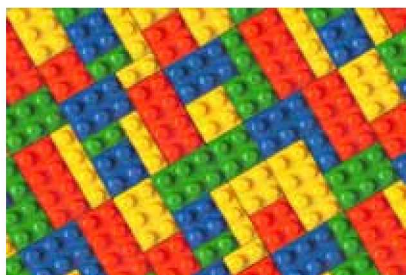


8 Opportunities for capturing heat and ways to use it

Part of the energy required to convert ores to metals is required to drive chemical reactions, but most of the rest is heat used to melt or soften the metal and to allow diffusion. Virtually all of this heat is lost to air. It sounds as if we should try to capture this heat, either for re-use within the same process, or by cascading it through other industrial processes which require heat at a lower temperature. What's the opportunity to achieve this?



Lego® Bricks

In this chapter we're going to play with Lego blocks—but it's a special type of Lego we've invented: each block represents a process in the long chain of processes required to convert ores into final steel and aluminium goods. Metal in some form flows through each block, being upgraded as it passes. There are also other inputs to each block, and other by-products are exhausted. We could include a long list of these other inputs and exhausts—money, energy, lubricants, labour, chemicals and so on—but the only other inputs and exhausts we'll consider here are heat energy. Armed with the right box of blocks, we can now build a model of the whole connected set of processes that interest us. In the last chapter, we asked whether we could make any individual block more efficient. In the next one we're going to explore whether we may in the future invent any new blocks. In this chapter our concern is about how they're connected. If we connected our blocks together in a different way, could we save significant energy? The processes in use today have been developed independently, so would it make a big difference if we were allowed to design them all in one go? For example, we visited a steel factory in the North of England and watched red hot metal at around 800°C being rolled, but then left to cool in air, even though we knew it would be reheated later on. In Lancashire we saw aluminium cans being melted and poured into ingots which cooled in air, so they could be shipped to Dusseldorf where they are reheated for re-rolling. In Wales we saw scrap steel recycled in an electric arc furnace and poured into long thin 'blooms', then transported two miles, and re-heated prior to rolling. In each case it looks as if heat energy could be saved if we (had an unlimited budget and) could reconfigure our processes. So let's play with Lego.

Temperature histories for case study products

If every component made of steel or aluminium is different, then every product must be made using a different set of processes, which makes it a little difficult to generalise in our search for opportunities to move Lego blocks around. The only way we can begin the search is to look for representative case studies that will illustrate the key points. We've done that, and Figure 8.3 on the next page introduces our nine case study parts, split between steel and aluminium, and with a range of different geometries and process routes.

To understand the requirements for heat energy in making these parts, we've talked to all the companies involved in making them—along the journey from ore to finished part—to obtain their temperature histories, and we've shown these in the Figures 8.1 and 8.2. This data is as comprehensive as we can manage—although different manufacturers might use slightly different temperature cycles

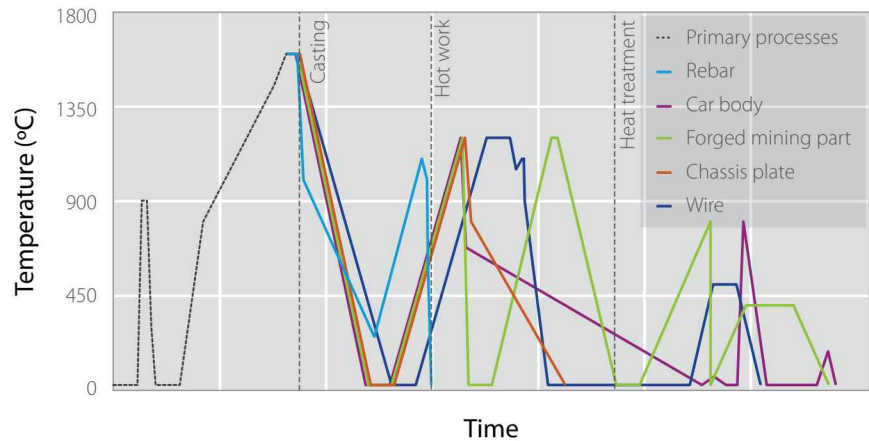


Figure 8.1—Time/temperature histories for steel products

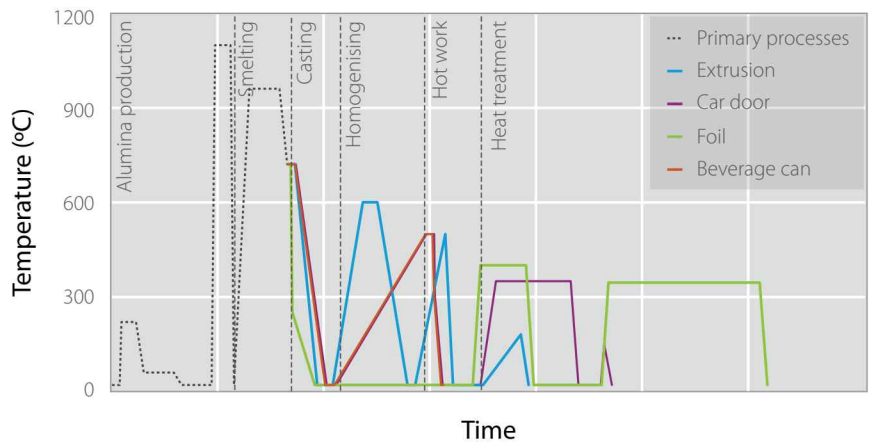


Figure 8.2—Time/temperature histories for aluminium products

(a cycle here is a single peak on the graph—heating and cooling) for the same product. You can see that we've been a little cavalier with the time axis—because our primary concern is about the peak temperature in each cycle, rather than its duration. On each graph the lines are all identical up to the point of casting—because they all require the same primary processes, apart from the need to add different alloying elements to create the right composition for each part, and this doesn't influence the temperature. The lines diverge from casting onwards.

Forged mining part

Forging steel allows complex, high strength parts to be produced. A billet is softened by heating and compressed between shaped dies to achieve the desired geometry. A heat treatment consisting of quenching and tempering gives a strong and tough product.



Car body

In both steel and aluminium, car doors have exacting requirements for both surface quality and formability. The surface must be free of defects in casting and quality is improved through subsequent hot and cold rolling stages



Rebar

Steel rebar is cast as square billets which are hot rolled to the desired bar diameter. Strength and ductility required are imparted by quenching and self-tempering, where the outer surface is cooled rapidly to form a brittle high strength microstructure, and tempered by the still-hot core to restore ductility.



Beverage can

Aluminium beverage can bodies require a formable sheet for drawing to the can shape, high strength to reduce sheet thickness and material costs, and a high surface quality for aesthetics. Hot and cold rolling processes give uniform formability, while cold rolling also work hardens the material to increase strength.



Wire

Steel wire has very high strength and ductility along its length. Cast billets are hot rolled to make wire rod, with the properties achieved by controlled cooling followed by work hardening as the rod is drawn to make wire.



Foil

Aluminium sheet is continuously cast and cold rolled through multiple passes. Annealing heat treatments are necessary to restore ductility so that large reductions in thickness can be achieved.



Heavy machinery chassis plate

Plate steel is cast as thick slabs and hot rolled to achieve the desired strength. The plates are cut, bent and/or welded during fabrication to produce the finished chassis part.



Extruded window frame

Complicated profiles are produced by extruding aluminium billets through a shaped die. An age hardening heat treatment increases strength.



● Steel parts

● Aluminium parts

Figure 8.3—Case design products

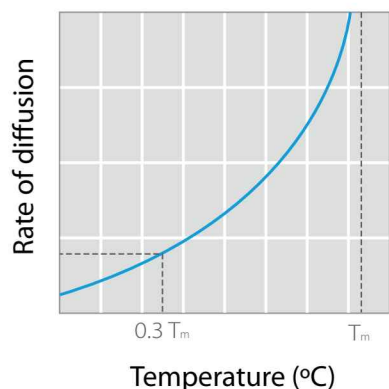


Figure 8.4—Effect of temperature on rate of diffusion

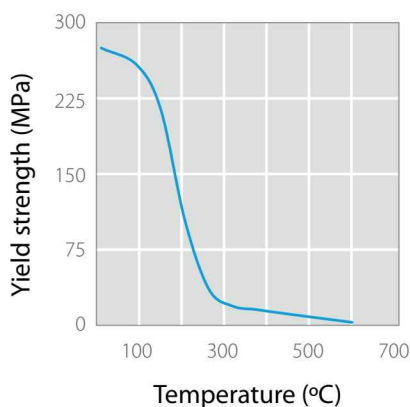


Figure 8.5—Effect of temperature on yield strength of an aluminium alloy (AA6061-T6)

We'll explore the processes used to make these parts in a moment, but let's first check that the peak temperatures in the two cycles make sense. At the Atomic Club in chapter 5, we saw that we need energy for three reasons when making metals: to drive chemical reactions, to allow diffusion, and to soften or melt the metal so that forming to shape is easier. In the last chapter we saw that the chemical reactions required to release metals from their ores occur more rapidly above their melting temperatures which for steel and aluminium alloys are around 1500°C and 660°C respectively. Diffusion, in which atoms move within the lattice of the solid metal, occurs at a rate related to temperature, and may occur even at room temperature. However the rate increases dramatically as the temperature approaches the melting point as the graph to the side shows. Softening, the reduction in the strength of the metal with temperature, evolves in the manner shown in the second graph to the side. In this case, a useful reduction in strength, say to 10% of the cold value, occurs at around 1200°C for steel and 550°C for aluminium. Our two temperature history graphs for our case study products show that casting and the primary production processes occur above the melting temperature, and subsequent processes all occur at a temperature that allows significant diffusion, with higher temperatures when deformation is required—so the graphs tie up with our understanding of why heat is required.

Now that we understand their temperature requirements, we can build our Lego models of the process chains for the case study products, and on the next page we've shown just two of them—for a car door (in steel) and a window frame (in aluminium). These diagrams allow us to estimate the heat energy inputs to the blocks. By looking at the histories and checking with the companies who do the processing, we can also show the heat energy discarded.

On adding up the energy flows into the two chains, we can see that making the car door requires 700MJ, while making the window frame requires 4880MJ. Most of this energy is 'lost', in the form of heat energy discarded in exhausts, radiated through walls, and as hot metal cools in air. We know that energy is neither created nor destroyed, so the 'lost' energy cannot really be lost. Bearing this in mind, how much of this discarded energy could we capture and re-use, to save on the inputs?

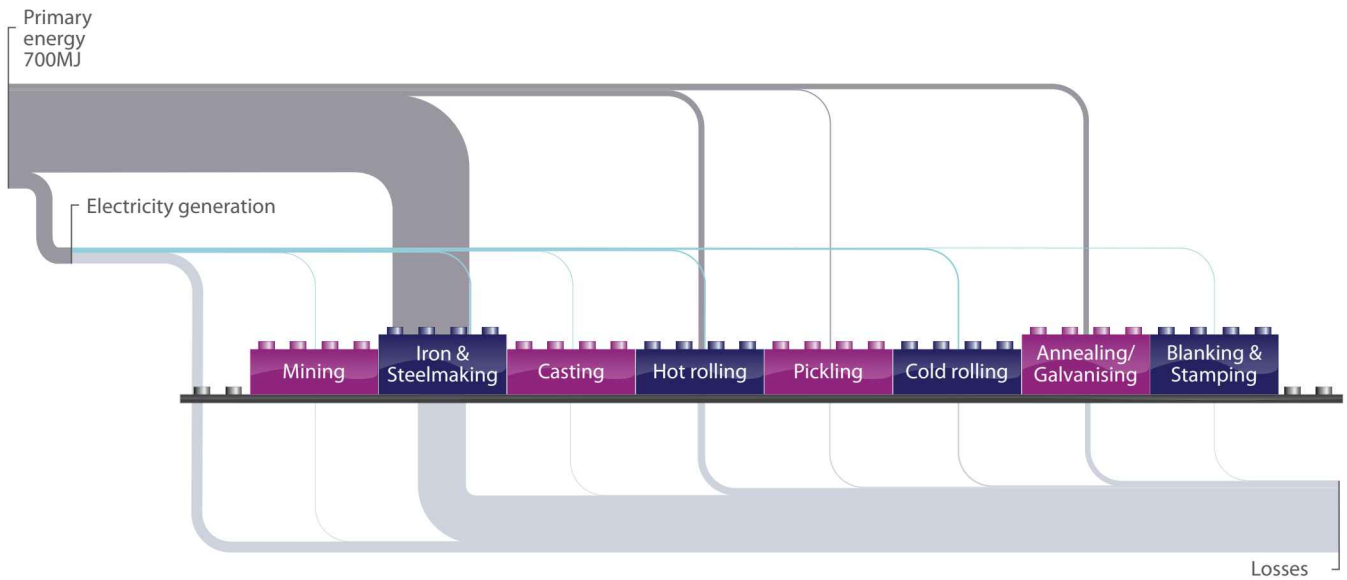


Figure 8.6—Energy used in steel car door production

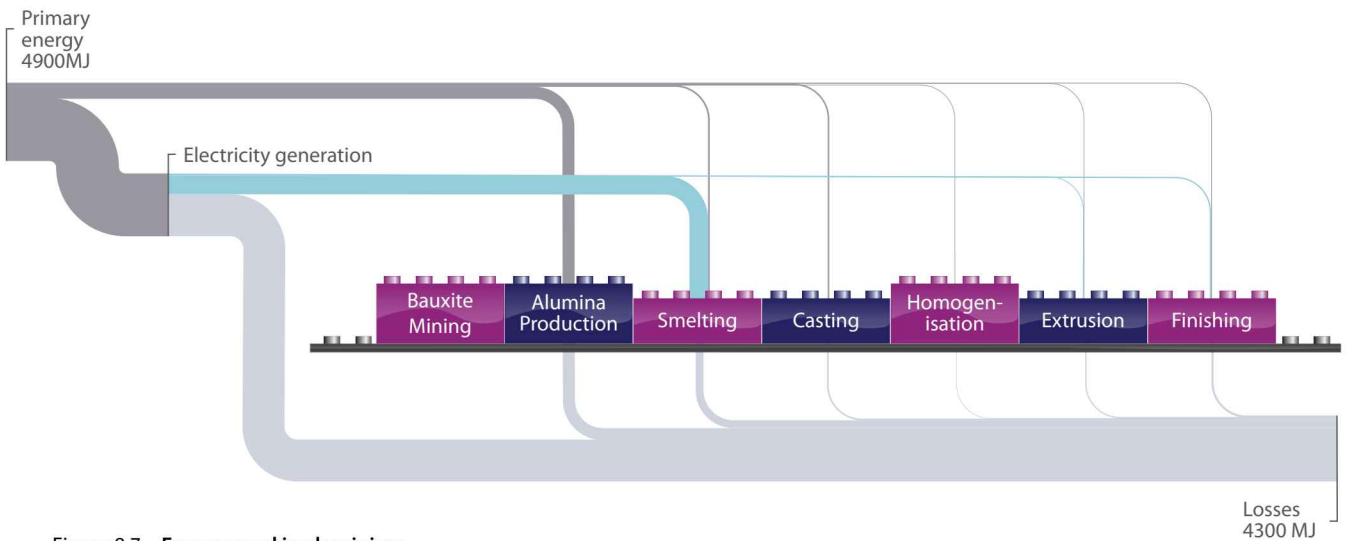


Figure 8.7—Energy used in aluminium window frame production

Exergy flows for the whole of steel and aluminium component production

It looks as if we've just made a typing error in the title. "Exergy"? Surely we meant "energy"? No, we did mean it, but "exergy", a word invented by the splendidly named Zoran Rant of Slovenia—is a largely unfamiliar word, but a very important one for us now. To find out why, we'll borrow an anecdote from our colleague Dr Rob Miller, who teaches thermodynamics in our department:

Let's imagine you're in the pub, and a dodgy character in an old coat sidles up to you and says "I've got a few megajoules of heat energy in my van round the back—are you interested?" Naturally you are—we're all concerned about the price of heating our homes, and keen for a good deal when some spare energy drops off the back of a lorry, know wot I mean? But your first reaction to the offer should not be "how much?" That way lies ruin. The right first question is "what's its temperature?" You should be ready to pay more for the same number of megajoules, if they're at a higher temperature.

The heat energy in a smaller mass of material at high temperatures is more valuable than the same energy in a larger mass of material at lower temperature. (Figure 8.8 illustrates this with a bath-time example of exergy). This is because the higher temperature energy can be used for heating or to generate other useful forms of energy, such as movement. In contrast the lower temperature energy cannot usefully be transformed or exchanged.

Heat is our main concern in this chapter, but the other forms of energy of interest when transforming metal ores into products are:

- chemical energy that may be released during combustion of fuels;
- electrical energy in electrical currents used to drive aluminium smelting as well as the motors and pumps used in most industrial equipment;
- mechanical energy contained in moving objects such as the rolls in rolling mills.

Could we 'capture' heat from the exhaust gases of furnaces, or from the hot metals we produce, and use it—either at a lower temperature, or by converting it to one of these three forms?



100 litres at +5°C



20 litres at +25°C

Figure 8.8—Both the bath and the shower require the same energy, but we'd rather have the hot shower!

Let's imagine we wanted to use the few megajoules of heat on offer in the pub to drive a train: the question of whether we can convert heat energy into mechanical energy depends on the temperature of the heat. We cannot avoid this, and we've known about it since Nicolas Léonard Sadi Carnot, after his release from the French army on Napoleon's final defeat in 1815 (paving the way for the eventual accession of his nephew Napoleon III who's getting ready to open our next chapter), wrote his 1824 book *Reflections on the motive power of fire*. Carnot showed that the maximum work you can obtain from heat depends on the ratio $(T_1 - T_2)/T_1$ where T_1 is the (absolute) temperature of the heat supplied, and T_2 is the temperature of the operating environment. We can't do much about T_2 , so the maximum work depends on the temperature of our supply of heat, and therefore hotter is better.

So, although it cannot be created or destroyed, not all energy is equal: electrical energy can be used for heating or moving, chemical energy may be used to generate heat or electrical energy, and hotter heat energy is more useful than colder heat energy. Zoran Rant's term "exergy" allows us to sort this out. Exergy is defined to be the maximum useful energy we can extract from some source of energy¹. In effect, therefore, we should be using exergy in every discussion of efficiency we ever have—we don't want energy efficient homes, we want them to be 'exergy efficient' because if we can use fuel that burns at a lower temperature to heat our living rooms, we can save the most precious high temperature fuels for where they're really needed. For this reason, our first Sankey diagram in chapter 2 showing the global transformation of energy sources into useful services was drawn using units of exergy—the maximum work that could be obtained from each energy source feeding our system.

And we can connect our interest in exergy in this chapter to the work of Gibbs, whom we met in the previous chapter. Gibbs explored the fundamental limits to energy requirements for chemical transformations from one compound to another, now known as the Gibbs free energy. More recently, Jan Szargut a Polish engineer, has related Gibbs free energy to a list of compounds present in the environment to determine the standard chemical exergy of compounds. Chemical and physical (heat) exergies are happily related and consistent: the chemical exergy is a measure of the work required to form compounds from their natural state by separating and reforming atomic bonds; the physical exergy is a measure of how much work some heat at a given temperature can do while cooling to ambient temperatures.

Unlike energy, exergy is not conserved. Take for example water falling over a waterfall, potential energy is converted firstly to kinetic energy and later to thermal energy. Energy is conserved throughout. Yet at the bottom of the falls we

no longer have the option of installing a water wheel to extract useful energy—the energy has been degraded to a lower quality and we have “lost” some exergy. Exercising exhausts excellent exergy to external extremes? Exactly!

So exergy is the right measure of our heat flows in making steel and aluminium components, and we can now return to our Lego models of the two process chains from earlier. Instead of showing mass and energy flows as before, the two revised Lego models in Figures 8.9 and 8.10 show exergy flows: the chemical exergy of the metal, the physical exergy inputs and outputs to each Lego block, and the lost exergy from each process. High temperature upstream processes, such as iron-making in a blast furnace or aluminium smelting, have recoverable exergy outputs in the form of combustible gases and hot flows of metal and exhausts. These outputs potentially could provide a useful service. For example hot exhausts can be used to preheat air coming into the process. In contrast, low temperature downstream processes have little or no recoverable exergy.

In order to introduce the idea of exergy flow we’ve so far concentrated on two of our case study products. However, in Part I of the book, we assembled enough

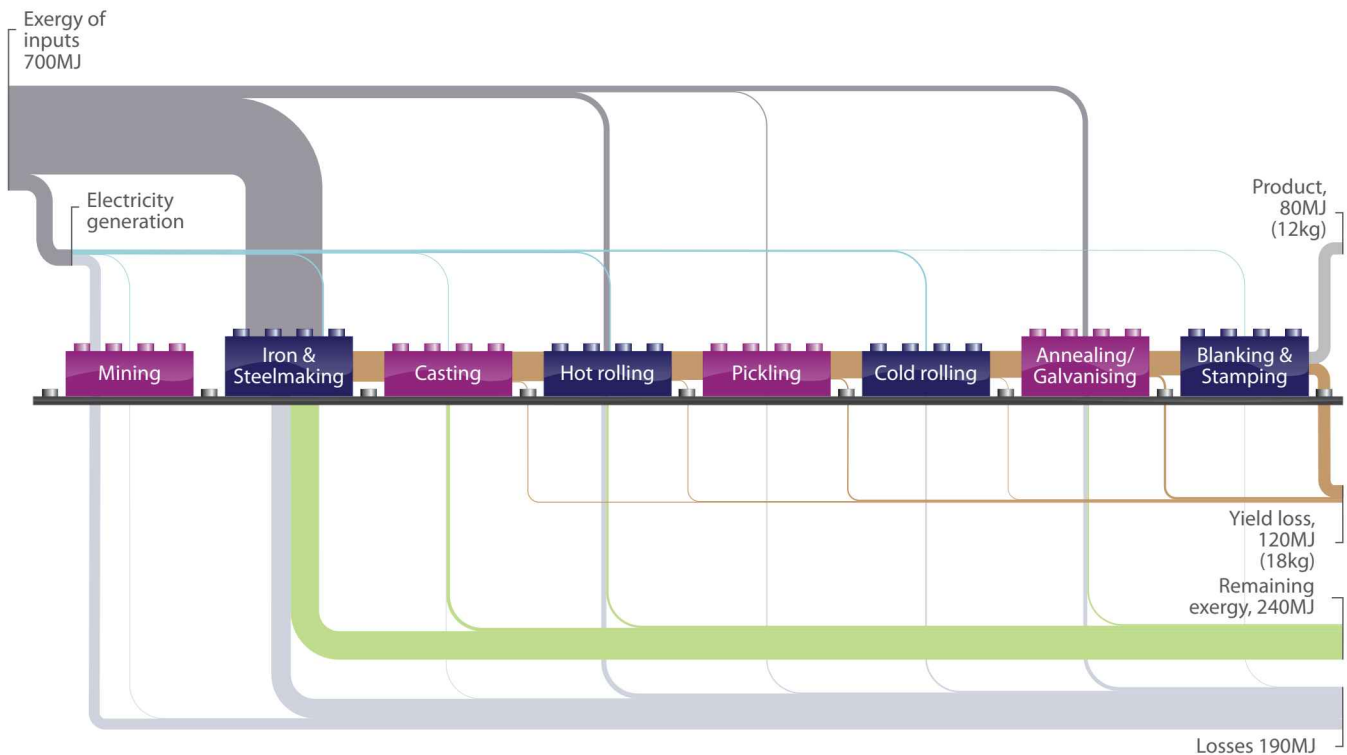


Figure 8.9—Exergy flow in steel car door production

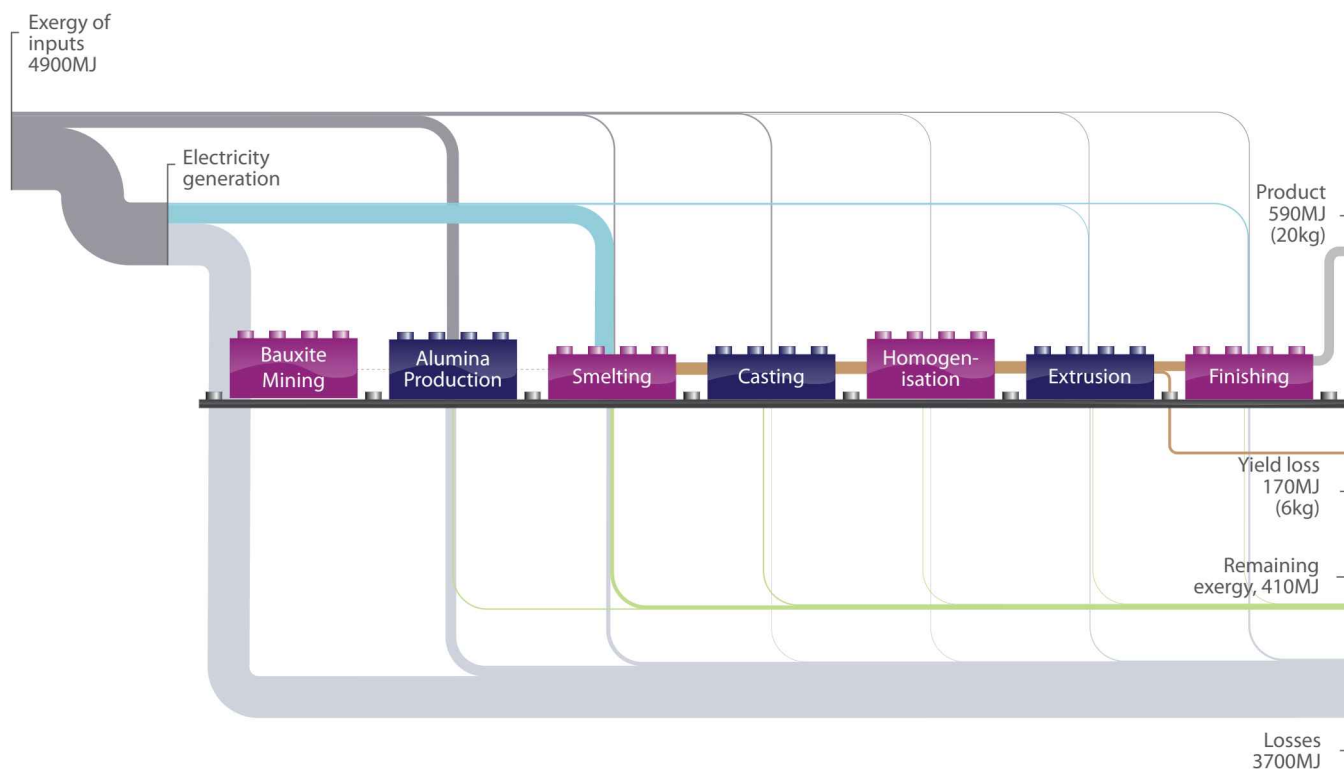


Figure 8.10—Exergy flow in aluminium window frame production

information to make an estimate of the exergy flows of the whole global process of making steel and aluminium components, and these are shown in Figures 8.11 and 8.12. The chemical exergy flow looks very similar to our earlier metal flow Sankey diagrams, because once the liquid metal has been extracted from ore, its chemical exergy hardly changes as the geometry changes. No further chemical reactions are involved. In addition to this flow of chemical exergy, we can also see the exergy flows associated with fuel and electricity use throughout the process. Had we shown energy flows rather than exergy flows, while we could see energy being discarded from processes we wouldn't be able to 'value' it—because we could do little with it if it was at low temperature. Instead, these two diagrams show exergy flows so the exergy discarded is, or at least could be, recovered to do useful work. We can see that around 10% of the output exergy in steel and aluminium is recoverable. This is an upper estimate based on the temperatures of the flows just as they leave the processes. Some of this output exergy is already recovered, as we'll see later in this chapter. The remainder of the exergy input is lost: diluted to useless low grade heat, dissipated through furnace walls and destroyed by the chemical reactions themselves.

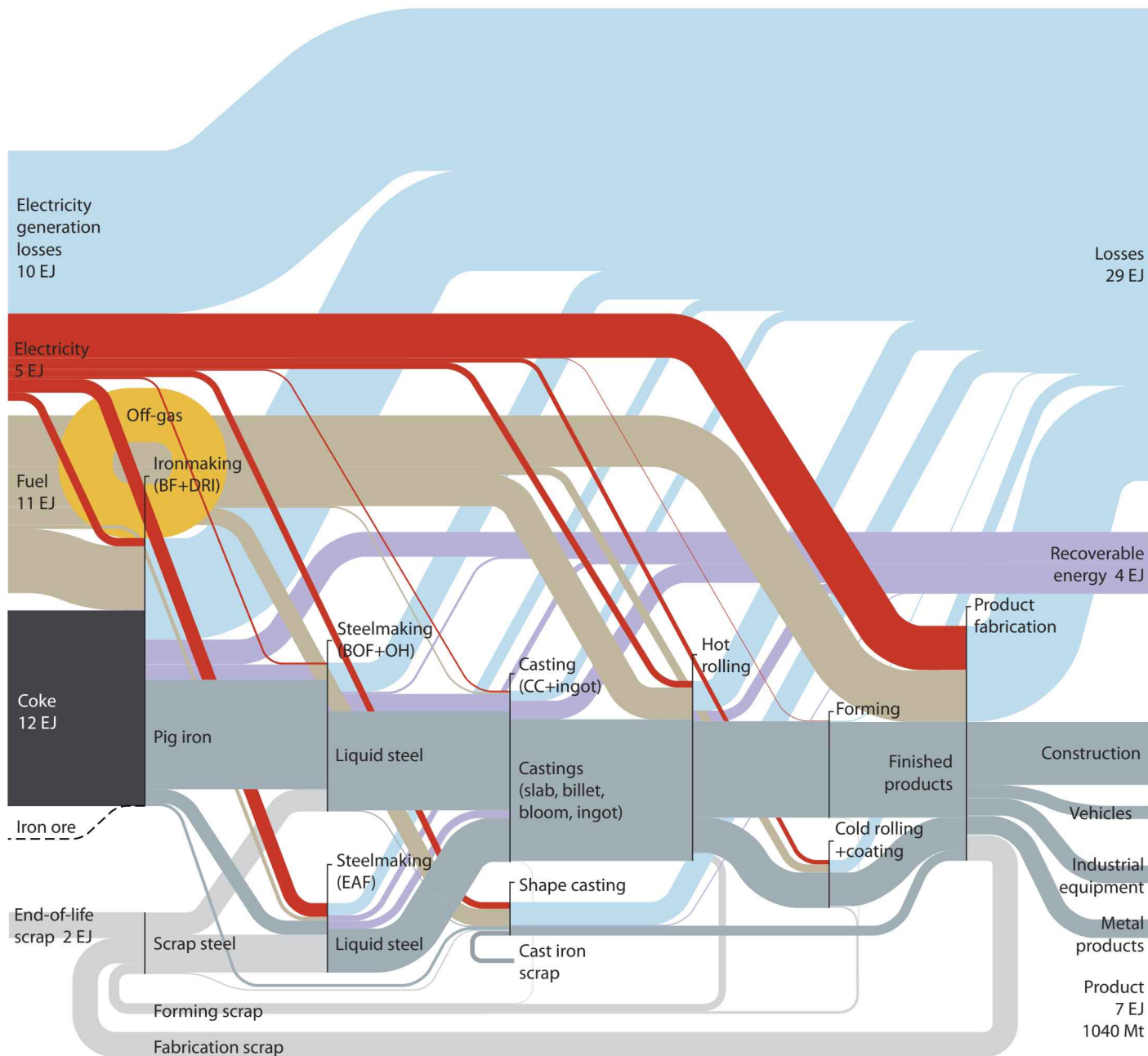


Figure 8.11—Global exergy flow for steel

The key message of these two diagrams of exergy flows is that energy used in the downstream part of the process, supplied as electricity, does work and is converted to low temperature heat with which we can do very little. However, the energy lost in the earlier part of the supply chain as heat at higher temperatures has significant remaining exergy value—and we'd like to exploit it.

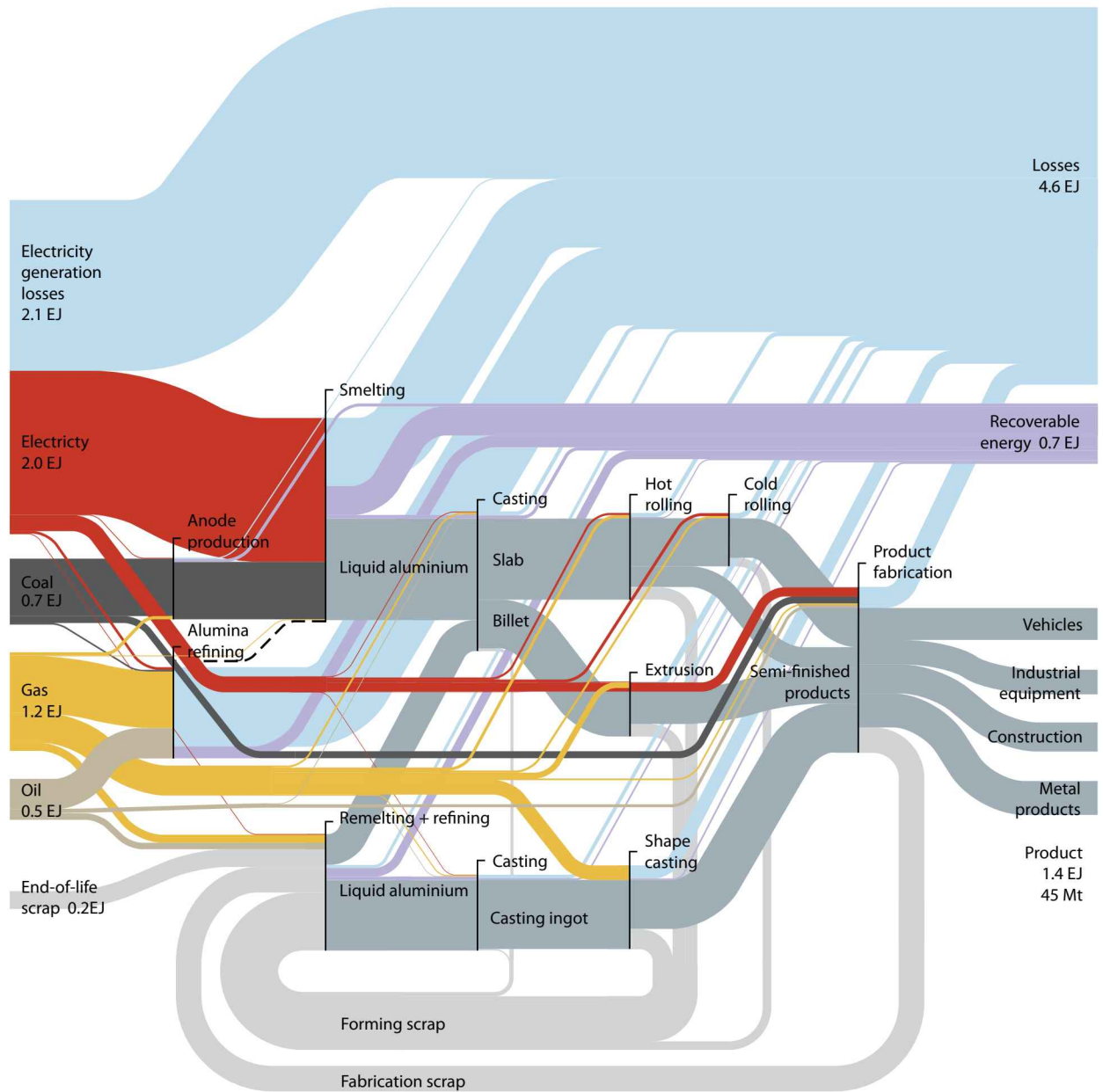


Figure 8.12—Global exergy flow for aluminium

So our use of exergy has revealed two opportunities: if we can cut out thermal cycles in the processing of our components, we can reduce the need for exergy input; where we're discarding heat at higher temperatures, we are also discarding useful exergy. The next two sections explore whether we can reduce the number of thermal cycles, or we can recapture those lost exergy streams?

Cutting out thermal cycles

Ideally we would make all steel and aluminium products with just one well controlled thermal cycle: we'd heat up ores to extract liquid metal, adjust the composition of the liquid, cast it, deform it to shape and provide time for required diffusion processes, so that by the time the metal returned to ambient temperature it was perfectly ready for use. The only immutable barrier to this ideal is that some metallurgical treatments depend on a second thermal cycle. For example, the processes of age hardening of aluminium alloys and tempering steel require high temperatures for diffusion but must occur after quenching (rapid cooling) to a lower temperature. Similarly, heat treatments such as annealing must be carried out after cold deformation to restore ductility to the metal and allow forming. Even in this case, the thermal cycle need not be as deep as in the graphs we showed for our case study products—if diffusion largely stops below one third of the melting temperature, we don't need to cool as far as ambient temperatures.

Even in cases where we need a second thermal cycle, we're still using more thermal cycles than absolutely necessary, and there are three good reasons for this: we may not have all the required equipment in the right place; it may be difficult to co-ordinate the flow of metal through all the appropriate equipment at the right time to catch the right temperature; some processes must be operated at ambient temperatures. We'll investigate these through a few examples of process innovation.

In early steelmaking practice, the Bessemer process, or subsequently Robert Durrer's basic oxygen process, occurred in a separate thermal cycle from the blast furnace. This was clearly costly, so all modern steelmaking processes are coupled: the pig iron from the blast furnace is transferred as a liquid to the basic oxygen furnace to avoid the extra thermal cycle. However, aluminium smelting in the Hall-Héroult process uses a lot of electricity, so production sites have traditionally been located near to sources of cheap electricity. These locations may be far distant from the next process, so the aluminium is cast as 100% pure aluminium ingots at the smelter, transported to the site where casting will occur, and then re-melted. Around 25% of the world's aluminium is re-melted in this way, for no metallurgical benefit—just because the equipment is in different locations. At a smaller scale, as we've already seen, aluminium recycling always involves 'sweetening' with pure ingots, and similarly pig iron is charged as a solid into electric arc furnaces. In both cases there is no benefit in starting from solid rather than liquid metal, and energy would be saved by avoiding remelting if the recycling equipment could be co-located and co-ordinated with the primary liquid metal processes.

The next opportunity to cut out a thermal cycle occurs between casting and hot rolling. We've seen in our Sankey diagrams of metal flow that most metal is rolled, both to control its geometry and to break up the grain structure created by casting. In the past in both steel and aluminium production, the liquid metal was cast as an ingot and cooled, and then re-heated prior to hot rolling. The steel industry has begun to move away from this practice. Instead of casting in ingots, steel is cast in longer thinner strips, using "continuous casters". This has the double advantage of allowing faster cooling rates for the liquid metal, and reducing the total amount of deformation required in subsequent rolling. The output of these continuous casters is cut into plates, and without cooling is immediately given some re-heating ready for rolling; this is known as hot charging, and obviously saves the energy required to cool and reheat the cast material. A recent innovation in Italy, described in our box story, one step beyond this hot-charging, connects

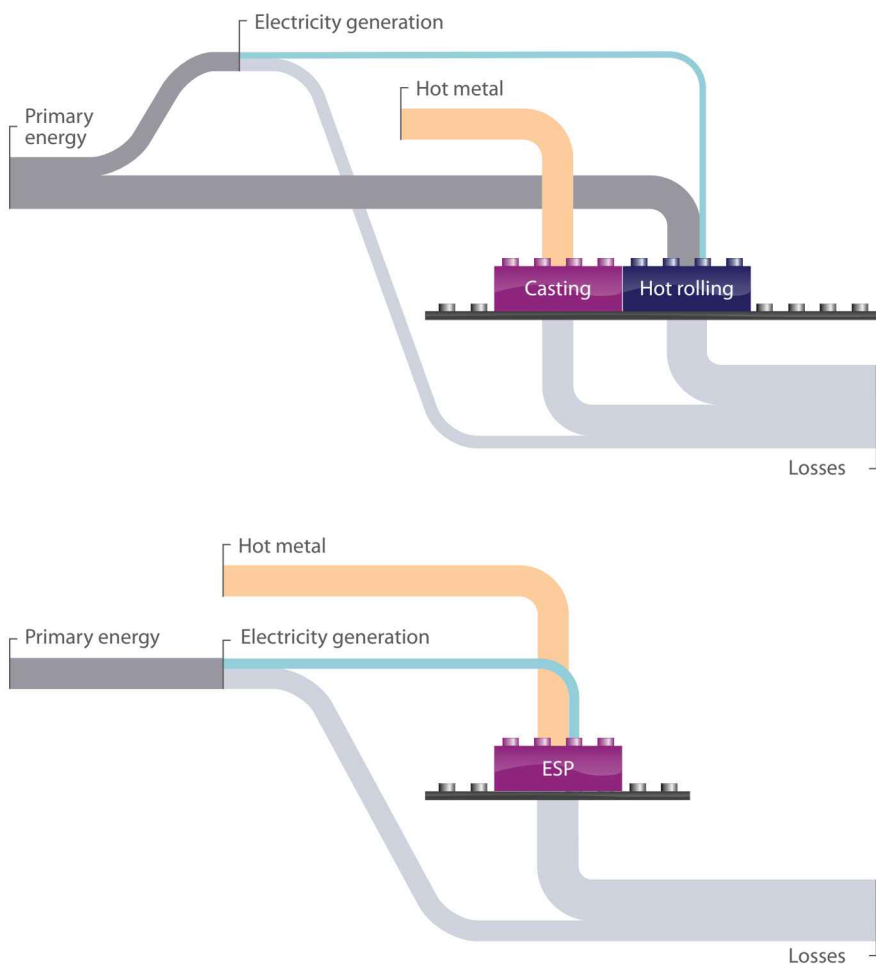


Figure 8.13—Comparison of Arvedi Endless Strip Production with separate casting and hot rolling steps

the continuous caster directly to the hot rolling line for production of steel strip. This process has therefore cut out the thermal cycle between casting and hot rolling, as shown in the Lego-block model of Figure 8.13, and as a result reduced total requirements for energy input.

In the aluminium industry, around 30% of the world's sheet and foil products (15% of all aluminium products) are made without hot rolling, by twin-roll casting. The box story on the next page explains the process and outlines the benefits. However, the process is most applicable to nearly pure alloys such as foil, because the lower alloy content gives a smaller freezing range and also because downstream processing is not as critical for pure alloys. Directly cast strip is more susceptible to surface defects such as porosity and 'surface bleeds', where the liquid metal breaks through the thin solidified surface. These defects occur due to the difficulty of maintaining consistent solidification with rapid cooling and unlike conventional casting of thick slabs, after twin-roll casting there is little opportunity for removing the surface layer or rolling. In the future, twin roll casting may extend to low alloy content, heat treatable aluminium products (perhaps inner panels for car bodies) and microalloyed steel products, removing the thermal cycle involved in hot rolling and saving 2-3 GJ/t.



Arvedi Endless Strip Production⁷

Thin slab casting technologies link the caster and rolling mill via a soaking furnace, where the temperature of the slab is homogenised and the production of the melt shop and rolling mill can be separated for easier scheduling. The heat retained from casting reduces the energy input in reheating for hot rolling. However, the largest energy savings are claimed by the Arvedi 'Endless Strip Production' (ESP) process operating in Cremona in Italy, where the cast slab is fed directly into the integrated rolling mill to produce an endless strip.

This process has a fast casting speed to achieve high productivity through the single line, liquid core reduction and direct high reduction at caster exit to improve internal quality, and inline induction heating for precise control of temperature.

A wide range of products may be cast and rolled through ESP, with energy savings of 1.25GJ/t compared to reheating strip from cold. Additional benefits include reduced formation of scale on the metal surface due to the metal spending shorter time at high temperatures, more uniform coils as the entire strip undergoes an identical temperature and deformation history, and lower thicknesses than can be economically achieved by conventional processes.

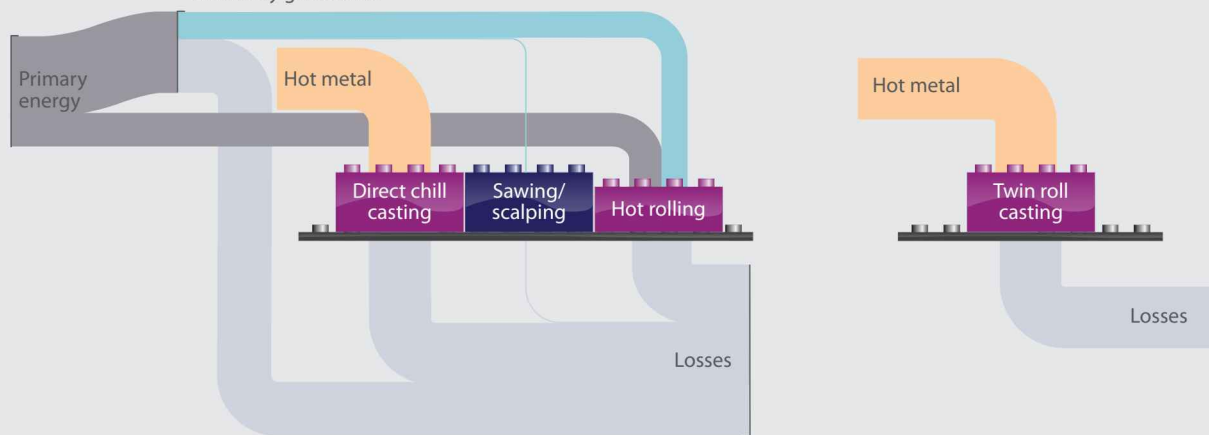
Most aluminium (the remaining 85 % of global production) is not twin-roll cast, but cast into large ingots, typically around 2m wide, 0.5m thick and 8m long. Because the ingots are so large, they solidify gradually from surface to centre, so the composition of the resulting metal changes through the thickness. The fast cooling rate creates a different microstructure and alloy concentration at the surfaces, so every face of the cast ingot must be removed or scalped. To allow scalping, the ingot must be cooled to ambient temperature because we don't yet have cutters that operate at hotter temperatures. This is expensive because the next process, hot rolling, operates at high temperature, so we have added an extra thermal cycle.

Twin roll casting: liquid metal to strip in one process

Twin roll casting is the most widespread method of continuously casting thin strips in both aluminium and steel. Liquid metal is fed between two cooled counter-rotating rolls, with solidification occurring on contact with the roll surfaces. Two shells form and grow towards the roll pinch, where they are fused into sheet by a combination of heat and pressure. Typical thicknesses are 2–4mm in steel and 4–8mm in aluminium. The process was originally proposed by Henry Bessemer and first commercialised by Joseph Hunter in the 1950's for casting aluminium strips. Today, aluminium twin roll casters are used to produce more than 30% of all aluminium sheet and foil products. The process works best with a short freezing range

(and therefore low alloy content), so is mainly used to make non-heat treatable alloys.

Steel strip casting has taken longer to develop due to the higher required process temperatures, but several plants worldwide have demonstrated the process for low carbon and microalloyed steels⁵. Twin roll casting has demonstrated large energy savings relative to conventional routes, but there are still practical difficulties in achieving a high quality and consistent surface finish and in improving the lifetime of key components, particularly the casting rolls and liquid metal containment.



After casting and hot deformation, the remaining thermal cycles in our case study products are required for heat treatments. Various innovations have aimed to reduce the need for these cycles, particularly by integrating a heat treatment into the period of cooling occurring after hot deformation. For the steel chassis plate and the forged mining part among our cast studies, the steel is typically quenched (rapidly cooled to freeze it into a strong but brittle crystal form called martensite) and then reheated for tempering (where diffusion allows some rearrangement of the atoms in the martensite to increase its ductility and toughness). In a clever innovation, in producing reinforcement bars, quenching and tempering take place in line with the rolling mill: the surface of the hot rolled bar is quenched by a water spray, to create martensite at the surface of the bar. Sufficient heat remains in the core of the bar that its temperature averages out to allow tempering. This quench and self-tempering process could save about 1-1.5 GJ/t and is theoretically possible in all cases, although it may be difficult to achieve in some forgings where thermal stresses can cause distortion and cracking.

We've seen that it is possible to cut out most thermal cycles as we move towards the ideal of only having a single thermal cycle, but many practical limits remain. There's also a clear commercial limit: it is easiest to create a single thermal cycle process for one particular product—one geometry of one alloy made in high volume. But the reality of customer needs denies this ambition. When production chains must produce a wide variety of different products, it is more difficult to co-ordinate them efficiently. However 'shorter' production chains are possible, and with the energy savings that may be made we should do all we can to implement them.

Recovering and exchanging heat

Having looked at cutting out thermal cycles, what about using the heat discarded from the various processes: can we exchange heat between one process and another? If we don't exchange it, can we do anything else with the heat?

Heat exchangers are familiar in daily life. The radiator in our car (at the front, where it experiences maximum air flow) exchanges heat between the hot water circulating round the car engine and the outside air. In turn the hot engine exchanges heat with the cooler water leaving the radiator in order to cool the engine. The fins at the back of our refrigerator exchange heat from the inside of the fridge with the air in the kitchen. And the radiator that warms our living room exchanges heat from the hot boiler with the cooler air in the room.

The amount of energy transferred by a heat exchanger depends on its area (the larger the better), the materials between which heat is transferred (liquid to liquid or gas to gas transfer is generally better, and solid to gas or gas to solid worse), and the temperature difference across them (the smaller the better). That last feature causes us a problem if we try to capture and reuse heat in steel and aluminium making: we can transfer most energy when there's a small temperature difference, but if we want to transfer the heat energy quickly (and therefore economically) then we need a large temperature difference. So we must find a compromise between quick and efficient heat recovery.

How effectively can we transfer heat between a hot gas or solid and a cool solid? Figures 8.14 and 8.15 show the 'recoverable exergy' from our earlier Sankey diagrams of global exergy flow and our options for recovering heat energy to provide a useful service.

The hot output flows are in the form of exhaust gases, cooling liquids, waste by-products (typically granulated solids) and the metal itself which is solid. In steel processing, the exergy in off-gases dominates, containing approximately 80% of the recoverable exergy of the outputs. In aluminium processes, the heat lost through pot walls while smelting is most significant despite being at a relatively low temperature of around 250°C. The most common way to recover heat is to use it to preheat inputs to furnaces (either air, fuel, or the material to be charged to the furnace and heated) or to generate electricity. These may be combined with cascading heat recovery (where heat recovered is used at high temperature first and then subsequently in lower temperature processes) for further savings.

The heat in exhaust gases is transferred to air or fuel by recuperators or regenerators. Regenerators are more suitable for higher temperature and dirtier applications as they are less susceptible to corrosion and dirt. Incoming (solid) material may also be preheated through direct contact with exhaust gases, for example through aluminium stack melters, or with the Consteel® process described in the box story on the next page. Exploiting these energy savings requires investment in a container or conveyor for preheating, and the preheat temperature must be controlled to avoid creation of harmful volatile organic compounds from dirty scrap. Preheating can increase furnace productivity and may reduce metal losses by trapping dust particles from exhaust gases and reintroducing them to the melt.

We've looked so far for opportunities to capture heat and re-use it within the same industry, but potentially we could exchange heat between different industries. This book is primarily concerned with five key materials, and like

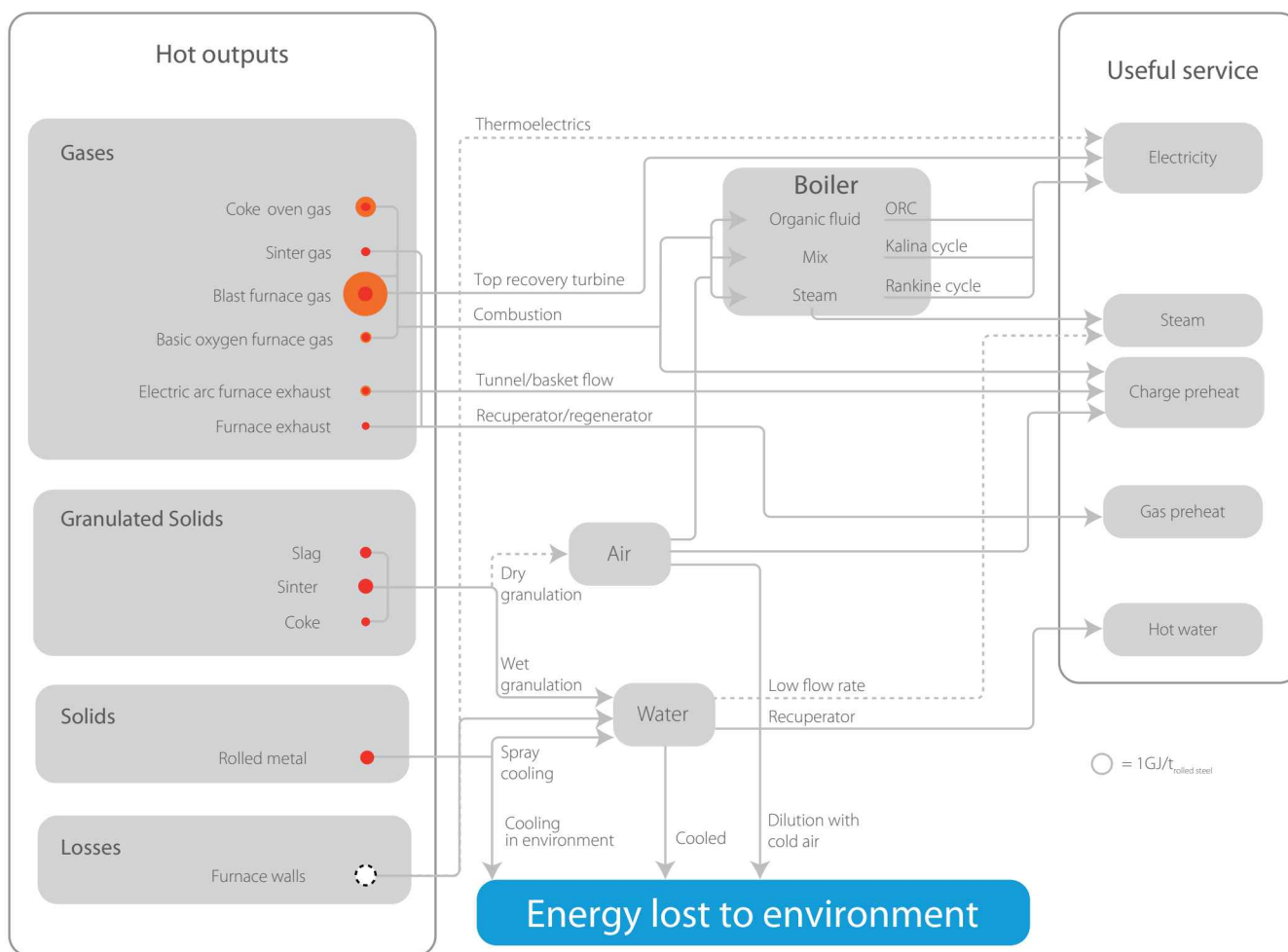


Figure 8.14—Exergy available in outputs from steel production and possible paths for waste heat recovery

steel and aluminium, cement requires very high temperatures (around 1450°C for clinker production), but the paper industry requires heat at around 150–200°C to evaporate water from wet pulp. Plastics manufacture also operates at lower temperatures (most thermoplastics melt under 200°C). In Oxelösund and Luleå in Sweden waste industrial heat is used to warm neighbouring houses², and we've encountered a pilot project looking at the use of waste exhaust gases to grow algae symbiotically with steel production, where the algae also sequester a small fraction of CO₂³. So, if we were given a free hand (and a huge budget) could we build an integrated materials processing facility sharing heat among several industries, as the industries in Kalundborg, described in the last chapter, share by-products? Integrated thermal design is common in the chemicals industries, where most heat transfer is from liquid to liquid, the most efficient mode for heat exchange. A

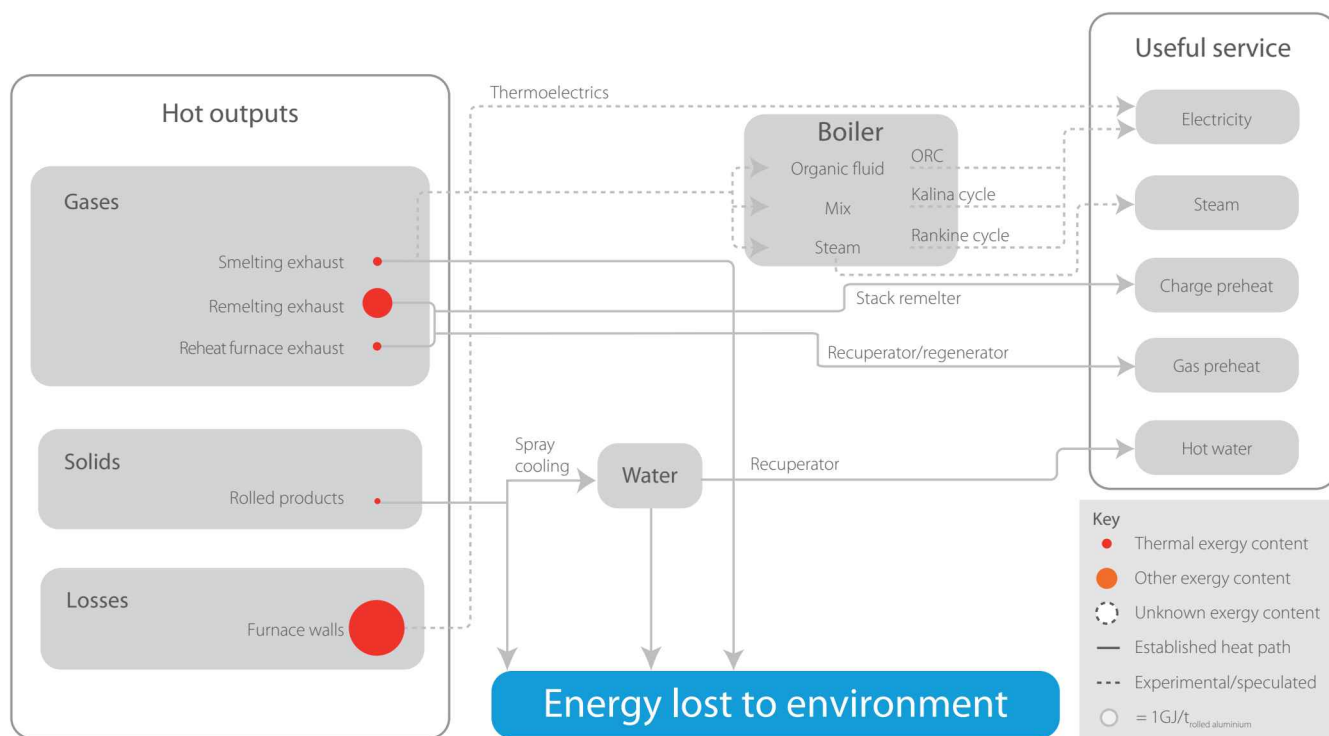


Figure 8.15—Exergy available in outputs from aluminium production chain and possible paths for waste heat recovery

technique called ‘Pinch analysis’ is often used to optimise such designs. The box story contains some details of pinch analysis, and we anticipate that analysis of a wider set of materials processing industries could reveal new opportunities for heat exchange.

Finally, could we develop a heat recovery technology to exploit the heat in solid hot metal? This could be possible with radiant heat transfer to boil a fluid, by preheating air using convective heat transfer or by conducting heat away from the solid surface, for example in heat pipes. Unfortunately, although our chart shows significant exergy value in the processed metals, in practice recovering it is difficult. Effective heat transfer requires high contact pressures, which might damage product surfaces. Allowing the metal to cool more slowly to permit heat exchange would allow the growth of unwanted surface oxide layers and lead to larger than required grain sizes.

In this section we’ve seen that while there is significant exergy available in the exhaust gases, by-products, and processed materials of both the steel and aluminium industries, it is difficult to exploit, mainly because it is in gases or solids and we would like to transfer it to incoming solids. As a result existing

practice is mainly focused on heat exchange between hot and cold gases or on the use of exhaust gas for pre-heating scrap.

Using waste heat to generate electricity

As well as heat exchange, it's also possible to generate electricity with waste heat or novel thermo-electric cells, and as electricity generation itself discards waste heat, could we usefully combine it with our other processes?

In modern power stations, the turbines are driven with steam at 500°C and a pressure of around 30 atmospheres. Blast furnace gas cannot create these temperatures or pressures, but recent research has shown that it can drive turbines via steam from liquids such as benzene or ammonia instead of water. A related development has shown that blast furnace slag can be cooled with air, rather than water, and the resulting hot air stream can also be used to heat a working fluid.

Thermoelectric conversion offers a different approach to generating electricity directly from heat with a solid state semiconductor converting heat flow into electrical power. To date, commercial thermoelectric devices have low efficiencies, around 5%, and are very expensive. However, these efficiencies may increase, and this approach may be able to use waste heat that cannot be exploited by any other



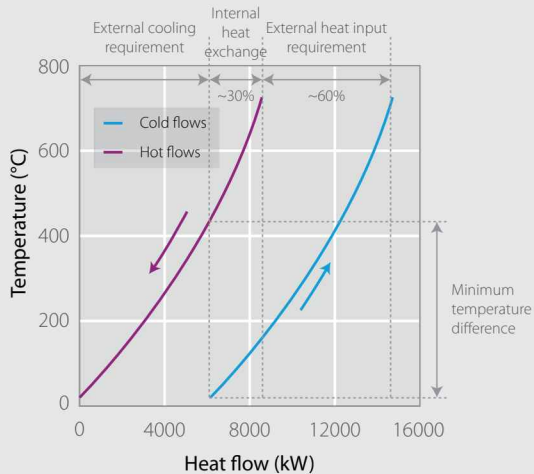
Energy recovery from EAF exhaust gases by Consteel®⁸

The Consteel® electric arc furnace (EAF) directs hot exhaust gas over an incoming conveyor of scrap in an insulated tunnel. This warms the incoming scrap to around 300-400°C through a combination of heat transfer and combustion of remaining carbon monoxide in the exhaust⁶. The preheated scrap falls from the conveyor into a molten bath of steel within the EAF, where it is heated further until it melts. This approach reduces the electricity needed to heat the scrap, and savings of 0.74GJ/t have been reported.

As well as energy savings, preheating can increase furnace productivity by reducing the time needed for melting with a given electrical current. Metal losses in the exhaust are reduced by trapping dust particles and reintroducing them to the melt, and as the furnace maintains a molten bath (a 'hot heel'), noise is reduced as there are no sparks generated as normally occurs with a bed of solid scrap.

route. For example, thermoelectric generation might be used to exploit the heat that must be conducted through pot walls in aluminium smelting to maintain a solid, unmelted layer to prevent corrosion of the refractory lining.

Power stations for electricity generation discard heat, and this could be used in production processes, in an approach, generally referred to as “Combined Heat and Power” generation or CHP. Electricity generation generally produces only low temperature heat (up to 200°C) which is not very useful in the high temperature steel and aluminium industries. However, in aluminium production, this heat can be used to generate steam for the initial stages of the Bayer Process for purifying alumina, and this application saves 15% of current primary fuel consumption⁴. Integrated steel plants have their own power stations for combusting the off gases of primary production, and steam may also be produced for use on-site.



Pinch analysis of the steel and aluminium industries

In the chemicals industry, pinch analysis is commonly used to derive a target for site-wide energy consumption. This target is based on the thermodynamic maximum amount of heat that can be recovered. Hot material flows (those at high temperature with heat available for recovery) and cold flows (requiring heating) are surveyed and combined to generate a graph of heat availability and demand at different temperatures. For a given minimum temperature difference that depends on the nature of the flows (solid, liquid, gas) and the cost/area of heat exchange, a ‘pinch point’ is defined and these composite flows will have a region of overlap that signifies the theoretical maximum amount of heat recovery that can take place. Outside of the overlap, the heating and cooling requirements must be supplied by external sources; heating in furnaces and cooling in air in the case of steel and aluminium.

To achieve the targeted maximum heat recovery, heat transfer across the ‘pinch point’ temperature should be avoided. We have found that further energy savings could be achieved beyond implementing current technologies, but that a more complicated heat exchanger network would be needed to achieve these savings.

Outlook

Steel and aluminium production requires many thermal cycles and the exhaust and hot outputs of these processes contain valuable exergy. It is possible to reduce the number of thermal cycles in many cases, but this may require new investment, and could be inhibited by the need to maintain process flexibility. Heat exchange, while theoretically very attractive, is difficult to implement because of the flows in which heat is available and required.

Having begun this chapter with Lego, and in passing met Napoleon III who at the time his uncle was deposed, was aged four, so presumably would have been playing with it if only it had been invented 130 years earlier, let's now find out how he developed as an adult...

Notes

Exergy flows for the whole of steel and aluminium component production

1. In more detail, exergy is always defined relative to some reference state – such as ambient temperature and pressure at sea level. Exergy is then the maximum work that can be extracted from some source of energy while bringing the source to the same state (temperature, speed, voltage, pressure) as the surrounding environment. In metal casting, for example, the exergy of the liquid metal might be defined as the maximum work that can be done by the heat in the liquid metal as it cools to room temperature.

Recovering and exchanging heat

2. SSAB, a steel producer in Sweden, supply 70% of the population of Oxelösund and Luleå with heating using exhaust gases from their processes (SSAB, n.d).
3. Tata Steel and Sheffield University recently conducted a research project at Scunthorpe steelworks, described by Zandi et al. (2011), where power plant exhaust gases rich in CO₂ were bubbled through an algal bioreactor. The algae grow and sequester CO₂ through photosynthesis.
4. The predication of a 15% saving in primary energy by co-generation is based on research completed for the European Union by Luo and Soria (2007).

Box stories

5. The Castrip® process operated by Nucor Steel in Crawfordsville, IN., has successfully cast and sold steel sheet by the twin-roll casting method. The current range of grades and their properties are documented by Sosinsky et al. (2008).
6. Memoli and Ferri (2008) describe the Consteel® technology and how both heat transfer from the exhaust and combustion of remaining carbon monoxide in a preheat tunnel contribute to energy savings.

Box stories

7. Image credit: Siemens press picture
8. Image reference: Tenova Consteel EAF plant