ARUP

Buildings & Infrastructure Priority Actions for Sustainability

Embodied Carbon

Steel

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This document is a snapshot in time of industry research, opinion, and knowledge. The information is subject to change as industry progresses and new information comes to light. This document is to be periodically reviewed and any comments or suggestions are welcomed via jo.spencer@arup.com and the BIPAS team. BIPAS is a multi-disciplinary group of engineers within Arup, funded via Arup's internal investment programme. We carry out research and create resources relating to sustainability, primarily for use within Arup but shared externally when it is appropriate. Our objective is to address those areas that engineers engage with on a daily basis, to enable them to address sustainability in an informed and effective manner.

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Introduction

Across the world in 2020, around 1900 million tonnes of crude steel were produced [1], with just over 50% of that used for buildings and infrastructure. Steel used in buildings accounts for around 8% [2] of the world's carbon emissions, and on average every tonne of steel produced leads to the emission of 1.85 tonnes of CO_2 into the atmosphere [2].

However, the greenhouse gas emissions (referred to in this document as 'carbon') and the carbon factor (the quantity of greenhouse gas emitted per kg of material) for every steel member can vary depending on:

- Raw material extraction
- Processing
- Manufacturing location and techniques
- Transportation mode and distance.

As designers we can exert influence via our designs and specifications by working collaboratively with contractors and clients. To do this, we need to understand the carbon emissions associated with the different parts of the steel manufacturing process and ensure that the impact of our decisions is felt throughout the supply chain.

This document provides information relevant to carbon steel products typically used in construction including:

- Structural steel sections (both open and closed) – used for beams, columns, bracing etc.
- Structural plate – used for connections, bespoke girders etc.
- Profiled metal decking – used for composite floors, roof and façade panels
- Structural bolts, shear studs, welds
- Structural reinforcement, cables, tendons, ties
- Light gauge structural channels, and metal framing systems
- Façade brackets
- Mechanical ducting, steel pipes and tanks.

This document aims to set out the factors that contribute towards the emission of carbon through the whole life cycle of steel products, stage by stage used for buildings and infrastructure. It also highlights the potential route to decarbonising the production of steel.

Using less material as an industry is **fundamental** to reducing emissions. We cannot rely on production processes to eradicate emissions. At an industry scale, there is limited scope to expand electric arc furnace production due to the quantity of recyclable steel that is available. Similarly, reuse of steel elements is only carbon-efficient if the sections are utilised to a sufficiently high level. This paper aims to provide the reader with information on the status of the industry and best practice, so that they can understand the impact of their design choices and avoid greenwashing.

Lifecycle

The stages referred to in this document align with the life cycle assessment set out in ISO 14040, whereby Stage A is ‘up-front’, Stage B is ‘in-use’, Stage C is ‘end-of-life’ and Stage D is ‘beyond life-cycle’. Figure 1 shows how a steel product’s lifecycle fits into the lifecycle assessment stages and the approximate proportion of carbon associated with each. This figure applies for the basic oxygen steelmaking process – however, steel can also be produced using an electric arc furnace.

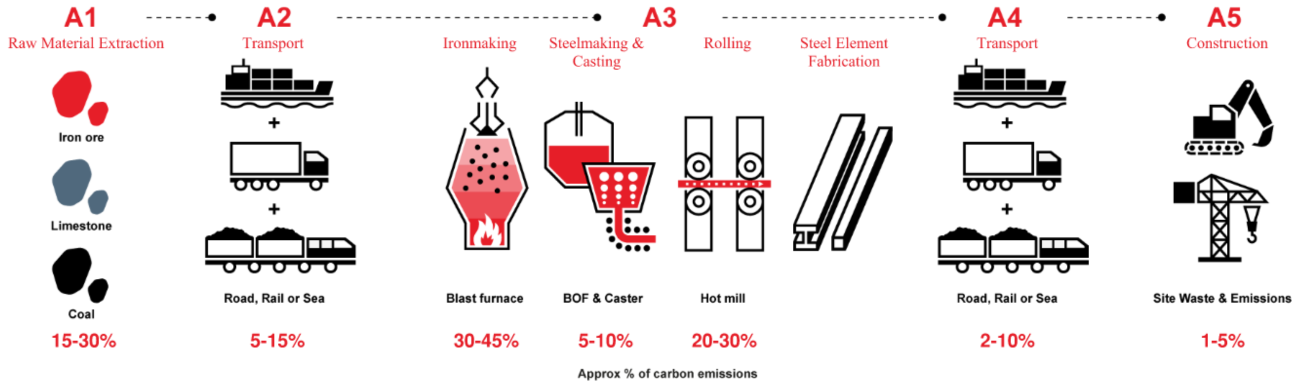


Figure 1
Steel product lifecycle, and approximate percentage of A1-A5 carbon each stage accounts for, based on blast oxygen furnace production and multiple resources including EPDs and various data extracts.

Stage A

A1 – Raw material extraction

Module A1 includes the carbon emissions of the raw material extraction and processing, and the processing of secondary material input (e.g. the recycling of scrap metal). It typically accounts for 15-30% of the A1-A5 carbon emissions of a steel product (ascertained from review of numerous steel production EPDs).

To create 1.7 billion tonnes of steel across the globe in 2018, the following raw materials were used [1]:

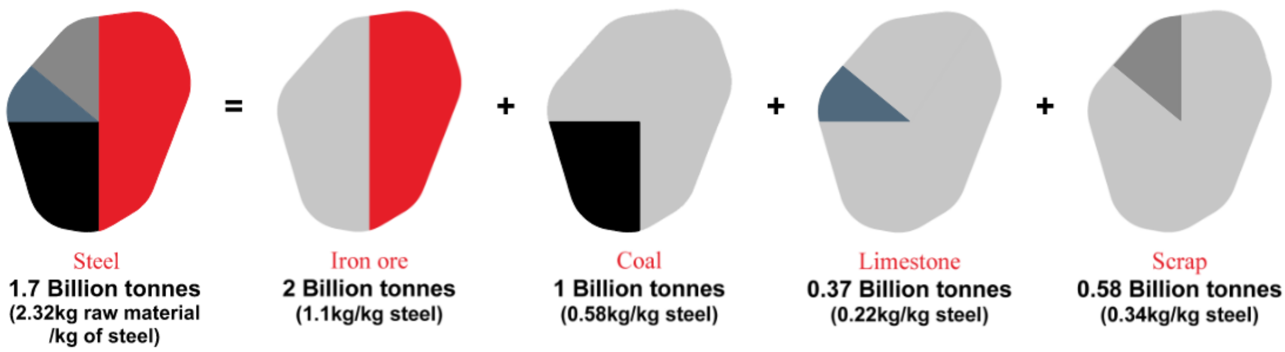


Figure 2
The raw materials used in global steel production annually, and the quantity required to manufacture 1kg of finished product (2018).

Iron ore

Iron ore is one of the most abundant metallic elements on the planet; 98% of all iron ore mined is used to make steel. It is mined in over 50 countries, but 80% of it comes from only four: Australia, Brazil, China and India.

Most of the iron mined in the world is from surface opencast mines, with drills, explosives and mechanical equipment used to extract it. It is then transported to nearby crushing and washing plants, where the iron ore is removed from the waste rock.

Iron ore mining accounts for 34Mt CO_2e/year, with 55% of this attributed to use of diesel in mobile equipment, and 35% from the use of non-renewable electricity [3]. Decarbonisation of the grid and switching to equipment that uses hydrogen fuel cells and battery electric vehicles, could enable the mining process to achieve much lower emissions.

Coal

Around 15% of the coal mined in the world is used in the production of steel [1]. Coal is turned into coke (by baking in a coke oven to force out the impurities) and is used to chemically reduce the iron ore to iron, and as a fuel source to heat the furnaces.

Recoverable coal reserves exist in about 80 countries, but of the 7.7 billion tonnes mined in 2020, 50% was from China, with India, Indonesia, USA and Australia also mining a significant amount [4].

Coal mining accounts for approximately 2000 MtCO_2e/year. A large proportion (70%) is attributed to methane released into the atmosphere during the underground extraction. To decarbonise the coal mining industry, similar changes to those listed for the iron ore mining industry are required. However, carbon capture technology (the process of capturing any greenhouse gases before they enter the atmosphere and storing them in underground chambers, or in minerals) is needed to prevent disturbed methane from reaching the atmosphere.

Recycled steel

Steel is the most recycled material in the world with around 670 million tonnes (85%) recycled globally in 2020 [1]. The existing supply chain for recycled steel is highly developed, with scrap material having been used to produce new steel in electric arc furnaces for several decades. This scrap metal 'feedstock' generally comes from local or regional sources including manufacturing and construction waste, demolition waste, and the recycling of electrical goods.

When steel is recycled via an electric arc furnace (see section A3), some of the impurities can be hard to remove, which can impact the ability to form new thin profiled elements. For this reason, a large proportion of the world's scrap feedstock is therefore used to produce reinforcing bars and hot rolled structural steel sections.

This recycling of material can sometimes come at the expense of re-using elements. By re-using elements, the processing emissions associated with recycling steel are removed; However, they may require testing and certification procedures to be undertaken prior to re-use.

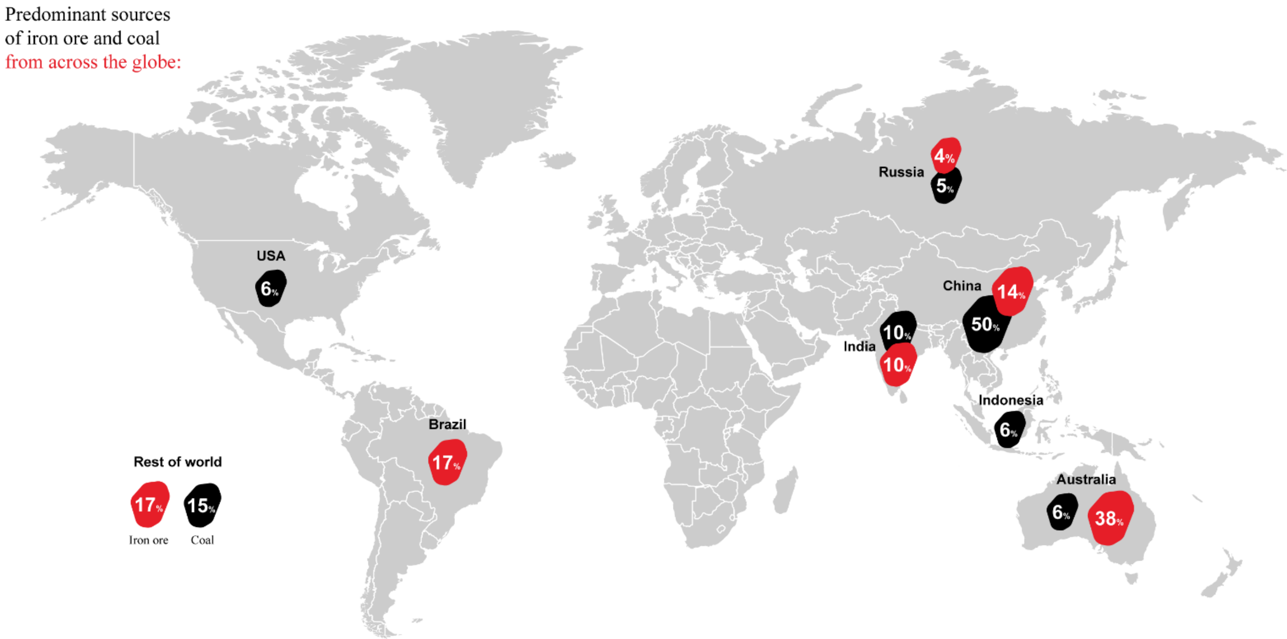


Figure 3
Main sources of the raw material required for virgin steel production [4].

A2 & A4 – Transport of materials to the mill and finished products to the site

Module A2 includes the carbon emissions attributed to the transport to the manufacturer, and module A4 includes the carbon of the transport from the manufacturer to the construction site. A2 typically accounts for 5-15% of the A1-A5 emissions, while A4 typically accounts for between 2-10% of the A1-A5 carbon of a steel product.

The constituent materials of steel can be transported significant distances and several times before they reach their 'in-use' destination. Steel mills tend to be located close to the consumer market, as opposed to the raw material extraction sites, so a mill in the UK would likely import heavy raw materials from a considerable distance away, but the steel produced would generally be for the UK or European market.

In the global market the production and demand for steel within a country is therefore relatively equal. The 5 largest steel producing countries are China (53% of global steel), India, Japan, USA and Russia (less than 6% each), who are also the 5 largest consumers of steel. China is the world's largest net exporter; However, this equates to only 5% of the steel they produce [5]. Not all mills will produce all types of steel products, which can mean products have to be moved between countries to satisfy supply and demand.

The type of transport mode used to move the raw materials, semi-finished, and finished products, will depend on the location of the mines, processing facilities, and the construction site. Typical modes are summarised as follows:

- Raw material is generally transported from the mine to the closest port by road unless rail infrastructure is in place.
- It will then be transported by sea to a steel mill, which generally are located near to ports.
- From the mill, semi-finished products will typically be transported to a stockholder, then to a steelwork fabricator, before being delivered to the construction site. This inter-country transport is typically by road unless the site location means sea or rail is more convenient or cheaper.

Figure 4
Carbon associated with the transportation of steel elements.

At early design stages the location of the steel mill and where the raw materials have come from is not usually known. Table 1 can be used to estimate the carbon associated with transporting material depending on the distance. The distance from steel mill to site is most likely to be national or regional.

Table 1
Default A4 transport carbon emissions if specific locations are unknown [6].

Location of mill compared to the site	Carbon emissions $kgCO_2e/kg$	Assumption
Local <50km	0.005	Transported 50km by road
National <300km	0.032	Transported 300km by road
Regional <1500km	0.161	Transported 1500km by road
Global >1500km	0.183	Transported mostly (10,000 km) by sea and then 200km by road

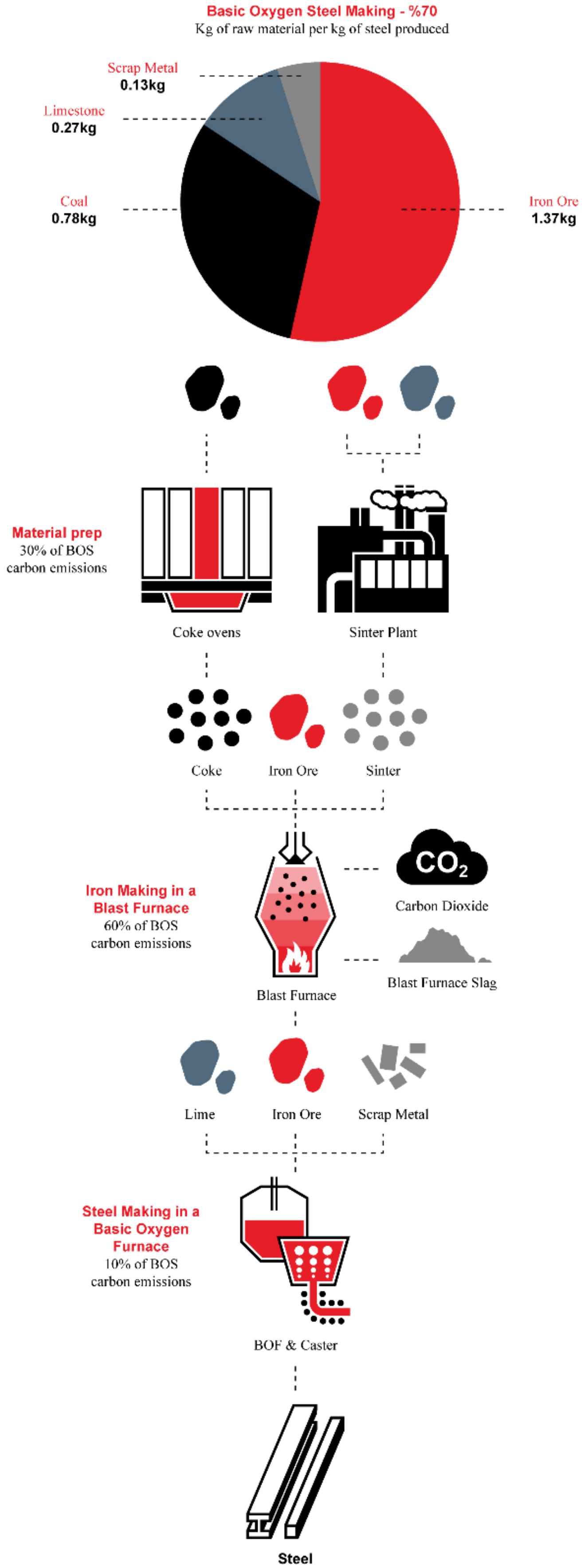
The decarbonisation of transport is on its own journey to net zero. The electrification of railways, and development of hydrogen powered heavy goods vehicles (HGVs) are two changes which will hopefully see their carbon contributions fall over the coming years. In theory, carbon emissions associated with the transportation of steel could become zero.

A3 – Manufacturing

Module A3 includes the carbon emissions of the manufacturing of the steel products. For steel this can be distinctly split into two parts: the **processing** of the raw materials into steel, and the **fabrication** of the steel into a finished construction product.

Processing

The processing part of the A3 module typically accounts for 35-55% of the A1-A5 carbon emissions of a steel product. There are currently two predominant methods by which steel is processed once the raw materials have reached the steel mills: **'basic oxygen steelmaking'** or by **'electric arc furnace'**. Some steel is also made by a process called **'direct reduction'.**



Basic Oxygen Steelmaking (BOS)

Basic Oxygen Steelmaking (BOS) is used to produce approximately 70% of global steel [1]. It's mainly used for producing steel products from virgin iron ore. The typical recycled content value of primary steel making is approximately 25%.

The BOS process involves numerous steps, including:

- Coking - converting coal to coke in a coke oven.
- Sintering - turning iron ore and limestone fines into sinter in a sintering plant.
- Iron making - coke and sinter are added to a blast furnace along with limestone pellets and additional iron ore, which is then blasted with hot air until a reaction occurs at around 2000°C. The reaction produces carbon dioxide, molten/pig iron, and slag, which is used to create ground granulated blast furnace slag (GGBS) for use in concrete.
- Steelmaking - pig iron is put into a basic oxygen furnace along with lime and a small amount of recycled steel and blown with pure oxygen at very high velocities at an approximate temperature of 1600°C. The reduction in the carbon content and other impurities occurs to leave a liquid steel which is then cast into semi-finished products often using a continuous casting process.

Approximately 80% of the carbon emissions associated with the process are from the burning of the coal/coke required to get the temperatures high enough for the processes to occur. The other 20% is carbon released from the chemical reactions that occur.

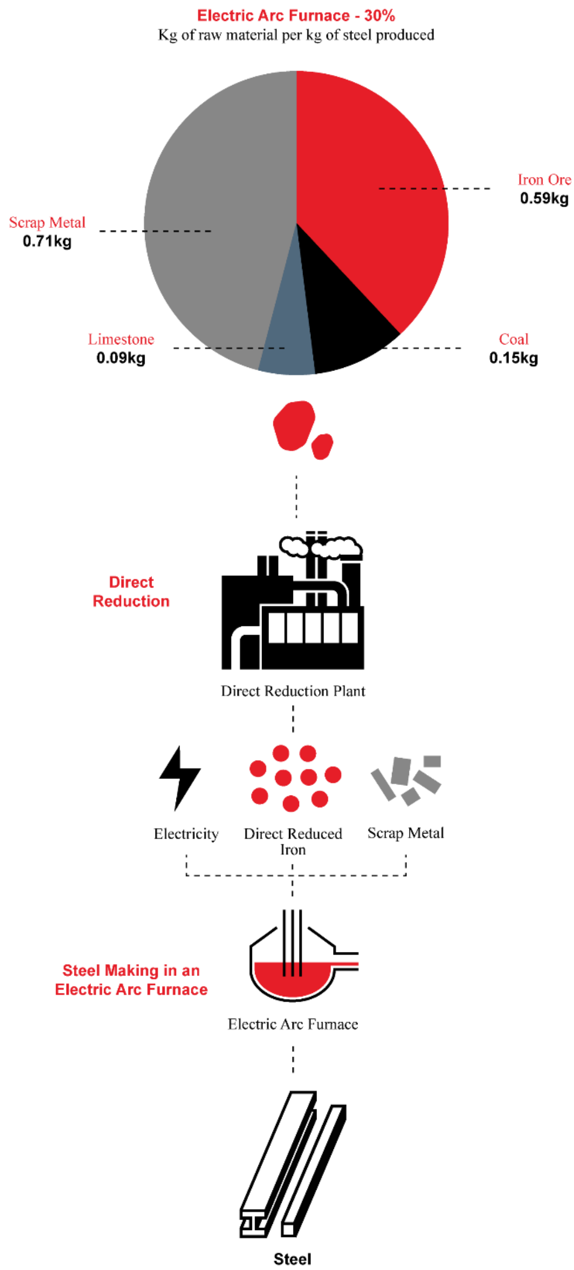
Various methods are being investigated to reduce emissions during the ironmaking process, including the recycling of the emitted gas to reheat the furnaces and generate electricity. Integrating carbon capture plants with the furnaces has also been trialled in some mills around the world. It is unlikely that the basic oxygen steelmaking process could ever be net zero.

Electric Arc Furnace (EAF)

Electric arc furnaces (EAF) are used for approximately 30% of global steel production [1]. It is predominantly used for producing steel products from recycled steel elements (approximately 90% recycled content).

The EAF steelmaking process generally involves placing the recycled scrap steel into an arc furnace. Electricity is fed into giant graphite electrodes which 'arc' to the steel. The steel is melted both by the current passed through it and the radiant heat emitted. Sometimes a small amount of pig iron or iron ore that has undergone direct reduction is also added to the furnace.

The majority of the carbon associated with the EAF process comes from the electricity required in the furnace. With the decarbonisation of the grid, the carbon emissions from EAF production will naturally decrease towards net zero. However, production of all steel using electric arc furnaces is not an option while steel demand outweighs the supply of 'end of life' steel due to the need for recycled material. Currently approximately 90% of steel is recycled so there is limited scope to increase the amount of steel produced by EAF.



Direct Reduction (DRI)

Direct reduction involves removing the oxygen from iron ore to convert it to iron without having to melt it. This is mostly done by heating to temperatures of around 1200°C in the presence of a reducing gas.

Due to the high quantities of gas used, DRI is expensive and less efficient than the other steel production methods. It is therefore not very common with less than 1% of world steel production made this way. The direct reduction furnaces that exist are generally built alongside an electric arc furnace to provide the small amount of virgin steel that is required for the EAF process.

However, in recent years companies such as Hybrit in Sweden have experimented with producing steel through direct reduction using hydrogen produced from water (green hydrogen). If the hydrogen used was produced using a net zero process, in theory the steel production could be net zero. However, this technology is still in the pilot phase of development and currently requires huge amounts of renewable energy. Any wide-scale net zero production of steel from virgin iron ore using either this method or another is not expected for at least another 20+ years.

Summary

Steel from EAF results in much lower carbon emissions than BOS steel production. However, the route to reducing carbon emissions is not as simple as converting all blast furnaces to electric arc furnaces due to the finite amount of recycled steel.

New low-carbon methods of processing steel are therefore required while demand for steel elements continues to outweigh supply of recycled material.

Direct reduction of steel using hydrogen is one such low-carbon steel production method being trialled, but still has some way to go before it could be used for wide-scale production.

Until development breakthroughs are made, our primary focus should be to reduce the quantity of materials we use.

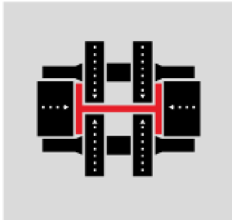
Post-processing

The secondary production, fabrication and finishing part of the A3 module typically accounts for 20-40% of the A1-A5 carbon emissions of a steel product.

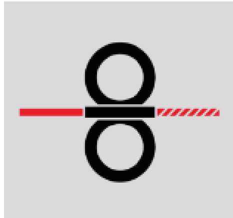
At the processing mill following primary steel production, steel is generally formed into rectangular sections using a continuous casting process, before being cut into blooms, billets and slabs. These 'semi-finished' products can sometimes be transported to another facility elsewhere to be manufactured into a 'finished' product. Depending on the product this can involve several of the following stages and processes:

Secondary production

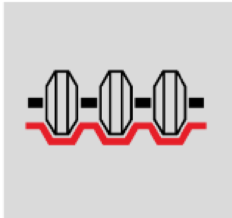
Rolling: Many steel products are rolled including steel sections, reinforcement bars and metal deck/panels. Rolling is used during both hot rolling and cold forming processes. Hot rolling typically accounts for 0.2-0.3kgCO_2e /kg of steel. It involves reheating the steel (often by electromagnetic induction or in a gas fired soaking pit) to temperatures between 400-900℃ to exceed the crystallisation point of the alloy. It is then fed through a rolling mill, before being slowly cooled.



Steel Section Rolling



Rebar Rolling



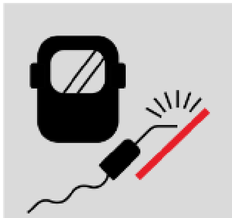
Metal Deck Rolling

Fabrication processes

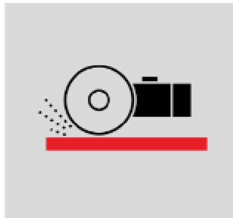
Joining: Many fabricated items require joining, which is often done by arc welding. An electric arc generates heat to melt the parent material and a filler material (supplied as a consumable electrode). When these cool they fuse together to form a joint.

Machining: Steel elements often need to be cut and drilled to create a finished product. Westok, a steel beam fabricator, do plenty of cutting and joining to create their ribbon-cut and plate beams.

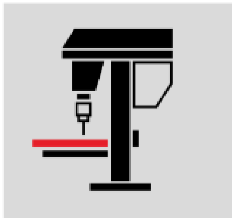
Bending: The shape of a steel element can often be altered by applying a force to bend it. Large steel sections such as structural beams can require pre-cambering. There are two main methods, 'cold-bending' (applying a force at room temperature until deformation), or 'hot-bending' where portions of the element are heated to incite differential expansion and contraction.



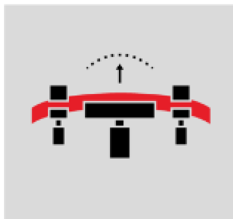
Steel Plate Welding



Steel Plate Cutting



Steel Drilling

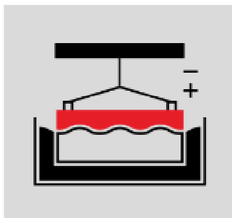


Element Bending (pre-cambering)

Coatings and finishes

Painting: Paint is the most common method of protecting steel. In fabrication shops it is usually applied using an airless spraying system where a spray gun releases atomised particles to enable a relatively controlled dispersion of paint onto the steel member.

Galvanising: To protect steel from corrosion it can be covered in a sacrificial coating. The galvanising process typically accounts for 0.1-0.3 kgCO_2e/kg of steel and involves immersing the element in a bath of molten zinc at a temperature of around 450℃.



Steel Galvanising

Each of these processes use different pieces of equipment with varying energy consumptions. Drilling uses very little energy and therefore has little carbon associated with it, whereas galvanising, and any process which involves the heating of steel to high temperatures to be able to manipulate it, is much more carbon intensive. Many processing mills and fabrication workshops are investing in decarbonising their processes. This is primarily focussed on using more efficient equipment, and more equipment powered by electricity rather than gas.

A5 – Site construction

Module A5 includes the carbon emissions of the construction related activities associated with the steel elements. This includes the emissions of the equipment used for installation, as well as the emissions associated with the waste material. A5 typically accounts for between 1-5% of the A1-A5 carbon emissions of a steel product.

Site waste

The volume of site waste, and the associated carbon emissions, varies depending on the steel element and processes used by the contractor. The amount of site waste is often linked to the amount of manufacturing waste (part of module A3). The majority of "waste" steel (scrap) is recovered. The items listed in Figure 5 show how this varies depending on steel building product:

- Large structural steel sections are usually pre-cut, and pre-drilled in the manufacturing stage, so manufacturing waste may be high, but on-site waste is very low.
- Light gauge steel used for partitions or to support building services are unlikely to be pre-cut on arrival to site, and so site waste can be higher.
- Cladding and decking sheets often require more cutting and manipulation on site, so generally lead to a higher site waste but lower manufacturing waste.
- Steel reinforcement can arrive at site pre-formed (meshes or pre-bent shapes), however bars can often still be cut on site with offcuts generally discarded. Site waste can therefore be quite high, whereas manufacturing waste can be negligible.

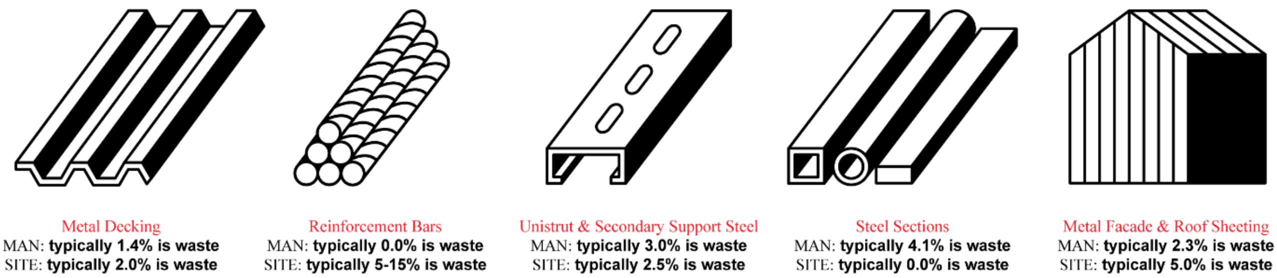


Figure 5
The typical manufacturing and site waste associated with different steel products [7].

Site emissions

Site emissions can vary depending on the installation preferences of the contractors or sub-contractors involved. A large steel structural frame will nearly always involve the use of at least one crane, which are typically powered by electricity or occasionally by a diesel generator.

Other typical equipment used during the construction of a building include access lifts, static/mobile working platforms, plasma cutters, stud weld guns and bolt fasteners. As the majority of these are powered by electricity, if the site is powered by renewable energy (or a decarbonised local electricity grid), the carbon emissions of these processes could theoretically be zero. Other equipment such as piling rigs and excavators are typically powered by diesel.

Stage B

Buildings are typically designed for a service life of 50-60 years, and bridges are typically designed for a 120-year design life. The rate of corrosion of unprotected steel over this time can vary significantly depending on the environment it is exposed to. However, steel is relatively durable, so maintenance during the life cycle can be minor if it has been specified and detailed correctly.

There are a several alternative methods to prevent or limit corrosion, such as galvanising and painting. Corrosion and fire protection by painting typically has a lifecycle much shorter than that of the element it is intended to protect, meaning regular recoating as part of maintenance works can be required. However, the carbon emissions associated with this compared to the initial A1-A5 stages are generally very low.

Stage C and D

Stage C includes the emissions associated with demolishing and removing steel components from a building, while Stage D includes emissions associated with re-using or recycling steel elements. If an element is re-used, the Stage D value can often be shown as negative on an environmental performance declaration (EPD) to account for the future use of that element in another product's lifecycle.

At the end of a building's life, it is usually demolished with the constituent materials removed and re-used, recycled or sent to landfill depending on the element. The carbon associated with the extraction and transportation of the steel can vary depending on the product. For example, structural steel sections or light gauge steel can generally be un-bolted with relative ease, whereas reinforcement will require a concrete crusher to extract.

For some years, due to the relatively high cost of steel, there has been a developed steel recycling industry. Across the world approximately 80% of all steel is either recycled or reused, and for steel elements used in the construction industry this is even higher at 91%. This recycled material is predominantly re-formed for use in new products using the electric arc furnace process described earlier in this guide.

Figure 6 outlines the approximate proportions of steel which is either reused, recycled, and put in landfill for different products:

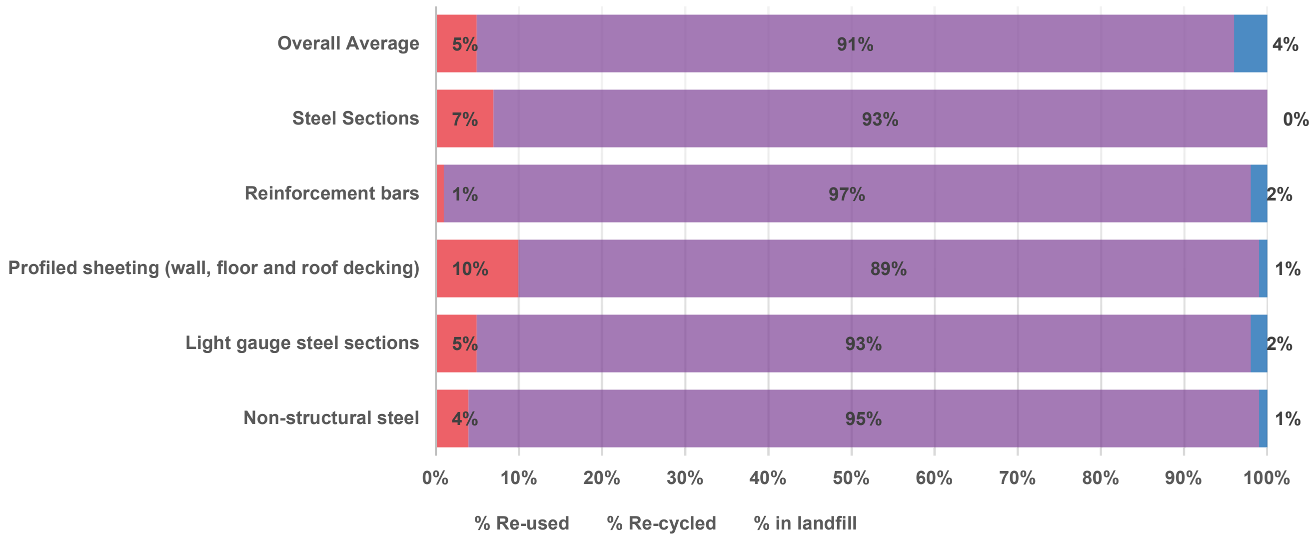


Figure 6
Percentage of steel products reused, recycled, and put in landfill [8].

Route to Net Zero

The steel industry is changing, and there is great opportunity to decarbonise the way we manufacture, procure, and use steel. For example, electrification of vehicles, use of hydrogen powered excavation equipment, and carbon capture technology enables us to reduce the carbon intensity of the extracted raw materials. In steel production, new low-carbon methods of processing steel are being trialled but reducing coal use is key. Alternative fuel sources such as green hydrogen in direct reduction is one possibility. Electrification of fabrication and construction equipment, plus the increase of off-site fabrication to reduce waste, can also help on the route to net zero. However, the easiest and most obvious way to reduce carbon emissions, like any other material, is simply to use less of it.

As designers we have direct impact on:

The correct use of steel on projects: Are there lower carbon alternative materials that could be considered?

The weight and quantity of steel elements: If we do use steel, design efficiently and optimise to minimise the number of elements and their sizes. Heavier material also burns more fuel during travel.

Ensure structures are designed with a high material efficiency: Use higher strength grades where this is technically appropriate.

Engage with contractors and their supply chains: Ensuring design intent and specifications are followed is crucial. Whilst we will have limited impact on the way steel elements used on our projects are transported, we may be able to influence which mill/fabricator they come from and build knowledge through mill specific EPDs.

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[8] National Federation of Demolition Contractors, "Eurofer Survey," 2013.

Further Reading

Internal Arup documents

2022 NST 03 – Understanding Embodied Carbon in Steel - Australia

2010 NST 06 – Sustainability Clauses for the Specification of Steel

Arup Steel Specifications

External documents:

https://www.theclimategroup.org/steelzero

https://www.responsiblesteel.org/about/

https://www.istructe.org/resources/guidance/making-your-steel-specification-more-sustainable/

https://www.istructe.org/journal/volumes/volume-99-(2021)/issue-4/developing-a-low-carbon-circular-economy-for-steel/

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