

## 7 Energy efficiency

in existing processes

*To reduce the energy required to make steel and aluminium, the obvious first focus is the current processes which use most energy. However, because energy has always been a significant cost to the operators of the intensive processes, they have already sought out and applied almost every available option. What are the limits to future energy efficiency, and what remaining options are there to approach these limits?*

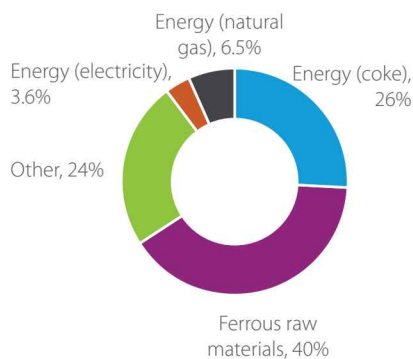


Figure 7.1—Costs in steel production

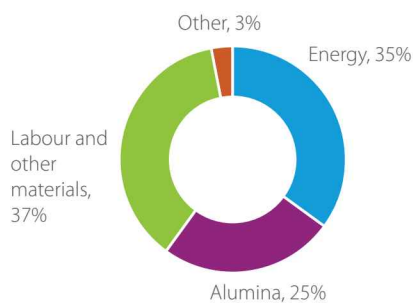


Figure 7.2—Costs in aluminium production

In the TV series *The Apprentice* a group of highly motivated candidates compete to be chosen for a well paid job through a series of episodes designed to test what we're told are their 'business skills.' In fact, virtually all episodes test the same skill: marketing a new product or service into an already well populated commodity sector, whether perfume, magazines, fish or chocolates. This is of course one important business skill. But our friends who teach entrepreneurship tell us that while most new businesses that fail in their first year do so for lack of sales and hence the skills being tested in *The Apprentice*, the most likely cause of failure in the second year is a failure to control costs in delivering the products. Costs don't make good TV, but they are at the root of all business decisions in the materials processing industries because, regardless of marketing, the products are essentially indistinguishable. We have agreed international standards for steel and aluminium (and also cement, paper and plastic) which specify the composition, processing and properties of all the standard products, so buyers can switch suppliers easily. If all suppliers are equal, the price is in effect fixed at the lowest price any supplier can sustain. And if, as a supplier, you can't control the price, then your profits depend on controlling your costs. So next time we get the chance to run the BBC, we'll be moving on from *The Apprentice* because we've now learnt that focusing ruthlessly on your own advancement is the skill that gets the prize, and instead we'll be screening *The Cost Manager*—it already sounds like a hit!

The two pie charts show a typical breakdown of costs in primary steel and aluminium production. Energy purchases account for a third of the costs of both basic steel and aluminium production. As a result, these energy intensive industries have, for more than a hundred years, had a strong incentive to pursue energy efficiency. These costs will continue to motivate managers of average or

Gospel, blues



poorly performing sites to raise their standards to those of current best available technology.

In the Atomic Club in chapter 5 we saw that we need energy to drive reactions to raise the temperature of metals to allow diffusion and to make deformation easier. In this chapter we'll start by defining the least energy we would ever need to make our two metals. Then we'll evaluate the efficiency of existing processes to make metal from ore and from scrap.

## How little energy could we use to make metal goods?

Iron and aluminium are both chemical elements appearing in the periodic table as Fe and Al respectively, but are rarely found in nature as pure elements. Only if you happen to stumble upon a meteorite. This is because iron and aluminium have a natural affinity for oxygen. When they are mined as ores, they are in the form of oxides with the pure elements tightly bound to oxygen atoms.



Haematite



Bauxite

Iron ore occurs naturally in several forms. The two most common forms are magnetite and haematite, both of which are oxides, with different ratios of iron to oxygen atoms. Ore deposits are commercially interesting if the ores make up at least a quarter of the extracted rock, the rest is typically quartz (silica) which must be removed. To do this, the rocks are crushed, and the ore is separated from the remainder, by use of magnets for magnetite, and by flotation in water for haematite. Iron is then extracted from these oxides by a chemical reaction in which the iron oxide is mixed with a stream of hot carbon monoxide, which itself is made by blasting a stream of hot air through coke. (Coke is made from coal by baking at around 1000°C in a low oxygen atmosphere, to remove water, coal-gas and coal tar without combustion.) At around 2000°C, the oxygen atoms in the iron oxide have a stronger attraction to the carbon atoms in the gas than to the iron atoms in the mined ore, so bond to the carbon to form carbon dioxide (CO<sub>2</sub>) and leave behind a nearly pure pool of liquid iron, as shown in Figure 7.3. This 'pig iron' also called 'blast furnace iron,' retains about 5% carbon, and is a stiff but brittle metal. In an odd quirk of language, steel is actually a purer form of iron than 'cast iron'. Bessemer's invention, mentioned earlier, was to blow pure air through the liquid pig iron to remove the remaining carbon by igniting it, to form

carbon monoxide or carbon dioxide. In 1948, the Swiss engineer Robert Durrer discovered that this process was much more efficient if oxygen rather than air was used, and this is the basis of most current steel making.

Aluminium is most commonly found in the earth's crust as an oxide within bauxite, which contains about one third aluminium oxide (also known as alumina). Aluminium atoms have a stronger attraction to oxygen than iron or carbon, so aluminium cannot be separated as easily from its oxides by the same process as iron. Instead, the mined ore is first purified in the Bayer process, before being separated by electrolysis in the Hall-Héroult process. Karl Bayer, working in St Petersburg in Russia in 1887, discovered that if Bauxite is washed in caustic soda (sodium hydroxide, NaOH), the alumina within it dissolves, and after being filtered, dried and heated to 1050°C, is released as a white powder. The remainder of the Bauxite in the caustic soda is the 'red mud' which we identified in the first chapter as an environmental concern because it is strongly alkaline, and because we make roughly twice as much red mud as alumina. Alumina has a melting point of around 2000°C, but dissolves at 1000°C in liquid cryolite from which pure aluminium can be extracted by electrolysis. (Cryolite—meaning 'chill stone'—sounds like an invention in a James Bond film, but is a naturally occurring mineral compound of sodium, aluminium and fluorine, first found in Ivittuut, West Greenland in 1799.) Despite being at one end of the only road in Greenland connecting two towns, and despite having Greenland's highest recorded temperature (30°C), the town was abandoned when the cryolite deposit



Ivittuut

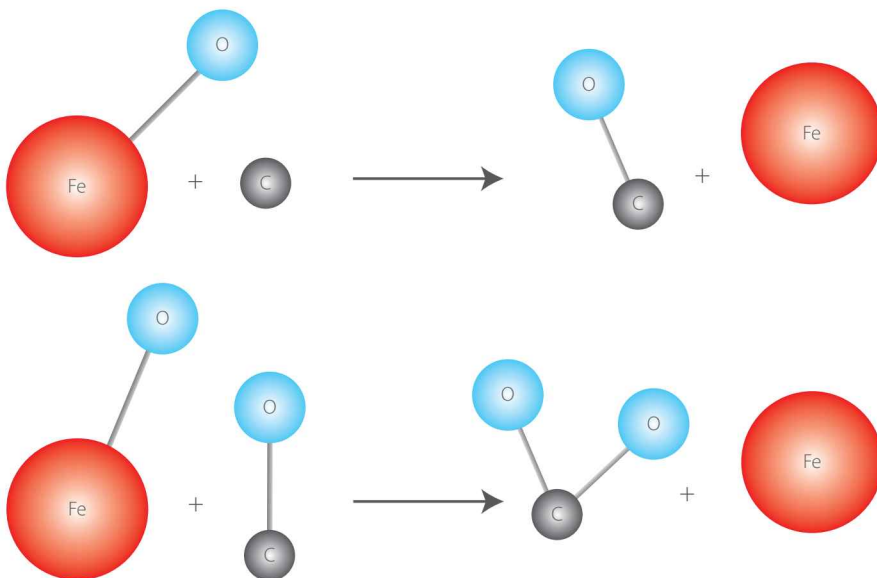


Figure 7.3—Schematic of the iron reduction process

was exhausted in 1987. A synthetic version of cryolite is now used for aluminium production, and presumably Greenland's Road Atlas business has also collapsed.

The electrolysis process involves passing a large current through the solution of alumina in liquid cryolite, from a carbon-based positive terminal (the anode) through to the graphite negative terminal (cathode) as shown in Figure 7.4. As a result of the electric current, the aluminium and oxygen are separated: the aluminium forms a bath of liquid metal at the base of the cell, and the oxygen bonds with carbon from the anode, which is consequently consumed and converted into  $\text{CO}_2$ .

We've given a little detail about these chemical reactions to demonstrate that both require high temperatures, and both release  $\text{CO}_2$  as part of the process. In looking for efficiencies in these two processes, a good starting point is to understand the limits to energy requirements for the reactions, and we can do that by turning to the work of Josiah Willard Gibbs, an engineer at Yale University, in the second half of the 19th Century. There is an unbeatable limit to the amount of energy required to heat water to  $100^\circ\text{C}$  before making your coffee, and it doesn't matter how much money you offer to inventors, they will never beat this limit. Gibbs showed us that there is a similar limit for extracting metals from ores.

Gibbs examined chemical reactions, such as those that transform metal oxides to pure metal, and showed that they involve an exchange of energy with the external world. Energy may be released during a reaction, as occurs during combustion of fuels or in oxidation, for example when iron rusts: the energy stored in gases and solids after the reaction (the atoms of the fuel or iron bonded to oxygen atoms) is lower than that of the separate fuel or iron and oxygen. Alternatively, energy may be required (absorbed) by a reaction, as happens when pure metals and oxygen are separated (deoxidation, described above), because the energy stored in the separated metals and oxygen is greater than when they were combined. Because oxidation releases energy, it can occur without any external energy input, and this is why metals are found as oxides in nature. Gibbs showed that the energy required to drive the chemical reaction of deoxidation is the absolute minimum energy we could ever use for producing a metal from its oxide. As a result of Gibbs' work, we know that the absolute minimum energy to make steel from ore is  $6.7\text{GJ/tonne}$  and for aluminium is  $29.5\text{GJ/tonne}$  of liquid metal produced<sup>1</sup>.

The best technology in use today is able to extract pure aluminium and iron from their oxides using just over double the absolute theoretical minima calculated by Gibbs<sup>2</sup>. In contrast, a typical car operates much less efficiently, at around 10

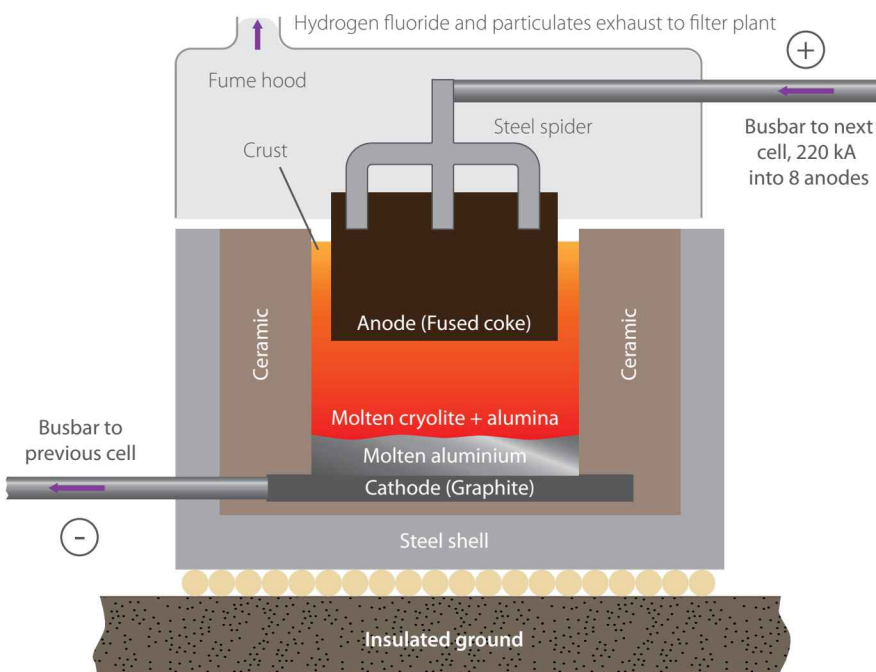


Figure 7.4—A Hall-Héroult cell

times the theoretical limit. Achieving the absolute minima predicted by Gibbs would require an impossibly ideal process: mining of ideal pure oxides without any impurities, perfect insulation, and perfect heat re-capture over an infinite area and infinite time. The fact that the ratio of current best technologies to the theoretical limit is so low signifies a remarkable maturity of the two technologies and this is of great importance as we consider the future of both industries.

## The difference between average and best practice energy use

Gibbs has given us an invaluable definition of the absolute limit to energy efficiency in making metal from ore, and best practice is around double that limit. In Chapter 9 we'll take a look at attempts to develop novel processes that take best practice even closer to the limit. However, before reviewing these efforts, we can ask a simpler question: what's required to raise the performance of today's average processes to the standards of best practice?

This question has motivated substantial efforts led by our colleague Professor Ernst Worrell in Utrecht, who has over many years published thorough and comprehensive surveys of energy efficiency options for our two metals. Some general strategies that apply to most energy efficiency initiatives include improved

process control and better scheduling of operations. Many of the specific options for efficiency in producing metals are about heat, either using less of it or capturing waste heat and re-using it, and this is the topic of the next chapter. In the rest of this section, we'll explore five opportunities revealed by Prof. Worrell's surveys: coke substitution in steel making; more efficient electrolysis for aluminium production; better use of by-products; energy efficient furnaces; efficient motor driven systems. We'll end by assessing the total savings we could achieve with all our options for energy efficiency.

### Coke substitution in steel making

Producing coke for steel blast furnaces is both energy intensive and expensive. However, coke can partially be replaced by injecting pulverised coal, natural gas or oil directly into the blast furnace as a fuel. Pulverised coal is cheaper than coke because it can be made of lower quality coal and grinding coal takes little energy. In some countries, oil and natural gas may be a cheaper fuel than coke, and natural gas releases less CO<sub>2</sub> per unit of heat. However, as well as providing heat and acting as a chemical reductant (removing oxygen from iron ore) coke also has a structural role in the blast furnace. Unlike coal, coke remains hard at the high temperatures in the blast furnace, creating an open structure through which the hot gases can flow easily, giving a more efficient reaction. This structural function cannot be replaced by other fuels, so some coke is always required. Trials suggest that up to half of the coke currently used in a blast furnace could be replaced by pulverised coal<sup>3</sup>. Coke substitution, particularly by pulverised coal injection, is already widely applied, but could be increased in the future.

### More efficient electrolysis for aluminium production

The key inefficiencies in average primary aluminium production relate to maintaining a constant alumina concentration in the electrolysis cell, removing accumulated gases that increase the electrical resistance of the cell and maintaining operating conditions at their optimal level. Point feeders are increasingly used to add alumina in smaller, more regular amounts around the centre of the cell to help maintain a more constant alumina concentration. Cutting transverse slots into the anodes, facilitates easier removal of the CO<sub>2</sub> generated during the electrolysis reaction. Operating an electrolysis cell can be made more efficient through better computer control of a range of operating parameters, including the temperature, current and electrolyte concentration within the cell.

## Better use of by-products

Processes that convert ore or scrap to liquid metal create other by-products, such as gases that could be combusted for energy or used to drive a turbine, and solid slags with both chemical and thermal energy. In steel production, around 80% of the energy released from processes is contained in exhaust gases, and most of this is chemical energy in gases that can be combusted. The hot gases released from coke-making are rich in hydrogen and carbon monoxide, providing as excellent fuel which can be used to run the coke ovens and replace natural gas in other parts of an integrated steel plant. The energy content of the gases from the blast furnace and basic oxygen furnace are dilute compared to traditional fuels, so are typically mixed with natural gas before combustion, and may be used on-site to generate electricity or as a fuel for furnaces in downstream processes such as hot rolling. Blast furnace gas can reach pressures of around two and a half atmospheres and if driven through a top recovery turbine, can generate electricity at an efficiency of around 20%. A different opportunity for efficiency which is already used widely in some countries is to trade solid wastes with other sectors. In particular, blast furnace slag may be granulated and used as a substitute for clinker in cement with no compromise in properties. Cement may have slag contents up to around 85%, giving energy savings up to 2GJ/t compared to the UK average<sup>4</sup>. A much wider example of this type of trade in by-products, often called industrial symbiosis, is the Kalundborg site in Denmark, which is described further in the box-story.



## Industrial symbiosis in Kalundborg, Denmark

'Industrial symbiosis' refers to the practice of trading waste between businesses. The hope of such trading is to find mutual benefits to businesses, through cost savings, and to the environment, if the total consumption of resources and generation of waste is reduced.

The most famous example of industrial symbiosis is the Danish industrial park in Kalundborg, where energy, water and by-products are traded between Asnaes power station, Statoil refinery, Novo Nordisk Pharmaceuticals, the municipality of Kalundborg, Lake Tisso and others. For example, cooling water from the refinery is piped to the power plant, where it is treated and used in the plant boiler. After generating steam and electricity, the hot water, may be used for district heating in the town.

These partnerships began in 1959 and continue to develop with little intervention from government or other bodies. Analysis of the trading, particularly of water, showed that the main economic benefit does not come from the revenue generated by selling waste, but from other internal savings such as avoiding expensive treatment of waste water<sup>16</sup>.

## Energy efficient furnaces

Figure 7.5 shows a continuous process heating up some material. The material is fed in at room temperature, heated within the furnace and, having experienced whatever reaction was required, leaves at a high temperature. In the furnace, fuel is combusted with oxygen, and the material is heated through radiation or by convection of the gases in the furnace. The fuel and oxygen must be heated up to the temperature of the flame as part of the combustion process, and this requires energy, so the available heat is less than the chemical energy in the fuel. Typically, only 30–50% of this chemical energy provides useful heat for the process, and 20–30% preheats air. Most of the remainder is lost in exhaust gases, with other losses including heating the furnace itself, conduction through walls to the environment, hot gases escaping, and through cooling water used to ensure that critical equipment does not over-heat. The options for designing efficient furnaces are well known: burning the correct air–fuel ratio or using pure oxygen rather than air; recovering heat from exhausts; increasing capacity, and operating furnaces continuously to reduce start up energy and losses through walls; using higher performance insulation; reducing air leakage through improved charging and better seals; improving control systems and sensing to reduce heat demand. Using these strategies we can already make very efficient furnaces, achieving heating efficiencies (heat delivered to the material being processed divided by chemical energy in the fuel) close to 70%. However, many existing furnaces in the materials processing industries are old and operate well below this optimum level<sup>5</sup>.

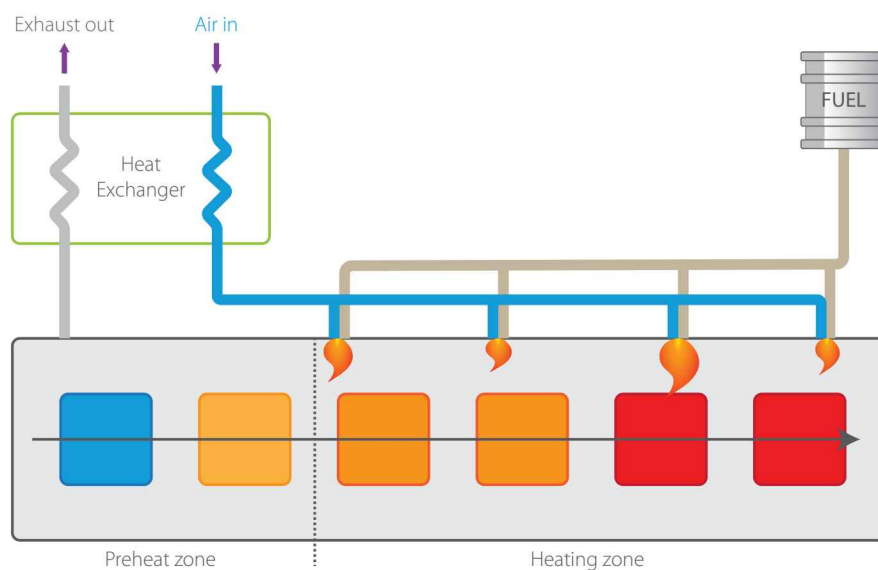


Figure 7.5—Continuous heating furnace with heat recovery



For some furnaces, heat loss is actually a requirement to avoid damage to the equipment. In aluminium smelting, heat is deliberately lost to maintain a thermal insulating and protective solid layer of cryolite at the cell walls (liquid cryolite is highly corrosive, particularly for steel). Other low volume batch furnaces are only run intermittently, requiring additional energy to warm up the furnace after each stoppage. The box story below discusses how to use less energy in these cases.

The IEA's analysis of energy efficiency finds that the majority of remaining improvements in the steel industry are in blast furnace improvements and about half of the remaining improvements in the aluminium industry are in smelting improvements, such as better furnace insulation. Efficient furnaces are already a high priority.

### Efficient motor driven systems

In industry as a whole, about 60% of electricity is used in motor driven systems<sup>6</sup>. The steel and aluminium industries are both exceptions to this average, due to the intense electrical requirements of electric arc furnaces in secondary steel production and smelting in primary aluminium production. However, we estimate that 19% of all primary energy in making steel products (combining energy required by the steel industry with that for downstream manufacturing) is used in electric motor driven systems and the equivalent figure for aluminium products is about 5%<sup>7</sup>.

### Minimising heat loss from intermittent furnaces

In small batch furnaces, with frequent cycles of heating and cooling, significant energy is used in each cycle to heat the furnace shell to the operating temperature<sup>17</sup>. The heat input ( $Q_p$ ) needed to warm up the furnace can be found by multiplying the average temperature of the furnace walls, by the mass ( $m$ ) and specific heat capacity ( $c_p$ ) of the wall material (usually steel), using the formula:

$$Q_T = mc_p \left( \frac{T_{\text{inside}} + T_{\text{outside}}}{2} \right) \quad Q_w \approx \frac{k}{w}$$

It takes more energy to heat a thick heavy wall than a thin wall. But this must be balanced against the thermal heat loss through the walls ( $Q_w$ ), which depends mostly on the wall thickness ( $w$ ) and thermal conductivity ( $k$ ) of the insulation material: a thick, well-insulated wall loses less heat. When a furnace is operated continuously, as is the case for most larger furnaces, the heat required to heat up the furnace walls can be ignored.

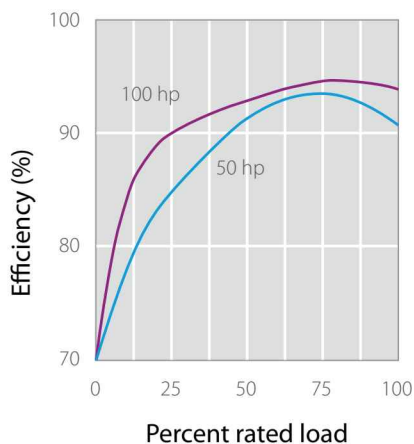


Figure 7.6—Variation of motor efficiency with varying load

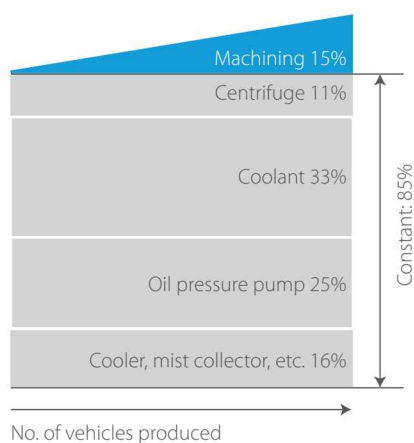


Figure 7.7—Energy requirements for a machine at Toyota<sup>18</sup>

Electric motors, at their best, convert electrical energy to mechanical work with nearly perfect efficiency. Conventionally each motor is designed for a particular speed and load, so ‘at their best’ means that the motor is used at this rating. Figure 7.6 demonstrates firstly that larger motors are usually more efficient than smaller ones, and secondly that motors become inefficient when they are used far below their capacity. The second point arises remarkably often, both because actual demands vary, and because designers specify bigger motors than required, to ensure they don’t burn out. However, this inefficiency which is now well known, has led to intense government efforts to promote the use of ‘variable speed drives’ which improve overall efficiency over a much wider range of loads.

Variable speed drives are well covered in other places<sup>8</sup>, but instead we want to think about two other aspects of efficiency related to electric motor driven systems: can we reduce the total amount of work they’re asked to do? can we ensure they’re only turned on when we need them? The IEA reports that avoiding over-specifying motors, by selecting them according to their actual torque and speed, could save around 20 to 25% of current electricity use. To find out if we can also reduce their specification, we conducted a detailed survey of motor driven systems, used in pumps, fans, forming and machining, handling equipment, compressors and refrigeration. We found that in applications related to pumping, an increase of a quarter in pipe diameter and reduction in pipe-bends would reduce loads by two thirds, and that in materials forming and removing systems, loads could typically be reduced by a half<sup>9</sup>.

Figure 7.7 shows an analysis of a machine tool used by Toyota, with the total electrical energy input on the y-axis, and the fraction of the capacity of the machine being used on the x-axis. The graph is very surprising: even when the machine is doing no useful work, it is using 85% of its maximum power. That seems crazy, but occurs because the work of machining, cutting away pieces of metal, is very small compared to the effort of running the machine’s cooling, lubrication and material handling systems, yet all of these remain turned on even when the machine is doing no productive work. We’ve seen similar results for other machine tools<sup>10</sup>, which seem to reflect two decisions: sometimes machine designers simply don’t think about turning off these ‘auxiliary’ features of their machines when they’re not working, because energy efficiency wasn’t part of the design brief given to them; other times, machines have some inertia which requires a start-up or stabilisation period, and if the arrival of work cannot be anticipated, it apparently makes sense to leave all the auxiliary systems running to avoid delay overcoming this inertia. Clearly this could also be addressed by different approaches to design.

We suspect that the really big motors used in the early stages of metals processing, for instance to power the hot rolling mills, are already operated with high efficiency. However, further downstream, in manufacturing and construction, it's likely that there's more opportunity for future efficiency. Through a combination of correct specification, reduced loads in use, and better motor management when not in use, we estimate that we could save 50% of all energy used in electric motors throughout the production chains for steel and aluminium goods. This translates to about 9% of the total energy used for steel products and 2.5% of that for aluminium goods.

## Overview of energy efficiency options

Reviewing the five reasons for performance variations in making metal that we've discussed here, the IEA estimate that upgrading all sites to best available technology would save 13% of current emissions for steel, and 12% for aluminium<sup>11</sup>. On top of this we have estimated an additional saving due to improvements in electric motor driven systems of 9% total energy for steel products and 2.5% of that for aluminium goods.

To conclude the section with a small caveat, the efficiency options we've examined here would all lead to energy saving, but one feature of metal production may lead to increased energy intensities. For both steel and aluminium production, significant effort is required to grind and separate the basic oxides from their naturally occurring forms in rocks. As more readily-available ores are mined, we may in future have to exploit less perfect sources with more impurities, leading to an increase in energy requirements. Already, in the aluminium industry, the electrical power needed to produce one tonne of primary aluminium has increased over the last ten years, due to a reduction in the quality of the bauxite available<sup>12</sup>.

## Recycling as efficiently as possible

We opened this chapter by defining three sub-sections, and in the first of them we described the chemical reactions required to extract liquid steel and aluminium from ores. We need to return to the reactions at the start of this section, because they raise an important question about recycling: when we're melting used metal and mix up a range of alloys with different compositions, can we remove any elements we don't want, or can we only deal with unwanted elements by dilution? It is difficult to remove metallic elements from liquid aluminium so dilution is common. Therefore, the mixed-up melt must be 'downgraded' to the

highest grade alloy that can be made with whatever composition we've stirred up. Aluminium casting alloys have a much higher silicon content than wrought alloys, so unseparated aluminium is usually recycled into casting alloys. We saw earlier that aluminium recycling for drinks cans can be achieved within a 'closed loop' but even then the melt is 'sweetened' with at least 5% pure virgin aluminium, to ensure the composition is within required limits. Zinc and tin are common contaminants of steel scrap (zinc is used for galvanising and tin for tin-plating of packaging) but in both cases we have processes that can remove these surface coatings prior to steel melting.

Because it's so difficult to remove unwanted other metals from the melt, and the quality of products made by recycling depends strongly on the separation, it's better to separate different alloys during collection. Both our metal flow Sankey diagrams earlier showed that most recycling of both metals is of scrap generated during production, rather than for post-consumer scrap. This is partly because of the volumes available, but it is also easier to use, because production scrap is generally better sorted. However, in chapter 4 we predicted that future supplies of post-consumer scrap will increase, so separation will become more important if we want to maximise the benefit of recycling. Designers today should plan how their products are to be recycled at the end of their life to avoid degrading quality. Our overall capacity for secondary production must increase significantly, and in turn this gives us a great opportunity both to invest in the most up to date equipment, and to bring the recycling processes closer to where new metal is required. Potentially we may also introduce more sophisticated separation of the waste stream in future, with alloy compositions separated appropriately. Technology already exists to achieve this, but its cost and speed are not commercially attractive.

Recycling involves melting, and then adjusting the composition of the liquid metal. Generally, different types of furnaces are used for the two metals. Most steel is recycled using an electric arc furnace. In this process (which sounds like a Chinese firework display in a submarine), a strong electric current is passed across the scrap, initially causing a lightening storm of sparks, until sufficient metal has melted. The process is attractive because it removes surface contaminants and has proved to be less energy-intensive than other designs. In contrast the challenge in recycling aluminium is that it oxidises rapidly when heated: the relatively pure aluminium atoms will bond with oxygen during melting, unless the oxygen is excluded. We can minimize this oxidation by excluding oxygen from the molten surface, by operating the process in an inert atmosphere. Alternatively, when melting small pieces with a high surface area to volume ratio (such as swarf from aluminium machining) the scrap feed is sunk under the surface of an

existing pool of liquid aluminium, to prevent additional contact with oxygen<sup>13</sup>. Aluminium recycling furnaces are typically gas powered, and come in three types. Reverberatory furnaces are used for melting a narrow range of feedstock, for example, scrap with a known composition, by passing a hot stream of combustion gases over the aluminium. Rotary furnaces, which as the name suggests rotate during operation, can be used to melt a wider range of scrap feedstocks and therefore require a greater quantity of flux to mop up impurities. A third type of furnace, the induction furnace, which uses electricity rather than gas, is used for a small proportion of aluminium recycling, and typically only for very clean scrap.

As we saw in chapter 4, it looks as if we will be able to recycle a maximum of 90% of the steel and aluminium that reaches the end of its life. Robert Ayres suggests that achieving this will rely on the development of new separation technologies to remove copper from recycled steel<sup>14</sup>. Improvements in furnace technology may reduce the energy used in recycling metal, and another focus will be technology to separate different types of metal scrap from the waste stream. As steel is magnetic, even small amounts of steel scrap can be separated easily. Aluminium which is not magnetic is currently separated by use of eddy-currents, but this method is imperfect. The key challenges for future aluminium recycling are to increase recovery of small amounts of aluminium, for example, the aluminium foil used in packaging, and separate wrought from cast alloys<sup>15</sup>.

## Outlook

Existing metal production processes, both from ore and from scrap, are already extremely efficient, because the strong commercial motivation to reduce purchase costs has driven extensive research and development. It will be difficult to invent significantly more efficient chemical reactions, but there are some opportunities to improve furnace design and operation, and potentially the use of electricity to power motor drive systems could be halved. Recycling will become more effective as we separate our waste streams by alloy type.

In the next chapter we'll ask whether we can save energy through better heat management along the production chain. If you're a gas molecule who's been combusted, we can try to use your heat again, but we can't recycle you as gas because, as they might say at the end of an episode of *The Apprentice*, "you're fired!"

## Notes

1. Standard chemical exergy (exergy is described fully in chapter 8) values for elements have been recently updated by Rivero and Garfias (2006).
2. Worrell et al. (2008) describe the best practice energy intensity values for selected industrial sectors: 14.7 GJ/t to make cast steel from iron ore (2.2 times the minima); 70.6 GJ/t to make cast aluminium from bauxite (2.4 times the minima). These intensities are direct energy values (i.e. the metered fuel and electricity at the production site), which is a practical minimum equivalent to the case where all electricity is made with renewables or hydro-power. If instead primary energy values are used, assuming an electricity generation and distribution efficiency of 33% raises the cast steel value marginally to 15.9 GJ/t (2.4 times the minima), but has a more dramatic effect on the electricity intensive making of cast aluminium, raising the value to 174 GJ/t (5.9 times the minima). However, hydro-electric plants contribute 50% of the electricity for aluminium smelting (IEA 2009), and using the IEA methodology (IEA 2010c) of counting hydropower as the gross electricity production, gives a more realistic primary energy intensity of 124 GJ/t (4.2 times the minima).
3. Pulverised coal trials are described in IEA (2008a).
4. Hammond et al. (2011) have surveyed the UK materials industries to determine the average and best practice embodied energy and carbon emissions for a range of building materials with results periodically updated in their 'Inventory of Carbon and Energy'.
5. Based on the efficiency savings identified as part of the US Department of Energy's Industrial Technologies Program and reported in US DOE (2007), which has worked with industry to identify and implement best practices for process heating furnaces.

### Efficient motor driven systems

6. From IEA (2009) page 191, electric motor drives are used extensively in industry and it is estimated that they account for 30% of all electricity use.
7. USDOE (2004) reports a breakdown for fuel/electricity use in the steel industry – roughly 60% fuel and 40% primary energy in the form of electricity. Subtracting electric arc furnace consumption, and taking 60% of the remainder as being used in motors (IEA (2009)), approximately 19% of energy use in the supply chain for steel products is in electric motors. Using a similar method with a breakdown of 80% primary electricity in aluminium production from Worrell et al. (2008) and subtracting smelting, we find 6% of energy use in the supply chain for aluminium products is in electric motors.
8. International standards exist for defining the efficiency class of three-phase motors for example IEC 60034-30:2008 described in CEMEP (2011).
9. Energy savings through more accurate motor specification are detailed in IEA (2009). The calculation of further energy savings from motor load reduction are described in Cullen et al. (2011).
10. For example, Avram & Xirouchakis (2011) find the highest energy is consumed when a milling machine is idle and Devoldere et al.

(2007) find 65% of the energy consumption of a press brake is used when it is not producing parts.

11. These numbers come from the IEA's (2009) report on Energy Technology Transitions for Industry. The percentages are calculated compared to 2008 direct and indirect emissions for steel (2.9Gt CO<sub>2</sub>) and 2007 emissions for aluminium (360Mt CO<sub>2</sub>). The direct and indirect emissions values do not include emissions for product fabrication, as we couldn't find any information on energy efficiency improvements in fabrication operations. If the fabrication emissions had been included, the percentage emissions reductions would be even smaller.
12. The lowest electricity intensity for primary aluminium production was 15,100 kWh/tonne in 2002, but since then, the electricity intensity has been higher. IAI (2011b) report the electricity intensity in 2008 as 15,400 kWh/t.
13. Boin and Bertram (2005) give metal yields for aluminium scrap melting ranging from 70% for foil to 95% for building scrap.
14. Ayres (2006) claims that recycling rates for steel, aluminium, and copper will approach 90% once a process for removing trace contaminants is developed.
15. In the USA, the DOE is supporting research into advanced sorting and recycling technologies for aluminium, particularly in anticipation of an increase in the amount of wrought aluminium used in vehicles. Two technologies being investigated are: laser-induced breakdown spectroscopy to separate wrought and cast scrap, which uses lasers to vaporise a small amount of aluminium so that the chemical composition can be measured; selective etching plus colour sorting to separate different wrought alloy grades, where different categories of wrought aluminium turn a different shade (bright, gray or dark), when etched with a chemical (Secat, 2005).

### Box Stories, Figures and Tables

16. Energy use breakdown based on data collected by Toyota Motor Corporation and published by Gutowski et al. (2005).
17. This theoretical analysis of furnaces is reported in more detail in Ashby (2009).
18. Further details of Kalundborg are given by Jacobsen (2006).