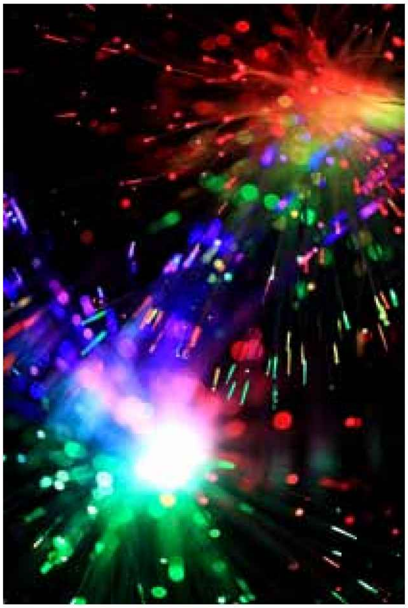
5 Energy and emissions

in making steel and aluminium components

Many of our concerns about sustainable materials relate to the requirements for energy to process them, so we need to find out where the energy is used, and how that use evolves. In response to concerns related to climate change, we need to know in particular which processes emit most greenhouse gases.



Wohhhhhhh!

We're going clubbing, but let's have a drink first. See that small bottle with the cork stopper? Glug-glug-glug, Oh Man! The world's expanding around me, everyone else looks so small. We fly to the club, and almost everyone looks like us, but there's a few big guys in the line and they move to a different beat. Inside, the dancers are packed in close and we're shaking, and I don't know if it's us making the heat, or the heat that makes us move. There's a couple over there, a bit mismatched but they're nice and tight, and … wham! Some other guy, came out of nowhere, knocks into them, and would you believe it, now she's split from her partner and is all wrapped up with the new one. And look, there are those big guys, and they can really move. They're doing that big arm thing with the double twist, and somehow they've found each other. Maybe it's easier to do their moves when they all get together. Now the DJ's giving us a break, and he's slowing it down, and we're all still and cool. But wait—what's happening over there? The walls front and back they're moving in, while the other two are going out. Nnnnggg! We're all packed right in, and we can't move. But now the DJ's had an inspiration, and he's put on a fast track, and we're all moving like crazy. And you know what? Now we're moving, side to side, in and out, and we must all be spilling into the space where the walls are moving out, and that's relieving the pressure of the walls coming in. Alright! It's hot, we're shaking, but the squeeze is gone and we've got the beat. Wohhhhh!

Got it?

That potion really was powerful—Lewis Carroll with another 150 years development in the lab—and we all shrank 10 thousand million times to become atoms. And we've seen in the club everything we need to know about energy use in making our two metals. The dancers (atoms) shake more when it's hotter and less when cooler, and when they're shaking more it's easier for them to move past each other. The big guys, alloying elements, prefer being close to each other, but can only move (by diffusion) when it's hot. The close dancing couple? Two different atoms bonded together tightly (they might be iron and oxygen in a naturally occurring ore, like Haematite, say) but when they were hot, a carbon atom was able to knock them apart, and also get his arms round her (the oxygen) and carry her off, the hound. And when the dance floor cooled and the walls moved in, no one could move, so they really felt the squeeze. But when they could move again as the temperature went up, they could slide past each other much more easily, and rearrange themselves sideways. Metal deforms more easily when it's hot.

In making steel and aluminium, we need energy for three things: to drive chemical reactions to rearrange the bonds between different atoms; to create enough heat for diffusion to allow atoms to reorganise, so changing the distribution of alloying elements, relieving stress around dislocations, and allowing bigger grains to grow; to raise the temperature so the metal can deform more easily. In this chapter we'll first look at how energy needs are met by existing processes. Then we'll explore the conversion of process energy requirements into process emissions. Adding these up, we can examine global emissions figures, and by looking at their history, we can begin to forecast how they may develop in the future. Finally we'll explore the difficult problem of allocating energy and emissions from processes to products.

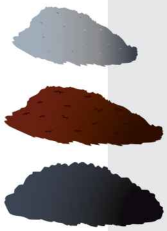
Energy use in the process of making steel and aluminium components

The next two double pages show how the three requirements for energy are in the processes we use to make steel and aluminium. We've started from greyed out versions of our two metal-flow Sankey diagrams from the last chapter, and shown on them all the key processes required to convert ores mined from the ground into finished metal components. For each process we've also shown an estimate of the annual energy required to drive the steel[1] and aluminium processes[2]. (The energy values are reported in exajoules (EJ) one of which is equal to a billion billion joules, as we saw in Figure 2.5, we use just under 500 EJ of energy each year). There's a lot of information on these pages, but nothing happens except what we saw in the Atomic Club.

The energy values in the Sankey diagrams are given as primary, rather than final energy values as discussed in chapter 2. We've shown the processes on top of our Sankey diagram of flow, because one of the big concerns of the trade associations for steel and aluminium, who have the best data on energy use, is it's only possible to understand energy needs for metal production if we show the exact route by which the metal is made. For example, for both steel and aluminium, making liquid metal out of scrap takes much less energy than making it from ore, particularly so for aluminium. But some metal flows between the primary (from ore) routes and the secondary (from scrap) routes. So, the trade associations are absolutely right that we can't give a convenient single number to answer the question "how much energy does it take to make steel/aluminium?" because the answer depends on the exact combination of processes involved. For both metals, we can always use a much lower number if our product was made entirely from scrap and not ore.

The number of processes involved also influences the total demand for energy. The diagrams show us that the liquid metal processes are the energy intensive ones: for both metals, making liquid metal, whether from ore or scrap, uses far more energy than any other stage in the process. Downstream, once the metal has been formed into a stock product, the energy required to shape it into its final form depends strongly on how many processes are involved. A steel I-beam (known as a double T beam in Germany, and a grrrdr (tr. girder) in Scotland) is made with very few processes: it's hot rolled to shape, then cut to length and a few bits are welded on. In contrast, a steel car door requires a long series of process steps: cold-rolling (to give the required surface quality); galvanising (adding a coat of zinc for protection against rust); blanking (cutting a specific shape from the two metre wide coil of strip made in the rolling mill); deep-drawing and punching to give it the required 3D shape, and cut out holes for instance for the window and door handle; hemming (folding over the sharp edges); welding and assembly onto other parts of the door; painting; paint baking (hardening the paint and, remarkably, making a final change to the microstructure of the steel so it has maximum strength, having been designed to be more ductile for the deep drawing process). Each process requires more energy so it takes more energy to make more complex parts. However it is still the liquid metal processes that dominate total energy inputs. We've not attempted to show what happens after the component is completed because generally the process of assembling components into finished products, and the logistics of moving products from their point of manufacture to their point of sale, takes much less energy than any of the component manufacturing stages.

Steel process map



Blast furnace

16 EJ

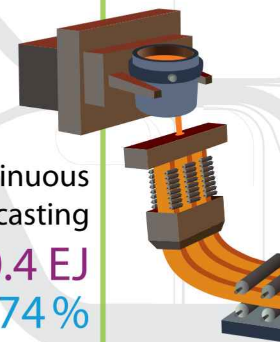
7 %

Coal and iron ore are processed and fed with lime into the top of the blast furnace. Hot air and additional fuels are blown in from the bottom. Coke reacts with air to form carbon monoxide, which reduces iron oxide to iron. The lime reacts with impurities in the ore to form a slag. Liquid iron collects at the bottom of the furnace and is tapped into ladles.

Basic oxygen furnace

0.2 EJ

Oxygen is blown through the liquid iron and this oxidises the remaining carbon into CO and CO_2. The reaction is exothermic (gives out heat) and steel scrap is added to reduce the temperature in the furnace. The molten steel is refined in a separate ladle furnace.

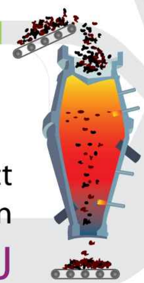


Continuous casting

0.4 EJ

74 %

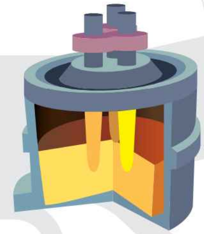
Molten steel is cast continuously into slabs, blooms or billets, and water-cooled. The majority of steel produced is cast continuously, although a small fraction is still cast as ingots.



Direct reduction

0.7 EJ

In direct reduction, iron ore is reduced into iron in a shaft or rotary furnace using natural gas or coal.



Electric arc furnace

2.7 EJ

86 %

Carbon electrodes are lowered into the furnace and a high temperature arc forms between the electrodes and the metal charge. If the charge is not completely scrap, carbon or other fossil fuels may be injected with oxygen for the reduction reaction.

Shape casting

2.1 EJ

46 %

Iron or steel is melted before pouring into a mould. Once solidified, the casting may undergo cycles of heat treatments to achieve the desired properties.

Steel (overview)

Energy = 38 EJ

Electricity = 39 %

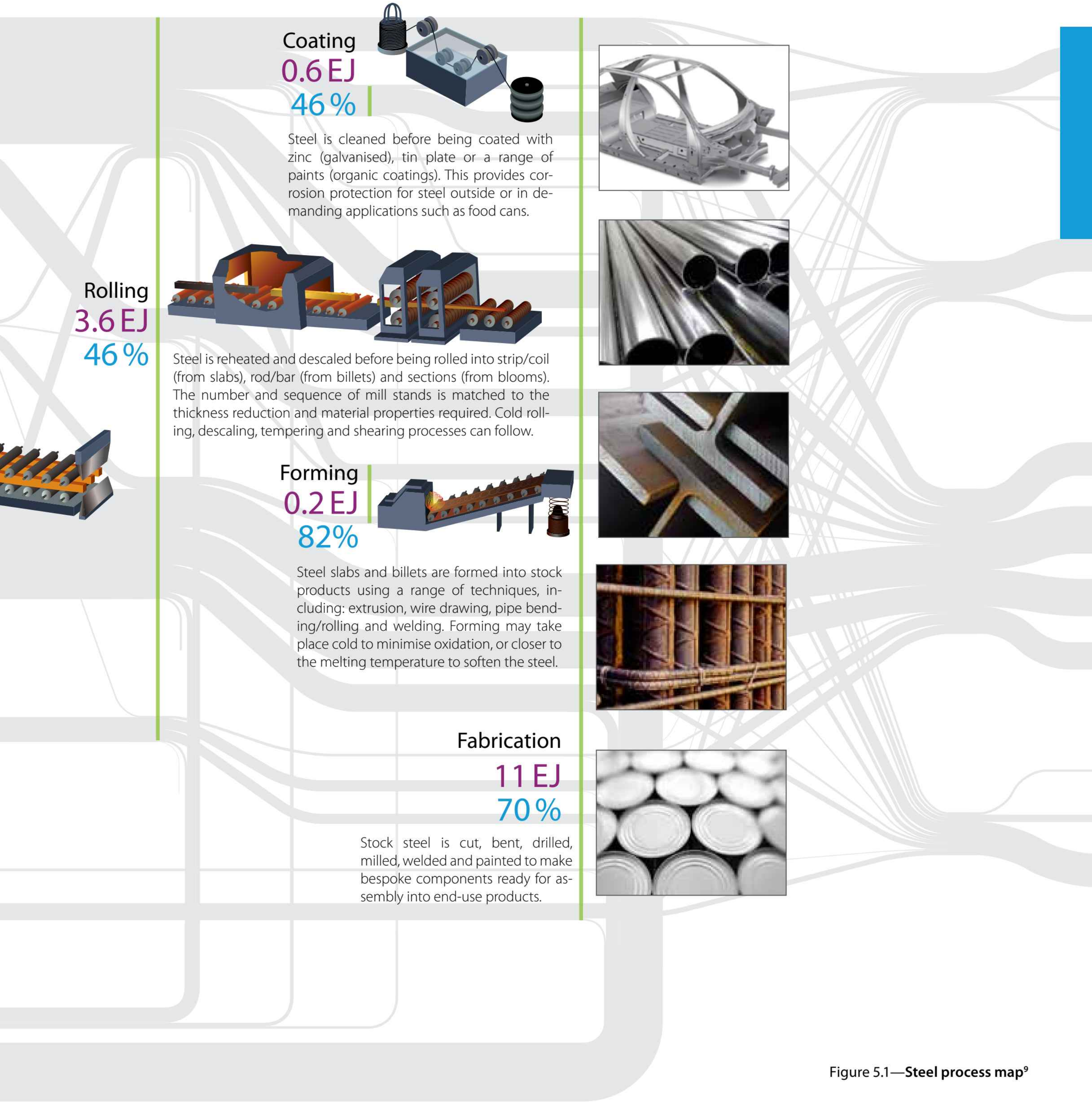


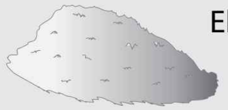
Figure 5.1—**Steel process map**[9]

Aluminium process map

Alumina mining +refining

1.1 EJ

2 %



Bauxite is mined—mainly from open cast mines—washed and crushed before being dissolved in hot sodium hydroxide (caustic soda) in 'digesters'. The aluminium oxide reacts to form sodium aluminate, leaving residues, which sink to form 'red mud'. The solution is cooled and the water removed, leaving alumina as a white powder.

Electrolysis

5.0 EJ

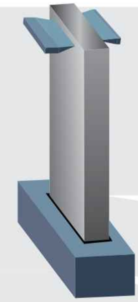
100 %

Alumina is dissolved in cryolite (sodium aluminium fluoride) at about 950°C. Electric current passing from the suspended carbon anodes to the graphite cathode lining the electrolysis cell causes the deposition of molten aluminium at the bottom of the cell (or pot) where it is periodically tapped.

Ingot casting

0.05 EJ

44 %

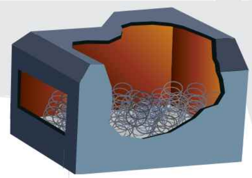


Crucibles of liquid aluminium from the smelters are cast via the direct chill route, where large rectangular or log shaped ingots are lifted up from a water cooled casting mould.

Scrap remelting

0.04 EJ

30 %

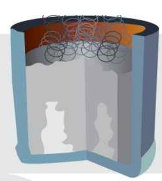


Clean, wrought process and post-consumer scrap is melted, mostly via the hot combustion gases in reverbatory furnaces, but sometimes using the heat generated during electromagnetic induction in induction furnaces.

Scrap refining

0.15 EJ

14 %



Scrap is melted in rotary or ladle furnaces. Salt is used as a fluxing agent to remove impurities, resulting in the production of slag. Refiners produce mostly foundry ingot and so add silicon and metals like copper and magnesium to achieve the required composition.

Alloy ingot casting

0.03 EJ

44 %

Alloying elements, such as silicon, are added to crucibles of liquid aluminium from the smelters, and then purified before casting by blowing gases through the melt. Liquid aluminium is cast into smaller ingots ready for shape casting.

Aluminium (overall)

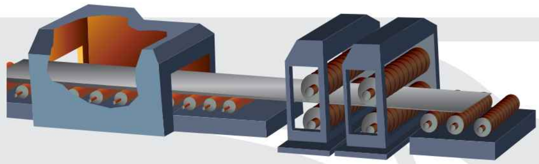
Energy = 7.6 EJ

Electricity = 76 %

Rolling

0.23 EJ

72 %

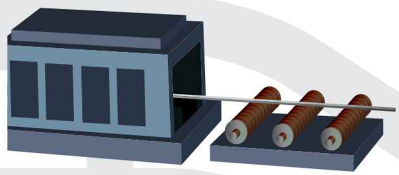


Ingots are preheated to around 500°C before rolling. Several rolling passes are required to reduce the ingot to the required thickness for sheet (4-6 mm) or plate. Some sheet is cold rolled further down to 0.05 mm for foil, and passed through annealing furnaces and slitting if required.

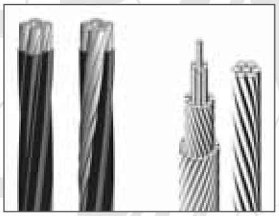
Extrusion +drawing

0.09 EJ

19 %



For extrusion, the billet is typically heated to 450-500°C and pushed through extrusion dies at a pressure of 500 to 700 MPa. Extrusion billets may have a diameter of 50 to 500 mm. For wire drawing aluminium rod is drawn through a series of dies with a decreasing aperture.



Shape casting

0.17 EJ

1 %

Sand casting and die casting are the most important types of mould casting, sand casting moulds are one-use, whilst die casting moulds are generally re-used, being made of cast iron or steel. Foundry ingots are melted and the molten aluminium is poured into the moulds. Pressure may be applied during die casting.

Fabrication

0.62 EJ

70 %

Aluminium stock products are cut, bent, drilled, milled, welded and painted to make bespoke components ready for assembly into end-use products.

Figure 5.2—**Aluminium process map**[9]

We'll conclude this section with two pie charts to show estimates of the total energy involved in making aluminium cans and steel car door panels. The energy for liquid metal production dominates all else for both products, which ties up with what we saw earlier about total energy use in China. So we've got a clear motivation to focus on (a) energy efficiency in liquid metal production and then (b) finding ways to use less liquid metal. That pretty much summarises what we mean about looking at the problem with one or both eyes open.

CO_2 emissions arising from the processes of steel and aluminium making

In addition to energy we are interested in emissions, Tables 5.1 and 5.2 show the emissions intensity of the key processes: how much CO_2 is emitted for each unit of metal processed. Our numbers for process energy can be measured precisely, with meters recording the supply of fuel or electricity to each process over some period, divided by the total mass of metal leaving the process in the same time. As we discussed previously, there are reasons why some of these numbers will only be made public as estimates, but any company wanting to understand the drivers of its energy consumption can measure them accurately.

The same is not true for CO_2 emissions. Although under laboratory conditions these emissions can be measured, in practice this is rare, so instead CO_2 numbers are calculated or inferred. Direct emissions of CO_2 from fuel combustion or from the chemical reactions which reduce ores to metals can be calculated with reasonable accuracy from the mass of ore and fuel being processed. Indirect emissions related to electricity generation can be collected, with significant effort,

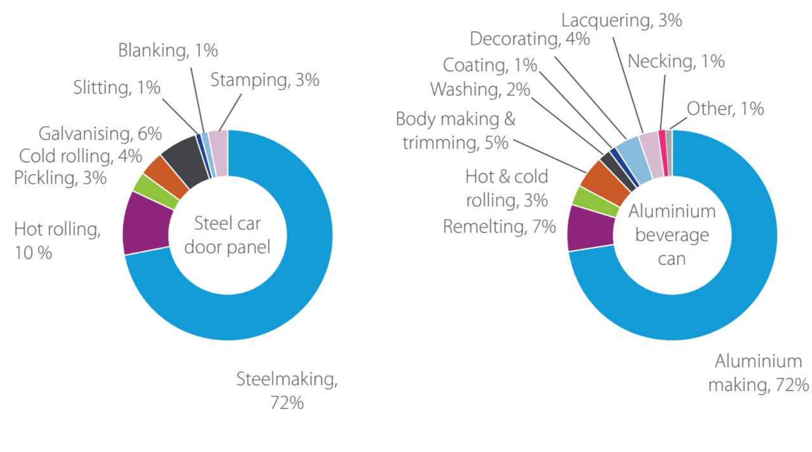


Figure 5.3—**Estimates of total energy involved in making components** [4]

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]

by chasing the electricity back to its source. However, emissions from electricity generation vary widely, with hydro-electric power (commonly used for aluminium smelting) having the lowest intensity, and coal-fired power stations the highest. As a result, the emissions intensities of identical processes may be quite different in different locations. For the major processes used in making steel and aluminium, emissions intensities have been studied widely, by companies, trade associations and academics, and the numbers in the tables reflect our best estimates of these values.

Behind this allocation of emissions to electricity purchasing lies a further, political question that has had little attention, but is highly significant. If within a country there are a range of different power stations, each with different emissions intensities, is it reasonable for one company to claim all the benefits of using the lowest emission supply?

This is what happens in aluminium smelting at present, and the aluminium industry would correctly state that they are purchasing a large part of their electricity requirement directly from very low emitting hydro-electric generators. However, if the smelter ceased to operate at that location, the hydro-power would still be available, and would be reallocated to other uses in the country. It seems to us that we should therefore have just one average emissions intensity for all the electricity in a country, the same for all users. If that happened, the emissions intensity of aluminium would be increased. For obvious reasons, the aluminium industry would disagree with us, and as they are the main source of data on emissions, the numbers shown in Table 5.2 are indicative of currently reported emissions intensities.

The numbers in the tables demonstrate that for both metals, liquid metal processes lead to the highest emissions. The relative impact of downstream processes is higher for emissions than energy, because most energy used downstream is in the form of electricity.

Global energy and emissions history and projections

Although we have good records of total production of both steel and aluminium since the modern production processes were invented, we're much shorter of historical energy numbers, and don't really have any history of global emissions numbers. Instead we have a rough idea of the global average energy intensity of making steel from ore, shown in Figure 5.5. This approximate data illustrates that

Process	Emissions ($t\ CO_2/t$)
Bauxite extraction	0.02
Alumina production	1
Anode production	0.1
Electrolysis	5.4
Scrap preparation	0.3
Scrap remelting	0.3
Scrap refining	0.6
Ingot casting	0.2
Hot rolling mill	0.2
Cold rolling mill	0.2
Extrusion	0.3
Wire drawing	0.6
Shape casting/secondary casting	0.5
Foil mill	0.9

Table 5.2—**Emissions estimates per unit processed for major steel and aluminium production processes**

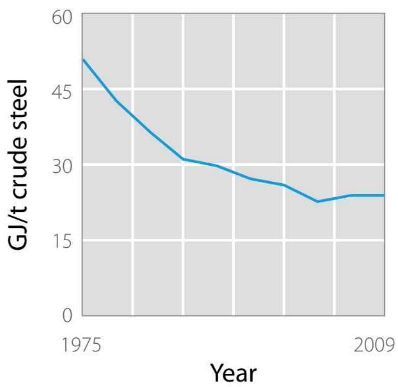


Figure 5.4—**The history of energy intensity improvements in primary steel production**[6]

steel production has become much more efficient over time, although it appears to be reaching a plateau. Figure 5.6 shows the historical development of CO_2 intensity for different countries, but we can't be sure exactly what this means as the changes in CO_2 intensity will be influenced by a whole range of factors including the technology mix, electricity mix and any efficiency improvements.

The data records for aluminium energy intensity is a little better as the IAI have kept historical data on the electricity requirements for aluminium smelting since 1980. Although we are generally reporting primary energy figures, in Figure 5.7 we've used final electricity values to show the improvement over time due to increased energy efficiency, without the disguise of changes in the mix of electricity generation. Again, we can see significant improvements in the energy intensity over time, but signs are that the rate of improvement is slowing.

We ended our analysis of demand in the previous chapter with a forecast, and within that, we made an assessment of the availability of material for future recycling in order to anticipate the likely future ratios of primary to secondary production. This gives us a basis for making a forecast of future energy and emissions. If we assume that energy and emissions intensities remain about the same as now, and that the mix of products remains about the same, we can forecast energy needs and CO_2 emissions in 2050 by applying our process energy and emission factors from the table to the relevant forecast metal flows. We've done that to create the next two graphs, which form a reference for our forecast of future emissions for the two materials. And these graphs demonstrate why we decided to write this book: without other changes, emissions for both metals will increase significantly, and although our forecast shows slightly less growth in emissions than demand due to the increased fraction of liquid metal being made by recycling, we clearly have a problem if we want to cut emissions by 50%. So, better keep reading…

Allocation of energy and emissions figures to products

Now, back to the Atomic Club, but after everyone's gone home, and only the owner Boris is left. Boris has recently opened a letter from Brussels, which has ruined his day. The Belgian bureaucrats have announced that Boris has to provide a carbon certificate to everyone leaving his club, identifying exactly how much CO_2 has been emitted as a result of their visit. Poor Boris: as if life's not busy enough already what with counting the cash and adding the water to the vodka.

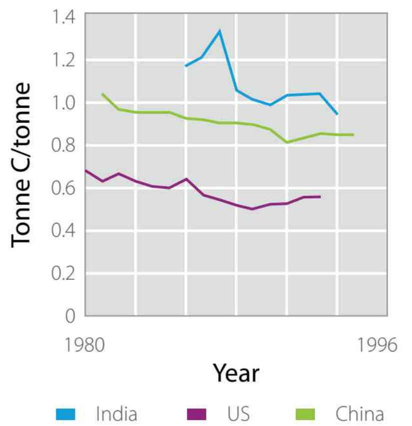


Figure 5.5—**History of CO_2 intensities for the iron and steel industry in selected countries**[7]

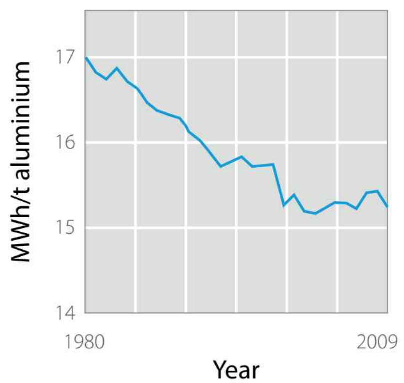


Figure 5.6—**Historical electricity intensity of primary aluminium production**

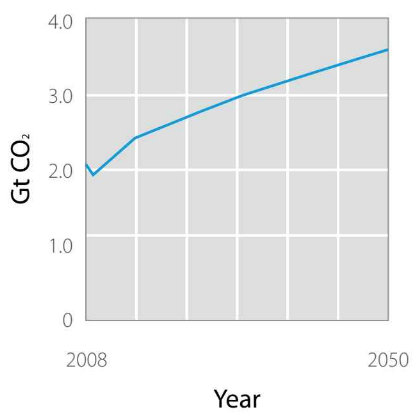


Figure 5.7—**Forecast CO_2 emissions in steel production if business continues as usual**

What's a fair basis for allocating CO_2 emissions to clubbers? Presumably we have to start with the total CO_2 emissions related to the club's energy purchases. The club only buys electricity, but Boris has two suppliers, as he buys some of his electricity from a local wind farm. They only send in the bill after each three months of use. So Boris has to guess what his bill will be for the next three months, and divide it up evenly between his customers. But, he doesn't yet know how many people are going to come to the club in the next three months, and he also has a suspicion that the party from the local aluminium smelter will only come in if they can buy 'green' tickets related to the wind farm electricity only, and without question, the bankers will want tickets based on the emissions 25 years ahead. But the problem gets worse. Making the materials to build and fit out the club required energy, so how does that fit in? And what about Boris' choice of transport to get to work: does it matter whether he comes to work on a bike or by car? And what about the emissions of the bands who recorded the music played in the club?

The problem Boris faces is in fact insurmountable. It isn't possible to allocate his emissions to his clients accurately because (a) he doesn't know what his emissions will be over the next period (b) he doesn't know how many punters will come in that period (c) he can't define clearly for which emissions he is responsible and (d) it isn't clear what fraction of the emissions should be attributed to each punter: should a 5 minute visit collect the same number of credits as a three hour stay? Despite this, we're currently surrounded by efforts, many driven by people in Belgium, to attribute carbon emissions to products and services. See the box story on the following page for some of the most common approaches.

This whole effort around emissions attribution simply doesn't make sense. Our concern is global emissions, so any exploration of whether particular choices or decisions are beneficial or not depends on whether they have a good or bad effect globally. If I switch from primary to secondary aluminium in making my product, that makes no difference whatsoever to global emissions unless I have somehow increased the amount of secondary production and decreased the amount of primary production occurring. To do that I need to find a new supply of material for recycling that would only exist because of me. If I divert wind-power from a new wind farm in the North Sea from the national grid to power my factory, it makes no difference to the country's total emissions because the wind power was going to be used by someone. And so on and so on and so on. Our only guiding principle is to establish whether some change causes a significant global reduction in emissions. So we have great doubts about any attempt to attribute emissions to products because it's so difficult to do so in a sufficiently consistent way that the sum of all attributed emissions is uniquely equal to the sum of all emissions.

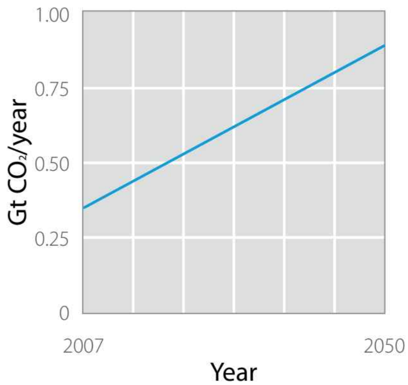


Figure 5.8—**Forecast CO_2 emissions in aluminium production if business continues as usual**

We've been clubbing, we've done some hard estimating, we've tried to help Boris solve his problems with Belgian bureaucrats, and we're all worn out. Time to rest now—ready for a day's shopping tomorrow.

Attributing emissions to products

There are three methods in current use to allocate carbon emissions from processes to products and services. These methods would be plausible if the sum of all emissions attributed to products equalled the sum of all industrial emissions.

- 'Carbon footprints' are calculated by summing the emissions directly and indirectly caused by an activity, to give a single emissions figure in grams of CO_2. There is no agreed approach to calculating such footprints, although Non-Governmental Organisations such as the UK's Carbon Trust have attempted to define methods. Carbon footprints are increasingly reported on consumer products, with the intention of allowing consumers to compare similar products. However, the methodology is ill-defined and consumers have little understanding of such labels, so their purpose is as yet unclear.
- In contrast, the technique of Life Cycle Analysis (LCA) is much more established and is defined in ISO standard 14040. The ISO standard assumes that LCA is used for comparing two similar ways to complete the same product. A boundary is defined round a system which is broad enough to encompass all differences between the alternative products. Every process within this boundary is examined and numerical values are calculated for drivers of any environmental concern within the boundary, for the two approaches. The LCA study then calculates the difference between the two approaches, and anticipates how this will lead to environmental harm. This approach is well defined, and rigorous. Unfortunately almost all current users of the LCA method fail to apply it correctly as a comparison, and instead claim that it predicts absolute impacts associated with a particular product. It doesn't, and as a result, almost all recently published LCA studies are misleading. They are so dependent on the boundaries used that they can be manipulated to create any answer. We have yet to find a single LCA study in which the company who paid for the study is responsible for the largest environmental impact.
- Input-Output (IO) analysis assigns emissions to monetary flows and tracks these emissions through the production system from initial production to final demand. This method of analysis is comprehensive and complete and allows us to convert emissions from production to consumption in a consistent manner. Unfortunately assigning emissions to money flows can be quite misleading, and while the IO approach is logically consistent, it requires a huge data set, which is generally unavailable in sufficient detail, or for recent years. The analysis is performed for sectors, so cannot create results for individual products.

Hybrid methods, which combine IO and LCA analysis, have been developed, but many of the same problems with data (reliability, detail and boundaries) remain.

Notes

1. The energy numbers for the steel processes come from a wide range of sources including a report by Ernst Worrell and colleagues on the world best practice energy intensity values for selected industrial sectors, including steel (Worrell et al., 2008) and a report from the IISI (the old name for the World Steel Association) (IISI, 1998). Best practice values were converted into estimated average values by multiplying by a factor of 1.1.
2. The energy numbers for the aluminium processes come from a wide range of sources including Ernst Worrell and colleagues' best practise report (Worrell et al., 2008) and a report by the US DOE (BCS, 2007).
3. The energy data for fabrication processes is based on data we collected for case studies of metal products and their supply chains and is published in our report, Going on a metal diet. (Allwood et al. 2011a)
4. The energy data for making components is based on data we collected for case studies of metal products and their supply chains and is published in our report, Going on a metal diet.

CO2 emissions arising from the processes of steel and aluminium making

5. Like the energy numbers, the emissions numbers for steel and aluminium production processes are collated from a wide range of sources. For aluminium, most of the upstream data is taken from IAI analysis (IAI, 2007) and much of the downstream data is taken from the US DOE report (BCS, 2007). For steel, several of the values were taken from reports for the EU's Integrated Pollution Prevention and Control directive and from a study of the Canadian steel industry (Canadian Steel Producers Association, 2007).

Global energy and emissions history

6. This graph has been put together from a number of sources. The World Steel Association has produced an indexed graph of the energy intensity of primary production for 7 years between 1975 and 2004 (World Steel Association, 2004). We can use a data point of the absolute energy intensity of steel production, from Yellishetty et al. (2010). Finally, we can use energy intensity values from Tata (2011) to give us some more recent data points.
7. This figure is from Kim and Worrell (2002), but it includes the effects of changing technology (OHF to BOF for example) so does not just describe improvements due to energy efficiency.
8. Pelletising is another way to prepare iron ore but it is used far less than sintering and uses about 0.8 GJ/t steel produced. For simplicity, only sintering is described in the Sankey diagram.

Images

9. Some images on these diagrams adapted from World Steel Association graphics.