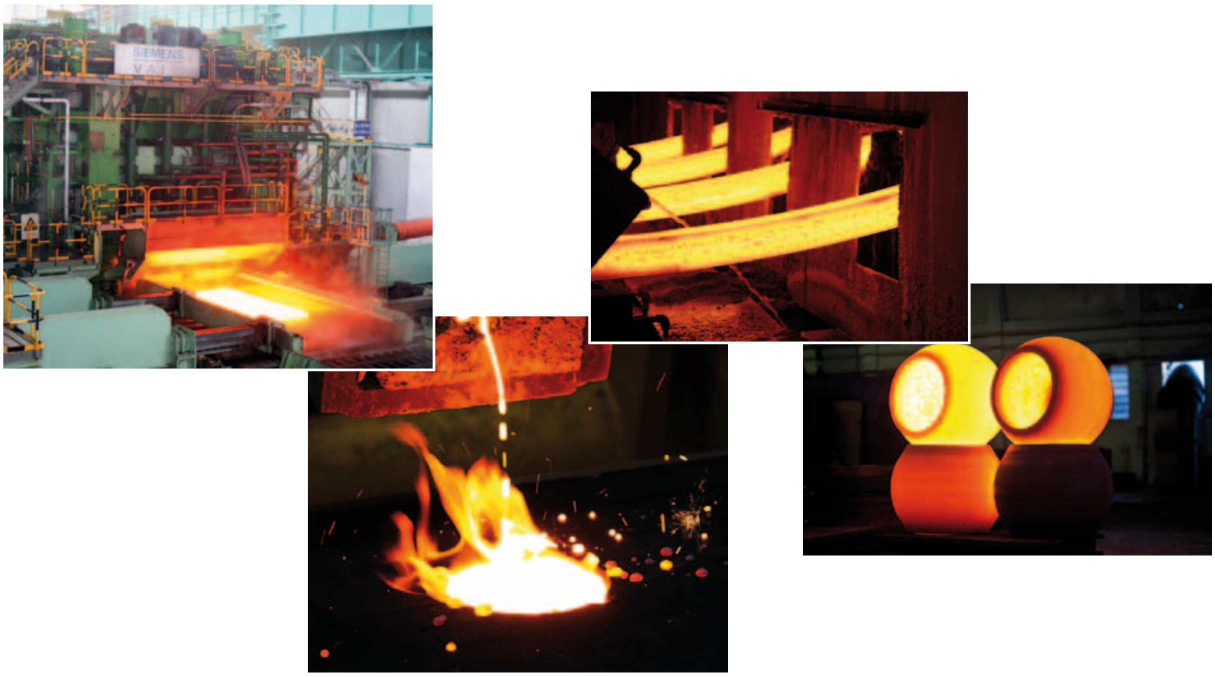
Taking Our Metal Temperature

Energy and carbon savings by managing heat
in steel and aluminium supply chains



WellMet 2050

Taking our metal temperature

Energy and carbon savings by managing heat in steel and aluminium supply chains

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WellMet2050 is a £1.4m 5–year 8–person research programme at the University of Cambridge, funded by the Engineering and Physical Science Research Council (EPSRC) of the UK government to look at all options to reduce global carbon dioxide emissions associated with steel and aluminium. The project is supported by a consortium, of over 20 global companies, with whom we are developing case studies, demonstrators and analysis to reveal the emissions benefit, business opportunities and technical challenges of a raft of emissions reduction strategies.
WellMet2050 is focused mainly on long-term strategies related to material efficiency, and is now exploring four themes:

- re-using metal without melting
- less metal, same service
- longer life and more intense use of metal assets
- compression of the metals manufacturing process chain

This report presents the findings from the fourth theme.

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Taking our metal temperature: summary

Through hundreds of years of cumulative experience in steel and aluminium production, we have developed highly advanced and specialised supply chains that can produce strong, complex and aesthetically pleasing products. Energy costs are large in these industries and historical developments have focused on reducing energy consumption—this is becoming an ever more critical driving force. As heating requirements dominate energy consumption in these high temperature industries, it is time to pause to take our metal temperature; what savings may be made through clever management of heat in an integrated supply chain?

Existing supply chains

Both steel and aluminium supply chains consist of primary and secondary production of liquid metal followed by casting, forming and fabrication of finished products. We can visualise the significance of each energy and material flow by tracing the magnitude of energy consumption in each individual process, and the available energy in their outputs. Comparing energy inputs to the theoretical minimum energy to produce the metal carried forward in the supply chain, we appear to be investing more energy than is physically necessary. Where does this energy go?

Most is lost as inefficiencies—losses due to irreversibilities in the process or energy flows that cannot feasibly be recovered. Primary producers have historically made great strides in improving efficiency and will continue to develop more efficient technologies. We calculate that the efficiencies of these processes are already 40–50%, so there are probably only limited further gains to be made here. The remainder of the energy is lost as chemical energy in byproducts (combustible gases), thermal energy in hot products, and embodied energy in process yield loss. If we are to reduce the energy required to make steel and aluminium products, then we must reduce the demand for energy inputs by integrating processes in shorter supply chains, and seek to recover as much energy as possible from the outputs of these processes.

Shorter supply chains

Looking at a range of case study products covering several supply chains in both steel and aluminium, we see that multiple cycles of heating and cooling are currently required. If we assume metal must be melted once in making metal products, then our ideal supply chain has one thermal cycle where all hot processing after casting occurs while the metal is still hot, avoiding all subsequent energy inputs and inefficiencies in reheating. Two approaches are considered; the linking of existing high temperature processes so that metal is not cooled between them; and alternative supply chains that avoid some processes altogether.

The dominant 'hot' processes are melting, casting, hot working and heat treatment. To link these processes in a single thermal cycle, we must avoid remelting, charge the cast metal to be hot worked with the maximum possible temperature, and begin the first steps in heat treatment immediately after this hot work. We have found some examples of these approaches being used today—for example in rebar production we saw continuously cast billets hot charged to the rolling mill and quenched straight after hot rolling. In looking for alternative supply chains, we found that the primary focus was on processing nearer to net shape; casting thin strips, direct casting or additive manufacture all allow metal products to be produced with fewer steps. However, both casting directly and existing additive manufacture techniques use more energy and have lower throughput than conventional processes.

Overall, a single thermal cycle from casting through working and heat treatment is theoretically possible, but would require further development of direct charging from caster to rolling for more products, direct quenching, and thin strip casting technologies, as well as new technologies for hot inspection, scalping, and sawing, and for new plants to be built using the strategies identified.

Heat recovery

Even with a single thermal cycle, processes will inevitably have hot outputs that if left to cool in the atmosphere would lead to significant loss of energy. Metals processing occurs at high temperatures and therefore process outputs have valuable energy content—heat recovery is practiced for some, but not all of these outputs today.

Studying the energy content in process outputs from the steel and aluminium supply chains, we can see thermal energy in hot exhaust gases, slags and other solids and in the metal itself, as well as significant chemical energy in combustible exhausts from steel production. Heat recovery is most established for hot gases, with developments in dry quenching and granulation allowing heat recovery from cokes, sinters and slag, but there is currently no promising technology for recovering the valuable energy in hot metal products.

Our metal temperature

Technologies for more efficient management of heat by process integration in shorter supply chains are available, but we need to increase their capabilities and, more importantly, their usage. Given the expensive shift in production required, supply chain compression is a long-term strategy, but has potential for significant energy saving.

Analysis of existing supply chains

If we had to lift the world's global production of steel (1200Mt) and aluminium (60Mt) to the summit of Mount Everest, we would surely do everything we could to avoid doing so multiple times, and an enterprising individual would inevitably invent a way of recapturing its useful energy while bringing it back to earth. In fact, melting our key metals requires more than 10 times this energy[1], we often remelt or reheat several times in a supply chain, and a significant amount of this heat dissipates into the atmosphere. In this section, we find out how much energy we use in the supply chain, and explore its purpose.

Use of energy in existing supply chains

On the next two pages we've created Sankey diagrams to show how and where energy is used in metal production. Metal flow is traced along the supply chain from left to right with the scrap losses shown separating from the product flow and returning for remelting. The map is drawn in units of exergy to allow the material and energy flows to be compared on the same scale (see box stories: Combining material and energy flows and How were these Sankeys created). At each major process step, the inputs of energy (electricity, coal/coke and gas and oil fuels) are shown. This energy (top left) is either carried forward as exergy in the metal or lost. Losses (top right) may be in the form of chemical exergy in by-products (primarily combustible gases), heat (both recoverable and low grade waste heat), or exergy destroyed during irreversible combustion (in electricity generation and furnaces).

Making steel and aluminium is energy intensive because removing oxygen from iron ore and alumina is thermodynamically difficult. The reduction reactions can only occur at high temperatures. Iron ore is smelted at 1600°C using coking coal as the energy source and aluminium is smelted at 900°C in an electrochemical process. These temperatures are above the melting point for each metal allowing the molten metal to be easily cast into ingots or products. The majority of energy use in the metal supply chains is for these front-end primary processes.

For steel, almost half of this energy is consumed in the reduction reaction to produce molten "pig iron" (with 5% carbon content) with a small fraction staying with the product as thermal heat (shown purple). The reaction produces a valuable by-product called blast furnace gas which contains unreacted carbon monoxide and is used as a fuel for heating in other parts of the integrated plant. Molten pig iron is charged to steelmaking in basic oxygen furnaces—the process of removing carbon generates energy so that scrap may be melted as part of the process. Steelmaking in the electric arc furnace does not require a reduction reaction, and is therefore less energy intensive than primary production. We can see that if the process scrap loops were eliminated by increasing yields to 100%, then equivalent of all energy inputs to the electric arc furnace could be saved.

In continuous casting, liquid steel is cooled from 1600°C to room temperature— this product heat loss is significant and we will see later that it is currently unused. There is only a small energy input needed as the metal is supplied in liquid form. 'Product casting'—pouring steel or iron into individual moulds—is energy intensive for relatively low metal volumes, so has the potential for significant improvement. The hot rolling, cold rolling, forming and fabrication steps do not change the exergy of the metal, and therefore the energy inputs become losses. We will ask later if these processes can be eliminated with shorter supply chains.

A similar story emerges for the aluminium Sankey, where the electricity input for smelting, together with the energy in the carbon anodes, dominates energy use (65% of total energy consumption in making aluminium products). Only 29% of this energy is carried forward as chemical and thermal exergy in the liquid aluminium. Alumina refining is also energy intensive, although only used for purification—the alumina fed into smelting has no chemical exergy. The recycling loops of melting process and end-of-life scrap have a relatively low energy consumption (2% of total)—most of this input would be eliminated if we could increase process yields to 100%. As with steel, the downstream forming and fabrication processes do not change the exergy of the metal, and if we could alter the supply chain their energy inputs (14% of total) could be eliminated.

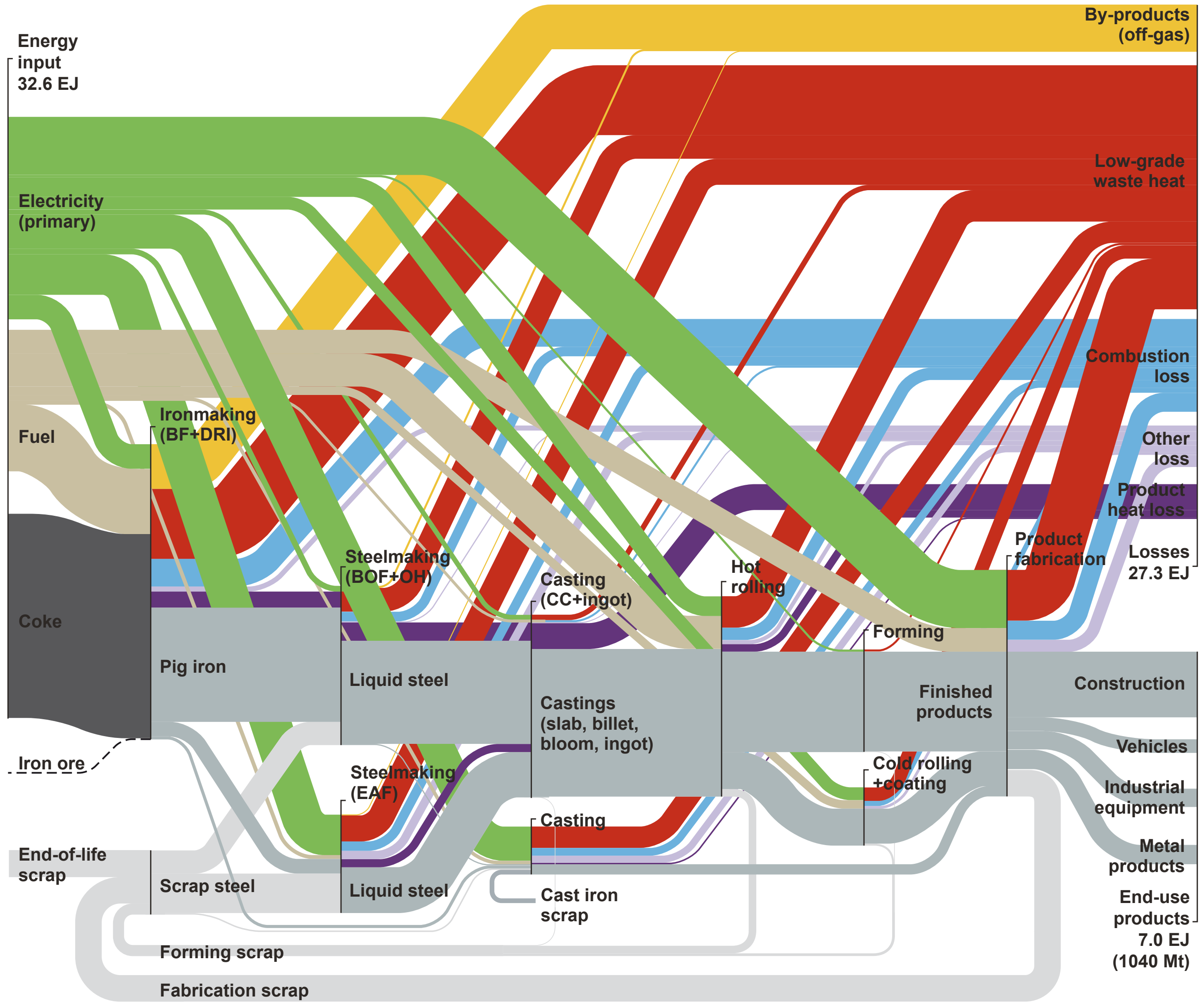
How much energy could we save?

Based on the Sankey diagrams, how much could be saved in a perfect world? If we could eliminate all losses from the supply chain we would be left with the theoretical minimum energy requirements.

	Units	Production from ore	Production from scrap	Total Production
Steel				
End-use production volume	Mt	670	370	1040
Percentage breakdown by mass	%	64%	36%	-
Current energy input	EJ	-	-	32.6
Current energy intensity	GJ/t	-	-	31.3
Theoretical minimum energy	GJ/t	6.7	0	-
Theoretical minimum energy plus melting	GJ/t	8.1	1.4	-
Aluminium				
End-use production volume	Mt	22	22	44.4
Percentage breakdown by mass	%	50	50	-
Current energy input	EJ	-	-	8.2
Current energy intensity	GJ/t	-	-	184.7
Theoretical minimum energy	GJ/t	32.5	0	-
Theoretical minimum energy plus melting	GJ/t	33.6	1.1	-

Table 1: Energy use in the steel and aluminium industries

Global steel exergy flow



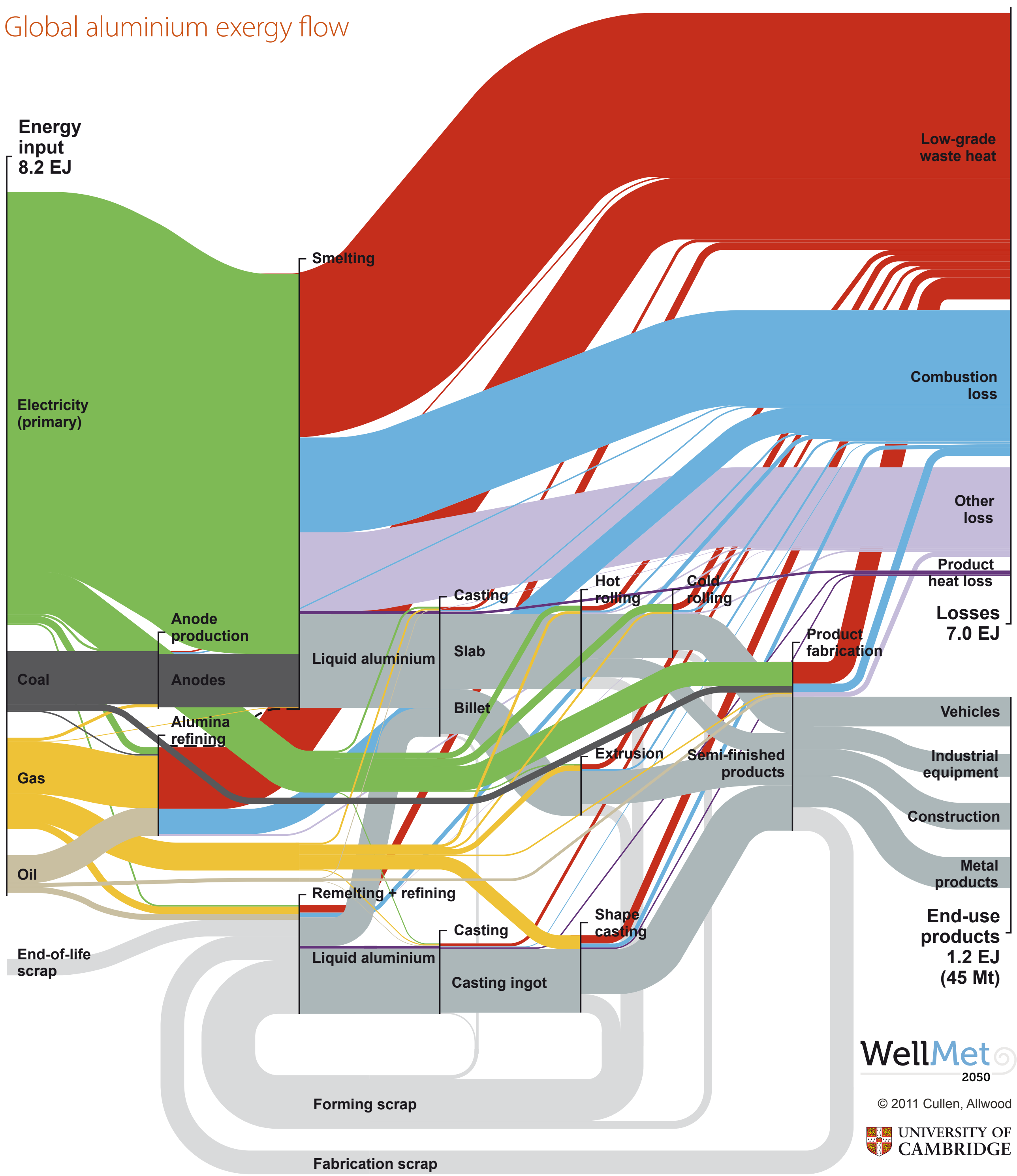
Combining material and energy flows: Exergy

Metals supply chains process a range of inputs, including natural gas, steam, electricity, and ore, to produce metal goods as well as an equally wide variety of waste outputs; hot exhaust gases, dirty liquids and slags. To analyse and properly compare these incompatible inputs and outputs, we use the concept of exergy, representing the potential of each flow to do useful work while reaching the same state as the environment. By looking at exergy, we aim to identify the most valuable 'waste' streams and ask if they need be created at all, and if so, can we do something useful with them? For our study, we are concerned with the chemical and physical exergy components of the flow (therefore assuming that the kinetic and potential components are relatively small):

Chemical exergy: Energy released in the chemical reaction in returning the species to its environmental state; iron ore or bauxite for steel and aluminium respectively. *Steel has a chemical exergy of 6.7GJ/t and aluminium 32.5GJ/t.*

Physical exergy: Determined by the temperature of the metal or temperature and pressure of the flow. Higher temperature flows have more exergy and therefore more potential to do useful work. *When melted, steel has a physical exergy of 1.4GJ/t and aluminium 1.1GJ/t in addition to the chemical exergy.*

Global aluminium exergy flow



How the sankeys were created

Sankey diagrams are used to visualise flows of mass, energy, water and greenhouse gases across systems ranging from the smallest engines, to the entire global eco-system. Our Sankey diagrams are presented in units of exergy (the potential to do work, measured in joules) allowing both materials and energy to be compared on the same basis. Exergy is traced through a number of process steps: from the metallic ore, through the production system and to end-use goods. Each major process step is shown by a vertical black line, with three possible outputs: useful metal, process scrap and losses.

A list of data sources and calculations made to create these exergy sankeys are provided in the working paper '*Global exergy flows for steel and aluminium production*'[W1]. We are relatively confident on the upstream processes of steel and aluminium production, casting, and rolling, but finding verified energy data for the fabrication processes is difficult. A mix of regional data, factory case studies, balancing equations and expert opinion are used to validate the data, and a health check has been performed to balance our data for energy consumed with top-down estimates for total energy consumption from the International Energy Agency[3].

Table 1 lists the total mass of products manufactured from steel and aluminium and the energy consumed to make them. We can see that on average producing a steel product requires 31.3GJ/t and an aluminium product 185GJ/t. The absolute theoretical minima, where iron and aluminium ores are refined with no yield or energy losses, are directly formed to the shape of the final product, and with all heat perfectly recaptured, are 6.7GJ/t and 32.5GJ/t. Adding the requirement that metal be melted once and none of this heat is recaptured, these minima are 8.1GJ/t and 33.6GJ/t, significantly less than our average energy consumption today. We have seen from the Sankey diagrams that this difference is caused:

1. Through process inefficiencies such as heat loss through furnace walls, combustion losses, and process irreversibilities
2. Through yield losses from forming and fabrication, which require an energy input for remelting
3. By processing that requires energy inputs downstream of liquid metal production
4. By thermal energy of hot outputs, including off-gases, hot by-products and the metal itself
5. By chemical energy stored in byproducts such as blast furnace gas

Improvements in process efficiency of primary production, which is the largest energy consumer in the supply chain, are documented in the box story '*Historical improvements in primary process efficiency*' below. Industry has already made significant gains in this area and the developments are shown to be slowing as the theoretical minimum energy is approached. Energy savings through eliminating yield loss are discussed in our previous report 'Going on a Metal Diet'[2].

The work of this report focuses on points 3 and 4 of the above list. Can we reduce or remove entirely the energy inputs that occur downstream of primary production by using a shorter supply chain, and can we recapture the thermal energy that is otherwise lost? Developing a shorter supply chain should be our first strategy for two reasons; as can be seen from the Sankey diagrams the potential energy savings are much larger, and also because the extent to which we improve or eliminate processes will limit the available energy for heat recovery.

Historical improvements in primary process efficiency

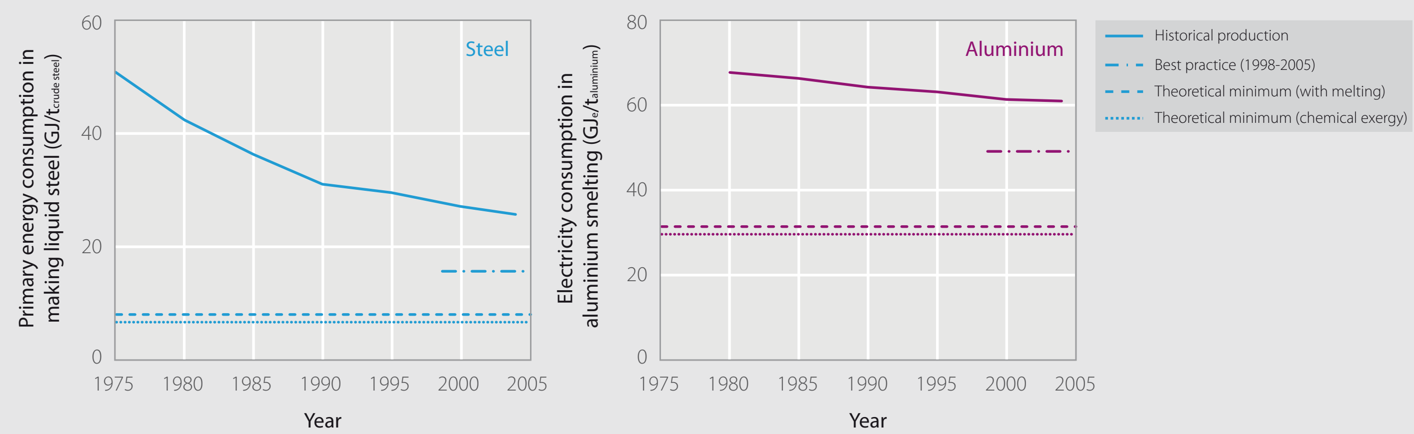
Primary steel and aluminium production is energy intensive, with energy purchasing constituting approximately one third of production costs[4,5]. Comprehensive data on average and best practice energy consumption in the steel and aluminium industries is not available, but the best estimates show a trend of historical efficiency improvements that are tending towards the theoretical minima. These historical trends, together with current best practice[6] and the theoretical limits based on exergy are shown in the graphs below.

The steel production graph shows primary energy intensity for the production of liquid steel, encompassing sintering of the iron ore, coking, ironmaking in a blast furnace and steelmaking in a basic oxygen furnace[4]. For aluminium, the electrical energy consumption for the smelting process is shown[5]—primary energy consumption will vary depending on the electricity source and efficiency of generation. Additional energy consumption occurs in alumina production and anode manufacture but is not shown here. Significant developments leading to energy efficiency improvements in the steel and aluminium industries include:

Steel: re-use of by-product gases from coke ovens, blast furnaces and basic oxygen furnaces either as a fuel substitute or for electricity generation; recovery of waste heat for preheating of fuels, scrap and raw materials; and continuous casting and rolling processes.

Aluminium[5]: Replenishment of alumina in smaller and more frequent quantities to maintain the optimum electrolyte concentration, i.e. point feeders; operation of cells at higher amperages and lower current densities; and use of larger smelting cells, which require less energy to maintain constant operating temperatures.

However, there are fundamental thermodynamic limits to the minimum energy required for metal production; these are shown as dashed lines, with the upper dashed line including energy requirements for melting the metal. Based on these limits, current best practice steel production is 43% efficient on a primary basis and aluminium production is 17–42% efficient depending on the electricity source and efficiency of electricity generation. These values are well above the average exergy efficiency of global energy use which is about 10%[7].



Technical assessment of shorter supply chains

Heating and reheating metal is responsible for most energy consumption in the steel and aluminium supply chains. To reduce energy consumption, ideally the metal would undergo a single thermal cycle from melting to finished product, but are there processes that make this possible, in what products could these processes feasibly be used and how much energy could be saved in this way?

For eight case study products covering a range of process routes in both steel and aluminium (described below), we have examined the temperature history of the metal through its supply chain and identified multiple cycles of heating and cooling in all cases. These cycles may be used to enhance the properties of the final product, but also occur for logistical reasons such as geographic separation or process scheduling, and often it is a combination of these two factors that dictates the temperature history of the metal.

Temperature histories

The temperature history for each of our case study parts is given at the top of the opposite page, starting with liquid metal being cast and ending with the cold finished product. The times for storage and transportation have been adapted to show the groups of operations taking place. In all cases multiple cycles of heating and cooling occur, shown by peaks and troughs in the graphs.

The first 'hot' process is casting; continuously casting the liquid steel to a slab, bloom or billet, and casting aluminium ingots by direct chill casting or continuously casting aluminium sheet for foil. Aluminium alloys may require homogenisation to achieve a uniform microstructure. For the car door and beverage can this homogenisation process takes place during preheating for hot rolling. Most products then undergo hot work, where the metal is softened by heating to allow large deformations to take place. This occurs twice for the forged mining part, where it is hot rolled and then reheated before forging.

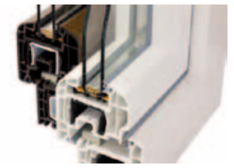
Finally, heat treatments are carried out to alter the properties of the metal. Quenching of steel generates a strong but brittle product, and tempering restores ductility. This is used for both rebar and the forged mining part. Wire rod is heated and held in a molten lead bath to increase strength before drawing in a process known as lead patenting. Annealing is used in both metals where large deformations must be made while the metal is cold, for example in the extensive cold rolling of aluminium foil (requiring two annealing steps) or to ensure the sheet for car doors can be formed. After forming, the painting and drying cycle for the car doors is used to achieve the required strength. A similar age hardening treatment is used for the extruded aluminium window frame.

Metal processing also occurs while the metal is cold. Cast metal is inspected, transported, cut to length and in some cases the edges and surfaces removed before hot rolling. After hot work and heat treatment, the processes carried out vary depending on product but include cold rolling, machining, forming, and more manual handling for transporting the metal.

Case study products

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



Extruded window frame

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

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.

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.

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.

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.

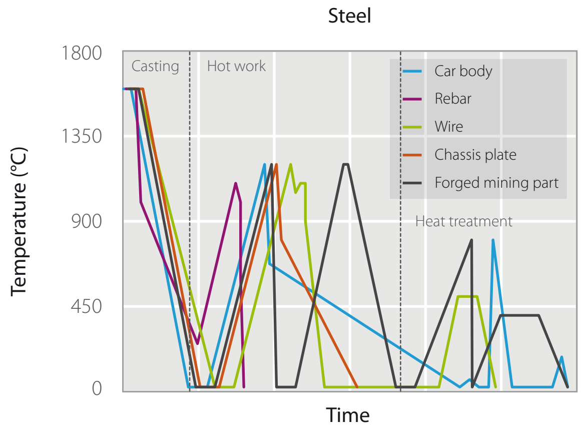
Heavy machinery chassis plate

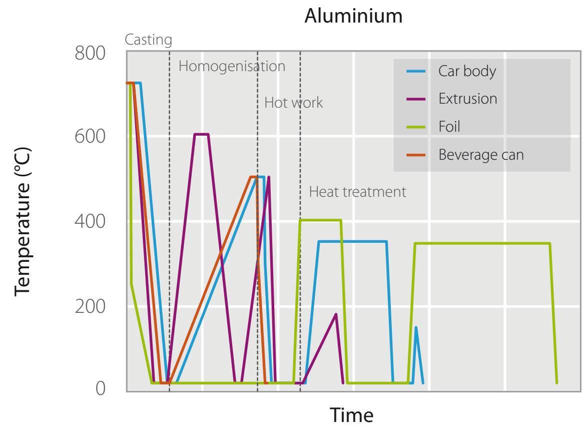
Plate steel is cast as thick slabs and hot rolled to achieve the desired strength. The plates are cut, bent and/or welded during fabrication to produce the finished chassis part.

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. The part is machined to meet required tolerance and for a good surface finish, and a heat treatment consisting of quenching and tempering gives a strong and tough product.

Case study products and the key features of their supply chains – more detail on the findings of the case studies may be found in the working paper[W2]





In practice, what process routes exist that can achieve one or close to one thermal cycle? Through discussions with the metals industry and manufacturers of the case study products, and information from literature, we have identified a range of approaches in developing shorter supply chains, either through integration of the current supply chain by linking thermal cycles, or by following alternative process routes such as net-shape casting.

Supply chain integration

Supply chain integration may be less disruptive than developing new processing routes as the fundamental methods of processing the metal remain the same. To link the hot processes shown in the temperature histories, we should only melt once, cast metal should be kept hot before hot working, and heat treatments should take place in-line after hot working. Each of these approaches is discussed below.

Avoiding remelting before casting

Steel and aluminium making processes are carried out at high temperatures to give favourable thermodynamic conditions for the reduction reactions. Molten liquid metal is produced, permitting alloying and casting into the desired shape. The historical drive to improve energy efficiency has removed most remelting steps for steel and aluminium, but there are still exceptions.

Converting alumina to aluminium uses a lot of electricity and smelters have traditionally been located near sources of cheap hydropower to reduce carbon emissions. Initially, remote smelters produced pure aluminium ingots which were sold as a commodity and shipped closer to the aluminium product markets. This requires the ingots to be remelted and alloyed before products can be made, at an extra cost of 3 GJ/t. The current trend towards more integrated smelting and rolling operations has largely eliminated this additional melting step. In Europe as few as 5% of primary ingots are remelted before forming, and globally the figure is estimated to be 25% (~10Mt)[8]. Use of primary foundry ingots (smaller 4–25kg ingots) to dilute scrap in remelting could be replaced by remelting the scrap at the same location as primary production, although logistically this would require more scrap transport.

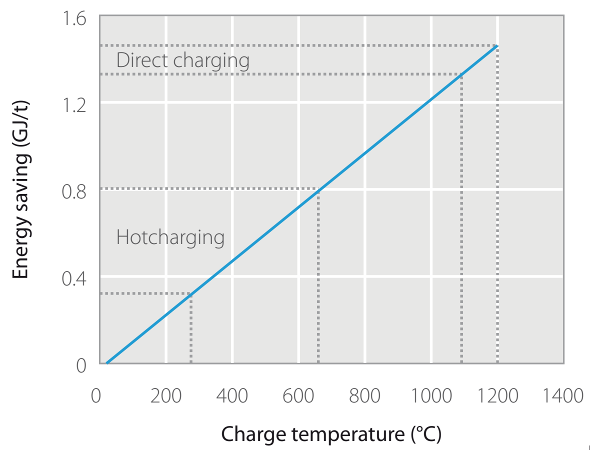
Modern integrated steel plants (BF-BOF route) transfer molten blast furnace iron directly from the blast furnace (BF) to the basic oxygen furnace (BOF) with no remelt step. However the charge of pig iron to an electric arc furnace (about 8% worldwide) is almost always in solid form; the option to use liquid pig iron could be pursued subject to geographic location. A similar approach could be taken with cast iron products.

The inefficient practices of remelting during steel and aluminium production are difficult to improve because of geographic and economic constraints, but their relative fraction will decrease as newer more integrated steel and aluminium plants are constructed to meet future growing demand.

Hot charging cast metal to hot working

Conventionally metal is cast, cooled to room temperature, and reheated for hot working. If heat is retained, the cast metal could be hot charged to a furnace or if hot enough directly charged to be hot worked, saving some or all of the energy needed for reheating.

Hot charging is an established process in the steel industry, where hot cast slabs are cut and transported directly into a reheat furnace for hot rolling. The charging temperature is limited by the temperature gradient between surface and centre; as the centre falls below the solidification temperature, the average temperature is significantly lower. Thicker slabs take longer to solidify and have a lower hot charging temperature. For typical hot charging temperatures (300 to 700°C), energy savings of 0.35–0.80GJ/t may be made as shown in the figure below. Additional benefits include increased furnace productivity, less grain growth so higher strength and ductility, and reduced oxidation.



To achieve even greater energy savings by charging at temperatures above 700°C, the cast products must be directly charged to be hot worked. The Arvedi Endless Strip Production (ESP) process, described in the following box story, has achieved a direct link between caster and rolling mill for the production of steel sheet. Only a little reheating is necessary before direct charging to the rolling mill, with energy savings of 1.25GJ/t.

Hot charging is not currently practiced in aluminium production. Direct chill cast aluminium ingots have different composition and microstructure at the surface compared to the rest of the ingot, and therefore a 20–30mm layer must be removed by a mechanical scalping process that takes place when the metal is cold. Electromagnetic casting eliminates this differential surface structure and therefore the need for scalping, but control of the ingot shape is difficult. An alternative approach might be to develop hot scalping and sawing technologies.

Direct heat treatment

After hot working, it is common for both steel and aluminium to be heat treated to enhance the properties of the final product. We noted several opportunities where the first heat treating step after hot working may be carried out directly with no cooling or reheat:

Quench and self-tempering: For the steel plate and for the forged mining part, the hot rolled plate and billet are typically allowed to cool and are reheated for each of the quenching and tempering steps. In contrast, in rebar production, the quenching and tempering processes take place in line with the rolling mill; the surface is quenched by a water spray and tempering occurs through the heating effect of the hot metal in the core. A quench and self-tempering process is theoretically possible in all cases, saving 1–1.5GJ/t, although may be difficult to achieve in forgings where thermal stresses can cause distortion and cracking.

Direct line patenting: Ultra-high strength steel wire has a fully pearlitic microstructure that is developed through a heat treatment of reheating the rod to 450°C and submersion in molten lead; this batch process is known as lead patenting. The reheating step may be eliminated by conducting a continuous heat treatment known as direct line patenting after hot rolling, where the wire rod is briefly submersed in molten salt baths before cooling in air.

Carrying out heat treatments in aluminium after hot work is more challenging as the material has typically cooled to room temperature before solutionising. Theoretically it would be possible to charge directly from hot rolling to a furnace where the metal can be reheated for solutionising or age hardening, but this is prevented by the different throughputs of semi-continuous hot rolling and the batch process of heating in a furnace.

Generally, the first heat treatment stage could be linked with the hot working process, but subsequent thermal cycles, such as annealing, are necessary as part of the development in properties and cannot be eliminated without a compromise in the final product or by utilising a different process route.

In summary we have seen that there are many opportunities to save energy through supply chain integration, but there are two key barriers to their adoption: existing assets may prevent integration; and integration is most effective when only a very narrow product range is made. However, most metal companies must serve a diverse range of customers, and the requirement for flexibility works against the ambition of integration.

Arvedi Endless Strip Production

Thin slab casting technologies link the caster and rolling mill by 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. However, the largest energy savings are claimed by the Arvedi 'Endless Strip Production' (ESP) process operating in Cremona Italy, where the cast slab is fed directly into the integrated rolling mill to produce the endless strip.

Enabling technologies developed for this process include a faster casting speed (up to 6.5m/min) to match caster and rolling mill productivity, liquid core reduction and direct high reduction at caster exit to improve the 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 from cold. Additional benefits include less scale formation 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 steel strip can be hot rolled to lower thicknesses than are economically achievable using conventional process routes due to the novel reduction technologies used. (Photo credit: Siemens press picture)

Alternative processes

As well as compressing the existing supply chain, we may consider alternatives that have fewer thermal cycles from liquid metal to finished product. Casting nearer to net shape could eliminate the need for hot working, for example by thin strip or direct casting. A more radical approach is the use of additive manufacturing where the product is built up from small units rather than removing material from cast semis. For these processes, what energy savings are possible, and could they replace existing supply chains?

Thin strip casting

Commercial thin strip casting processes exist for both aluminium and steel, although mainly limited to low grade steel sheet and low alloy content aluminium products such as foil. The most common methods of thin strip casting are by twin roll casting (TRC) described in the box story on the following page, and belt casting. These processes both operate using a continuously moving mould (the roll or belt) rather than the oscillating copper collars of ingot casting. With direct and prolonged contact and no slip between cooling metal and the mould, higher heat transfer rates, faster casting speeds and thinner casting dimensions may be achieved.

Hot rolling (typically one pass) occurs either directly in line with the caster in the case of steel or as a part of the casting process itself for aluminium. No reheat is required and as the strip is already close to the final desired thickness, less energy is needed for mechanical deformation. This can be seen by comparing Sankey diagrams showing the flow of exergy for the production of aluminium coil by the conventional direct chill casting/hot rolling route and by twin roll casting. For production of a 1t coil, an energy saving of 2.8GJ may be made by eliminating the hot rolling process and reducing the amount of process scrap that is remelted. Literature on steel twin roll casting claims a similar energy saving of 2GJ/t of coil[9].

Thin strip casters have a smaller footprint and capital cost than integrated mills, but also lower productivity and so are best suited to incremental capacity addition. When casting thin, there is less opportunity in downstream processing to achieve the desired properties in the final product, surface quality is not sufficient to meet the most demanding applications, it is not possible to cast the highest specification grades with larger alloy contents, and the formability of cast thin strips is lower than conventional strip.

Direct casting

Direct casting refers to a set of 'net-shape' processes where liquid metal is cast in the shape of the finished part so that there is no need for forming processes such as rolling or forging. As well as potential energy savings through eliminating any reheat requirement for hot forming, this process route is attractive as casting to net shape eliminates the need to produce 'semi' products such as coiled strip, billets, blooms or slab, which have significant yield loss during fabrication.

Common direct casting processes include sand and die casting. Liquid metal is poured into a mould (compacted sand or machined steel) where it forms the required shape and solidifies. These casting processes require a complicated metal feed system to allow air to escape, to filter out impurities, and to continue to feed liquid metal as the cooling part contracts. Metal is lost in this feed system, with average yields in the range 60–80%.

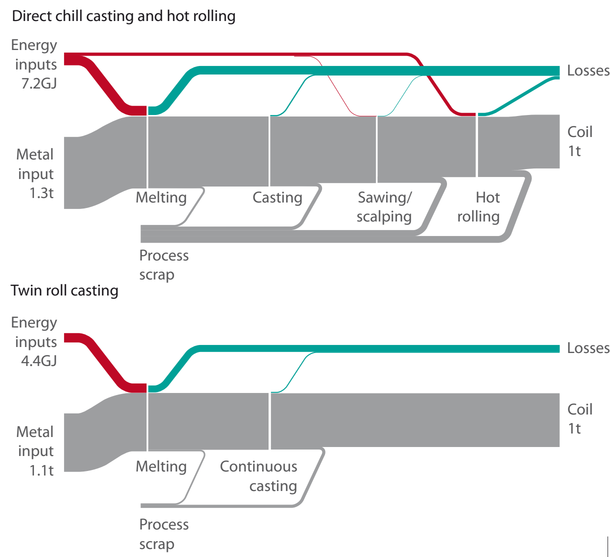
Casting metal parts directly is in theory an ideal process, but is primarily used to produce relatively small quantities of more complicated products such as pistons. The need to fill the mould without solidification occurring constraints its geometry; large parts with thin features, such as sheets, rebar or a beverage can may not fill completely if at all. The surface of directly cast products typically requires machining, and the bulk properties cannot match those of a wrought alloy that has undergone significant deformation during processing.

We can see from the exergy Sankey diagrams on pages 3 and 4 that steel and aluminium casting is currently very energy intensive. While direct casting is an important processing route, it cannot be applied to all products to achieve energy savings.

Additive manufacture

In additive manufacturing processes parts are built up in small increments. Metallic additive manufacturing processes broadly split into two categories depending on their feedstock: powder and non-powder based technologies. Each category can be further sub-divided into processes which melt the base material during processing, and those which don't.

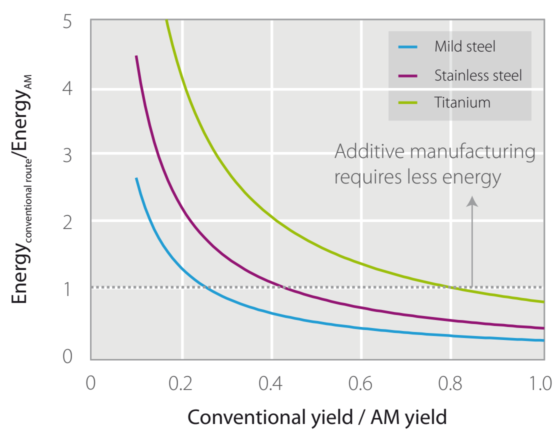
Compared to conventional metal forming routes, additive manufacturing processes are very energy intensive due to the creation of feedstock and use of lasers for heating or melting. A range of values are quoted in the literature for various processes, for example 84GJ/t for Selective Laser Melting (SLM)[10] up to 10000GJ/t for Direct Metal Deposition (DMD)[11]. However, savings may be made through the high yield of the process. If a conventional process route has low yield and/or the energy



consumption of metal production is high, then the overall energy consumption of additive manufacture may be lower as shown in the figure below (using the energy intensity of SLM).

Additive manufacture also allows for the manufacture of more complex, optimised parts. Allwood et al[12] have shown that 20–30% weight saving is typical in optimised parts, with significant use-phase emissions reduction in automotive and aerospace applications. Additive manufacture will only save energy in applications where there is very low yield with a metal that is energy-intensive to produce, and/or where mass savings in a part can have a significant impact on the use phase energy consumption.

As well as being energy intensive, additive manufacture is currently expensive, slow and if producing parts directly does not provide an



opportunity for processing by deformation to improve properties. Additive manufacturing processes that could quickly produce finished parts directly from liquid metal without using energy intensive lasers are not available today, but should substantial developments be made in process speed and product properties, they may emerge as an ideal technology for the implementation of short supply chains.

Barriers to supply chain compression

In this section, we summarise the fundamental limits and additional technical barriers to shorter supply chains that have been identified from discussions on the case study products.

Fundamental limits

These limits are based on the metallurgical changes needed to give the properties desired in the final product.

1. Minimum deformation: The deformation that occurs during rolling, forging and extrusion is used to achieve the mechanical properties required in the product. Thickness reductions are needed to break up as-cast microstructures (20–30% reduction), for grain refinement in hot rolling, and for development of a cold rolling texture to aid forming (60–80%). This gives a minimum as-cast size and limits the application of thin strip casting technologies and the temperature at which hot charging can occur.

2. Minimum temperatures/holding times for hot processes: Hot working and heat treatments have optimal temperature and holding times based on the physics of the changes occurring within the metal, and are necessary to achieve certain metallurgical properties. Some heat treatments could be made shorter by improved sensing and control of metal temperature, but energy savings will be small compared to removing heating cycles entirely.

3. Low temperature processing for metallurgical reasons: Some processes are fundamentally 'cold' in that they require low temperatures to achieve the desired changes. Quenching must involve cooling below a defined temperature, and usually at a fast rate. Cold working will not improve strength if carried out hot. In the products that require the properties imparted by these processes, we have no choice but to carry them out cold. Age hardening and tempering after quenching and annealing after cold work must occur as a separate 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 the roll surfaces. Two shells form and grow towards the roll pinch, where they are fused together by a combination of heat and pressure into sheet with typical thicknesses of 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 the casting of 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 current production is mainly of non-heat treatable alloys

Steel strip casting has taken longer to develop due to the higher process temperature, but there are several plants worldwide that have demonstrated the feasibility of the process for low carbon and microalloyed steels[13]. Twin roll casting has demonstrated large energy savings relative to conventional routes, but practical difficulties remain 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.

Technical barriers

There are also significant barriers to supply chain compression due to the limits of today's technology.

4. Productivity: Process throughputs vary significantly along the supply chain and this inhibits development of a linked single supply chain. Steel and aluminium production are semi-continuous processes feeding into either continuous casting of steel or semi-continuous direct chill casting of aluminium. Hot and cold rolling can be continuous processes but operate at higher production rates, while downstream heat treatments, extrusion, forging, and direct casting steps are almost entirely batch processes.

5. Low temperature processing for technical reasons: In contrast to the processes that require low temperatures for metallurgical reasons, processes such as scalping, machining and inspection require low temperatures due to the limitations of today's technology and are therefore good targets for research. Manual handling can only occur at low temperatures for safety reasons. High temperature alternatives may be possible, but are likely to be expensive due to the cost of materials that can withstand these high temperatures.

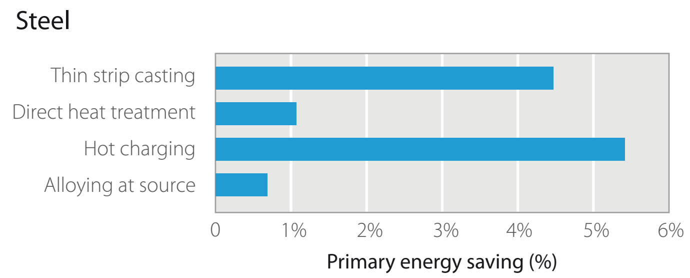
6. Existing assets: It will be difficult to retrofit these solutions on impractical sites, and a common complaint is that the location and scheduling of subsequent processes would make it impossible to implement hot connection of either casting and rolling or hot working and heat treatments. As we replace existing metal production assets, we should aim to co-locate them and to focus the range of products that are made.

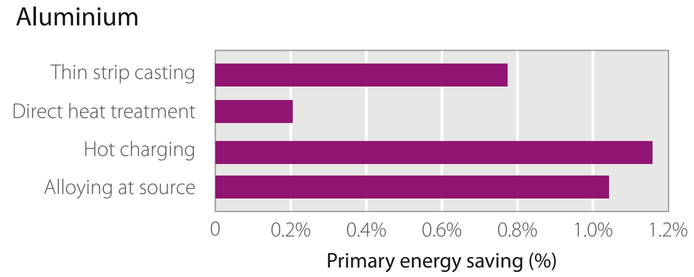
7. Surface finish: Very high surface finish standards are required for applications such as car bodies and cans to aid coating, distributing lubrication in forming, maximise fatigue life, and for aesthetics. Shorter process chains such as thin strip casting have less processing opportunity to meet these exacting standards. They may be achieved given optimum process conditions, but cannot be met consistently with current technology, for example due to roll wear in a twin roll caster.

Energy savings

Having identified several strategies for implementing shorter supply chains and explained the limits to their application, we can estimate the global primary energy savings from applying them widely within the supply chain, shown in the following figures. A theoretical limit with 100% implementation of the strategies is shown– all technical and logistical barriers are assumed to be solved in the long term. Detailed calculations are explained in the working paper 'Energy savings from shorter supply chains'[W3].

In steel, notable savings may be made particularly through more extensive use of hot and direct charging from caster to rolling mill.





This is technically possible in all cases we have looked at but limited by the need for flexibility—making a smaller range of products on a single site would be beneficial. Further use of thin strip casting is limited in high spec applications which require surface quality beyond that currently achievable by this route. Consumers may have to compromise on surface finish in order to use continuously cast sheet. For products that are quenched, direct heat treatment after hot work (as with rebar) would achieve modest energy savings. In aluminium, continuing recent developments towards alloying at source to avoid remelting primary ingots and again more widespread implementation of thin strip casting promise the largest savings. If hot scalping and sawing were possible, hot charging ingots could be implemented for further energy savings.

Using these approaches at their theoretical maximum, we may save 10% and 3% of current primary energy consumption in the steel and aluminium industries respectively.

Outlook

Through our analysis of the temperature history of eight case study products, we have found that metal products typically undergo several thermal cycles in their supply chain; cooling after casting, reheat and cooling again for hot work, and further cycles for heat treatments that take place over a much longer time period.

There is no metallurgical reason for cooling to take place in most cases, and we have identified processes that allow integration of the current supply chain by keeping the metal hot and alternative process routes that allow us to cast nearer to net shape and avoid subsequent hot working. The primary limits to implementation of these processes are the difficulty of achieving the required properties or surface quality in the final product, lack of technologies for hot scalping aluminium and hot inspection of castings, and the logistical aspects of connecting processes with different schedules and productivities. These are significant barriers to the implementation of the identified strategies—if we can overcome them, we may be able to reduce total energy consumption by 10% and 3% for steel and aluminium respectively.

Heat recovery

Inevitably metal must be melted for casting and cooled for use, and therefore even with short supply chains some opportunity will remain for recovering the thermal energy of the metal and other by-products as they cool. Hot outputs are effectively a free source of energy, although the high temperatures and dirty flows make heat recovery technically challenging and expensive. What energy is available for recovery, where can it be used and how much energy does heat recovery save?

We have surveyed processes in the steel and aluminium industries to determine the thermal energy content and temperature of their hot outputs and technologies for heat recovery and use. Despite an obvious potential for energy savings, it is clear that not all hot outputs are utilised. We investigate the barriers to implementing heat recovery based on discussions with industry.

Hot outputs

Where and how much energy is available in the hot outputs from steel and aluminium processing is shown in the maps (opposite page) tracing the heat in hot process outputs to either provide useful services or to the environment. The area of the circles is proportional to the exergy content, either thermal or 'other' which includes pressure and chemical exergy.

These hot output flows come in the form of exhaust gases, cooling liquids, waste by-products that are typically granulated solids and the metal itself, which must be kept fully solid to be useful as a product. In steel processing, the exergy in off-gases dominates, containing approximately 80% of the exergy of the outputs. In aluminium, the heat lost through pot walls while smelting is most significant despite being at a relatively low temperature of around 250°C. This is due to the need to maintain a solid cryolite layer internally to protect refractories from corrosion—heat is purposefully conducted away to maintain a temperature gradient.

To extract heat from a stream, the overall heat transfer coefficient and the area for heat transfer must be large (see the box story 'Thermodynamics of heat recovery' for more information), favouring heat recovery from gases and liquids which may be distributed over a heat transfer surface easily. Granulated solids can also have a large area of heat transfer if the particles are small. Solid products must maintain their shape, so only the surface heat is easily accessible and transfer of this heat to a fluid is preferable.

The wasteful flow paths shown typically involve cooling with water or in open air, for example wet cleaning of dirty exhausts, wet granulation of slag or sinter, and spray cooling of rolled products. A large flow rate of water is used to cool products quickly with a small temperature rise in the water. Low temperature water has a small thermal exergy, and therefore there is little incentive to apply thermal energy recovery. Circulated cooling water is cooled in the environment by a cooling tower and the energy is lost.

Heat recovery technology

The 'useful' paths in the heat flow diagrams allow the waste heat to displace process energy requirements by providing a service; electricity, steam or hot water that may be used internally or exported to another process, or preheating charge or combustion air to reduce energy consumption for process heating.

To avoid the loss of exergy in water or open air cooling, we must maintain temperature in heat transfers—as each transfer has a minimum temperature difference, fewer transfers are preferable. For example, dry cleaning of blast furnace gas using a cyclone keeps the gas hot and boosts the energy recovered by a top recovery turbine as it expands the gas from high to low pressure. The chemical energy of the turbine exhaust may still be recovered by combustion. In dry slag granulation, a flow of air between atomised drops solidifies the slag and heats the air to temperatures

Thermodynamics of heat recovery

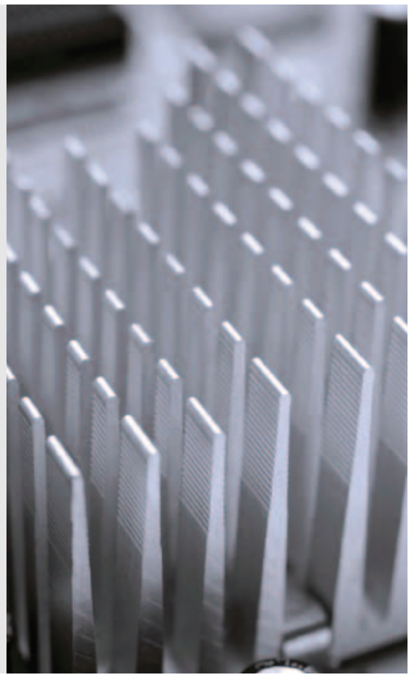
If we want to transfer heat from something hot to something cold, the laws of thermodynamics are an unavoidable constraint on how effectively we can do so. We can't create or destroy energy, but we may dilute it to such a low temperature that is effectively useless, and in fact this is exactly what can happen when trying to capture waste heat by transferring it to successively lower temperatures. For waste heat recovery, the heat source is a hot process output that we want to cool (for example exhaust gas, hot water or solid product) and the sink may be either an intermediate transfer medium (for example water/steam) or a an input flow that requires heating such as preheating cold scrap or combustion gas. Heat exchangers are designed to transfer as much thermal energy, Q, as possible from the hot source to the cold sink. This depends on three operating parameters:

$$Q = UA\Delta T$$

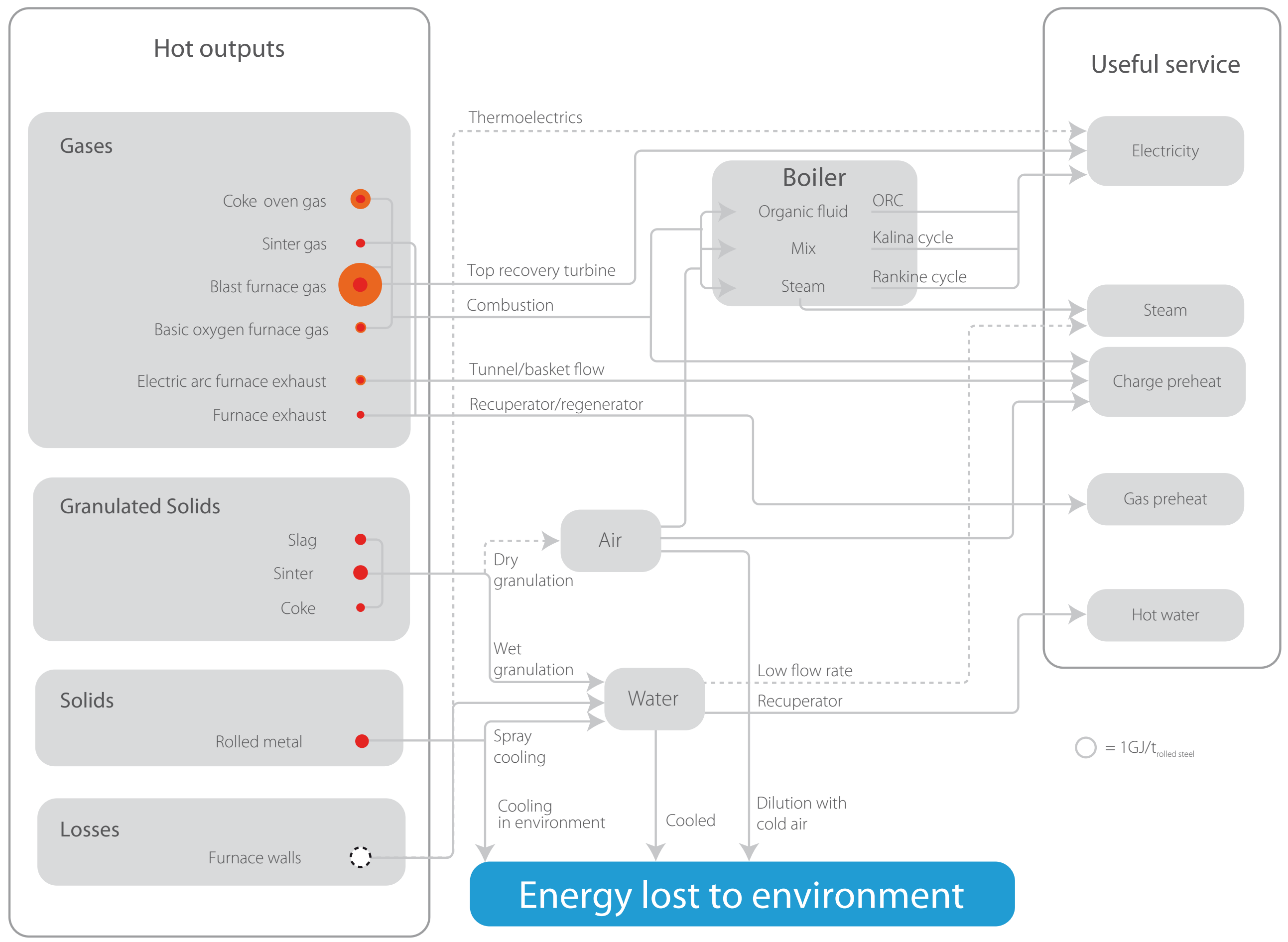
U = Overall heat transfer coefficient—depends on the materials used, temperature, and geometry of the heat transfer surfaces

A = Area of heat exchange—larger areas allow more thermal energy to be recovered, but increase costs

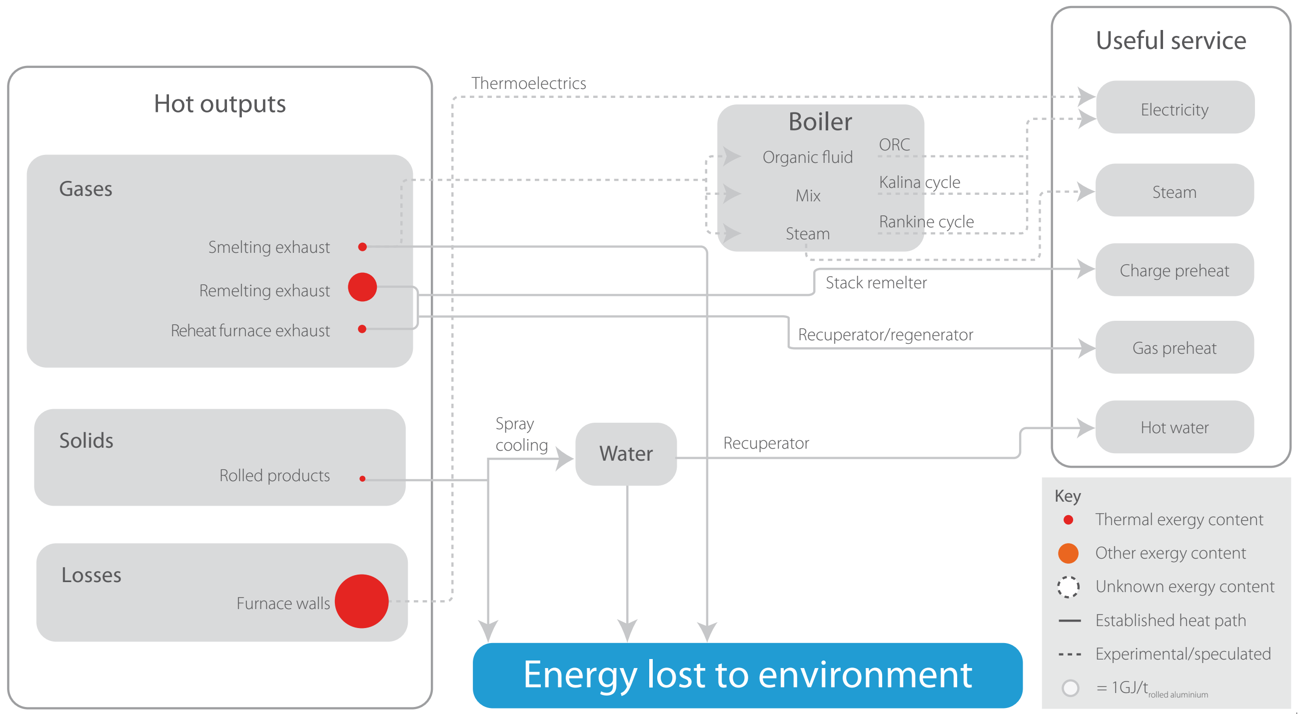
ΔT = Mean temperature difference between hot source and cold sink—A larger temperature difference gives a bigger heat flow (and therefore a smaller, cheaper heat exchanger is required) but limits the maximum change of temperature in each stream and therefore the maximum amount of heat that can be recovered.



Steel



Aluminium



of up to 600°C, a level which is useful for preheating incoming charge, or for use in a boiler. The granulated slag may then be used as a substitute for clinker in cement production

In waste heat boilers, the hot flow is used to evaporate water and superheat steam. This steam may be used directly or converted to electricity through a Rankine cycle, where the steam is expanded in a turbine to generate electricity. Rankine cycles operate most economically at a boiler temperature of 400°C[14]; research is ongoing on lower temperature cycles with different working fluids, for example benzene or ammonia with an Organic Rankine Cycle (ORC) or through a mixture of fluids with a Kalina Cycle. Generating electricity is less efficient at lower temperatures.

Preheating combustion air or fuel using the exhaust is carried out using recuperators or regenerators. A recuperator has continuous heat flow from hot to cold streams, through an intermediate barrier that prevents mixing. A regenerator has two beds that are alternately charged and discharged with thermal energy by switching the hot and cold streams. Regenerators are more suitable for higher temperature and dirtier applications as corrosion and heat transfer through a dirty surface are not critical.

Incoming material may be preheated by direct contact with exhaust gases, e.g. through aluminium stack melters, basket melters connected to electric arc furnaces (EAF) or simply by having an unfired preheating zone in a continuous furnace. The CONSTEEL process involves a counterflow of scrap against exhaust gases from an EAF in a sealed tunnel to achieve higher energy savings than static scrap preheating. Energy savings must be balanced with the extra capital cost of providing a container or conveyor for preheating, and the allowable preheat temperature is limited due to the creation of harmful volatile organic compounds if the scrap is dirty. As well as energy savings, preheating can increase furnace productivity and reduce metal losses in the exhaust by trapping dust particles and reintroducing them to the melt.

There may be a window for developing a heat recovery technology utilising heat from hot metal; however keeping metal hot for a long time results in unfavourable oxidation (and metal lost as scale) and grain growth (reducing mechanical properties of the metal, although these may be recovered in subsequent processing.) Possible routes include using radiant heat transfer for fluid boiling, to preheat air using convective heat transfer or to conduct heat away from the solid surface, for example by use of heat pipes. Contact and particularly the high contact pressures required to achieve good heat transfer may practically limit this option.

An area receiving significant research attention is thermoelectric conversion, where a solid state semiconductor converts heat flow through it into a voltage difference and electricity generation when a load is applied. Commercial thermoelectrics have efficiencies up to only 5%, and are very expensive. Their advantage is in their suitability to capture energy that is difficult to capture by other means, for example through furnace walls. A potential application may be to generate electricity while conducting heat away through pot walls in aluminium smelting.

Barriers to implementing heat recovery

Heat recovery has an obvious benefit in reducing external energy use within any supply chain, but only some technologies have achieved industrial implementation on a large scale, and even these best practice technologies are not always used in all cases—why? The practicalities of implementing heat recovery and how this limits its use are discussed below.

1. Suitability of inputs and outputs: We have seen that there are technologies available for transfer between some different media, but we cannot currently interchange easily between all of them, for example there is no path for transferring heat from a cast slab to scrap that is to be melted. The timeliness and location of the hot flow output and heating requirements are important; if there is nothing to be heated, there is no use for waste heat recovery. Continuous processes have simultaneous and co-located hot and cold flows that are prime targets for heat recovery.

2. Maintenance: While the energy source for waste heat recovery is effectively free, heat exchangers may require frequent maintenance due to the high temperatures and often corrosive nature of the flows. The cleanliness of gas flows is important as deposits can reduce the heat transfer coefficient on heat exchange surfaces, and therefore the overall effectiveness of the heat exchanger. Thermal stresses due to large fluctuations in temperature may cause thermal shock, expansion and deformation, or creep over time.

3. Local energy cost: If energy is cheap, why invest effort in recovering it? While the energy inputs to waste heat recovery devices are 'free,' in that they inherently exist within the supply chain and would otherwise be wasted, the capital costs of heat exchangers can be significant and due to the high temperatures and dirty flows maintenance and cleaning are often needed.

4. Temperature difference and area requirements: The above factors are effectively fixed for a given situation of hot flow and heat recovery system, and therefore the final decision to be made is how big a heat exchanger is required. For a given energy cost, there is an economically optimum level of heat recovery system with a defined area of heat exchange.

5. Operating temperature range: The maximum temperature that a heat exchanger can withstand is limited by its material. Typically stainless steels can be used in applications up to 700°C, Nickel-based superalloys up to 850°C, and ceramics up to 1500°C[15], with higher temperature materials costing more. Flows that are too hot may be cooled by mixing with air/water mist and then introduced to the heat exchanger for recovery, but energy is lost. A minimum temperature is set by the acid dew point of the hot gas, typically 125–175°C depending on composition[16]. This is the temperature/pressure where acidic liquid will condense on the heat exchanger surfaces resulting in accelerated corrosion and reduced lifetime.

Energy savings

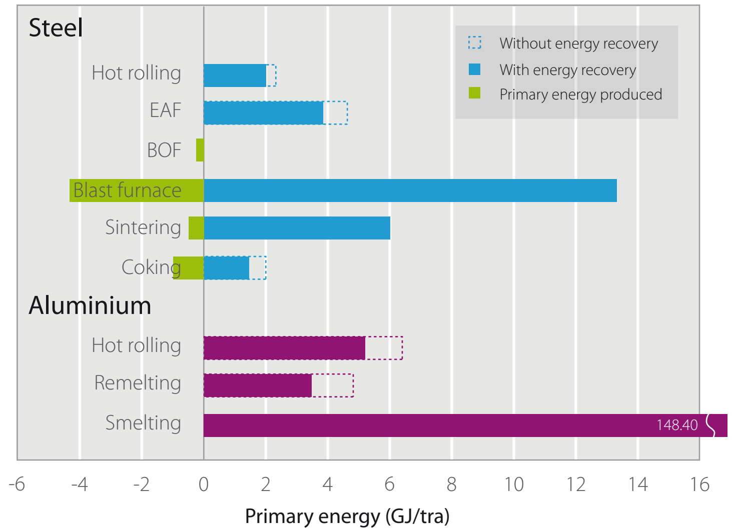
Energy savings may be made through reducing process energy consumption or producing energy that is useful in other processes. While the exact energy consumption and savings will vary depending on the details of specific plants, if we consider heat recovery in a typical efficient plant we may see the importance of its implementation. The following figures show process energy consumption with (solid bars) and without (dotted lines) heat recovery as well any primary energy that is produced and can be used elsewhere, having been normalised to the production of one tonne of rolled steel or aluminium. In steel production, process energy savings are made by preheating inputs for coking, in an electric arc furnace and in hot rolling, displacing heating requirements to reduce energy requirements by 20–30%. In the blast furnace, the most significant energy consumer in the steel supply chain, electrical energy of up to $0.15GJ_e/t_{iron}$ may be generated by a top recovery turbine, followed by combustion of the gas. Dry granulation of slag produces hot air which can be used with a boiler to generate $0.11GJ_e/t_{iron}$, with similar savings by dry cooling of coke and sinter.

Although research projects exist to recover heat from aluminium smelting, there is typically no heat recovery practiced due to the corrosive nature of the exhaust gases and the diffuse nature of the heat flow through the pot walls. Furnaces for secondary melting and reheating for hot rolling may preheat inputs with hot exhausts for energy savings of 20–30%, similar to steel. Overall, the energy savings that may be made using current technology are significant for steel—for the processes shown as much as 27% saved compared to no recovery (including credit for primary energy)—while for aluminium more modest savings of approximately 1% may be made due to dominant energy use in smelting. Expanding heat recovery to cover the entire temperature range of exhaust gases, to solid products and to losses through furnace walls would see further energy savings, although the exact magnitude will depend on how the heat is used.

Outlook

Looking at the heat available and the paths this heat can take through to provide useful services or be dissipated in the environment, we have seen that heat recovery options exist for hot gases (recuperators, regenerators, scrap preheat and boiling to create steam and electricity) and for the granulation of solids to generate hot air. When water is used for cleaning or cooling, the heat is diluted to a low temperature and is not useful for heat recovery. A significant opportunity remains to be exploited in the metal itself, but this may prove to be too technically challenging to recover.

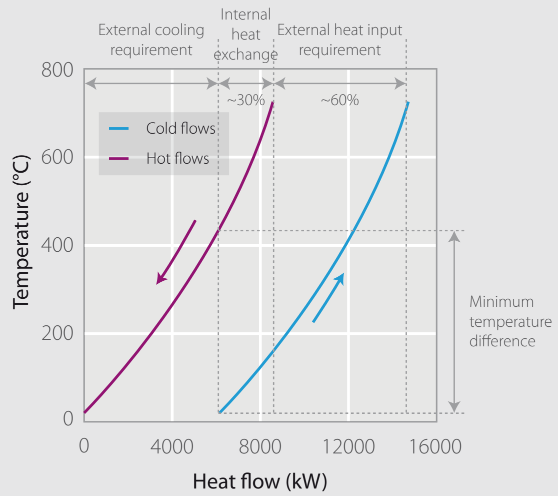
Significant energy savings may be made through implementing heat recovery, but it is not always used. This is primarily down to the economic decision balancing increased capital and maintenance costs with the amount of energy that may be saved, aiming to find an optimum heat exchanger design and size.



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. The application of pinch analysis to the steel and aluminium industries is described in an accompanying working paper[W4]. 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.



Actions and opportunities

Having taken our metal temperature, we have identified several opportunities for saving energy through a more integrated supply chain, starting from an ideal single thermal cycle from hot liquid metal to cold finished product, and applying heat recovery to displace the use of energy for process heating.

Based on our findings and estimates of energy savings, we are able to recommend a hierarchy of heat management for steel and aluminium supply chains:

1. Eliminate processes completely: As most processes have inefficiencies due to heat loss, irreversibilities, or waste generation, our first strategy should be to try to minimise the number of processes carried out. Avoiding remelting of primary metal saves $4.5GJ/t_{steel}$ or $3.9GJ/t_{aluminium}$, and casting thin strips to avoid hot rolling saves $2GJ/t_{steel}$ or $2.8GJ/t_{aluminium}$. Avoiding remelting is primarily a logistical challenge while implementing thin strip casting more widely requires technology and alloy development to improve surface finish and formability of the cast strip.

2. Process linking: There are few metallurgical requirements for cooling metal between hot processes; therefore most products could be made with one or two thermal cycles by linking the hot processes of casting, hot work and heat treatment. The largest energy savings may be achieved through hot or direct charging—a cast steel billet with an average temperature of 400°C hot charged into a reheat furnace for hot rolling saves 0.5GJ/t, or direct charged at 1100°C saves 1.25GJ/t. Although not currently possible with aluminium ingots due to the need for scalping and sawing at low temperatures, hot charging could save up to 1.1GJ/t.

3. Process heat recovery: Waste heat recovery technologies are well established for utilising the heat content in most hot process outputs. As well as traditional technologies such as recuperative burners in furnaces, we have also seen developments in dry cleaning and granulation for enhanced heat recovery from furnace gases and slag respectively. Energy savings of 0.3–0.6GJ/t are typical for most hot processes.

4. Use waste heat externally: External waste heat use by cascading from high temperature to low temperature industries may be thermodynamically favourable, but the concept requires logistical (location and timeliness of hot and cold flows) and technical development before implementation.

Supply chain compression is difficult to apply to existing assets due to variability in throughput and geographic separation of subsequent processes. Therefore, the majority of the strategies suggested require to new steel and aluminium plants specifically designed to use a shorter supply chain. Of the options presented, only hot charging cast steel at lower temperatures (around 400°C) and process heat recovery may be implemented with relative ease.

To widely implement shorter supply chains in the steel and aluminium industries, we recommend the following actions:

Senior management

Senior managers involved in the decisions leading to the design and commissioning of the supply chain should consider energy saving as a key performance metric:

- Metal should only be melted once—scrap melting and primary production should be co-located to allow this to happen
- New plants should be designed for nearer-net-shape thin strip casting, or where this is not possible, hot connection of caster and rolling mill as well as rolling and heat treatment.
- Logistical barriers to hot charging should be reduced e.g. by organising plants so they focus on small number of grades/products
- Collaborations should be made with other industries through sharing of waste heat sources where they cannot be used onsite

Metal consumers

Recognising that consumers have little direct effect on the supply chain choices made by metal producers, they may still act by removing barriers to shorter supply chains:

- Re-evaluate the functionality needed from metal—particularly surface finish when it is not critical

Researchers

A number of technology gaps have been identified that if developed would allow for further integration within supply chains. Researchers, including the WellMet2050 team, should look at:

- Hot scalping of aluminium ingots so that they do not need to be cooled completely before homogenisation/hot rolling
- Direct charging technologies similar to Endless Strip Production for long product shapes (rod, bar, sections)
- Designing direct heat treatment processes for all quenched products analogous to quench and self-tempering observed with steel rebar
- Improving surface finish and formability with thin strip casting technologies
- Developing a method of hot forming cast thin strip so that its relative lack of ductility is not a limit in its application
- Cheaper materials with better corrosion and creep resistance for heat exchangers to allow higher temperature heat recovery to take place
- Heat recovery from solids, and particularly a way of transferring this heat to provide a useful service
- Development of an integrated pinch analysis across all industries to calculate a global energy target for cascading heat recovery and proposal of a heat exchanger network design that can meet these targets

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W1 Cullen J (2011). Global exergy flows for steel and aluminium production.

W2 McBrien M (2011). Supply chain analysis of case study products.

W3 McBrien M (2011). Energy savings from shorter supply chains.

W4 McBrien M (2011). Pinch analysis of the steel and aluminium industries

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