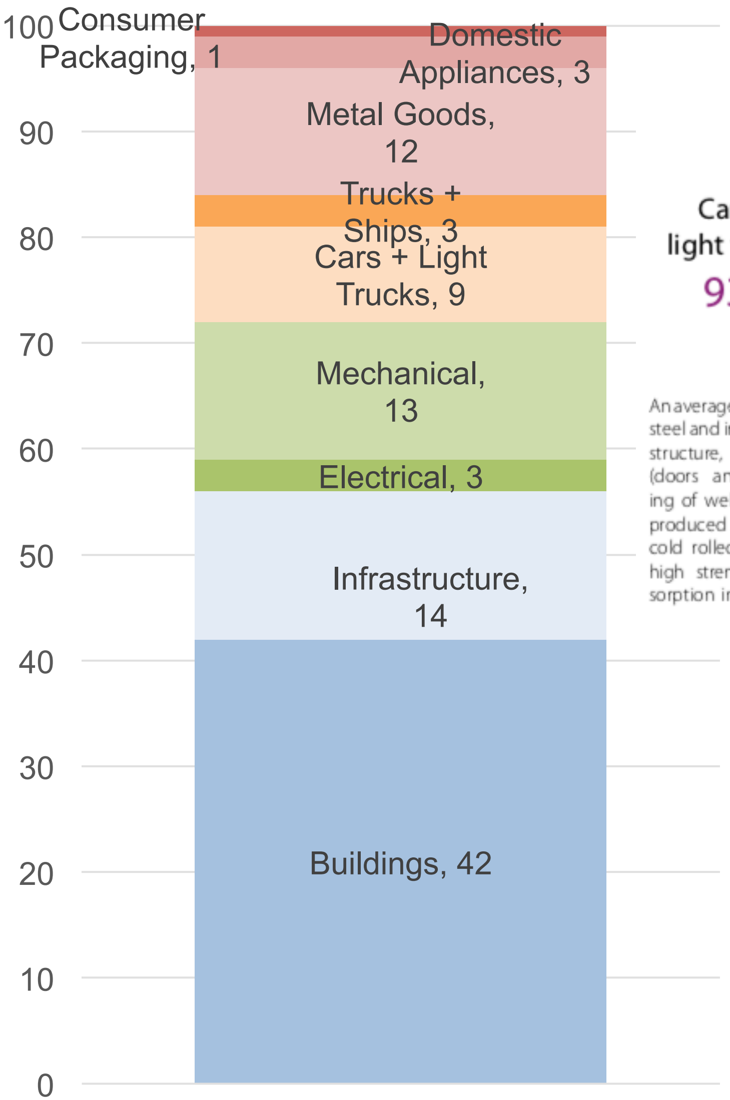
Electrical equipment
27 Mt
3 %

30 % of steel in electrical equipment is high silicon content electrical steel forming the cores of transformers or the stator and rotor parts of electrical motors. Other major uses include pylons (constructed from bolted, cold-formed, galvanized L-sections forming a light-weight durable tower); and steel reinforced cables (where wound galvanized steel wires provide the strength to carry conducting aluminium in long span transmission cables).

Mechanical equipment
137 Mt
13 %

This covers a wide range of equipment from small workshop tools to large factory-based robotic machinery and rolling mills. 40% of the steel is plate or hot rolled bar; tubes contribute a further 22%, as do hot and cold rolled coils. Cast products and wire rod contribute the remainder.

Our uses of steel



Transport

Cars and light trucks

93 Mt

9 %

An average car contains 960 kg of steel and iron. 34 % is in the body structure, panels and closures (doors and bonnets), consisting of welded, profiled sections produced by stamping formable cold rolled sheet. This provides high strength and energy absorption in case of a crash. 23 % is in the drive train, consisting of grey cast iron for the engine block and machinable carbon steel for the wear resistant gears. 12 % is in the suspension, using rolled high strength steel strip. The rest is spread between the wheels, tyres, fuel tank, steering and braking systems.

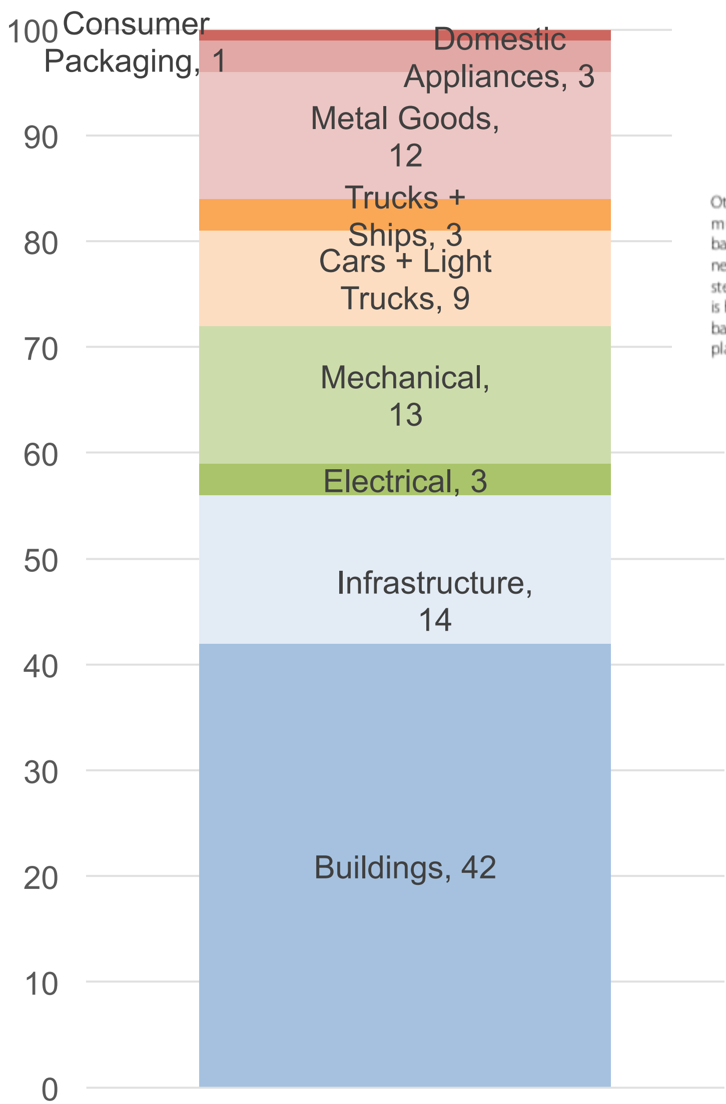
Trucks and ships

28 Mt

3 %

The basic steel components described for the car also apply to trucks, but unlike cars, all truck engine blocks are steel. Frame rails and cross members are usually high tensile steel, and the cab structure and outer skin is often made from galvanized steel. Steel for the ship hull is rolled primary mild steel, providing strong, tough, dimensionally consistent plates that are welded together.

Our uses of steel



Metal products

Metal goods
134 Mt
12 %

Other metal goods include a multitude of products, from baths and chairs to filing cabinets and barbed wire. 30% of steel entering this product group is hot rolled coil; 20% is hot rolled bar; and the remainder is either plate, narrow strip, or cast iron.

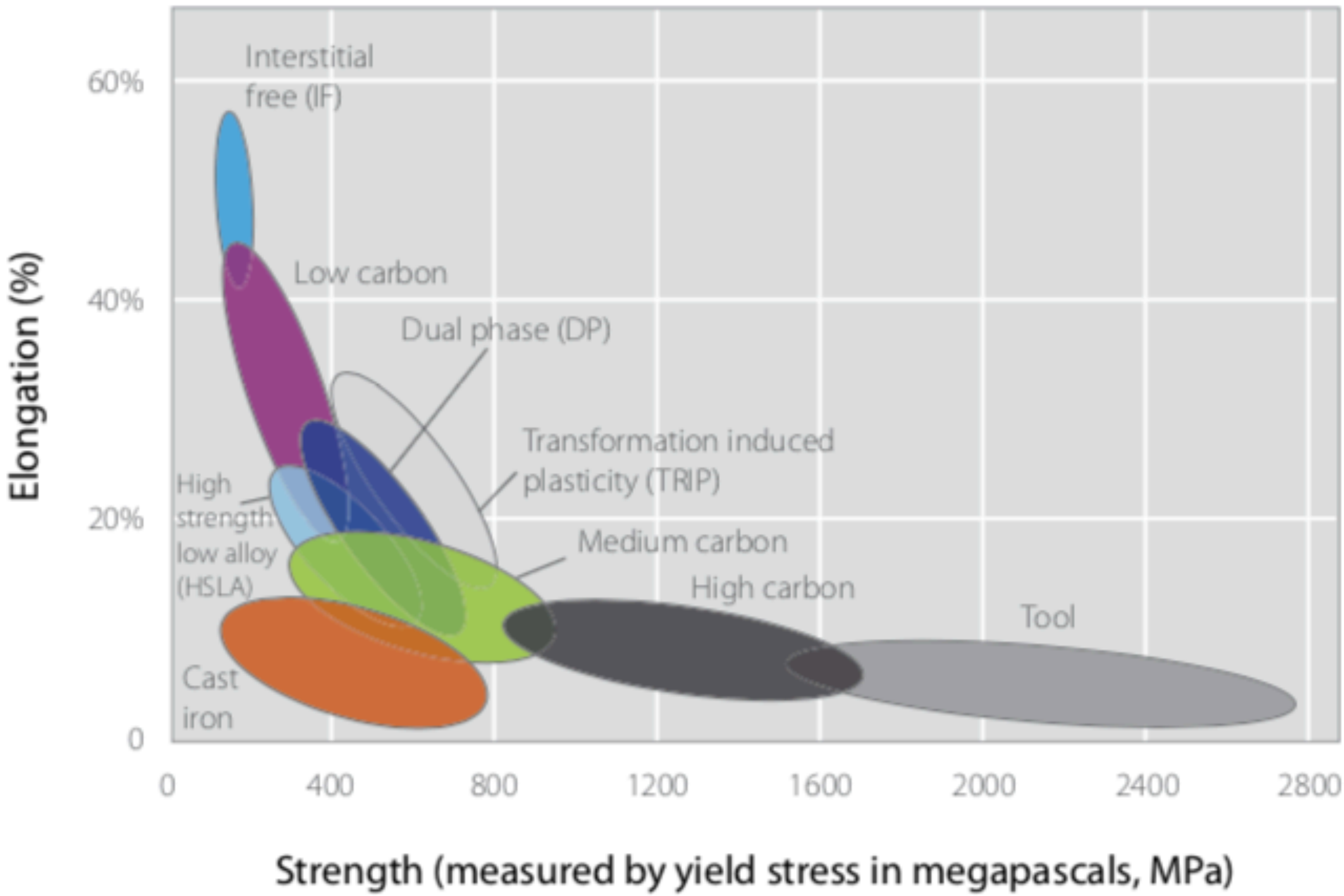
Consumer packaging
9 Mt
1 %

Steel use in packaging is dominated by tin-plated rolled steel, which doesn't corrode. 60% of this steel is made into food cans, providing durable packaging for the subsequent cooking and distribution. 40 % is used for aerosols.

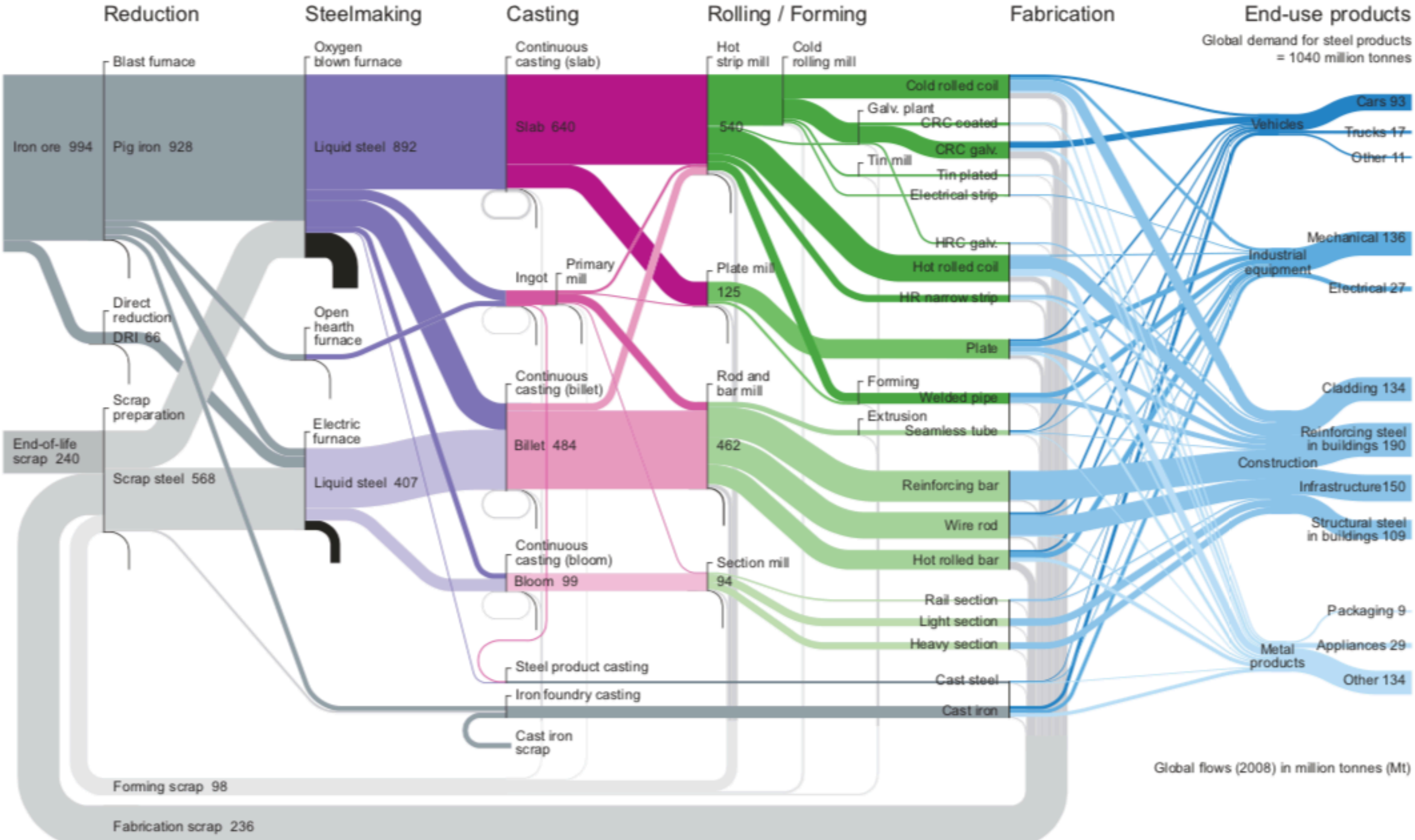
Domestic appliances
29 Mt
3 %

Appliances are dominated by white goods (up to 70%). The vast majority of steel used here is cold rolled coil, often galvanized or painted. Most of this steel is used for panelling. Other applications including washing machine tubs (welded rolled steel strip), motors, expanders in fridge/freezers and cast parts for transmissions.

Typical properties for groups of steels

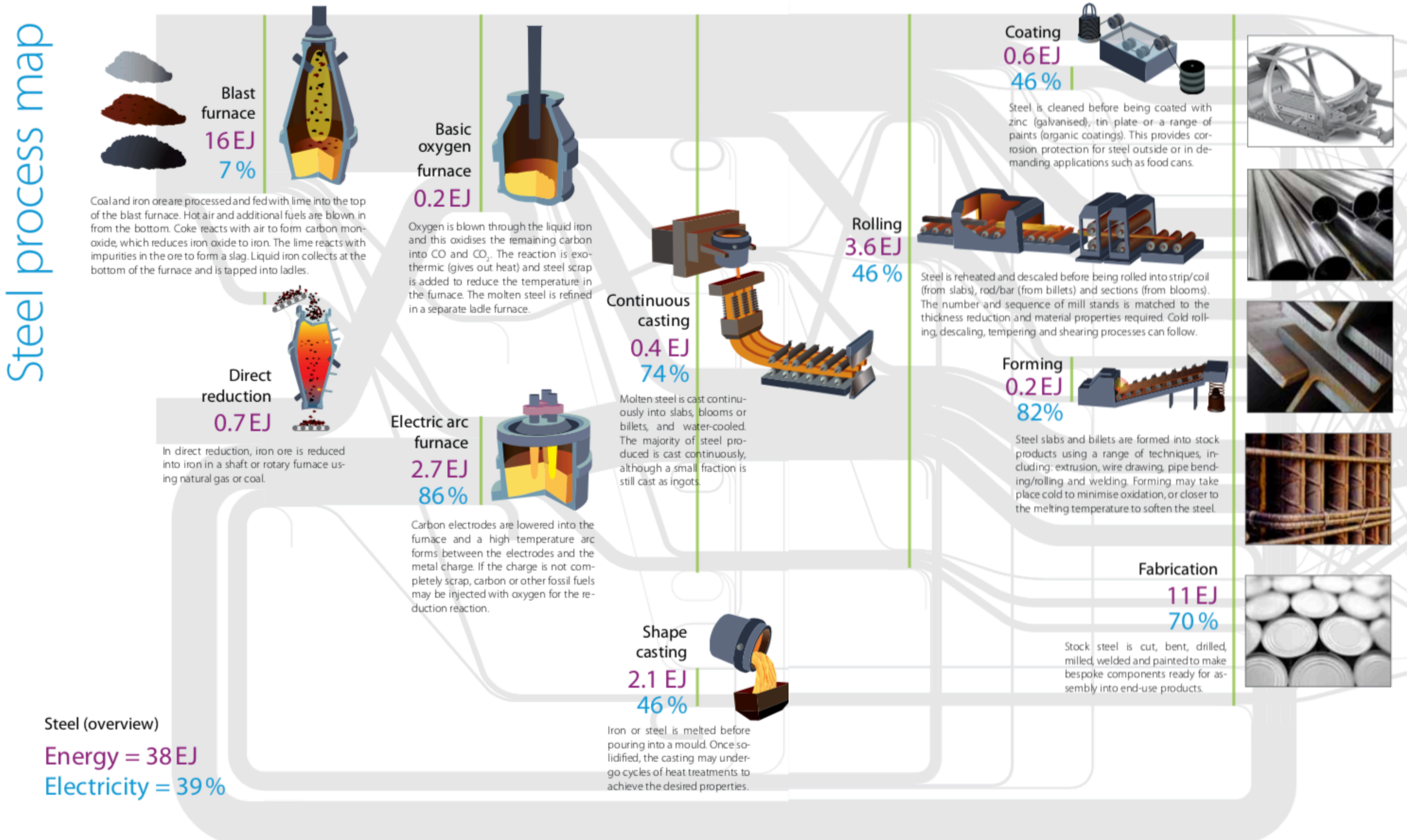


Sankey of Steel Flow



https://www.youtube.com/watch?v=9I7JqonyoKA

Most energy used in blast furnace + fabrication



Blast furnace and direct reduction chemistry present opportunities for decarbonization

These numbers depend on chemical production of CO_2

Direct Reduction:

$$2\ Fe_2O_3(s) + CO\ (g) \rightarrow 2\ Fe_3O_4\ (s) + CO_2\ (g)$$

$$x\ Fe_3O_4(s) + (4x\text{-}3)\ CO\ (g) \rightarrow 3\ Fe_xO\ (s) + (4x\text{-}3)\ CO_2\ (g)$$

$$Fe_xO(s) + CO\ (g) \rightarrow x\ Fe\ (s) + CO_2\ (g)$$

If electricity were greener, these numbers would be lower

Process	Emissions ($t\ CO_2/t$)
Iron making—blast furnace	0.5
Coking	0.2
Sintering	0.4
Direct-reduction	1.2
Steelmaking—oxygen blown furnace	0.2
Steelmaking—electric arc furnace	0.5
Scrap preparation	0.01
Steelmaking—open hearth furnace	1
Continuous casting	0.01
Ingot casting	0.05
Hot strip mill	0.1
Cold strip mill	0.4
Plate mill	0.1
Rod and bar mill	0.2
Section mill	0.2
Galvanising plant	0.2
Tinning mill	0.04
Extrusion	0.2
Primary mill	0.1
Forming	0.1
Steel product casting	2.4
Iron foundry casting	1.7
Fabrication	1

Table 5.1—**Emissions estimates per unit processed for major steel production processes**[5]

Novel processes for steel making

- Options for using less coke
  1. Substitution of other carbon fuels
  2. Hydrogen as a fuel
  3. Top gas recycling
- Alternative ways to make iron
  1. Direct reduced iron
  2. Smelt reduction
  3. Electrolysis

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Substitution of other carbon fuels

- Substitute coke by biomass, charcoal, waste plastics.
- Expansion in use limited by rate we can harvest biomass
  - If we replaced all coke in 30 Mt of steel consumption (what the UK consumes), the UK would need to use nearly half its land surface area for charcoal production.
  - Biomass substitution technically feasible, not really “sustainable”

Could H_2 be used as a reductant instead?

Direct Reduction:

$$2\ Fe_2O_3(s) + CO\ (g) \rightarrow 2\ Fe_3O_4\ (s) + CO_2\ (g)$$

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Hydrogen-based Reduction:

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Hydrogen-based Reduction:

$2\ Fe_2O_3(s) + H_2\ (g) \rightarrow 2\ Fe_3O_4\ (s) + H_2O\ (g)$

$x\ Fe_3O_4(s) + (4x\text{-}3)\ H_2\ (g) \rightarrow 3\ Fe_xO\ (s) + (4x\text{-}3)\ H_2O\ (g)$

$Fe_xO(s) + H_2\ (g) \rightarrow x\ Fe\ (s) + H_2O\ (g)$

Could H_2 be used as a reductant instead?

Hydrogen-based steelmaking is believed to be technically sound. But…

1. Overall emissions impact depends how H_2 is produced – no sufficiently-sized C-free source (yet)
2. Overall emissions impact depends how blast furnace is heated to operating temperature (900-1300 °C)
3. Large-scale adoption of hydrogen substitution looks extremely unlikely, even by 2050.
4. Hydrogen embrittlement

Journal of Cleaner Production 46 (2013) 27–35

Contents lists available at SciVerse ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Modelling a new, low CO_2 emissions, hydrogen steelmaking process

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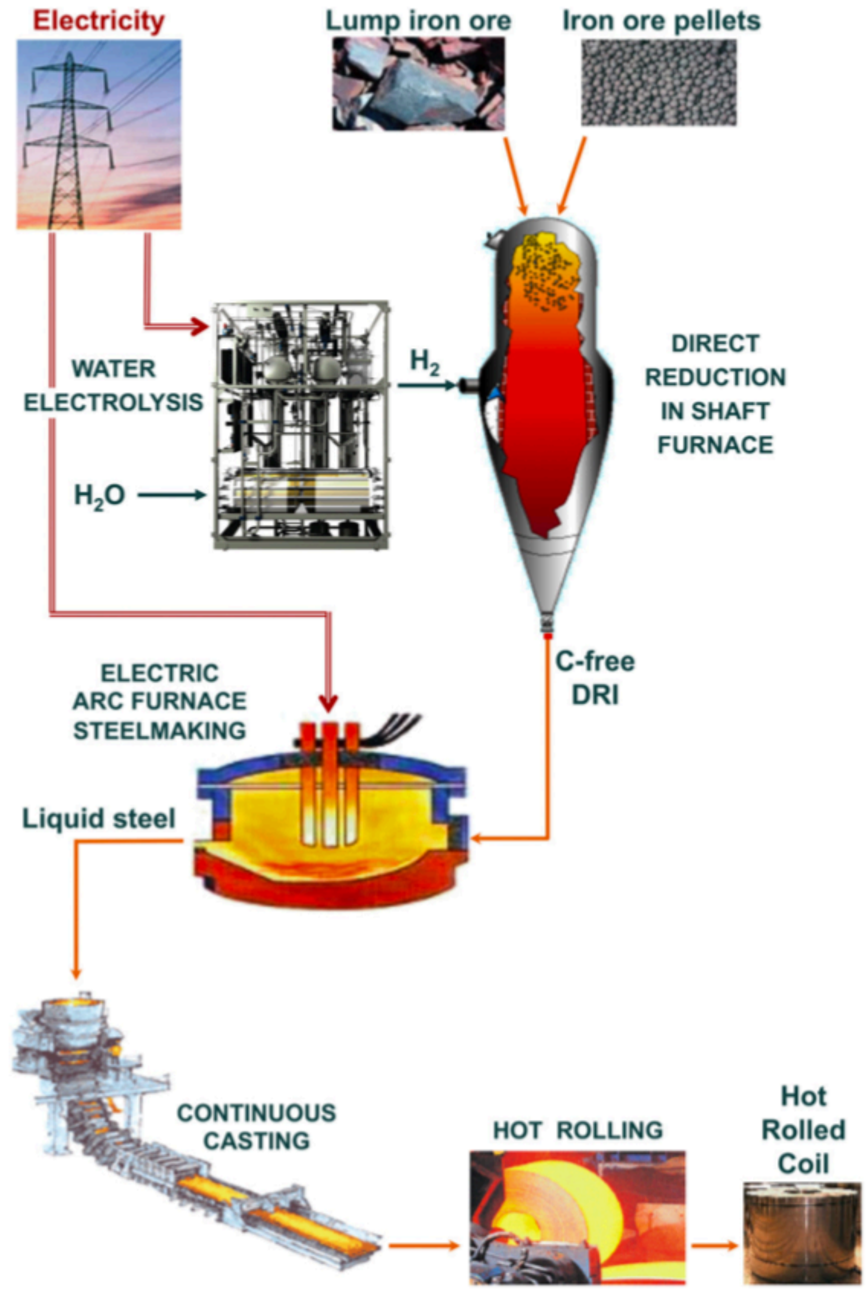
One potential C-free source is water electrolysis from renewable electricity



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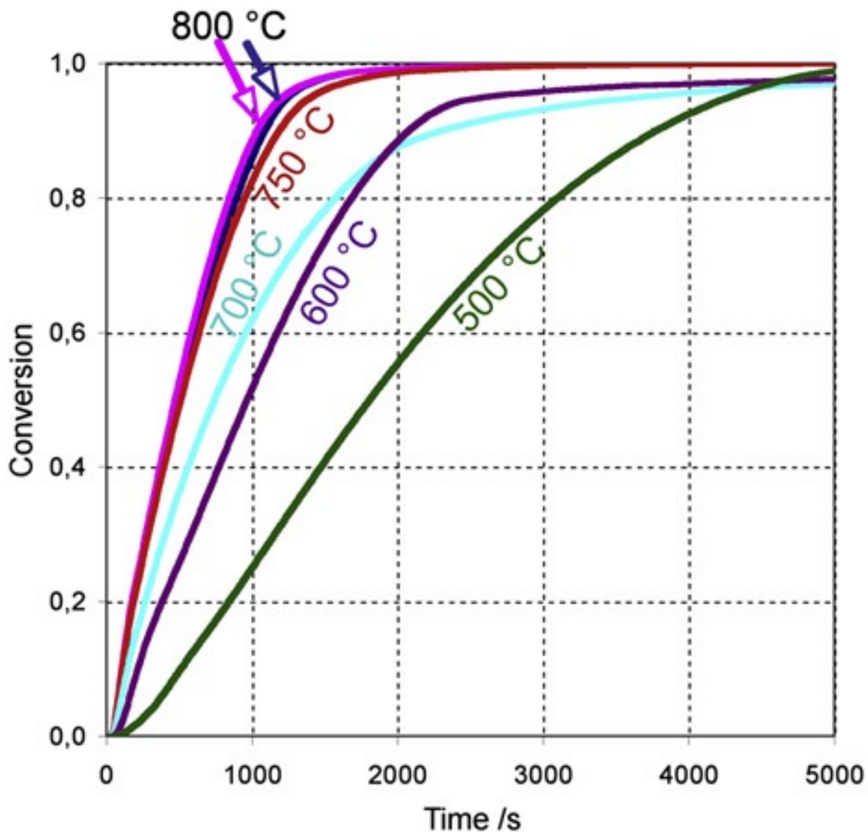
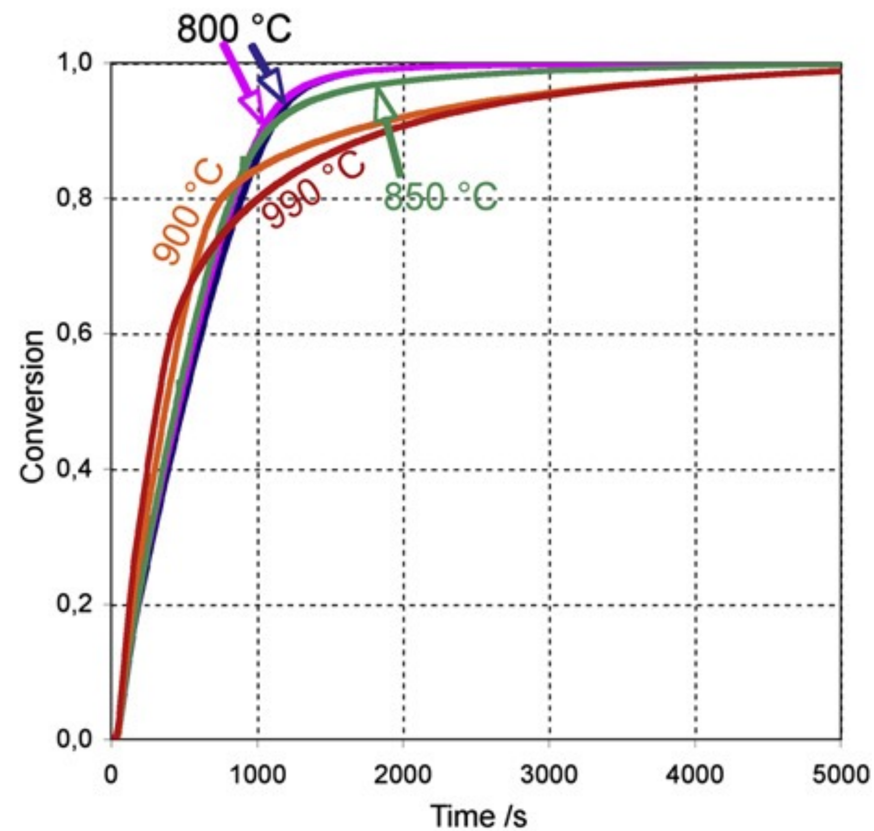
TGA Experiments indicate an optimal temperature of 800 °C for reaction of H_2 + Hematite → Fe + H_2O





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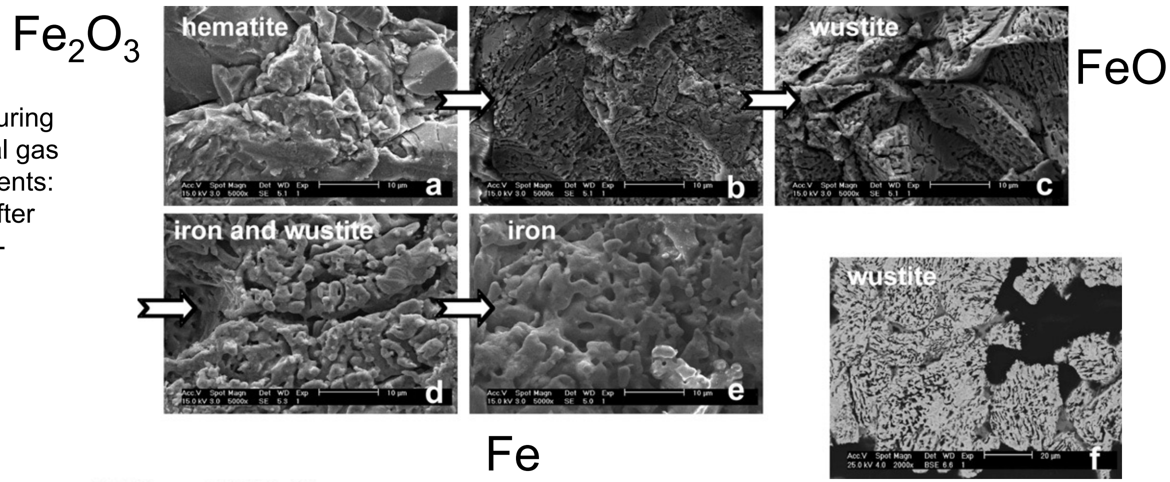
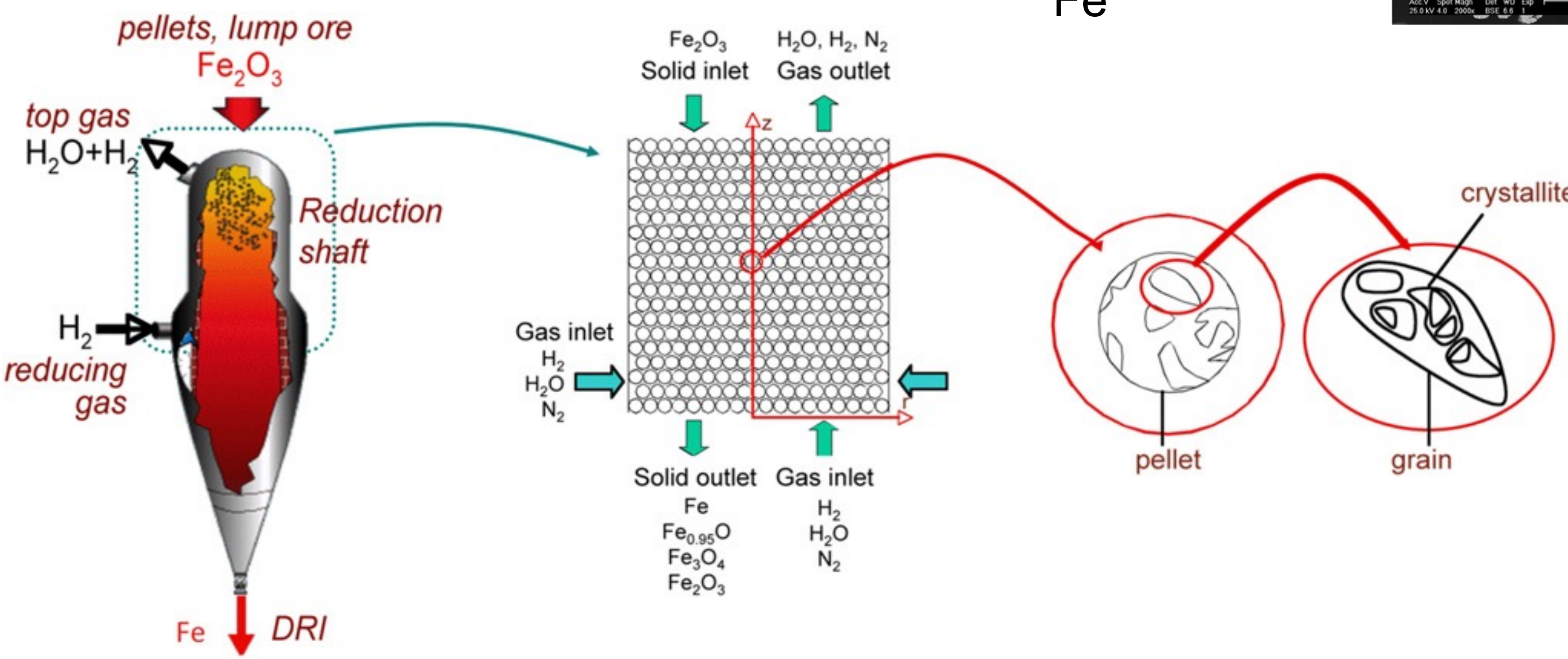
A kinetic sub-model was built to simulate the reduction of a single pellet by H_2

Fig. 4. Microstructure evolution of the solids during reduction at 800 °C by H_2 (200 mL /min of total gas flow, H2/He 60/40 %vol.). Interrupted experiments: (a) initial; (b): after 89 s; (c): after 206 s; (d): after 400 s; (e): fully reduced; (f): after 400 s, cross-section of polished sample.





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Model Results

- Complete conversion to metallic iron using pure H_2 could be obtained using a more compact reactor than current industrial DR furnaces
- Reduction by H_2 is faster than that by CO.
- Size of the pellets and the temperature of the inlet gas have a strong influence on the reduction rate: the smaller the pellet diameter, the faster the reduction and thus the more compact the reactor.
- The optimum temperature was 800 °C.
- At higher temperatures, the densification of iron due to sintering causes the reaction to slow down at high conversions.
- The next steps of this work should be to verify if the kinetics used are valid for entire pellets and to adapt the model for the reduction of iron ore by H_2/CO mixtures to validate the model against operation data of existing industrial DR process.

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Novel processes for steel making

- Options for using less coke
    1. Substitution of other carbon fuels
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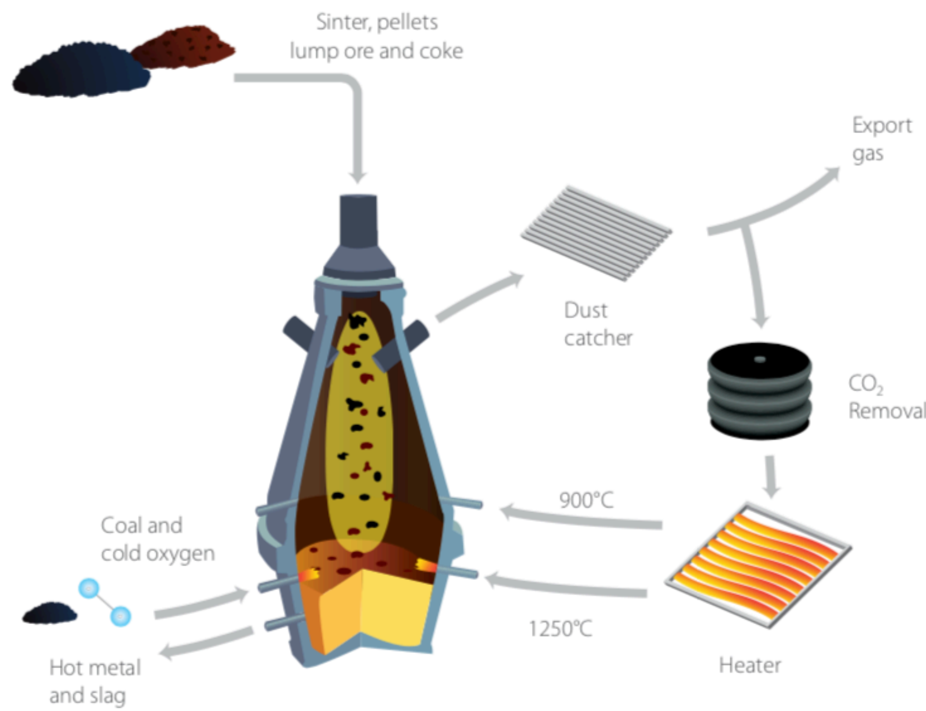
Top gas recycling

- Blast furnace off gases include CO and CO_2.
- Separate CO from gas stream, use it again as reductant (instead of new C, coke)
- Would want to use O_2 instead of air, because N_2 / CO hard to separate.
- Reduces CO2 emissions from blast furnace by 5 – 10%.
- Could be coupled with CCS if O_2 is used.



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Direct reduced iron (no coke) – widely used in countries with NG supplies

- No coke
- Lower T than blast furnace (800 – 1000 °C)
- High C/impurity concentration, thus
- Refine in EAF

- Most DRI sites use NG to heat, giving off CO_2.

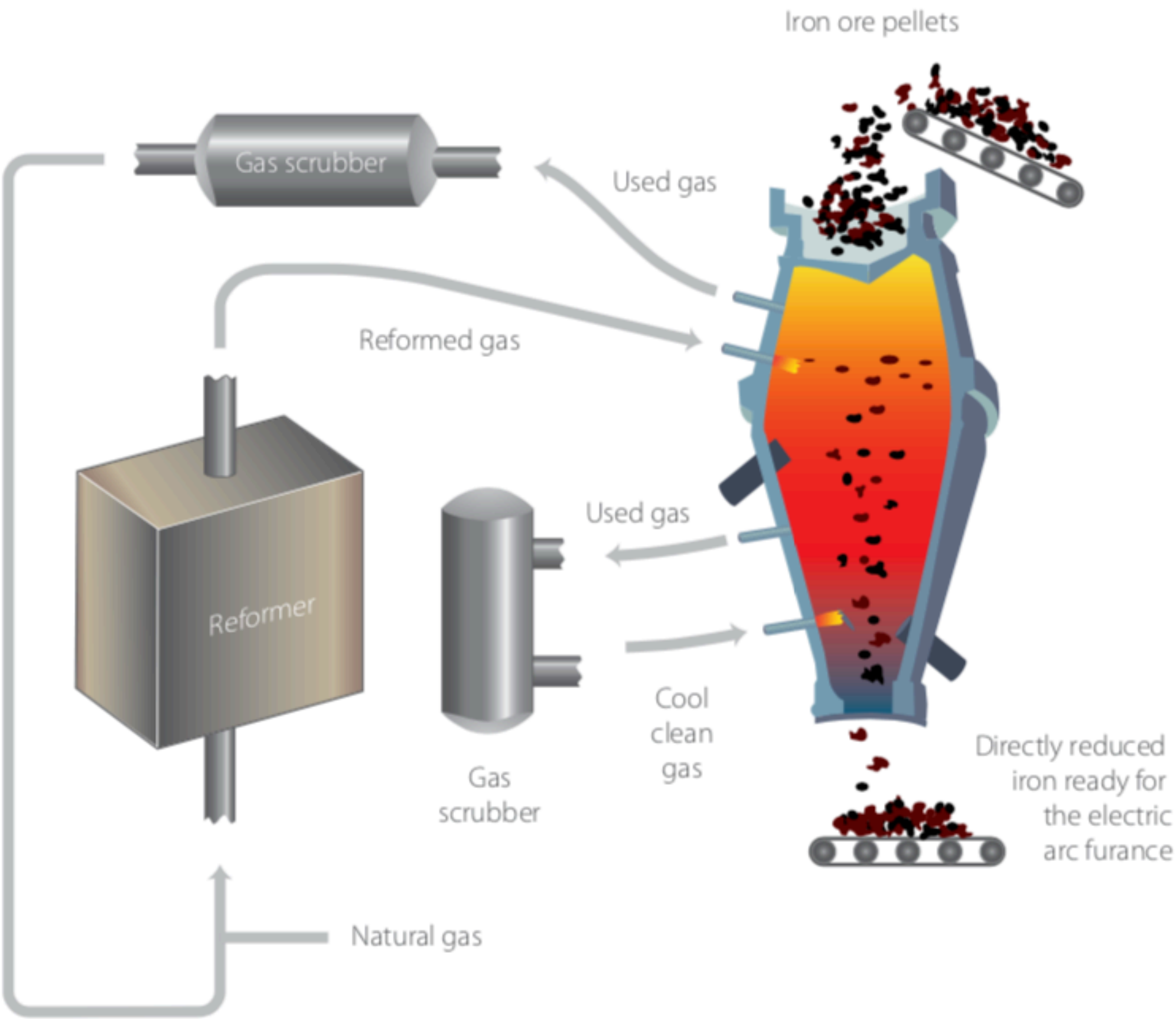

Figure 9.1—**Direct reduced iron production**[15]

Smelt reduction – demonstrations planned (Hisarna pilot plant in The Netherlands)

- No coke
- Lower T than blast furnace (800 – 1000 °C)
- High C/impurity concentration, thus
- Refine in connected pool of **molten** iron; coal and oxygen drive removal of C/ impurities

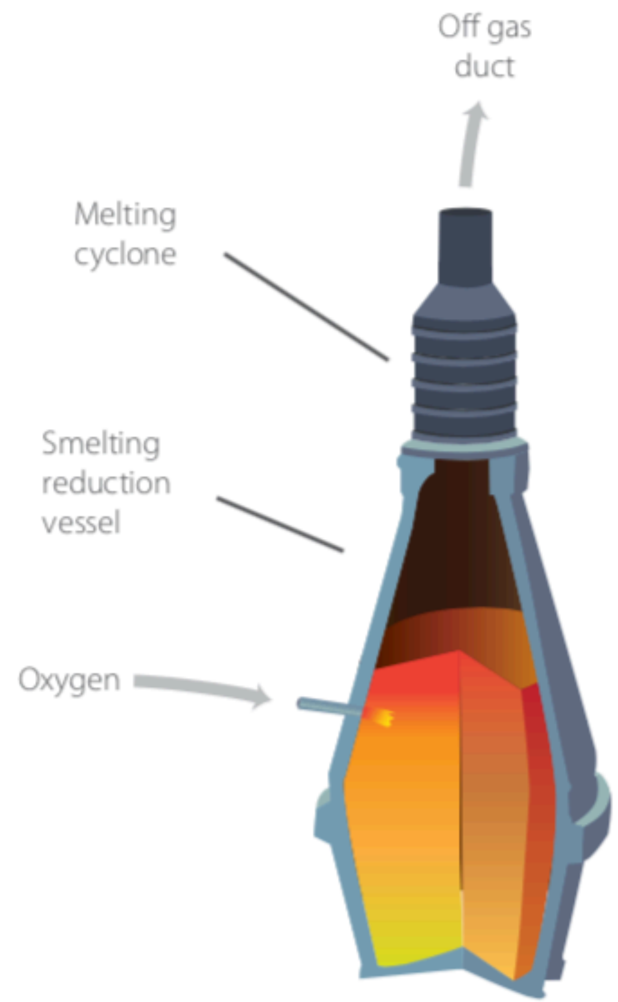

Figure 9.2—**Smelt reduction process**[15]

Electrolysis

- Electrowinning
  - Strong current passed into liquid via positive terminal (an oxide) so pure Fe is electroplated onto negative terminal
- Iron ore pyroelectrolysis
  - Current passed from inert positive terminal through molten iron ore at 1600 °C, forming liquid Fe while O_2 is released.

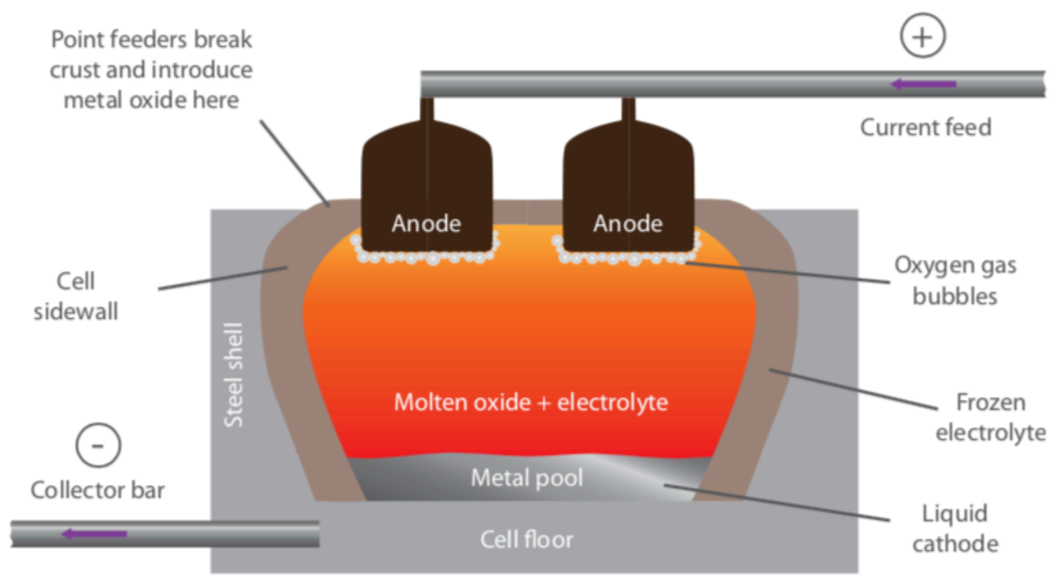

Figure 9.3—**Schematic of iron ore pyroelectrolysis**

Sustainable Steel?

Option	CO_2 abatement potential
Energy efficiency—best available technology	13% for all processes
Direct reduced iron	20 % compared to the blast furnace
Smelt reduction	20 % compared to the blast furnace
Electrolysis with nuclear power	80 % compared to the blast furnace assuming low carbon electricity
Top gas recycling and fuel substitution	10 % compared to the blast furnace
Electric motors in fabrication	50% reduction in energy

Table 11.1—**Summary of the emissions abatement from energy efficiency and novel technologies for steel**

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