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THE ROLE OF BIOMASS IN THE PRODUCTION OF IRON, STEEL AND CEMENT

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INTERNATIONAL CENTRE FOR
SUSTAINABLE CARBON

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PREFACE

This report has been produced by the International Centre for Sustainable Carbon (ICSC) and is based on a survey and analysis of published literature and on information gathered in discussions with interested organisations and individuals. Their assistance is gratefully acknowledged. It should be understood that the views expressed in this report are our own and are not necessarily shared by those who supplied the information, nor by our member organisations.

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ABSTRACT

The industrial sector contributes more than 30% of global CO₂ emissions and efforts to decrease these emissions have stalled. Ambitious CO₂ reduction strategies in some regions, for example, the EU, are being offset by increased production in others, particularly Asia-Pacific, which have processes with higher carbon intensities and faster-growing economies. Many features can contribute to decreasing greenhouse gas (GHG) emissions from industry, such as electrification, use of renewable hydrogen, efficiency improvements, retrofitting of carbon capture and storage (CCS), or fundamental changes in manufacturing approaches. This report examines the role that sustainable biomass resources and wastes could play in helping to decarbonise the iron and steel (I&S) and cement sectors, which, combined, were responsible for 12% of global CO₂ emissions in 2021. This includes biomass or biomass products supplying or supplementing process heat currently provided by coal, and in the case of I&S manufacturing, biomass products acting as a reducing agent and supplementing or substituting for coal or coke. The report considers the research, development and deployment (RD&D) status of the various opportunities for this substitution in I&S manufacturing with some case studies, including charcoal use in the smaller blast furnaces in Brazil and the development of ‘biocoal’ injection by AcelorMittal at their plant in Torero, Belgium. Charcoal is not a perfect drop-in fuel to displace coal and coke and much of the research direction concerns maximising substitution rates without compromising on performance.

The report also examines the important role that biogenic sources can have in displacing coal use in cement manufacturing. This is already commercial, and uses of many alternative fuels, including biogenic wastes are steadily increasing, as are rates of substitution. A case study of cement production by Schwenk in Germany indicates how a substitution rate of >94% alternative fuels can be achieved. Some of the operational strategies and challenges of higher substitution rates are also presented.

The effectiveness and level of alternative fuel use are influenced by regional factors, such as policies and regulations that support effective management of waste streams. Some of the barriers and challenges facing industrial decarbonisation, both technical, environmental, social, and ethical, are summarised in the report. Socio-technoeconomic modelling and life cycle analysis are critical tools for assessing the benefits and risks of using biomass. The biomass supply chain itself must comply with sustainability criteria such that carbon savings are maximised, and undesirable ecological or social impacts are minimised. Policy mechanisms will be vital for accelerating the decarbonisation of hard-to-abate industries and will include direct funding, incentivising demand for more environmentally benign products, and border adjustment tariffs to prevent carbon leakage. Technology roadmaps for decarbonising both heavy industries include major roles for CCUS, renewable hydrogen and electrification and a smaller, but important role for biomass.

ACRONYMS AND ABBREVIATIONS

BAT	best available technologies
BAU	business as usual
BF	blast furnace
BOF	basic oxygen furnace
CBAM	Carbon Border Adjustment Mechanism
CCS	carbon capture and storage
CCUS	carbon capture utilisation and storage
CRI	coke reactivity index
CSIRO	Commonwealth Scientific and Industrial Research Organisation, Australia
CSR	coke strength after reaction
CV	calorific value
DOE	Department of Energy, USA
DR	direct reduction
DRI	directly reduced iron
EAF	electric arc furnace
ECRA	European Cement Research Academy
ETS	Emissions Trading Scheme
FC	fixed carbon
GCCA	Global Concrete and Cement Association
GHG	greenhouse gas
GPP	green public procurement programmes
HTC	hydrothermal carbonisation
I&S	iron and steel
ICSC	International Centre for Sustainable Carbon
IEA	International Energy Agency
LCFFES	low carbon fuels, feedstocks and energy sources
LCV	lower calorific value
LOI	loss on ignition
NZE	net zero emissions
NZS	net zero scenario
PCDD/F	polychlorinated dioxins and furans
PCI	pulverised coal injection
SR	smelting reduction
SRF	smelting reduction furnace
SRI	smelting reduced iron
TOC	total organic carbon
TRL	technology readiness level
VM	volatile matter
VOC	volatile organic compounds
WSA	World Steel Association

Note: all monetary values are in United States dollars (\$) unless otherwise stated.

UNITS

°C	degrees centigrade
cm ²	square centimetre
ddpm	dial divisions per minute
GJ	gigajoules
Gt	gigatonne
kg	kilogramme
kha	kilohectare
mm	millimetre
MPa	megapascal
Ms	millisecond
Mt	million tonne
MtCO ₂	million tonnes of carbon dioxide
MW	megawatt
nm	nanometer
tCO ₂	tonnes of carbon dioxide
tcs	tonnes crude steel
tHM	tonnes of hot metal
t	tonne (1 tonne = 1.10231 imperial ton)
wt%	weight per cent
/d	per day
/y	per year

CHEMICALS

CO	carbon
CO ₂	carbon dioxide
K ₂ O	potassium oxide
N	nitrogen
Na ₂ O	sodium oxide
S	sulphur

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EXECUTIVE SUMMARY

Over 30% of global CO₂ emissions are from industry and are increasing at 1% per year. The main drivers for the increase in emissions are population and per capita GDP growth. These are partially offset by improvements in energy efficiency and carbon-emission intensities of industrial processes. Greenhouse gas (GHG) emissions from industry need to fall by 2% per year to the end of the 2020s and then by nearly 9% per year in the 2030s to meet net zero emission (NZE) trajectories. Two of the most energy-intensive, hard-to-abate industries are the manufacturing of iron and steel (I&S), and cement. Combined they are responsible for around 12% of global CO₂ emissions. Both industries rely heavily on coal and are the second major user of coal after the power sector.

There are various ways to reduce their emissions. This report focuses on the role that sustainable biomass resources and biogenic wastes could play. This includes biomass or biomass products supplying or supplementing process heat currently provided by coal. In the manufacture of I&S, biomass products can act as a reducing agent and supplement or substitute for coal or coke.

IRON AND STEEL INDUSTRY

The I&S industry is the second-highest industrial CO₂ emitter after electricity production, producing approximately 6% (3 Gt) of global emissions in 2021. China dominates production, followed by Europe, India, Japan, and Russia. The main technologies are the integrated blast furnace – basic oxygen furnace (BF-BOF) and the direct reduced iron – electric arc furnace (DRI-EAF). The nature and age of the fleet in each region impacts the timeline and strategy for decarbonisation. One of the various ways to reduce CO₂ emissions is fuel switching to biomass-derived alternatives. This approach can be implemented rapidly, but is dependent on a secure, sustainable, economic supply chain; Brazil, India, USA and China already have significant charcoal supply chains which could deliver a fraction of their I&S industries' fuel needs.

Current developments in research methods enable modelling on a region or even plant-by-plant basis. This can synthesise and model data including age and technology of the fleet, local supply chains, and local economic factors, to help inform decision-making by predicting carbon savings and cost.

The main sources of carbon are coke and coal (pulverised coal injection, PCI) in the BF, coke breeze in the sinter plant, added or injected coal and coke in the EAF, and coal gasification in DRI. There is a fundamental difference in the carbon science of coke compared to biomass-derived chars, such as charcoal, which affects the suitability of biomass-derived chars for I&S operations. Biomass, particularly charcoal, can contribute at different levels in each type of plant. For example, blending with coal in coke production (limited to 2–10%), substituting for coke breeze in the sinter plant (up to 40%), injecting in pulverised form in the tuyeres of the BF (up to 100% in theory, but less in practice), and displacing some coal or coke in the EAF (up to 60%). The estimated levels of substitution and the associated Technology Readiness Levels (TRLs) are depicted in Figure 1. A key R&D challenge is

understanding the fundamental changes in chemistry and physics of coal/coke substitution by biomass products, such that blending can be used to optimise substitution rates while maintaining satisfactory performance.

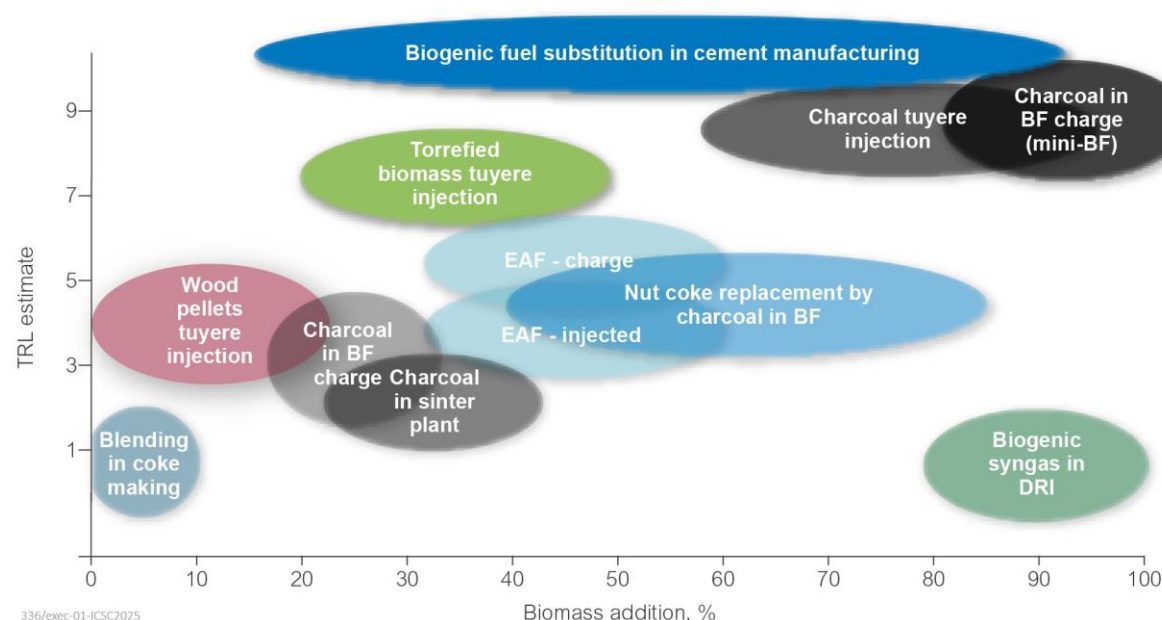


Figure 1 Estimated TRLs of different strategies for biomass addition in I&S manufacturing, and approximate substitution rates achieved (authors' work)

The industry has been slow to implement biomass products as there is a perception that they are expensive, with unreliable supply chains and, generally, do not match coke in performance. Certainly, charcoal cannot meet coke for its mechanical strength and low reactivity which means substitution in very large BF's is limited. However, in Brazil, which has smaller BF's, charcoal has displaced coke. Some of the key issues in utilising biomass and charcoal in I&S manufacturing include economics versus sustainability credentials. Local sourcing of well-managed forest supplies or waste residues helps to mitigate some of the concerns. Carbon taxes and regulatory standards will be required as effective incentives for wider adoption.

CEMENT PRODUCTION

Cement production is the third largest CO₂ emitting industry globally and is responsible for 5–8% of CO₂ emissions. The two main sources of direct CO₂ emissions in cement manufacture are CO₂ from calcining, which is inherent in the process and produces 55% of total CO₂ emissions from the sector, and CO₂ from fuel combustion to produce the necessary process heat, responsible for 38% of the total CO₂ emissions. Various carbon emission reduction measures have been used, including the use of alternative fuels with lower life-cycle CO₂ emissions. Partial substitution of fossil fuels with a variety of waste fuels or biomass reached 53% in the EU in 2021, and a global average of 23% in 2022. In theory, a 100% substitution rate is possible with modern dry kilns. An example is Schwenk's Allmendingen cement plant in Germany, where more than 94% of coal input has been substituted by alternative fuels, including a 75–85% biogenic share. Thus, the displacement of coal by alternative biogenic feedstocks

in the cement sector is commercial and practiced worldwide, at different substitution levels (see Figure 1). The GCCA roadmap anticipates the global average substitution rate of alternative fuels to reach 43% by 2050 through utilising biogenic feedstocks. R&D priorities include understanding and minimising the impact of impurities from biogenic fuels on cement, the role of thermal pretreatment of biogenic sources, and optimising firing strategies in different parts of the plant to maximise fuel substitution rates. The effectiveness and uptake of alternative fuel use is influenced by regional factors, such as availability, economics, and policies and regulations that support effective management of waste streams. Policy measures or incentives that promote the use of alternative fuels over fossil fuels would support this decarbonisation lever.

CONCLUSIONS

Early retrofitting of all carbon-reducing measures in energy-intensive industries is key to achieving maximum emissions reduction but both I&S and cement sectors will require significant initial investment to achieve this goal. Any improvement in efficiency will result in financial savings for the industry, but decarbonisation projects require large, upfront capital costs. Carbon taxes and regulatory standards can be an effective incentive, and border adjustment mechanisms can reduce the risks of leakage. There are wider environmental and societal co-benefits from improved efficiency and decarbonisation measures which can include improvement in air quality, reduction in water use, minimisation of waste, extending plant lifetime and maintaining and expanding workforce employment opportunities.

1 INTRODUCTION

The world's energy needs are growing, and to address the challenge of climate change, emissions across all sectors must be reduced. In the electricity sector, this is being tackled in many countries with a shift to renewables and low emission technologies combined with energy storage and modernisation of the power grid. Decarbonisation of the industrial sector is at a much earlier stage of commercial deployment. Industrial emissions make up more than 30% of global CO₂ emissions (IEA Bioenergy, 2021). Due mainly to process efficiency improvements, carbon emission intensities have decreased considerably in the sector since 1995. Nevertheless, total annual emissions are growing due to increased production, with high carbon intensities in emerging countries as they undergo rapid urbanisation and infrastructure development. As a result, global progress on industrial decarbonisation has stagnated (Wang and others, 2021; Barbhuiya and others, 2024a,b).

The International Energy Agency (IEA) estimates that emissions from the sector need to decrease by more than 90% over the next 30 years to limit global warming to 1.5°C above pre-industrial levels. Energy-intensive industries include the manufacture of iron and steel (I&S), and cement, which are responsible for around 6 Gt/y, more than 12% of global CO₂ emissions (Fan and Friedmann; 2021; Plaza and others, 2020). These two industries rely heavily on coal and are the second major user of coal after the power sector – with an estimated 1.1 Gt/y of metallurgical coal (coking coal) used in 2022 for steel production alone (IEA, 2023a). Achieving net zero requires a transition to decreased reliance on coal. Demand for I&S and cement production is growing, but both are difficult to abate; they are, consequently, not on track to achieve their decarbonisation targets. Drastic decarbonisation from these sectors requires a major research and development (R&D) effort combined with strategies and policies to promote their deployment (RD&D) while meeting UN Sustainable Development Goals (SDGs).

There is a disparity in carbon intensities of I&S and cement production in emerging versus developed economies which increases the risk of carbon leakage. In this context, carbon leakage happens where there are regional differences in climate policies. Ambitious carbon reduction policies raise the cost of production, and this leads to the possibility of the sector being undercut by imports that are produced with higher carbon intensities. Counter measure policies include the Carbon Border Adjustment Mechanism (CBAM) in the European Union (EU) (and the UK from 2027) which requires a consumer to document (and ultimately pay for) the embedded greenhouse gases (GHGs) in energy-intensive imports (EU, 2023a,b). The nature and speed of implementation of emerging technologies for decarbonisation depend not just on cost but also on geographical location, and the opportunities this presents, as well as the age and nature of the existing fleet.

While there are many features that can contribute to decreasing GHG emissions from industry, such as electrification, use of renewable hydrogen, efficiency improvements, retrofitting of carbon capture and storage (CCS), or fundamental changes in manufacturing approaches, this report focuses on the

role that sustainable biomass resources and wastes could play. This includes biomass or biomass products supplying or supplementing process heat currently provided by coal, and in the case of I&S manufacturing, biomass products acting as a reducing agent and supplementing or substituting for coal or coke. Biomass or biogenic materials are projected to have a modest but important role in the immediate to near term for retrofitting to existing plant as supplements to coal. The IEA has modelled the reduction in emissions required (over and above the policy in the Paris Agreement) in their Sustainable Development Scenario (SDS), which is consistent with reaching global net zero CO₂ for the whole energy system by 2070 (IEA, 2020). For the I&S sector, the SDS includes sustainable biomass increasing its share in the energy mix from less than 1% to 5% and contributing 6 % of the cumulative emission reduction by 2050 (IEA, 2020). In the IEA scenario, Brazil and China will be the largest users of this decarbonisation strategy. Similarly, alternative fuels, including waste and biomass resources could contribute to a 12% reduction in the cumulative CO₂ emissions from cement manufacturing by 2050 (IEA, 2018). Carbon dioxide is not the only pollutant of concern from heavy industry. Emissions of nitrogen oxides (NO_x), sulphur oxides (SO_x), particulates, dioxins and furans all add to the environmental and GHG burden. Some of these emission levels are improved through biomass use, but a discussion of this topic is outside the scope of this report.

This report explores the challenges, barriers and possible solutions of substituting coal and coke with biomass (or waste) products in I&S manufacture, and cement production. Current global emissions from these two heavy industries and the net zero emission targets for their future development are highlighted, together with their RD&D challenges and priorities. The pathway options for decarbonising cement manufacturing are discussed, with an emphasis on the status and future of using alternative fuels, including biogenic resources. Opportunities for substituting coal and coke in I&S manufacturing with biomass and biomass-derived products, such as charcoal, are explored focusing on the fundamental limitations for this action. The difference in chemical structure dictates both the quantity and nature of the carbons produced from biomass so optimisation of biogenic carbon products for I&S manufacturing is an on-going research challenge.

Bioenergy comes with a host of challenges, both ecological and economic. Charcoal is being produced far from its point of use in some cases, often using basic technology. Poor practices exist (Zemke and others, 2020), which have resulted in deforestation and negative social and environmental impacts. Life cycle analysis is critical for ensuring projects implement best available technologies (BAT) and deliver actual carbon reductions and co-benefits of sustainability, alleviation of poverty, decent working practices and other SDGs. Financing and policy options will be required to implement low-carbon interventions and overcome the economic and organisational barriers, as well as consumer behaviour in product usage and waste recycling.

FUEL SWITCHING TO BIOMASS AND BIOGENIC RESOURCES IS ONE OF A SUITE OF TECHNOLOGY OPTIONS FOR DECARBONISING CEMENT AND IRON AND STEEL MANUFACTURE. ITS PROJECTED CONTRIBUTION TO REDUCE CUMULATIVE EMISSIONS BY 2050 IS 6% IN IRON AND STEEL AND 12% IN CEMENT MANUFACTURING

2 CO₂ EMISSIONS FROM HEAVY INDUSTRY AND ROADMAPS FOR THEIR REDUCTION

2.1 INTRODUCTION

This Chapter introduces global iron and steel (I&S) manufacturing and cement production. For I&S production, the dominant technologies and carbon intensities are summarised, followed by a consideration of the policies and strategies for decarbonisation of key producers, China, India, EU, Japan and the USA. Similarly, for cement manufacturing, global CO₂ reduction pathways from the Global Cement and Concrete Association (GCCA) are outlined, before a more detailed look at the policies and strategies of key producers, China, India, the EU and the USA. Where appropriate, the role of biomass or alternative carbon-based fuels is highlighted, and this topic is revisited in Chapters 3–6.

2.1.1 Global coal use

The Paris Agreement was adopted in 2015, promoting a global effort to reduce GHG emissions and keep the rise in temperature to 1.5°C above pre-industrial levels. As of 2024, the United Nations' (UN) Convention on Climate Change (UN, 2024) had been ratified by 198 countries. This has led to each member state developing Nationally Determined Contributions (NDCs) and the associated strategies and policies to attain a trajectory for keeping global CO₂ levels at 430–480 ppm and so limit global warming. Coal is the most CO₂-intensive of the fossil fuels, and many countries are phasing out its use in the power sector. Nevertheless, global demand is increasing and reached 8.42 Gt in 2022. The countries with the highest growth in use are China and India (4.6% and 9% annual increase in demand in 2022, respectively) (IEA, 2023b). Coal demand in the power sector dominates the market, and it provides 46–49% of thermal energy. An estimated 22% of overall thermal coal and lignite use, 1.64 Gt in 2022, is for the industrial sector (IEA, Coal 2023b). Metallurgical (met) coal includes coking coal and coal for pulverised coal injection (PCI) in the blast furnace (BF). It is a primary reagent in steelmaking where it acts as both a reductant and a source of heat; global consumption was 1.1 Gt in 2022. The cement industry is also a large user of coal (Marmier, 2023; GCCA GNR, 2024). Combustion of fuels was responsible for about 38% of the total 2.5 GtCO₂ emissions from this sector in 2023 (WEF, 2022). Neither the I&S nor the cement industry are currently on track for the required reduction in emissions to align with the IEA's net zero emissions (NZE) scenario by 2050. The trend towards alternative fuels is discussed in Chapter 3,

2.1.2 Global CO₂ emissions from heavy industry

Total global CO₂ emissions in 2021 were 50.1 GtCO₂, approximately 30% of which was from combustion in heavy industry and other industrial processes. Heavy industry refers to the steel, cement and chemical industries, which depend on fossil fuels as their main fuel due to their unique chemical formation. Their performance in combustion to produce the intense energy required is

attractive for heavy industry and is responsible for approximately 60% of industrial emissions (WEF, 2022). Figure 1 shows the CO₂ emissions from different sectors for 2021, indicating that cement, steel and chemicals are responsible for 17% of the total.

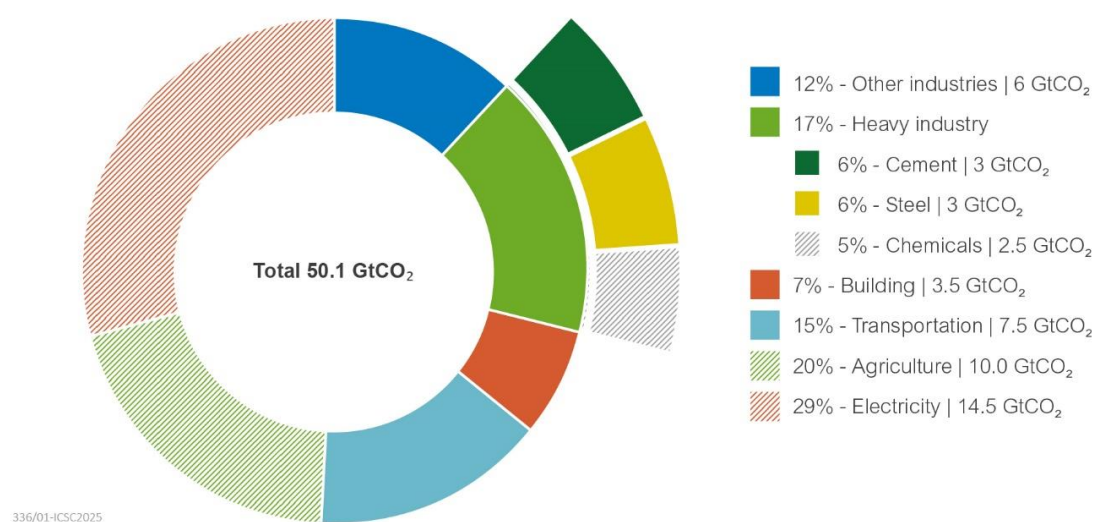


Figure 1 Total global CO₂ emissions by sector in 2021 (adapted from WEF, 2022)

Decarbonising heavy industry represents a huge global challenge since it underpins the fabric of modern society. Nevertheless, countries with NZE targets are producing or have produced, roadmaps on how to achieve this goal.

2.2 IRON AND STEEL INDUSTRY

Steel plays an important role in economies and its competitive manufacture is challenging to decarbonise. It is ubiquitous in buildings, and the infrastructure for energy, transport and other services, and has no appropriate substitute. The I&S sector directly accounts for 2.6 GtCO₂/y and relies on coal for approximately 75% of its energy demand (IEA, 2020). In addition, the sector is projected to increase by over a third by 2050 (IEA, 2020). Table 1 reports the countries with the highest CO₂ emissions for I&S manufacturing, with their current emissions and targets for 2050. Alternative fuels and technologies are a key requirement to decarbonise the sector.

TABLE 1 MATERIAL PRODUCTION AND CO ₂ EMISSIONS FROM HEAVY INDUSTRY BY COUNTRY (HASANBEIGI AND OTHERS, 2023; GARG AND OTHERS, 2023; WSA, 2024; TRANSITION ASIA, 2023; US DOE, 2022)					
Industry type	Country	CO ₂ emissions produced, MtCO ₂ /y	Emission reduction targets for 2050	Global production in 2023, MtCO ₂ /y	Largest producing companies in 2023, MtCO ₂
Iron and steel making	China	2103	BAU Scenario – 968 MtCO ₂ /y Net Zero Scenario - 78 MtCO ₂ /y	1019.1	China Baowu Group (130.77) ArcelorMittal (68.52) Ansteel Group (55.89)
	India	240–250	Net zero target carbon intensity reduction from 2.6 tCO ₂ /tcs to 1.5 tCO ₂ /tcs	140.8	Tata Steel Group (29.50) JSW Steel Ltd (25.91)
	EU	190	Net zero target to reduce CO ₂ emissions by 55% by 2030 and reach neutrality by 2050	126.3	Thyssenkrupp in Germany (10.35) SSAB in Sweden (7.78)
	Japan	134	Target to reduce emissions by 48% by 2030 compared to 2013 and reach neutrality in 2050	87	Nippon Steel (43.66) JFE Corporation (25.09)
	USA	86	BAU Scenario – 54 MtCO ₂ /y Advanced Scenario - 17 MtCO ₂ /y Net Zero Scenario – almost zero emissions	81.4	Nucor Corporation (21.2) Cleaveland Cliffs (17.27) United States Steel Corporation (15.75)
BAU – business as usual; tcs – tonnes of crude steel					

Each technology has its own carbon intensity. In 2023, approximately 71% of global steel was produced using the blast furnace-basic oxygen furnace (BF-BOF) with a CO₂ intensity of 2.33 tCO₂/t of crude steel (tCO₂/tcs). 29% was produced using the electric arc furnace (EAF method), either via direct reduced iron – electric arc furnace (DRI-EAF) or via scrap (recycling) EAF methods with CO₂ intensities of 1.37 tCO₂/tcs and 0.68 tCO₂/tcs respectively. Table 2 summarises the production of I&S from different routes for the top five steel-producing countries. Generally, the BF-BOF route dominates, but the EAF process is particularly important in India and the USA (WSA, 2024).

TABLE 2 IRON AND STEEL PRODUCTION USING DIFFERENT ROUTES FOR THE TOP FIVE STEEL-PRODUCING COUNTRIES IN 2023 (WSA 2024)

Country	Iron production route, Mt		Crude steel production route, Mt	
	Pig iron, Mt (BF)	Directly reduced iron (DRI)	Basic oxygen furnace (BOF)	Electric arc furnace (EAF)
China	871.0	Not available	918.2 (90.1%)	100.9 (9.9%)
India	86.3	49.6	61.4 (43.6%)	79.4 (56.4%)
EU	64.1	0.3	69.7 (55.2%)	56.6 (44.8%)
Japan	63.0	Not available	64.2 (73.8%)	22.8 (26.2%)
USA	20.6	5.2	25.8 (31.7%)	55.6 (68.3%)

The IEA has produced a roadmap towards more sustainable steelmaking (IEA, 2020). The report explores technologies and strategies that would be compatible with a 2050 Net Zero Emissions (NZE) policy for the sector. Such policies need to consider the age and nature of existing technologies and infrastructure, as the typical lifetime of a BF fleet is around 40 years. Two main contrasting future scenarios were compared by the IEA – the Stated Policies Scenario (STEPS, shaped by existing and announced policies under the Paris Agreement), and the Sustainable Development Scenario (SDS, which stipulates a more sustainable end point to reach the main goal of the UN’s sustainable development agenda). The SDS is consistent with reaching global NZE for the whole energy system by 2070 and requires a rapid reduction in emissions. In both scenarios, the I&S sector will still be using coal in 2050 because of its role as a reducing agent.

In the IEA’s SDS, CO₂ emissions from the I&S industry are reduced by 50% by 2050. A combination of material efficiency, low emission technologies and carbon removal technologies would be required to reach this goal (see Figure 2). In the short term, to 2030, most CO₂ emission reduction comes from material efficiency at 40%, mainly via demand reduction and technology performance. This includes using secondary production methods like DRI-EAF and increasing the amount of scrap in the raw material mix. Process optimisation, including waste heat recovery, would help achieve a 21% reduction in CO₂ emissions. Switching to low emission fuels including hydrogen and bioenergy (19%), electrification (4%), and the use of CCUS (16%) could help to achieve the long-term decarbonisation goal by 2050 but these technologies are not fully developed yet (IEA, 2022a). Bioenergy is projected to give 6% of cumulative emission reductions by 2050 in the SDS.

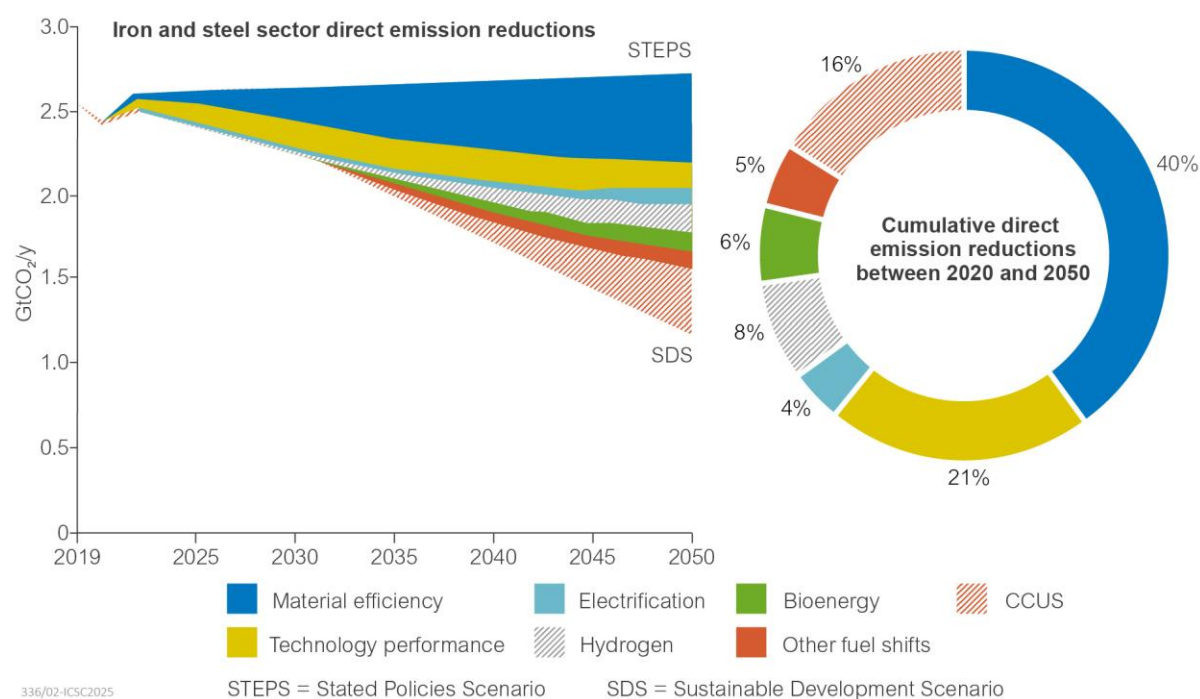


Figure 2 Decarbonisation pathways for the steel industry to meet the global NZE targets following the IEA's SDS (adapted from IEA, 2022a)

The different pathways explored by the IEA are scenarios to assist countries in their policy development. However, the decarbonisation routes for each country vary depending on the availability of the infrastructure and current and future assets required for each pathway. The following sections summarise some of the announced strategies and policy pathways for the most important I&S producers.

2.2.1 China

China produces more than 50% of the world's steel. The main production method is the carbon-intensive BF-BOF. In 2022, China used 718 Mt of met coal, 66% of global met coal consumption, for its steel production. The majority, 87%, of this was for coke used in the top charge in the BF, whilst 13% was used for PCI to provide heat in the BF (IEA, 2023b). In 2022, coal and coke made up 81% of the fuel mix used in China's steel industry; to meet their NZS this needs to fall by 70% by 2050 (IEA, 2023a).

China aims to achieve peak CO₂ emissions before 2030 and carbon neutrality by 2060, and the Chinese steel industry is on track for the 2030 target, largely due to an expected peak in the domestic demand for steel (IEA, 2021a, 2023b). Nevertheless, the I&S industry has an enormous challenge ahead and needs to reduce emissions from 2100 MtCO₂/y to 78 MtCO₂/y by 2050. China's roadmap for NZE outlines five key steps in decarbonising the I&S sector: reduce demand for steel; energy efficiency improvements; fuel switching; electrification and grid decarbonisation; a technology shift to low carbon emission steel making, and CCUS. Fuel switching involves a change in the mix of fuels used,

including a role for biomass, illustrated in Figure 3 (Hasanbeigi and others, 2023). Figure 4 shows the contribution to CO₂ emission reduction for each step of the NZS (Hasanbeigi and others, 2023).

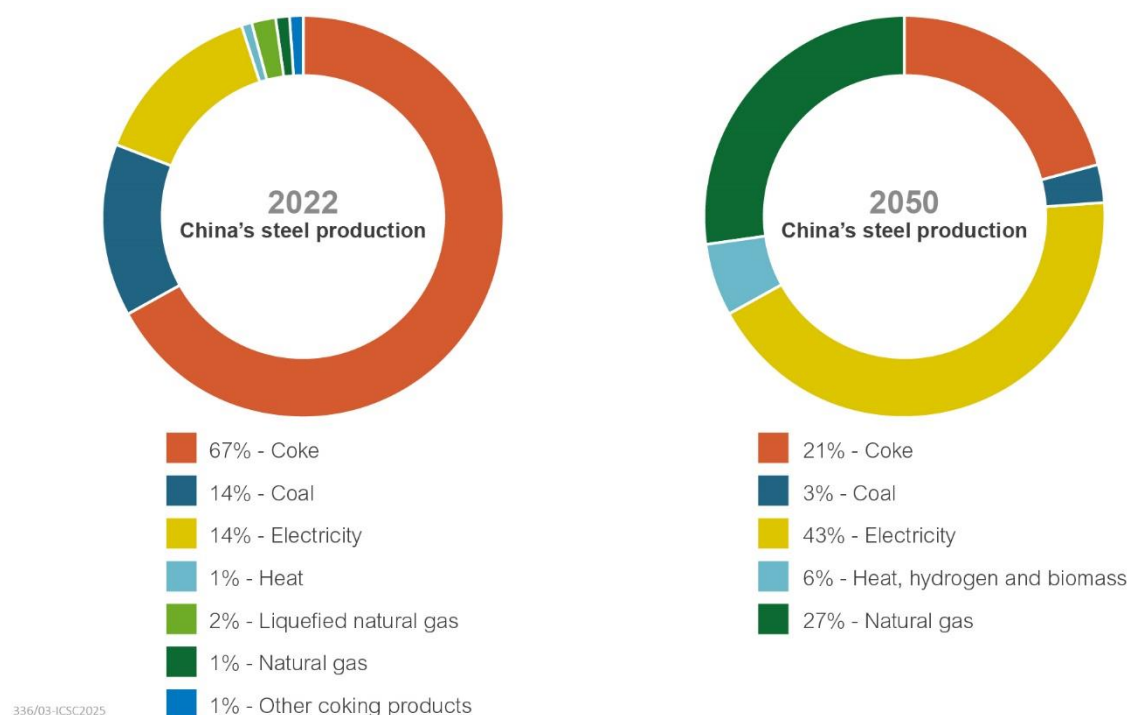


Figure 3 Fuel mix used in China's steel industry in 2022 and 2050 (adapted from Hasanbeigi and others, 2023)

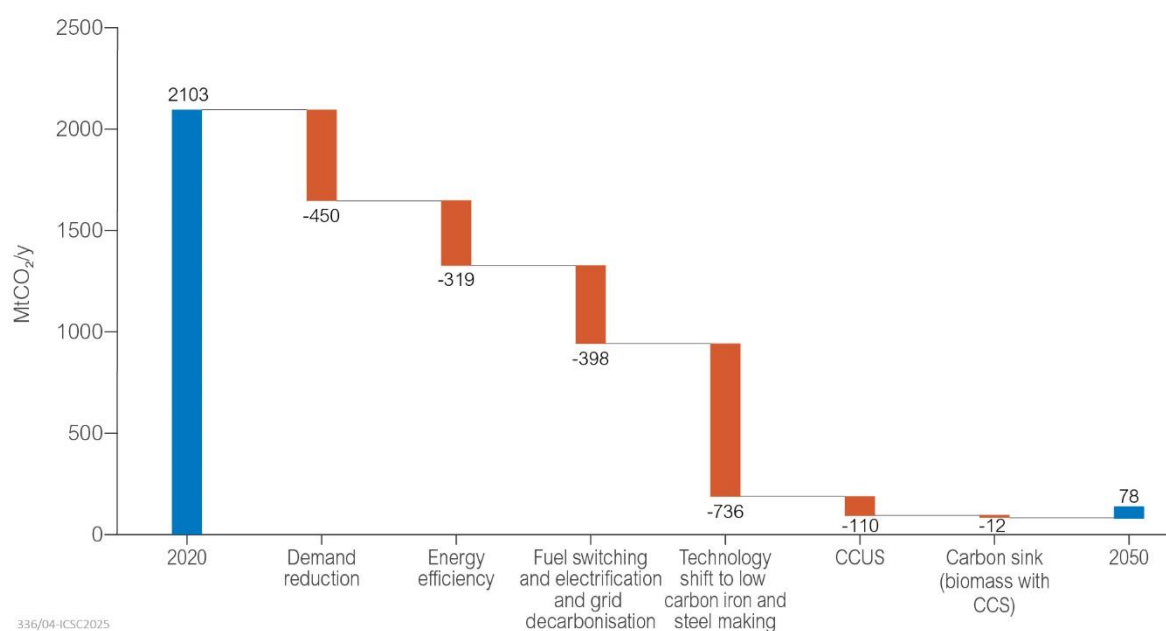


Figure 4 CO₂ reduction for China's NZE scenario pathway to decarbonise the steel industry (adapted from Hasanbeigi and others, 2023)

Reducing demand for steel can save approximately 450 MtCO₂/y in the NZS. Demand for steel in China's buildings and infrastructure is predicted to fall to 600–750 Mt by 2050. This is because most of the country's infrastructure is in place and there is a surplus of houses due to the declining

population (IEA, 2020; Bataille and others, 2021; Chen and others, 2021). Steel demand in China could also decrease by optimising its use, by making lighter and longer lifetime products, using alternative materials for building, and producing material that can be directly recycled instead of having to be melted (Zhou and others, 2019).

China can further reduce its CO₂ emissions by 319 MtCO₂/y by increasing the energy efficiency of steel production. Available technologies include Top Pressure Recovery Turbine Plants (TRT) and Coke Dry Quenching (CDQ) (Gangadharan and others, 2023; IISF 2022a,b). Various fuel-switching measures can help reduce emissions by 396 MtCO₂/y. These include switching from coal and coke to less carbon-intensive fuels, including natural gas, biomass, hydrogen and others, increasing the amount of renewable electricity on the grid and electrifying reheat furnaces, and increasing the production of steel from EAFs. This fuel-switching strategy is estimated to provide an 18% reduction in CO₂ emissions by 2050.

The biggest contributor to the carbon reduction in the NZS would be a shift in technology which could reduce emissions by 736 MtCO₂/y. Figure 5 shows the contribution of each type of steel making technology in China for 2020 and what is needed for the NZS in 2050. In 2020, 90% of China's steel was produced using the BF-BOF method which depends on coal and coke. In the NZS, the EAF method becomes the dominant technology with scrap EAF producing 60% of steel whilst DRI-EAF in combination with hydrogen and CCS contributes 13 and 11% respectively. The BF-BOF method would still be used but at a small level and in combination with CCS.

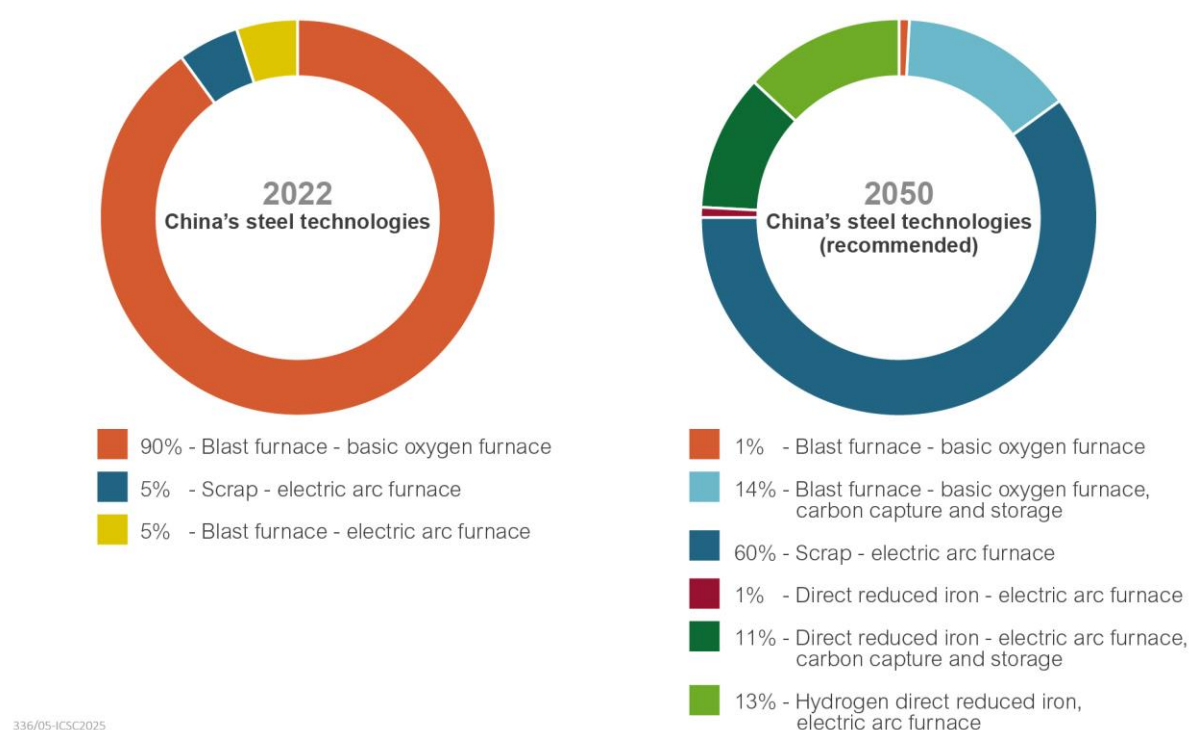


Figure 5 Steel making technologies in China for 2020 and those recommended in the NZS for 2050 (adapted from Hasanbeigi and others, 2023)

For the short to medium term, the NZS requires that China stops building new BF_s and stops relining old BF_s, which is capital intensive. Investment should instead be made in DRI with hydrogen plants to gain experience in the new technology, according to the IEA (2020). The government plans to improve the recycling systems for scrap steel, provide good policies and standards on emissions for low-carbon emission steel manufacturing and encourage energy efficiency and the use of low-carbon technologies through retrofits and incentives. Public bodies will be encouraged to procure less carbon-intensive products via Green Public Procurement Programs (GPP). Steel manufacturers are encouraged to develop programmes and pilot plants to test and improve the new technologies.

2.2.2 India

India is the second largest producer of steel. In 2023 it produced 140.8 Mt, approximately 7.5 % of global production. In India, steel is made via BF-BOF and DRI-EAF routes, as shown in Table 2 (WSA, 2024). It produces an estimated 240 MtCO₂/y, approximately 12% of India's total emissions. Due to its growing economy and ongoing development, demand for steel is anticipated to increase by around 4.5 times to approximately 576 Mt by 2050. Associated CO₂ emissions will increase threefold to approximately 800–900 MtCO₂/y (Garg and others, 2023; Hall and others, 2022). The potential increase in emissions will need to be countered by an accelerated roadmap for the NZE transition.

India's steel industry depends on coal (see Figure 6) and the NZS for India's steel decarbonisation relies on renewable hydrogen becoming the predominant fuel in 2050 (Garg and others, 2023), and the adoption of CCUS. Other measures include decreasing reliance on coal in DRI, improving energy efficiency, and using more scrap for steel production.

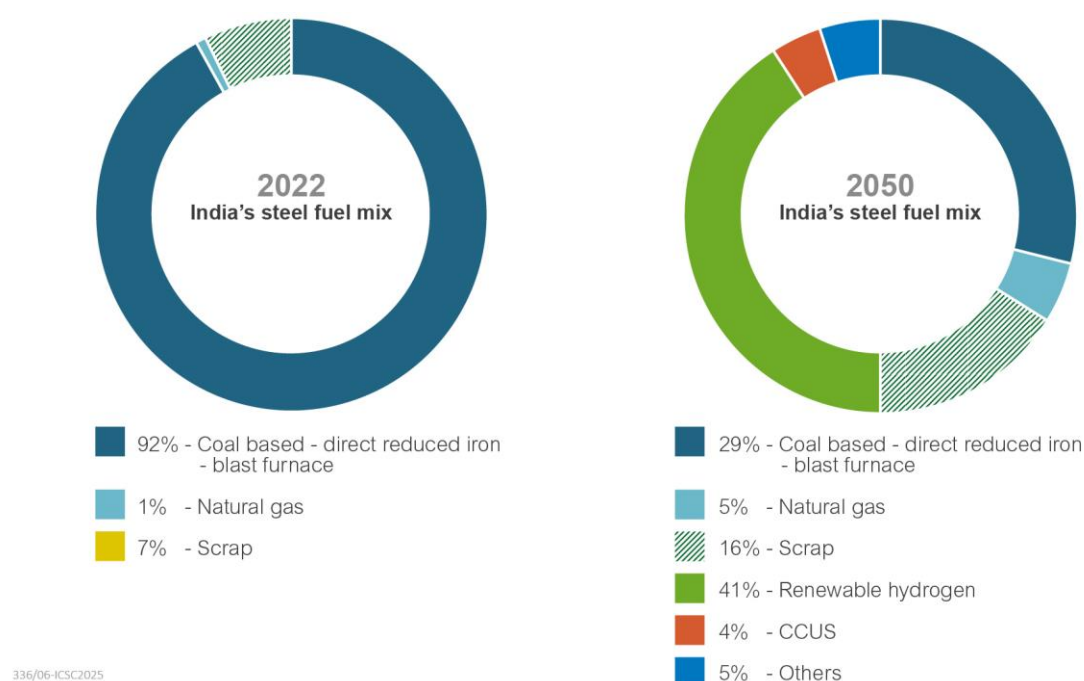


Figure 6 Fuel mix used in India's steel industry in 2022 and 2050 (adapted from RMI, 2023)

An important aspect is fuel switching to renewables for electricity (see Figure 7). The carbon intensity of the baseline is approximately 2.54 tCO₂/tcs; by implementing all the carbon reduction techniques, it will decrease by 40% to 1.5 tCO₂/tcs in 2050. Blending 25% scrap instead of 10% decreases emission intensity by 5% and blending conventional fuel with renewable hydrogen in a 1:1 ratio, reduces fossil fuel consumption and so reduces emission intensity by 14%. Producing all the electricity for the process using renewables would reduce CO₂ emission intensity by a further 11% (RMI, 2023). Note that operating with such a high level of hydrogen remains a research challenge.

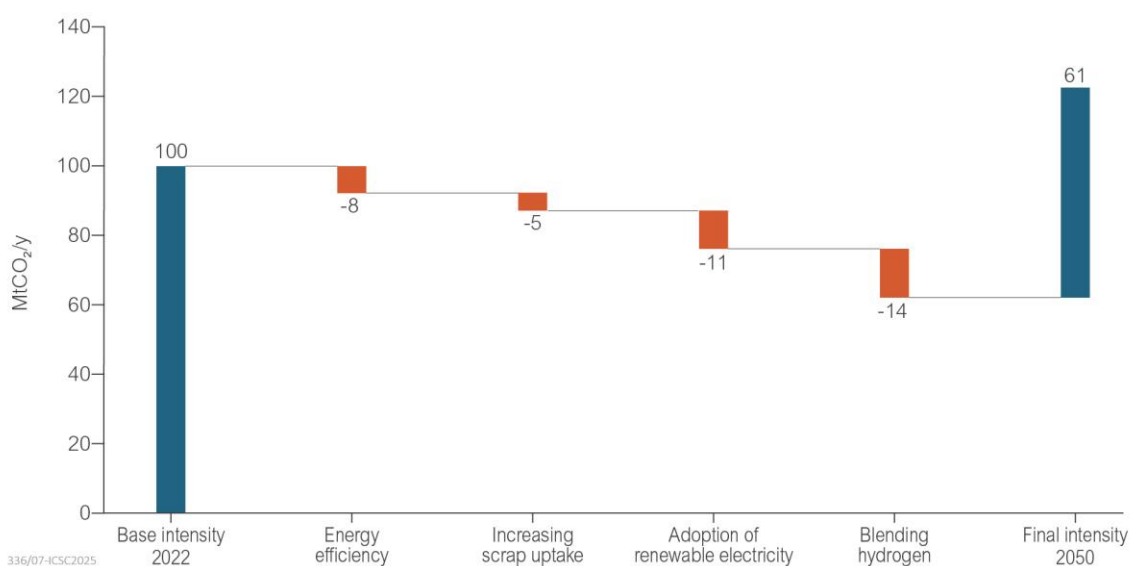


Figure 7 CO₂ intensity reduction for India's pathway to decarbonise the steel industry (adapted from RMI, 2023)

Investment needs to be made into new plants with low-carbon technologies to meet the long-term targets and older carbon-intensive production plants need to be made redundant as they approach end of life. The public and private sectors need to define green steel and implement standards for its production. Due to its higher cost compared to conventional methods, steel manufacturers need incentives, such as green bonds and concessional financing rates and the development of a carbon market to allow carbon credit trading (Garg and others, 2023; Hall and others, 2022; RMI, 2023).

2.2.1 European Union

The EU produced 126.3 Mt of crude steel in 2023 making it the world's third largest producer, and 5% of the EU's total CO₂ emissions were from the I&S industry. The EU has a target to reach carbon neutrality by 2050, which includes emission reductions from the steel industry. The major producers of steel in the EU are Germany (29%), Italy (17%), Spain (9%) and France (8%) (WSA, 2024). Steel production is stagnant because most of the EU economies are developed and an increase in production in one country cancels the decrease in production in another. As outlined in Table 2, the two main production routes are BF-BOF which produces over half of the steel, and scrap-EAF. Currently, scrap makes up 50% of the raw material mix for scrap-EAF; this is expected to increase to 60% by 2050 (European Parliament, 2021; IEA, 2020).

Besides material recycling and electrification of the steel industry, further steps need to be taken to reach NZE by 2050. The EU has been interested in using renewable hydrogen with DRI and low-carbon electricity. A major constraint of renewable hydrogen is the requirement of excess renewable power to make it. Certainly, current capacity cannot deliver short-term needs. However, it could be feasible in the longer term, provided mechanisms to lower the cost of production are in place. The technology is demonstrated: ArcelorMittal has a 2.5 Mt steel plant in Belgium using the hydrogen DRI-EAF process (European Parliament, 2021).

CCUS is also an option for decarbonising heavy industry in the EU although the challenge with the steel industry is the many different sources of carbon emissions in the process which make it more complicated to capture the CO₂ emissions at source (IEA, 2020).

The EU is making progress in its industry transition and released its Green Deal in February 2023. An important development for the I&S industry was the introduction of the CBAM in April 2023. This aims to phase out and replace free emissions trading allowances, reduce the risk of carbon leakage and support a level playing field between imported and EU-produced steel (EC, 2021). It should also encourage decarbonisation of production, but it will ultimately mean higher costs for the consumer. A consultation on a similar mechanism was undertaken in the UK in 2024 and will be introduced on 1 January 2027 (Gov UK, 2024; UK Steel, 2024).

2.2.2 Japan

Japan is the fourth largest steel producer worldwide with a production of 87 Mt in 2023 which was responsible for 134 MtCO₂ emissions, 13% of Japan's total emissions (Transition Asia, 2023). Currently, 75% of steel in Japan is produced using the BF-BOF method and the rest uses the EAF route. Decarbonisation of the steel industry is necessary for Japan to meet its NDC pledges and reduce CO₂ emissions by 48% by 2030 (compared to 2013), and several technologies are suitable for the decarbonisation pathway, although there are challenges.

Biomass does not appear to feature in Japan's decarbonisation strategies; rather hydrogen and CCUS are key players. Japan is exploring recirculation of reformed hydrogen-rich off-gases in BFs to partially reduce emissions through lower fossil fuel input requirements, the COURSE50 project (IEA, 2020). This is developed further in Super COURSE50 which involves partial substitution of coke by electrolytic hydrogen in the BF and aims to reach commercial scale by 2030 (IEA, 2020). If deployed with CCS, this technology reduces CO₂ emissions by 30% (Nippon Steel, 2021). The storage and transport of CO₂ is a significant barrier since the lack of infrastructure makes it an expensive option. Thus, developing COURSE50 further demands additional infrastructure combined with zero carbon electricity for the large quantity of renewable hydrogen required (Nishida and others, 2023). A gradual technology shift to secondary (recycled) steelmaking using recycled steel and hydrogen-DRI combined with large-scale EAF is also projected, which uses electrolysed hydrogen and renewable power (Nippon Steel, 2021). However, many countries, including Japan, are experiencing a shortage

of supply of recycled steel and so the long-term option for transition to NZE is considered to be via hydrogen-DRI-EAF. There is also an inherent challenge in that the reduction of iron ore with hydrogen is endothermic, while reduction with carbon (from coke) is exothermic.

2.2.3 USA

The USA is the fifth largest steel producer, responsible for 4.3% of global steel in 2023. Approximately 25% of the steel was produced via the BF-BOF method and 75% via the DRI-EAF route (see Table 2) (WSA, 2024). Natural gas is the predominant fuel in the DRI process as shown in Figure 8 (US DOE, 2022), so a lower fraction of coal is utilised, making CO₂ emissions from US steel manufacturing lower than other countries at 86 MtCO₂/y. This corresponds to an average carbon intensity of around 0.95 tCO₂/tcs for the USA, compared to around 1.95 tCO₂/tcs for China (US DOE, 2022).

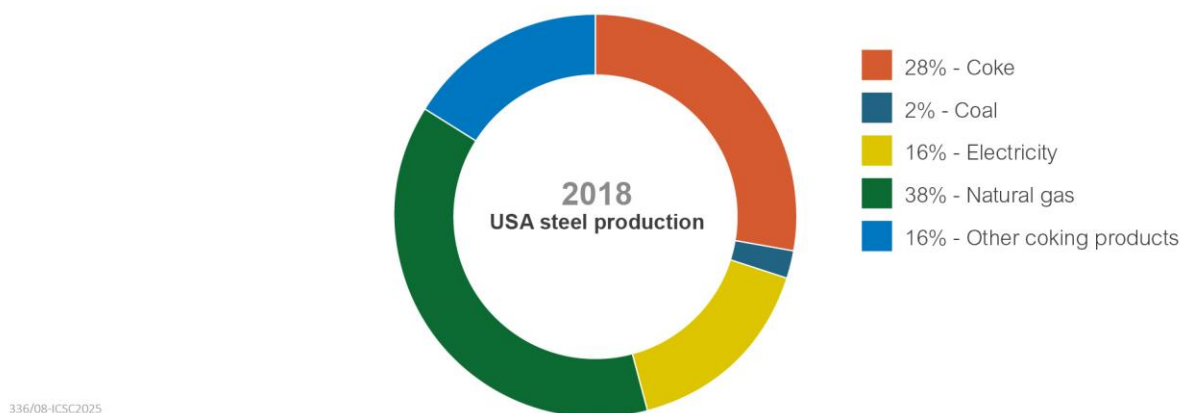


Figure 8 Fuel mix for the US steel industry 2018 (adapted from US DOE, 2022)

The USA has a target to reduce CO₂ emissions to nearly zero by 2050. Three scenarios have been identified in the roadmap for decarbonising USA industry (US DOE, 2022): Business as usual, BAU, slow improvement; Advanced scenario, higher rates of improvement, and Near Zero greenhouse gas emissions, the most ambitious (see Table 1). There are four main pillars to emission reduction of US industry – energy efficiency; electrification of industrial processes; low-carbon fuels, feedstocks and energy sources (LCFFES); and CCUS. LCFFES includes biobased feedstocks and hydrogen for either electrification of the grid or as an alternative fuel source (US DOE, 2022). In the Advanced scenario, emissions decrease to 17 MtCO₂/y even though steel production increases by 12%. For the Near Zero Scenario, Figure 9 shows the emission reduction impact of each carbon reduction step. In the BAU Scenario, the decrease in emissions is due to a decrease in emissions on the US electric grid. Further CO₂ reductions to achieve near-zero GHG scenario targets would require an increase in energy efficiency and electrification of thermal processes, as well as a switch to LCFFES. Wider penetration of CCS and CCU technologies powered solely by renewables would be needed to achieve NZE (US DOE, 2022).

Biobased feedstocks are specifically mentioned in the I&S decarbonisation roadmap for the USA as a near-term option for substituting for coal or coke, and there are calls for further RD&D on pretreating agricultural residues for this purpose, using charcoal in BF, and the use of biomass/biofuels in furnaces (US DOE, 2022). It recognises that local biomass resource constraints and availability for different steelworks will affect the economics and life cycle emissions of this approach. In the longer term, partial replacement of natural gas by renewable hydrogen coupled with CCUS of waste gases, blending of hydrogen in the BF, electrification of re-heat and downstream furnaces, and the direct electrolysis of iron without the need for carbon inputs are some of the step-change technologies.

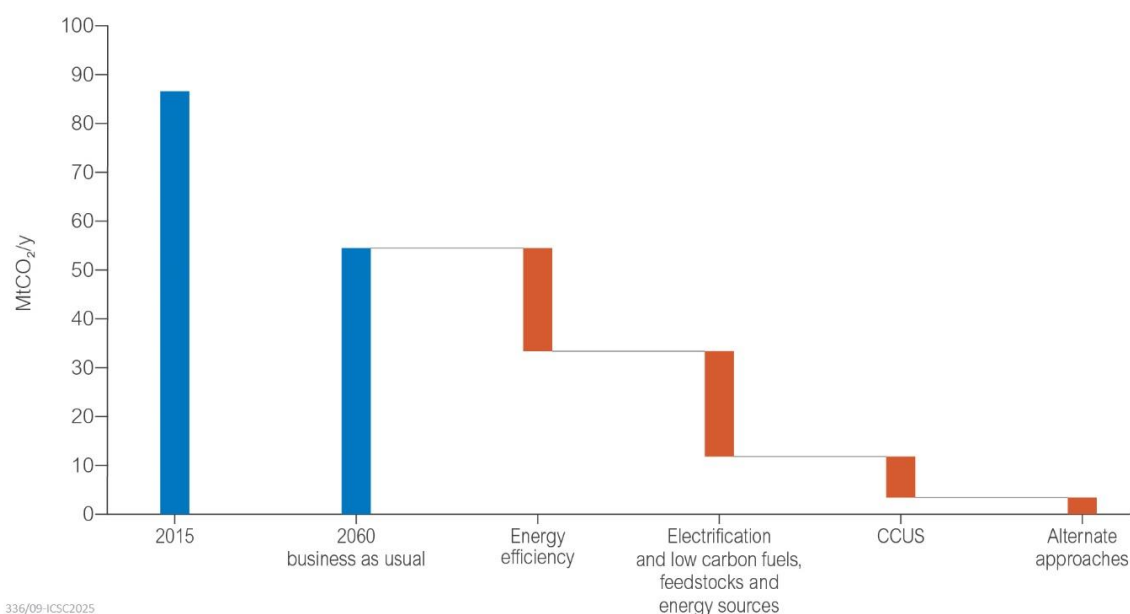


Figure 9 CO₂ intensity reduction for the USA's pathway to decarbonise the steel industry (adapted from US DOE, 2022)

2.3 CEMENT MANUFACTURING

Cement is another vital building material for developing energy and transport systems, buildings and infrastructure. Global cement production in 2023 was 4.1 Gt and responsible for approximately 2.5 GtCO₂. Table 3 lists the countries with the highest global CO₂ emissions for cement manufacturing, with their current emissions and targets for 2050. Some of the major companies operating in different parts of the world are also shown.

TABLE 3 MATERIAL PRODUCTION AND CO ₂ EMISSIONS FROM HEAVY INDUSTRY BY COUNTRY (GCCA, 2022; RMI, 2022; CEMBUREAU, 2024A,B; US DOE, 2022)					
Industry type	Country	CO ₂ emissions produced, MtCO ₂ /y	Emission reduction targets for 2050	Global production in 2023, MtCO ₂ /y	Largest producing companies in 2023, MtCO ₂
Cement	China	763.4	Long term 2040–50 – CO ₂ levels fall to 1/6 th of 2020 levels Long term 2050–60 – CO ₂ levels to drop to nearly zero	2100	China National Building Materials (Ref Best Diplomats, Largest Cement Producers in the World) Anhui Conch Cement Company Ltd (200.2 Mt)
	India			410	Ultra Tech Cement ACC Ltd Ambuja Cements
	EU		Short-term target to reduce emissions by 40% of 1990 levels Long-term target to achieve carbon neutrality by 2050	176	Buzzi Unicem (Italy) Cimpor (Portugal) Heidelberg Cement (Germany) Holcim (Switzerland)
	USA	69 Mt	Net Zero Scenario – emissions 3 MtCO ₂ /y	91	Lafarge Holcim Lehigh Hanson CEMEX USA

In cement production, limestone and other minerals are crushed, dried and calcined to form calcium oxide with the release of CO₂. This is followed by sintering at high temperatures to form clinker, which is mostly calcium silicate. The clinker is then removed, cooled and processed to form the final cement product. The cement is mixed with aggregates like gravel and sand to make concrete (see Chapter 3 for more details). The high temperatures required for calcining and sintering are produced by fuel combustion which provides about 70–80% of the total energy used and has a specific energy demand of 3.72 GJ/t cement (Clark and others, 2024). Globally, much of this energy demand is met by fossil fuels, and the carbon intensity has been estimated at 0.6–0.8 tCO₂/t of clinker (Barbhuiya and others, 2024a).

According to the GCCA (2022), CO₂ emissions from the cement industry need to be reduced by 25% for concrete and 20% for cement by 2030 (compared to 2020), and it needs to reach near zero emissions by 2050. The GCCA roadmap of different pathways to achieve this is shown in Figure 10. Much of the CO₂ emissions are from converting calcium carbonate to calcium oxide and so are difficult to avoid. Consequently, CCUS is a key requirement for decarbonisation. However, the emissions reduction from announced CCUS projects falls short of the 2030 target (IEA, 2023b). Other major reductions come from efficiency in design during construction and production, and savings in clinker production. Partial substitution of the fossil fuels used in clinker production by lower carbon alternatives, including wastes and biomass, is also emerging as an important decarbonisation strategy.

According to the IEA SDS, the global share of *biogenic* alternative fuels providing thermal energy will increase to 16% by 2030 (IEA, 2018). This is discussed in more detail in Chapter 3. Decarbonisation strategies vary by country depending on their production conditions and the assets and infrastructure available (GCCA, 2022).

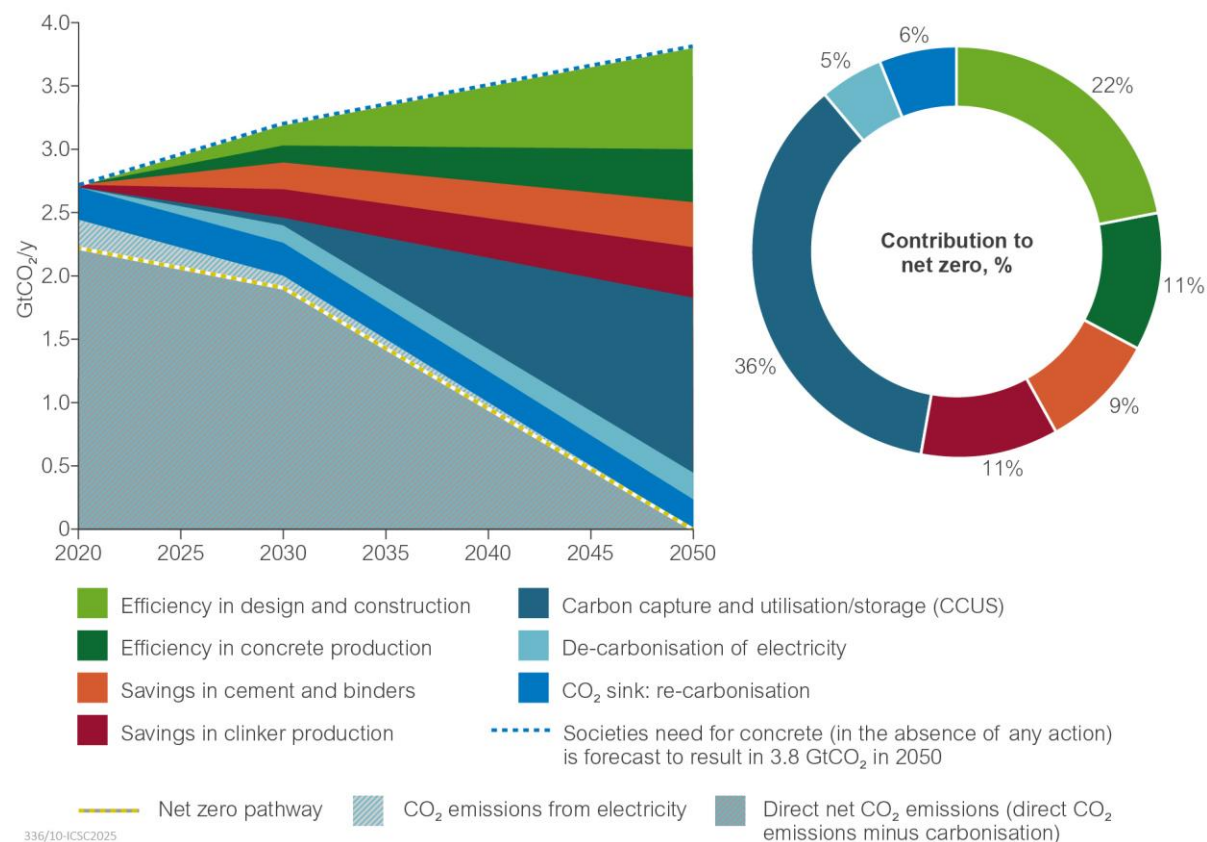


Figure 10 Decarbonisation pathways for the cement industry to meet global NZE targets (adapted from GCCA, 2022)

2.3.1 China

China is the largest cement producer. In 2023 it produced 2.1 Gt cement, approximately 50% of total global production, which resulted in 736.4 MtCO₂ (RMI, 2022). China's target is to reduce emissions from the cement sector to 16% of 2020 levels by 2030 and to achieve carbon neutrality by 2050. The approach to achieve this is shown in Figure 11 (RMI, 2022).

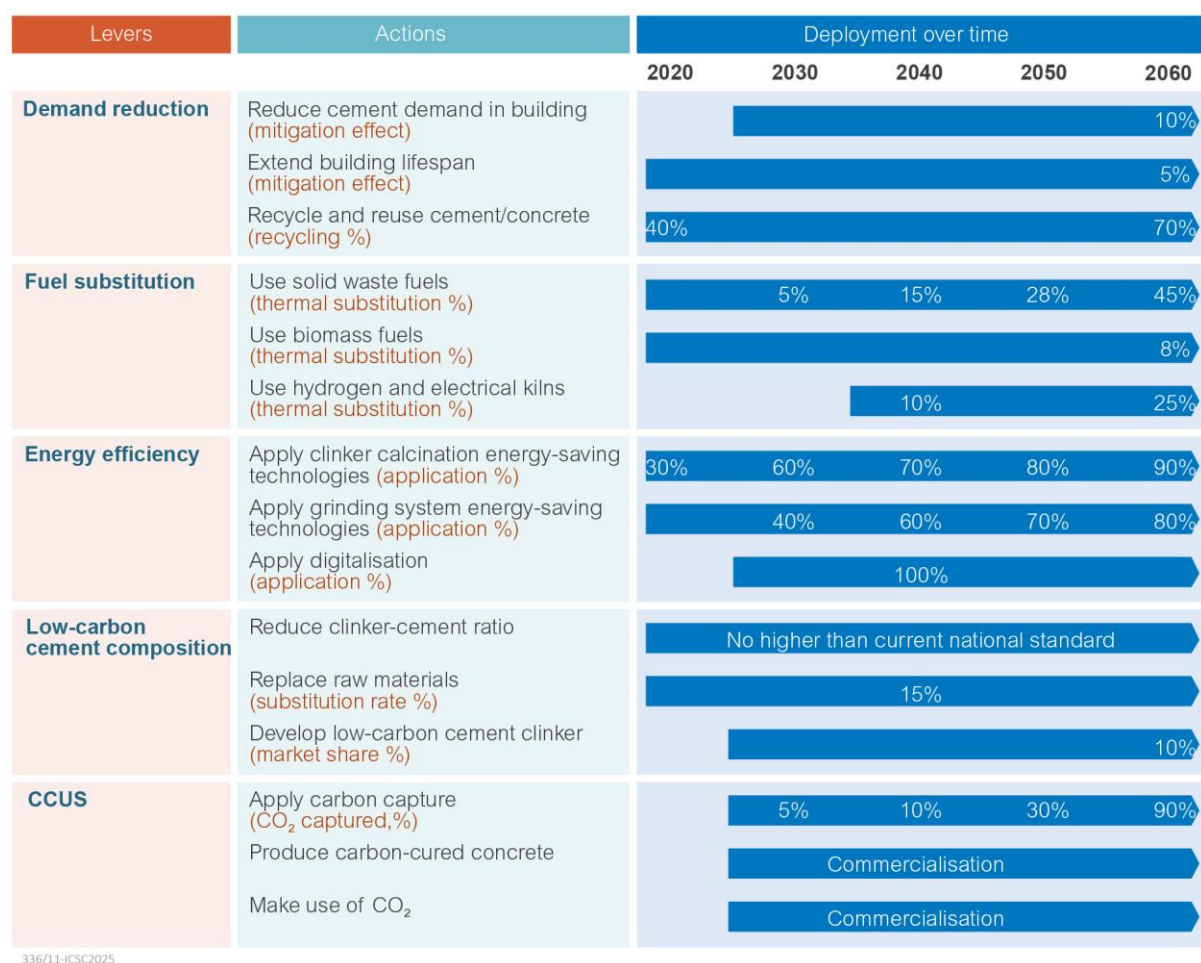


Figure 11 China's timeline to implement the decarbonisation levers to achieve NZE (adapted from RMI, 2022)

Figure 11 shows that demand reduction and energy efficiency are the key players in carbon reduction to 2030. In the long term (2050), alternative fuels, including biomass and waste, provide approximately a 36% CO₂ reduction, and CCS becomes a major player – nearly 30% of CO₂ would be captured. Beyond 2050 almost 70% alternative fuel substitution will be achieved and CCUS and production of renewable electricity will be commercialised making it possible to capture almost 90% of emissions.

2.3.2 India

India is the second largest producer of cement, representing 10% of global production in 2023. India is still a developing country and demand for cement is projected to double in the coming decade to enable the development of infrastructure. Thus, emissions in its BAU scenario are expected to double from 213 MtCO₂ in 2020 to 420 MtCO₂ in 2030. For the improved low-carbon scenario, emissions are expected to increase to 320 MtCO₂ in 2030 compared to 2020 levels (Kumar, 2023). However, India's target is to reach NZE by 2070. The keys to achieving the improved low-carbon scenario (Karthek and others, 2023; Kumar, 2023) are (i) improving energy efficiency, (ii) using renewable energy, (iii) reducing the carbon intensity of clinker production by substituting the limestone with slag from the

steel industry or fly ash from the energy industry, (iv) increasing the share of alternative fuels, including municipal solid waste (MSW) and biomass. This latter reduction measure is already happening. The net zero target involves the use of carbon-abating technologies like CCUS, but current projects are falling short of the trajectory needed.

2.3.3 European Union

The EU is the third largest cement producer, with 176 Mt cement in 2023. The EU's target was to reduce its emissions from the cement industry by 40% of 1990 levels by 2030 and reach carbon neutrality by 2050. Table 4 shows the emissions reduction from the value chain of the cement industry. Average emissions reported in 2017 indicated that reductions of 116 kgCO₂/t cement had already been achieved from the baseline emissions of 783 kgCO₂/t cement in 1990. Further reductions are required by improvements and efficiency savings in key operations to meet the 2030 target (Cembureau, 2024a,b).

Emission reductions for the 2050 target require further improvements in clinker production via the use of decarbonated raw materials (8%), and fuel substitution (90% alternative fuels and 50% biomass). CCS also has an important role (42%). In addition, the roadmap requires an improvement in thermal efficiency of the plant by 14% by 2050. (Cembureau, 2024a,b). A fuller description of the EU decarbonisation plans is given in Chapter 3.

CO₂ emission reductions, kgCO₂/t cement	2030 reduction needs for target of 399 kgCO₂/t cement	2050 reduction needs for target of -131 kgCO₂/t cement
Emission reduction from 1990 baseline (804 kgCO ₂ /t cement) as of 2021	147	147
Emissions reduction from clinker production	49	126
Emission reduction from cement production	18	154
Emission reduction from concrete production	31	74
Emission reduction through construction carbonation	77	60
Emission reduction via CCS/CCU	83	374

2.3.4 USA

The fourth largest producer of cement globally is the USA, at 91 Mt in 2023. Coal is still the primary fuel used in US cement manufacturing and the emissions from the industry are 69 MtCO₂/y. In a BAU scenario, emissions rise to over 80 MtCO₂/y by 2050 (US DOE, 2022) (see Figure 12). The Near Zero target for decarbonising the US cement industry is 3 MtCO₂/y by 2050. The most important pathway to achieve this is CCUS, but LCCFES also plays a large role, with contributions from energy efficiency

and electrification. To an extent, using biomass and biogenic fuels is recognised as a feasible option in the immediate term in the US decarbonisation roadmap, but regulatory issues associated with burning solid waste can make their use more challenging (US DOE, 2022).

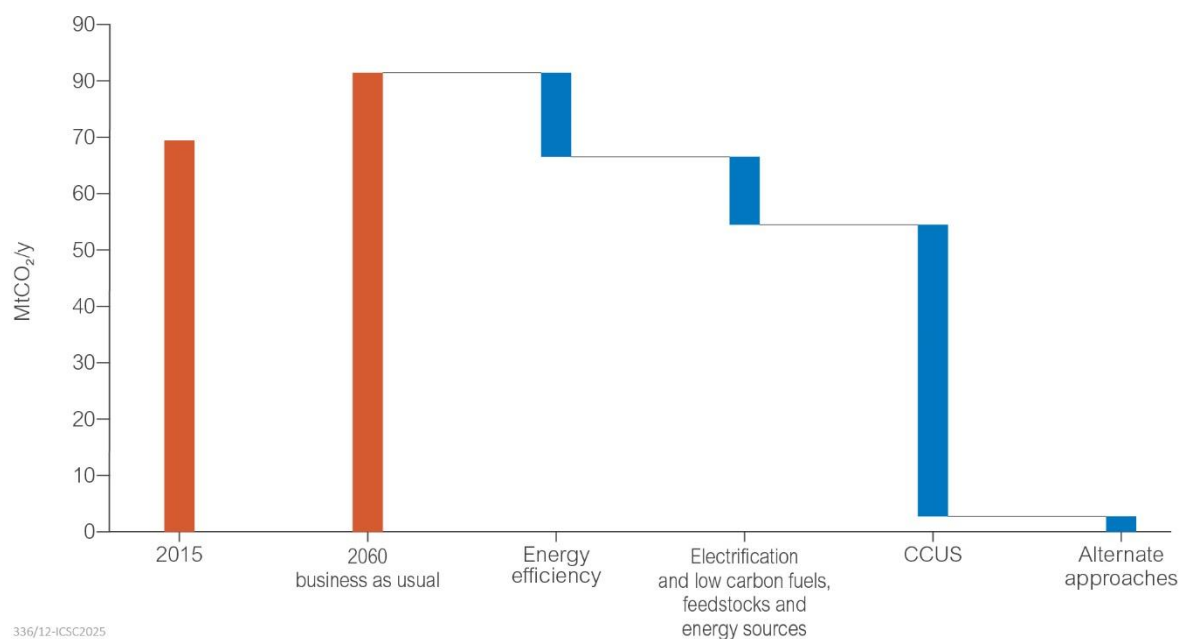


Figure 12 CO₂ intensity reduction for the USA's pathway to decarbonise the cement industry (US DOE, 2022)

2.4 COMMENTS

Globally, heavy industry is not on track to decarbonise (IEA, 2023c). There are many technology options to decarbonise I&S and cement manufacturing, and fuel switching to biomass sources has a role to play in the near term. This is small but significant for I&S production and will depend on the existing fleet and local resources. Globally, it has been estimated to have the potential to contribute a 6%/y (approximately 0.15 GtCO₂/y) reduction in emissions by 2050. Even so, the I&S sector will still be using coal in 2050 because of its role as a reducing agent. General strategies for reducing emissions in I&S manufacturing include technology switching, energy efficiency savings, fuel switching, and electrification of ancillary services. A technology shift to renewable hydrogen together with CCS features strongly in many roadmaps, and these need to be accelerated, and developed at scale, together with efficiency improvements and electrification. Currently, production of renewable hydrogen at a competitive price is a major constraint, together with insufficient surplus renewable electricity.

Similarly, decarbonisation of the cement industry is not on track to meet NZE scenarios (IEA, 2023d). Alternative lower carbon-intensity fuels, including biomass resources, have a larger role in decarbonising cement manufacturing; there was a global average of 23.25% alternative fuel substitution in 2022. Currently, fossil fuels provide the most thermal energy for the sector (90% in 2022) with biogenic wastes having a small share (4% in 2022). In the EU this share is higher and expected to increase to 2030 and beyond. Necessary measures to align with the NZS for 2050 include

continued decrease in the thermal energy intensity of clinker and the expansion of bioenergy and hydrogen fuels. According to the IEA SDS, bioenergy and renewable waste need to increase to a 16% share of thermal energy intensity by 2030. A challenge for both sectors is meeting increasing demand while decarbonising and maintaining a competitive market price; the EU's CBAM seeks to provide an approach to achieve this end.

CARBON DIOXIDE EMISSIONS FROM HEAVY INDUSTRY
CONTINUE TO RISE, AND IRON AND STEEL AND
CEMENT SECTORS ARE NOT ON TRACK FOR THE 2050
NET ZERO SCENARIO. SUBSTITUTING FOSSIL FUELS
WITH BIOGENIC RESOURCES IS ONE OF A SUITE OF
OPTIONS FOR INDUSTRIAL DECARBONISATION AND
EUROPE LEADS THE WAY IN THEIR ADOPTION IN
CEMENT MANUFACTURING

3 CEMENT MANUFACTURING AND DECARBONISATION OPPORTUNITIES USING BIOMASS

3.1 INTRODUCTION

The cement industry contributes 5–8% of global CO₂ emissions (Pisciotta and others, 2023; Barbhuiya and others, 2024a), making it the third largest CO₂ emitting industry after power generation and I&S (Benhelal and others, 2021). Around 80% of the cement produced is used for concrete, which is essential in modern infrastructure due to its versatility and numerous advantages in terms of durability, strength, flexibility, and affordability (Kelsall, 2023; GCCA, 2022). Moreover, concrete can be easily produced from widely available raw materials, such as sand, gravel, and water (Kelsall, 2023; GCCA, 2022). Therefore, demand for cement continues to grow globally; it is the second most used substance after water (Kelsall, 2023; Gagg, 2014). According to the GCCA (2022), demand for concrete is forecast to increase from 14.0 billion m³ in 2020 to 20 billion m³ in 2050 resulting in 3.8 GtCO₂/y emissions, assuming no changes to current practice. The demand for concrete will vary by region within this timeframe, but it is anticipated to increase in Africa, India and Latin America, following trends in population growth and urbanisation (GCCA, 2022). This chapter summarises the cement manufacturing process and levers for decarbonisation set out in the GCCA 2050 Cement and Concrete Industry Roadmap for Net Zero Concrete (GCCA, 2022) illustrated in Figure 10 (Section 2.3), with a focus on the role of alternative fuels, and biomass in particular.

3.2 CEMENT PRODUCTION PROCESS

The raw materials for cement manufacture are extracted from quarries and crushed before being processed in specific proportions to meet the specifications for the type of cement being manufactured. The European Cement Association (Cembureau, 2021) identifies 27 common types of cement, grouped into five general categories (CEM I Portland cement, CEM II Portland-composite cement, CEM III BF cement, CEM IV Pozzolan cement, and CEM V Composite cement), which can be of ordinary, high or very high strength, in addition to several special types of cement. Portland cement is the most used, comprising over 80% of EU27 production (Marmier, 2023; EC, 2018).

3.2.1 Process description

Cement production involves the mixing and milling together of a source of calcium carbonate, such as limestone, marl or chalk with minor quantities of aluminosilicate and iron ore-containing minerals, like bauxite, shale, clay or sand (Cembureau, 2021). In the *dry kiln* process, this powdered mixture, often known as *raw meal*, passes through a series of up to six cyclones, where it is dried and preheated at increasing temperatures (Cembureau, 2021) (see Figure 13). This is followed by combustion in a precalciner (or calciner), where temperatures of 900°C convert most of the calcium carbonate into calcium oxide releasing CO₂ in the process (Clark, 2024; Cembureau, 2021). The final stage is the

sintering of the precalcined meal in a rotary kiln. Here, it is heated to 1450°C which promotes further reactions of calcium oxide with other components of the meal and with fuel mineral matter to form mostly calcium silicates (Kelsall, 2023; Marmier, 2023; Cembureau, 2021). The rotary kiln is a gently inclined cylindrical refractory furnace which rotates 3–5 times per minute (Cembureau, 2021; Kahawalage, 2023), and the sintering process results in the formation of grey clinker nodules of 5–25 mm diameter (Pisciotta and others, 2023; Schumacher and Juniper, 2013) as the material travels down the kiln – from the kiln inlet to the hot end, where the main fuel burner (conventionally fossil fuel) is located (Marmier, 2023). Air is used to cool the cement clinker exiting the kiln; a necessary step that influences mineral formation and therefore product quality (Cembureau, 2021). In integrated plants, clinker is further processed on site to produce the final cement product. For Portland cement, this involves the addition of gypsum (as a setting time regulation aid) and grinding prior to packing (Kelsall, 2023; Huntzinger and Eatmon, 2009). Portland cement consists of >90% clinker and 5% gypsum (IEA, 2018). Cement clinker can sometimes be transported to other sites for further processing or finishing (Cembureau, 2021). For blended, lower-carbon cement, the finishing steps involve a partial substitution of clinker with supplementary cementitious materials, such as slag, fly ash, or limestone, so that the clinker-to-cement ratio in blended cement or the amount of clinker in the final product is lower than in Portland cement, resulting in a lower carbon footprint (Kelsall, 2023; Marmier, 2023). The dry kiln method is adopted by 90% of EU cement plants and has higher efficiency than the older, traditional, *wet kiln* method (Marmier, 2023). Wet kilns use a wet slurry of materials and are much longer than dry kilns, as drying, preheating, calcination and sintering all take place within the kiln (Cembureau, 2021).

Figure 13, shows the dry kiln process and here, the series of vertical cyclones, each with a counter-flow motion, are used to maximise heat transfer between the exhaust gases from the kiln and the raw meal during the pre-heating stage in the bottom cyclones (Pisciotta and others, 2023). Cooler gases from this step are used for the drying of raw materials in the top cyclones (Marmier, 2023; Cembureau, 2021). The introduction of the pre-calciner or calciner step prior to sintering in the kiln has the overall effect of a higher heat recovery efficiency and production rate, and a significantly shorter kiln (approximately a quarter of the length of wet kilns) (Marmier, 2023).

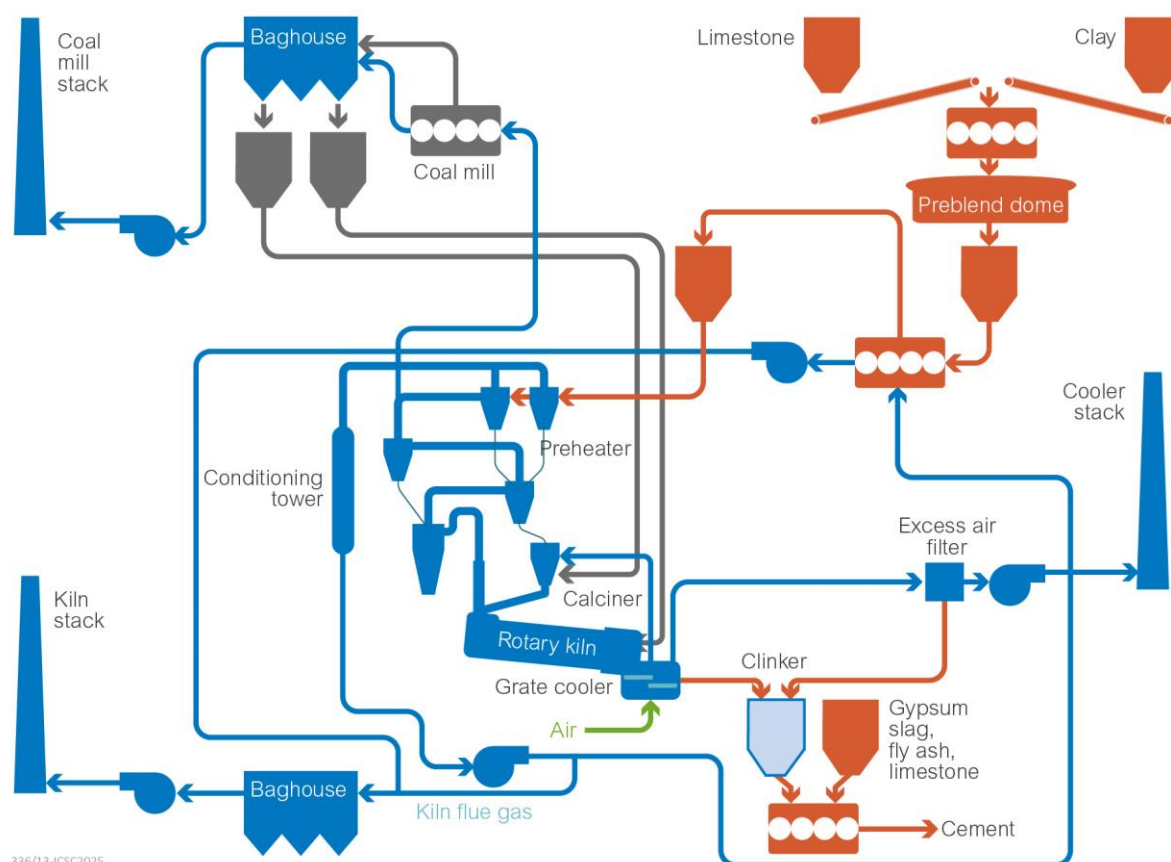


Figure 13 State-of-the-art cement manufacturing process (Kelsall, 2023)

Other rotary kiln technologies exist, with kiln dimensions ranging between 2–6 m diameter and 50–225 m length, such as dry kiln with preheater without pre-calciner, semi-wet/semi-dry process, and dry kiln without preheater (or long dry kiln); all have differing specific thermal energy demands and efficiencies depending on their configuration (Marmier, 2023; Kahawalage and others, 2023; Kusuma and others, 2022). The difference in energy efficiencies between the state-of-the-art dry process (with preheaters and pre-calcining step) and that of wet kilns can be significant. For example, in 2019, the average global production of grey clinker was reported to require 3.51 GJ/t clinker compared to production in wet kilns at 5.51 GJ/t clinker (Marmier, 2023).

3.2.2 Energy requirements of the cement manufacturing process and associated carbon emissions

Figure 14 presents a simplified flowsheet of a typical cement production process highlighting the type of energy required for the different process steps (and associated CO₂ emissions), grouped into three main stages:

- **Stage 1** – preparation of raw materials, including the preparation and handling of solid fuels (Clark and others, 2024). Most of the processes in this stage, such as conveying, crushing and milling are electrically driven. Any thermal energy requirements for the drying or heating of

raw materials and fuels are met using recovered heat from the kiln and the clinker cooling steps (Talaie and others, 2019; Clark and others, 2024).

- **Stage 2** – clinker production, which is the most energy demanding, requires process temperatures of 900°C in the pre-calciner and 1300–1500°C in the rotary kiln (Pisciotta and others, 2023; USGS, 2020; EPA, 2018). The thermal energy needed is provided by the combustion of fuels. As the only stage in the process requiring fuel inputs, it is an area where CO₂ emission savings can be made by using lower-carbon fuels such as biogenic wastes. Electricity is also needed in stage 2 for clinker cooling, operation of the kiln and ancillaries (see Figure 14).
- **Stage 3** – the milling of clinker and additives and packing of the final product, all requiring electricity.

Overall, 70–80% of the total energy used is in the form of thermal energy, while about 20–30% is electricity consumption, typically from fossil-fuelled power plants (Kusuma and others, 2022; Barbhuiya and others, 2024a).

Clinker production is where most of the CO₂ emissions are generated (see Figure 14). However, only about 38% of the total CO₂ emissions from this process originate from the combustion of fuels for process heat. Inherent process emissions, mostly from the decomposition of the calcium carbonate, constitute around 55% of the total CO₂ emitted, the remaining 7% are indirect emissions from electricity usage (Kelsall, 2023; Tyrer, 2021).

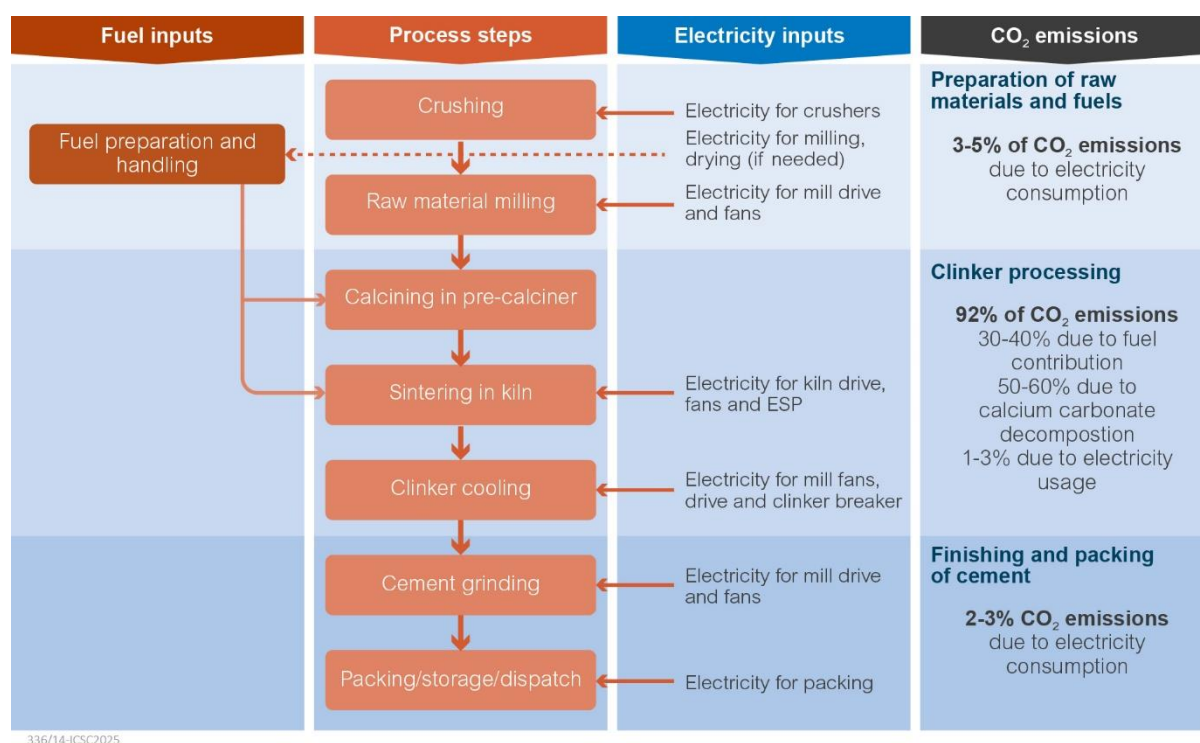


Figure 14 Simplified flowsheet of a typical cement production process (adapted from Talaie and others (2019) with CO₂ emissions data from Benhelal and others (2021)

The carbon footprint of the final product depends on clinker content, fuel types used for process heat, the carbon intensity of electricity used, and the overall energy efficiency of the plant, which is also dependent on kiln technologies (Barbhuiya and others, 2024a; Marmier, 2023). While there are several decarbonisation efforts underway, the carbon intensity of cement has remained just below 0.6 tCO₂ per tonne of cement produced since 2018 (IEA, 2023d). The IEA (2023d) states that “annual CO₂ intensity declines of 4% through to 2030 are required for the sector to get on track with the NZE Scenario by 2050”. This will require the implementation of a range of decarbonisation levers.

3.3 DECARBONISATION OPTIONS FOR THE CEMENT INDUSTRY

This section considers the main levers for decarbonisation of cement as per the GCCA 2050 Cement and Concrete Industry Roadmap for Net Zero Concrete (GCCA, 2022) (see Figure 10). For more information see Kelsall (2023).

Since most CO₂ emissions from cement manufacturing are inherent process emissions, and thus difficult to avoid, CCUS has been identified as the most effective means to reduce emissions. They have been estimated at 1370 MtCO₂/y by 2050, 36% of the CO₂ emissions from this sector (GCCA, 2022). CCS technology is emerging with several coal (Kelsall, 2023) and biomass (BECCS) projects in the pipeline (Jones and others, 2023), some including cement plants. The Heidelberg Materials Sement Norge (formerly Norcem) and its Brevik CCS project is an example, which reached ‘mechanical completion’ of its CCS facility in December 2024. It will enable them to capture 400,000 tCO₂/y (50% of the plant’s emissions) (Brevik CCS, 2024). The technology and status of CCUS and its role in the decarbonisation of the cement industry are covered in detail by the ICSC in Kelsall (2023).

Carbon-saving measures in clinker production include improving thermal energy efficiency to reduce energy demand. Technological advances, including moving from wet-process kilns to dry-process kilns, have reduced the overall energy intensity of the process within the last century (Kelsall, 2023). Kelsall (2023) summarises other opportunities to bring the average thermal energy intensity for clinker production closer to the theoretical minimum value of 2.8 GJ/t of clinker, from 3.6 GJ/t of clinker where it has remained stagnant (Kelsall, 2023; IEA, 2023d).

Other decarbonisation measures in clinker production include the reformulation of cement with a lower clinker-to-cement ratio in Portland cements and the substitution of clinker with supplementary cementitious materials such as ground limestone, silica dust and natural pozzolans. Circular economy approaches are becoming increasingly important within the cement and concrete sector, and measures aiming to minimise the environmental impact and improve the sustainability of the industry are being explored. These include the use of waste materials, for example, slag from steel production or fly ash from coal-fired power plants or industrial by-products to replace raw materials in clinker production; and the recycling and reuse of concrete waste to be used as aggregate in new concrete (Barbhuiya and others, 2024b; Marsh and others, 2022; Yu and others, 2021; Joensuu and others, 2020). These

approaches also reduce the amount of CO₂ emissions associated with the extraction and processing of raw materials and waste disposal (Barbhuiya and others, 2024b).

The use of biomass ash is being investigated as a supplementary cementitious material in concrete (Olatoyan and others, 2023; Campos Texeira and others, 2020; Cabrera and others, 2020; Cruz and others, 2019; Texeira and others, 2016), in cementitious composites (Danish and others, 2023; Sun and others, 2023), and cement/cement mixes (Medina and others, 2017; Khalil and others, 2014). Biomass fly ash has pozzolanic properties and so it has potential as a more sustainable substitute for coal fly ash – used in both low-carbon concrete and cement production, and whose availability is decreasing in OECD countries as power plants move away from fossil fuels (Olatoyan and others, 2023; Kusuma and others, 2022). According to Kusuma and others (2022), substitution rates of biomass ash in studies vary between 3% to 80% and depend on various factors, including the type of biomass, ash composition and properties (chloride and silica contents, unburnt carbon, Loss on Ignition (LOI), and particle size distribution), and standards for the final product. Treatment of biomass ashes may be needed to allow for a higher fraction to be used in some instances (for example, Sun and others, 2023; Danish and others, 2023; Salvo and others, 2015). However, more research may be needed to determine optimum substitution rates and the long-term durability and sustainability of concrete formulated with biomass ash (Olatoyan and others, 2023; Kusuma and others, 2022).

Carbon savings through the adoption of measures that reduce demand for cement and/or concrete include design optimisation, re-use of concrete and lifetime extension of seemingly redundant structures (Kelsall, 2023; GCCA, 2022). According to the GCCA (2022), these types of measures are forecast to result in CO₂ emissions reductions of 7% in 2030 and 22% in 2050.

The use of low- or zero-carbon electricity can decarbonise indirect emissions from electricity usage, and best available techniques for milling could also lower electricity demand at the plant (Marmier, 2023). While the demand for electricity is likely to increase to meet the increased production rates of cement, the decarbonisation of electricity is anticipated to result in CO₂ reductions of 54% by 2030 compared to 2020 levels, and a 100% reduction by 2050 (GCCA, 2022). This corresponds to a 5% reduction in the total CO₂ emissions from the sector (GCCA, 2022).

Permanent sequestration of CO₂ via carbonation of concrete is another potential decarbonisation lever for the industry. The setting of concrete or hardening process requires the absorption of CO₂ (carbonation) via reactions of calcium hydroxide and hydrated calcium silicate in the cement with CO₂ (Kelsall, 2023; MPA UK, 2022). Moreover, the carbonation process continues throughout the life cycle of the product and is accelerated when the surface area available for such reactions is increased when concrete is crushed (or recycled) on demolition (MPA UK, 2022). Consequently, carbonation can be enhanced via improved demolition practices and developing technologies that seek to increase the rate and amount of CO₂ that can be permanently removed and stored within either concrete itself or other construction products (such as concrete aggregate). For more details see Zhu (2024) and MPA

UK (2022). A reduction of 6% of the total cement sector CO₂ emissions is forecast by 2050 using this lever (GCCA, 2022).

Decarbonisation options for process heat include the use of electrical processes and switching to low- or zero-carbon fuels, such as hydrogen and alternative fuels including biomass (Marmier, 2023). The European Cement Research Academy, ECRA (2022) states that electrification of the cement process has the potential to decrease around 35% of total CO₂ emissions. There are limited studies on the use of hydrogen, usually as part of the fuel mix (with either biomass or coal) and/or in combination with other technologies, which conclude that substantial carbon reductions can be achieved (Williams and others; 2024; Juangsa and others, 2022; Hanson, 2022; El-Eman and Gabriel, 2021; Khadka, 2021). The main barriers identified are the availability of carbon-neutral hydrogen and/or costs (ECRA, 2022). In contrast, the combustion of alternative fuels as a lower carbon substitute to fossil fuels at different shares is expected to increase. These fuels consist of various domestic and industrial wastes, including biomass waste. Thus, biomass has a role in the reduction of carbon emissions from cement manufacturing as a substitute for fossil fuels and, moving forward, also in BECCS.

3.4 THE ROLE OF ALTERNATIVE FUELS AND CO-PROCESSING

3.4.1 Current use of alternative fuels and biomass

Process heat for cement manufacturing has conventionally been generated from fossil fuels, particularly coal, petroleum and natural gas. In the last three decades, there has been progress in decarbonisation via the partial substitution of fossil fuels with lower carbon alternatives, such as waste fuels and biomass; the average was 23.25% fuel substitution globally in 2022 (GCCA GNR, 2024), (*see* Figure 15). Even so, coal and petroleum coke remain the primary sources of fuel for the cement industry globally and made up 82% of fossil fuel use in the sector in 2022 (GCCA GNR, 2024). In the EU cement industry (*see* Figure 16) an average of 53% of the thermal energy for cement manufacturing was sourced from alternative fuels in 2021, compared to a global average of 20% , which according to the European Cement Association, represents a saving of 7.8 Mt of coal and 23 MtCO₂ (Cembureau, 2024c).

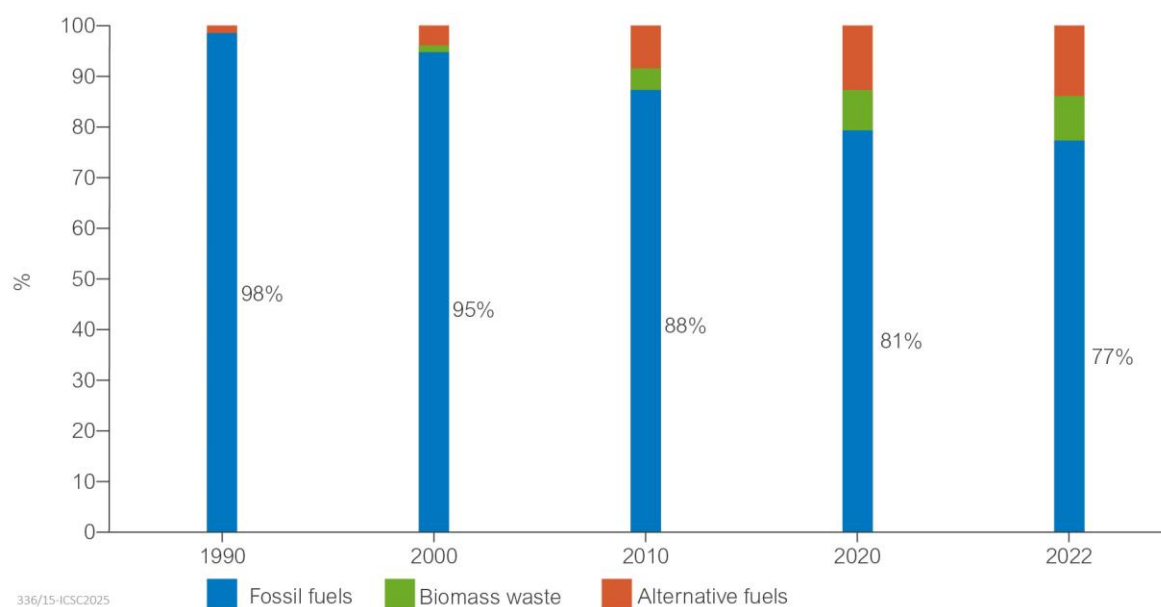


Figure 15 Global usage of fuels for process heat (GCCA GNR, 2024)

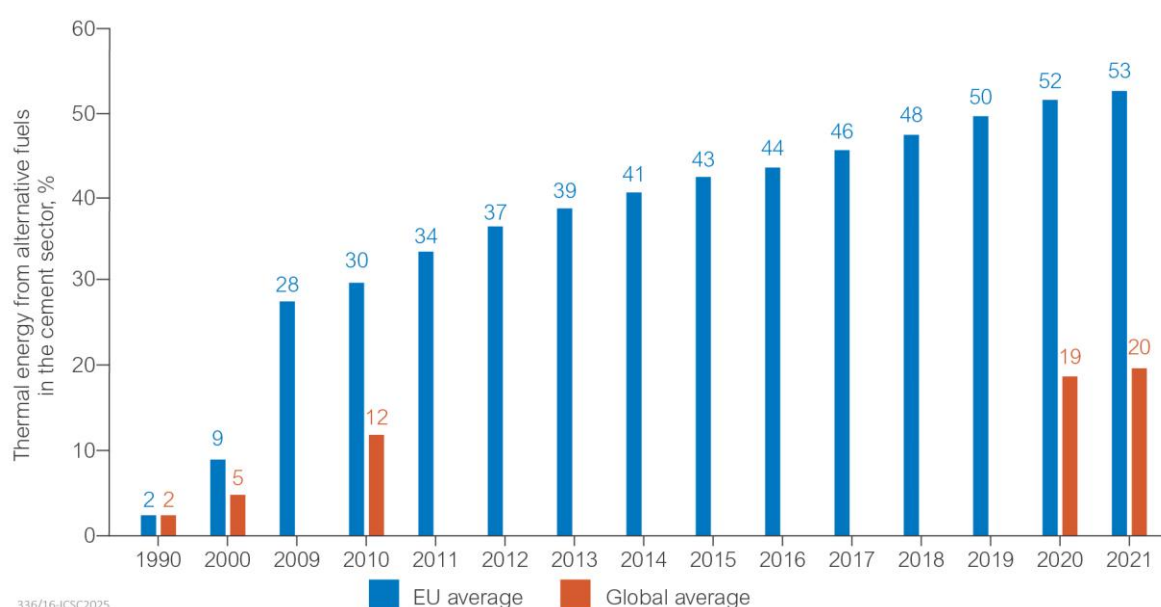


Figure 16 Share of thermal energy from alternative fuels including biomass (adapted from Cembureau, 2024c, modified with data from GCCA GNR, 2023)

The European cement industry wishes to increase its use of alternative fuels, with no foreseeable technical impediments to achieving an average of 60% by 2030 (Cembureau, 2024c). Under favourable conditions for alternative fuels, for example, facilitating regulations, and suitable pretreatment of waste streams, fossil fuel substitution of up to 95% could be feasible (Cembureau, 2016). Some EU countries, such as Poland, Czechia and Austria were able to source up to an average of 76% (on a country level) of their thermal energy from alternative fuels in 2021 (Cembureau, 2024c), and some cement plants are substituting up to 95% (annual average) (ECRA, 2022). A few are able to operate at

nearly 100% alternative fuels, such as Schwenk Zement's Allmendingen plant in Germany (see Box 1) and LafargeHolcim's Retznei plant in Austria (Cembureau, 2020; Marmier, 2023).

Technically, a 100% substitution rate is possible because conditions in modern dry kilns enable the combustion of a variety of waste, including hazardous organic materials. Key features include high temperatures in the rotary kiln (with a flame temperature of 2000°C in the main burner), long residence times and excess oxygen, which together with turbulent and intense mixing within the kiln ensure complete combustion of organic materials, and even the destruction of stable organic compounds (Beguedou and others, 2023; GIZ/Holcim, 2020; ECRA, 2017; Nørskov, 2012; Kartensen, 2008). Other advantages include alkaline scrubbing of problematic gaseous species (hydrogen fluoride, hydrogen chloride, sulphur dioxide), and high capture of particle-bound heavy metals in the clinker matrix (except for highly volatile species like mercury and thallium) (GIZ/Holcim, 2020). Notably, the formation of dioxins and furans (PCDD/F) is prevented by avoiding any significant exposure to the temperature range which favours their formation (Kartensen, 2008; GIZ/Holcim, 2020). Such conditions allow for the co-combustion of non-recyclable waste, such as rubber tyres, unrecyclable plastics (waste packaging), waste textile fibres, processed sewage pellets and chemicals (spent solvent), thus avoiding landfill or incineration. Some wastes are excluded however, including commonly restricted wastes, such as electrical or electronic waste, asbestos containing waste, corrosive waste, nuclear waste, batteries and infectious medical wastes (Schwenk, 2022; GIZ/Holcim, 2020; ECRA, 2017).

Any ashes from the alternative fuels are in contact with the raw meal in the calciner and kiln, and so are incorporated into the clinker matrix, thus substituting a fraction of raw materials. This substitution is around 5% in European clinker production (Cembureau, 2024c). The simultaneous utilisation of waste for process heat generation and for clinker production is known as *co-processing*, which is considered key in the circularity of the European cement industry and in addressing local waste management challenges (Cembureau 2024c). However, alternative fuels often require pre-processing, and their quality dictates their suitability for different feeding points within the cement manufacturing process to avoid negatively impacting the product and process emissions (GIZ/Holcim, 2020; Kartensen, 2008). Nevertheless, the energy recovery efficiency from these types of fuels is generally comparable to that of combined heat and power waste incinerators (70–80%) (ECRA, 2017) and can be up to 95% in modern kilns (Beguedou and others, 2023). This is much higher than waste-to-energy plants (average 26% efficiency) (GIZ/Holcim, 2020).

The alternative fuels (excluding biomass) that were used by the cement industry in 2022 are illustrated in Figure 17 (a) (GCCA GNR, 2024). Figure 17 (b) shows the breakdown of the biomass waste fraction used globally in 2022. This consisted mostly of agricultural and organic waste, nappies and charcoal (33%), animal meal (18%), and wood and non-impregnated sawdust (sawdust free from resins, preservatives or other substances derived from fossil fuels) (17%) (GCCA GNR, 2024). However, it must be noted that the 'Getting the Numbers Right', GNR data does not cover 100% of the industry

(GCCA, 2023). Cleaner biomass fuels, such as wood and energy crops could potentially be used when locally available and if economically feasible (ECRA, 2022).

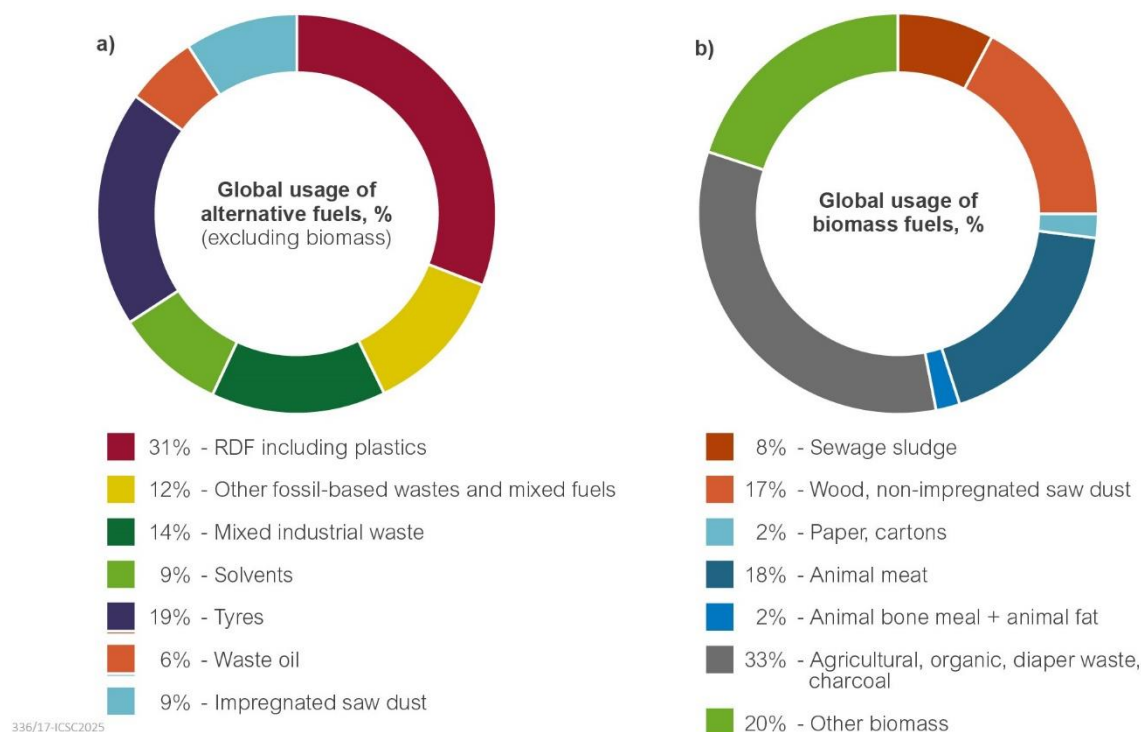


Figure 17 Global usage of (a) alternative fuels (excluding biomass) and (b) biomass fuels for cement process heat, 2022 (adapted from GCCA GNR, 2024)

Global production of cement resulted in an average of a net 580 kgCO₂/t cementitious material in 2022, representing an overall 23.25% CO₂ savings per tonne of cementitious material compared to the 1990 baseline (GCCA GNR, 2024). According to the GCCA GNR (2024), these CO₂ savings have been achieved through increasingly higher substitution shares of alternative fuels since 1990 for a 21% reduction of fossil fuel usage, together with a 17.7% increase in energy efficiency and a 9% reduction in clinker to cement ratio.

The substitution of fossil fuels by alternative fuels other than biomass makes for a less costly and locally available option and has advantages in terms of carbon savings by rerouting landfill waste and avoiding its associated methane emissions. In addition, there are no waste disposal requirements as no solid waste is generated, rather any ash material is incorporated in the cement. However, most waste fuels used cannot be considered low or carbon neutral, as this is dependent on their biogenic fractions, and as such, carbon reductions when switching to alternative fuels are limited (Kusuma and others, 2022). Even when substituting fossil for biomass fuels, there are differences and discrepancies in the accounting of CO₂ depending on the protocol used. As noted by Marmier (2023), biogenic CO₂ is not considered carbon neutral in the calculations in the GCCA's GNR database (GCCA GNR, 2023, 2024), as it is under the EU Emissions Trading Scheme (ETS).

Nevertheless, carbon reductions can still be achieved by using fossil fuel-based wastes compared to coal or pet-coke (Marmier, 2023; GCCA, 2020) (see Section 3.4.4). The feasible substitution rate depends on the region, as the main barriers are considered to be political and legal in nature rather than technical. The availability and cost of these types of fuels depend on the sophistication of the waste management systems and markets (ECRA, 2022). While advanced waste management is certainly the case in some European countries, in developing countries and emerging economies the adoption of alternative fuels and co-processing has been lagging. This is compounded by economic and financial barriers, little experience with fuel pretreatments and co-processing, and social concerns and reservations about waste incineration (GIZ/Holcim, 2020). Overall, the GCCA roadmap foresees the substitution share of alternative fuels increasing to a global average of 22% by 2030 and 43% by 2050, with around a third being biogenic in origin (ECRA, 2022; GCCA, 2022).

3.4.2 Challenges in the use of higher shares of biomass in the fuel mix

Alternative fuels have the potential to completely replace fossil fuels in cement plants, and this has been achieved in a few European facilities. Moreover, carbon savings are maximised with higher biogenic shares. However, there are some technical challenges associated with higher biomass shares in cement plants. These limitations are related to the lower fuel quality of biomass wastes, in general, compared with coal or pet coke, such as high moisture and low energy contents, and depending on the waste, also troublesome elements in the kiln, like sulphur and chlorine (Cavalett and others, 2024; ECRA CSI, 2017). Moisture contents and the net calorific value of the fuel mix should be within a certain range to meet the thermal demands of the calciner and the rotary kiln (ECRA, 2022). For dry kilns with preheaters and calciner, depending on the fuel characteristics, they can be fed to the calciner, or a small fraction of alternative fuels can be fed at the kiln inlet (also called secondary firing) in addition to the kiln main burner (GIZ/Holcim, 2020) (see Figure 18). The low energy contents of biomass (10–18 GJ/t) make it more suitable as input for the lower temperature calciner unit, which uses up to 70% of the total fuel for thermal energy in dry kiln plants, and as such, alternative fuels and/or biomass can substitute 100% of fossil fuels in the calciner (ECRA, 2022).

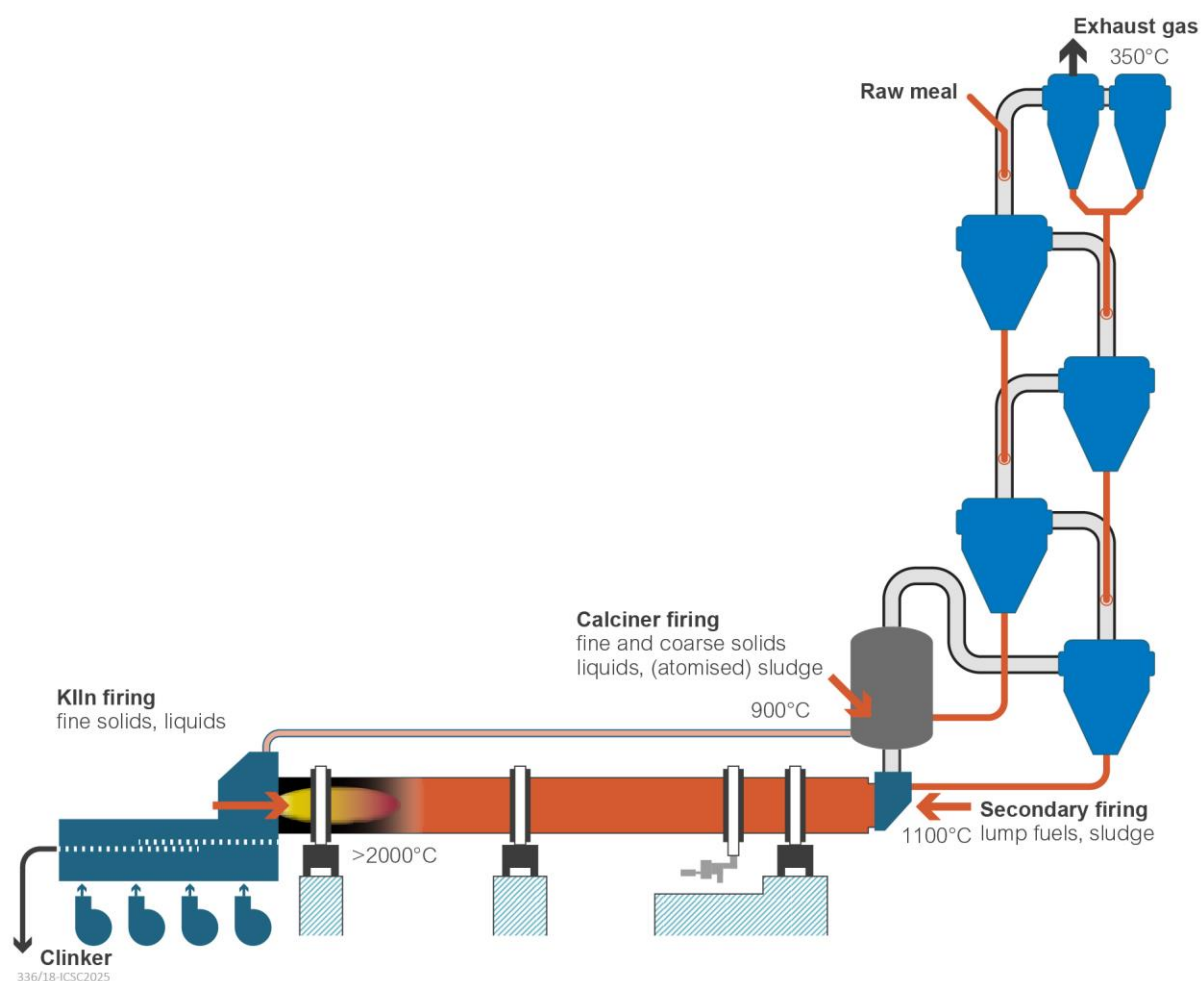


Figure 18 Alternative fuel feed points of a state-of-the-art cement kiln (GIZ/Holcim, 2020, adapted from Geocycle)

The use of alternative fuels at high substitution rates lowers energy efficiency overall. Higher fuel input rates are required than when using fossil fuels, due to their lower energy density (ECRA CSI, 2017). Some fuel properties, such as higher moisture contents, can result in a small increase in thermal energy requirements (GCCA, 2022). In addition to the low calorific values (CV) of alternative fuels, issues may arise at high substitution rates due to high sulphur and chlorine contents. These may be either incorporated in the clinker or concentrated within the plant (ECRA, 2022). Chlorine is undesirable in concrete and therefore in cement, with codes and standards having set limits in concrete to protect against active corrosion in reinforced steel structures (Yousri and others, 2020). At the plant, fuel sulphur, chlorine and alkali contents increase the potential for the formation of rings in the rotary kiln and coatings in several areas, such as in the kiln inlet and lower cyclone stages, due to the formation of sticky compounds (ECRA, 2022). These issues can reduce the energy efficiency of the process, as it may result in kiln stoppages to allow for buildup removal (ECRA, 2022; Beguedou and others, 2023). A bypass in the kiln inlet for partial extraction of chlorine-rich gas may be used to minimise the concentration of chlorine in the system from processing fuels but this can increase the energy demand (ECRA, 2022; GIZ/Holcim, 2020; ECRA CSI, 2017).

Pre-processing or pretreatment of wastes may be necessary for some alternative fuels in cement manufacturing, and this also applies to biomass materials. This increases both the costs and energy demand of the process. The most essential and common pretreatment is drying and milling as there are limits for both moisture and particle size for the different feeding points. For example, the main burner typically requires particles larger than 20 mm to ensure complete gas-phase combustion (ECRA, 2022). Wastes with high moisture contents, such as sewage sludge, pulp waste and RDF, require drying prior to use. Drying can be done at the plant using the raw gas from the preheater tower, kiln, or recovered waste heat from the cooling of the clinker (ECRA, 2022). The introduction of fuels with excess moisture contents to the kiln increases the thermal energy demand for the drying necessary before ignition, and the energy demand for fans and other ancillaries due to the higher ‘wet gas’ volumes produced (ECRA, 2022). The combustion of wetter fuels in the kiln also impacts residence time and could prevent complete combustion, even when the particle size is within an acceptable range. This all adds to the costs. As the costs of alternative fuels and biomass are strongly correlated to their quality (ZKG, 2014), the economics becomes a trade-off in terms of the price of fuel, carbon saving, and additional process steps.

3.4.3 Combustion of alternative fuels and biomass in the calciner

The pre-calciner or calciner is the most suitable feeding point for alternative fuels and biomass, as it can accept fuels with much lower CVs (11 to 13 GJ/t average minimum) than those required for kiln firing (GIZ/Holcim, 2020; ECRA, 2017). Coarser fuels than for the main firing at the kiln can also be fed into the calciner, as it has good oxidising conditions and residence times of up to seven seconds (GIZ/Holcim, 2020). However, to minimise disturbances in the gas flow for a homogenous calcination of the raw meal and for optimal process control, fuel particles should be small enough to be carried by the gas flow into the kiln without dropping out before they have burned completely (ZKG, 2014; GIZ/Holcim, 2020). Chipped tyres, shredded plastics and textiles and coarse RDF are wastes that can be burned in the calciner (GIZ/Holcim, 2020).

To add flexibility to the system, pre-combustion burners and gasifiers (to convert the fuel into valuable gases such as carbon monoxide, hydrogen and methane) can be installed to circumvent or minimise issues that may arise from the use of alternative fuels if they were to be fed directly into the calciner (ECRA, 2022). Standard pre-combustion burners are commonly used as they have several features to improve the combustion efficiency of alternative fuels compared to calciners. These include a highly oxidising environment (21 O₂ vol%), high temperatures (1200°C), and residence times of up to ten seconds (ECRA, 2022). The injection of coarse alternative fuels can result in operational issues due to high loadings at the feeding point and combustion in less than-suitable areas in the calciner (as particles drop out from the gas flow); this negatively affects the homogeneity and degree of calcination of the meal (ZKG, 2014). Thus, advanced systems seek to avoid disturbance to the stability of the calcination process when using a more coarse or heterogeneous fuel mix. This includes step grate burners and even pre-combustion systems providing very long residence times of up to 45 minutes, although they are seldom used (ECRA, 2022).

Gasification is an alternative option for the utilisation of low energy density wastes (with CVs of 4.5–6.0 MJ/kg, for example) that meet the feeding requirements of the gasifier (ECRA, 2022). During the process, the waste is effectively dried and pyrolysed/gasified producing a lean gas to be used as a more homogeneous input to the calciner or kiln inlet (ECRA, 2022). The advantages are minimal detrimental impact on the stability of the calcination process, and the avoidance of an increase in the specific energy demand in the calciner for fuel drying (ECRA, 2022). The solid fraction remaining from the gasification process consists of the mineral fraction of the waste and ‘unburned particles’, which can be recycled or co-processed either at the kiln inlet or with the raw materials for clinker production, or discarded (ECRA, 2022). Challenges related to the quality of waste fuel inputs include issues with the accumulation of non-combustible materials in the gasifier and blockages of gas lines from the gasifier to the calciner (ECRA, 2022). Fluidised bed systems for >10 MW and fixed bed gasifiers for smaller capacities are mature technologies, although are yet to be widely adopted in the sector (ECRA, 2022). Gasification technologies under development for use in cement manufacturing include systems that use very high-temperature plasma generated via an electric arc to heat the gasifier, but their high costs are still a barrier to further development (ECRA, 2022).

3.4.4 Combustion of alternative fuels and biomass in the kiln

While many of the conditions in the main burner are beneficial for the combustion of alternative fuels (see Section 3.4.1), the temperature requirements are 550–650°C higher than the calciner, so it requires fuel inputs with minimum average net CV of 18 to 22 GJ/t (GIZ/Holcim, 2020). It has been suggested that the average CV of the fuel mix should be not less than 21 GJ/t for a substitution rate of up to 65%, and at least 23 GJ/t for higher substitution rates (65–90%) (Beguedou and others, 2023). These CVs are rarely seen in waste biomass fuels and so co-processing them in blends with higher CV alternative fuels is an option. Another important fuel requirement for firing at the main burner is particle size, which should be small enough so that they can be suspended in the kiln gases with sufficient residence time (GIZ/Holcim, 2020). Suitable wastes to be used as fuels at the kiln main burner are liquids in atomised form (waste oils, solvents and emulsions), and fine solids like RDF fluff, impregnated saw dust, animal meal and rice husks (GIZ/Holcim, 2020). The use of a ‘booster fuel’ with a high net CV (27–28 GJ/t), for example, waste oils, solvents, natural gas, or heavy oil, in relatively small amounts (4–5%) can aid in achieving high substitution rates of alternative fuels and biomass (over 80%) (Beguedou and others, 2023; Holmblad and Østergaard, 2020).

Secondary firing at the kiln inlet is also used for the addition of alternative fuels but it provides only 5–10% of the total kiln energy demand. It can accept coarse materials such as sludges and lumpy waste (filter cakes, bagged waste, whole tyres), which burn slowly in a fuel bed (GIZ/Holcim, 2020). Although only a limited amount of fuel can be burned in secondary firing, combining all strategies for using alternative fuels, means that substitution rates of up to 90% may be achieved (Beguedou and others, 2023).

Another important parameter in determining direct emission savings from alternative fuel substitution, besides its biogenic carbon fraction, is the emissions factor (kgCO_2/GJ) (GIZ/Holcim, 2020), which varies with fuel (see Figure 19). Biomass waste, such as agricultural residues and waste wood, has lower CV (typically 8–16 GJ/t) compared to fossil fuels, thus higher amounts are required for substitution (GIZ/Holcim, 2020). This is reflected in their emission factors. However, biomass affords the highest emissions savings due to its short carbon cycle. Its utilisation may be limited by local supply and competing uses and these may not be as economic or readily available as fossil fuels (GIZ/Holcim, 2020). Sustainability, seasonality, supply chain development, and pre-processing are some of the issues that must be considered when using agricultural residues (Jones and others, 2024). It has also been suggested that the replacement of coal in the kiln by >20% biomass may require thermal pretreatment (Pisciotta and others, 2023) to produce biochars with higher carbon content and net CVs (see Section 3.5).

Dried sewage sludge also has a lower CV and a higher emission factor, but all its carbon is biogenic, and its ashes are beneficial for the clinker matrix (CSI, 2014). Alternative fuels with high CVs, such as waste oil, tyres, non-recyclable plastics, and solvents, have lower emission factors than fossil fuels, so carbon savings can typically be realised, particularly if these contain biogenic shares, like waste tyres (GIZ/Holcim, 2020). Co-processing of waste in cement plants can also lead to a reduction in indirect carbon emissions by diverting waste streams from incinerators, landfills, and open burning. However, indirect emission reductions are difficult to estimate and are dependent not only on the ‘end-of-life scenario’, but also on waste biogenic carbon contents (GIZ/Holcim, 2020).

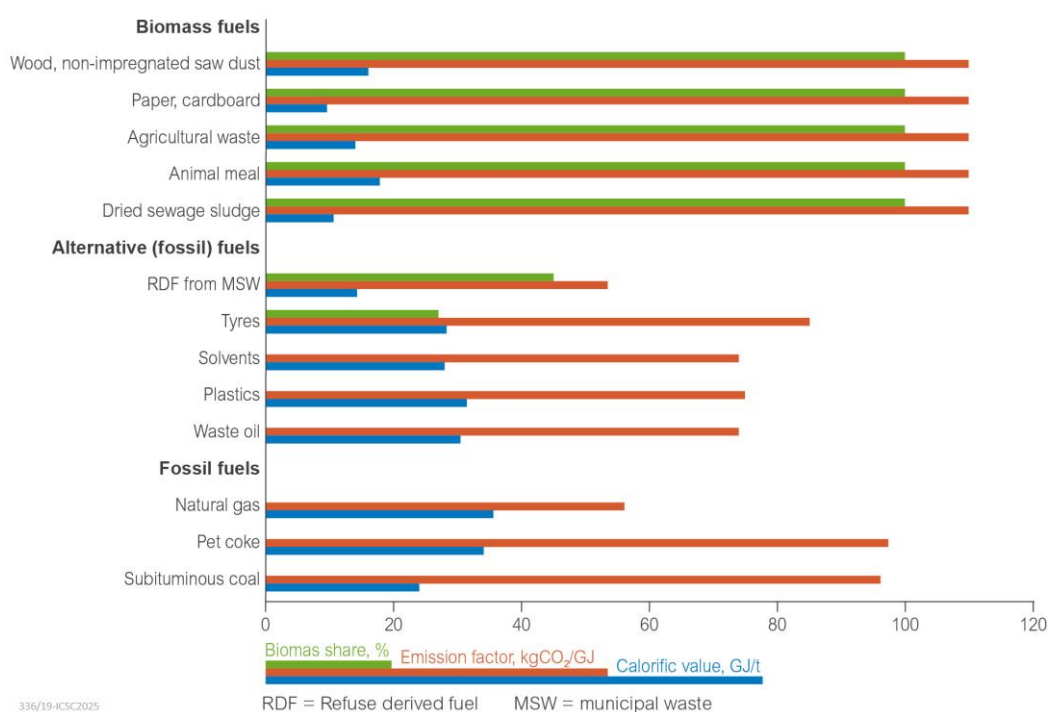


Figure 19 Typical biomass contents, emission factors, and CVs of various alternative fuels compared with fossil fuels. All data from GIZ/Holcim (2020), except for fossil fuels data. For fossil fuels, their emission factors were taken from the IPCC – Emission Factor Database (2023) and their Net CVs from DUKES (2024). Note that median values are shown whenever ranges were given.

Identified policies and actions that could increase the use of alternative fuels include: (i) *Nationally Appropriate Mitigation Actions* (NAMAs) which commit to GHG reductions in MSW management; (ii) Carbon pricing that supports the use of alternative fuels over fossil fuels (GIZ/Holcim, 2020). Other policies can have adverse implications. For example, in Germany, there is a requirement to recover phosphorus from sewage sludge from 2029, which restricts the future use of sewage sludge as an alternative fuel in cement kilns (BMUV, 2023; Schnell and others, 2020).

BOX 1: CASE STUDY – USE OF ALTERNATIVE FUELS AT SCHWENK, GERMANY

SCHWENK is a fifth-generation family business in Germany manufacturing cement and ready-mixed concrete, among other products, through its SCHWENK Building Materials Group (Schwenk, 2023). SCHWENK Zement operates four fully integrated cement plants and one milling plant, including the Allmendingen cement plant in Baden-Württemberg, which operates with nearly 100% alternative fuels (Cembureau 2020; Marmier, 2023).

As stated in their Sustainability report, 2022 (Schwenk, 2023), the substitution of fossil fuels by alternative fuels is one of SCHWENK's three main levers for the decarbonisation of cement, together with replacement of raw materials for clinker production (>14% in 2022) by using industrial wastes or by-products: *“used casting sand, broken concrete from roof tile production, filter dust from steel manufacture or residual materials that contain aluminium”*; and using waste heat for drying alternative fuels. At their plant in Karlstadt near Würzburg the surplus waste heat provides heating for the local swimming pool and so benefits the wider community. Reducing the clinker share in cement to <60% through the addition of fly ash from power plants or granulated slag from steel production as alternative aggregates is another measure to lower CO₂ emissions (Schwenk, 2023). SCHWENK is planning to use CCUS technology for their first carbon neutral cement plant to be built by 2030 (Schwenk, 2023).

Co-processing of alternative fuels, with the breakdown used in 2022 shown in Table 5, has resulted in >94% substitution of coal in all their German plants and in savings in raw materials due to the fuel ashes being incorporated in the clinker during the process (Schwenk, 2023). The biogenic carbon share of the alternative fuels mix used, is crucial for determining carbon savings. This is one of the advantages of co-processing sewage sludge (75–85%) coupled with its relatively high heating value when dried, which is comparable to that of the ‘brown coal dust’ it replaces (Schwenk, 2023). Sewage sludge is co-processed at their Allmendingen plant using a large Andritz drum dryer (4.6 m diameter and 17 m long) to evaporate a minimum of 14 t/h water for a 90% dry solids content using the waste heat from the kiln (Andritz, 2020). Further processing of the dewatered sewage sludge is done in a mixer to produce granules, followed by further drying resulting in a dried and sterilised fuel (Andritz, 2020). Overall, the use of alternative fuels has resulted in the replacement of 9.5 Mt coal at SCHWENK's cement plants since 1990 equivalent to savings of 20.9 MtCO₂ (Schwenk, 2023).

TABLE 5 ALTERNATIVE FUEL MIX IN CLINKER PRODUCTION BASED ON FUEL VOLUME USED IN 2022 AND BIOGENIC SHARE PER FUEL (SCHWENK, 2023)

Alternative fuel	Volumes used in 2022, t	Biogenic carbon share, %
Sewage sludge	547,301	75–85
Fuels from commercial and domestic wastes	472,095	26–35
Scrap tyres	29,050	27
Animal meal	28,032	100
Paper sludge*	23,715	70–90*
* paper fibre residues		

3.5 THERMAL PRETREATMENTS FOR BIOMASS WASTES

Thermal pretreatments (see Section 5.3.2) such as torrefaction and hydrothermal carbonisation (HTC) can be used to upgrade the fuel properties of lignocellulosic biomass feedstocks, including CV (Lucian and Fiori, 2017; Smith and Ross, 2016) so these products could be used as coal substitute in cement production. When pelleted, they offer several advantages including significant savings in transport costs due to the higher energy density (Jones and others, 2024). HTC is particularly suited to upgrading wet biomass (such as sewage sludge) without the need for pre-drying, therefore with potential for energy savings (ECRA, 2022). A detailed description of these pretreatments and their effect on agricultural waste can be found in Jones and others (2024).

According to the European Cement Research Academy (ECRA, 2022) as of 2022, there are several industrial projects worldwide, either starting or in continuous operation, using biomass waste hydrochar as fuel, and with the recycling of resultant ash as minerals in clinker production. These include cement plants in Belgium, China, Finland, France, Japan, Mexico, Spain, Sweden, the UK, and the USA. It was noted that the use of hydrochar from sewage sludge at scale would require the removal of certain metals prior to pretreatment. Also, phosphorus extraction from the sewage sludge chars via acid leaching may be necessary, possibly leading to higher sulphur contents in the hydrochar, restricting its substitution potential in cement kilns (ECRA, 2022). Overall, the substitution potential of sewage sludge hydrochars at the kiln main burner is considered limited due to their low net CVs (12 MJ/kg to 16 MJ/kg) and costs.

3.6 COMMENTS

Cement is a fundamental component of concrete, a material upon which modern life has been built and the demand for it is not expected to decrease significantly in the future. Most of the CO₂ emissions (55%) from the cement production process are inherent in calcining limestone and consequently CCS plays an important role in decarbonisation roadmaps for the cement industry. Nonetheless, the substitution of fossil fuels by alternative fuels including biomass has a key role in lowering the carbon footprint as thermal energy requirements are about 38% of total cement CO₂ emissions. Analyses of different mitigation options for the cement sector by Cavalett and others, (2024) and Fennell and others (2021) have identified that the most significant emission reductions can be achieved using biomass-based fuels together with CCS so that carbon neutrality can result; with opportunities for negative emissions when high shares of biogenic fuels are used. Potential challenges highlighted are related to the availability of sustainable biomass feedstocks and competition from other sectors (Cavalett and others, 2024). The use of alternative fuels has increased steadily since the beginning of the century, although slowly. The EU industry leads the way with an average of 53% fuel substitution in 2021, with a few plants that can run at 100% alternative fuels. The alternative fuels used are mainly waste materials, often processed into suitable inputs for either the calciner or kiln. Individual fuel types or their blends are highly heterogeneous by nature, both in terms of size and composition and

they may contain elevated amounts of undesirable components, like chlorine, sulphur, or hazardous substances. Fuel composition directly impacts plant emissions and cement quality, as fuel ashes are integrated into the clinker matrix. Careful monitoring of fuel composition and size to determine the most suitable feeding point, and investments in fuel storage, pre-processing and feeding equipment are therefore required which may increase capital and operational costs, and the specific energy demand of the product. However, waste materials, if widely and locally available, are low (or zero) cost and so are likely to result in economic savings overall.

Alternative fuel use has added benefits in terms of co-processing or recycling of ashes which can substitute some of the raw material needed in clinker production, providing further reductions in the cement carbon footprint. However, CO₂ savings are dependent on the biogenic share of the fuel. While sustainable biomass, such as residues or wastes, would be preferred to maximise carbon savings, their low CVs remain a barrier for 100% use in the kiln. Thermal treatments, such as torrefaction and HTC coupled with pelletisation or briquetting increase their energy density and may allow for higher shares to be used. Even so, their use may need to be complemented with higher CV fuels or technologies to achieve the high temperatures required in the kiln. The effectiveness and uptake of alternative fuel use is influenced by regional factors, such as availability, economics, and policies and regulations that support effective management of waste streams. These have a direct impact on the quality of waste streams and ensure that mostly non-recyclable or waste that cannot be processed in more sustainable ways is used in cement kilns. Measures or incentives that promote the use of alternative fuels over fossil fuels would support this decarbonisation lever.

ALTERNATIVE FUELS INCLUDING BIOMASS WASTES CAN
REPLACE 100% FOSSIL FUELS FOR THE GENERATION OF
PROCESS HEAT FOR CEMENT MANUFACTURING
PROVIDED REGIONAL SUPPORTING MECHANISMS ARE
IN PLACE.

4 IRON AND STEEL MANUFACTURE

4.1 INTRODUCTION

There are four main technologies for steel production: the blast furnace-basic oxygen furnace (BF-BOF), the direct reduction/electric arc furnace (DRI-EAF), the smelting reduction furnace (SRF), and the electric arc furnace which is used for recycling scrap metal (see Figure 20, Table 6) (Kelsall2023). The BF-BOF route dominates globally and generates approximately 70% of the world's steel. The EAF generates approximately 25% of the world's steel, while SR technology (not shown in Figure 17) is used in only 0.4% of global steel production and so is not discussed further. The DRI-EAF technology produces approximately 5% of global steel production and operates with either natural gas or coal.

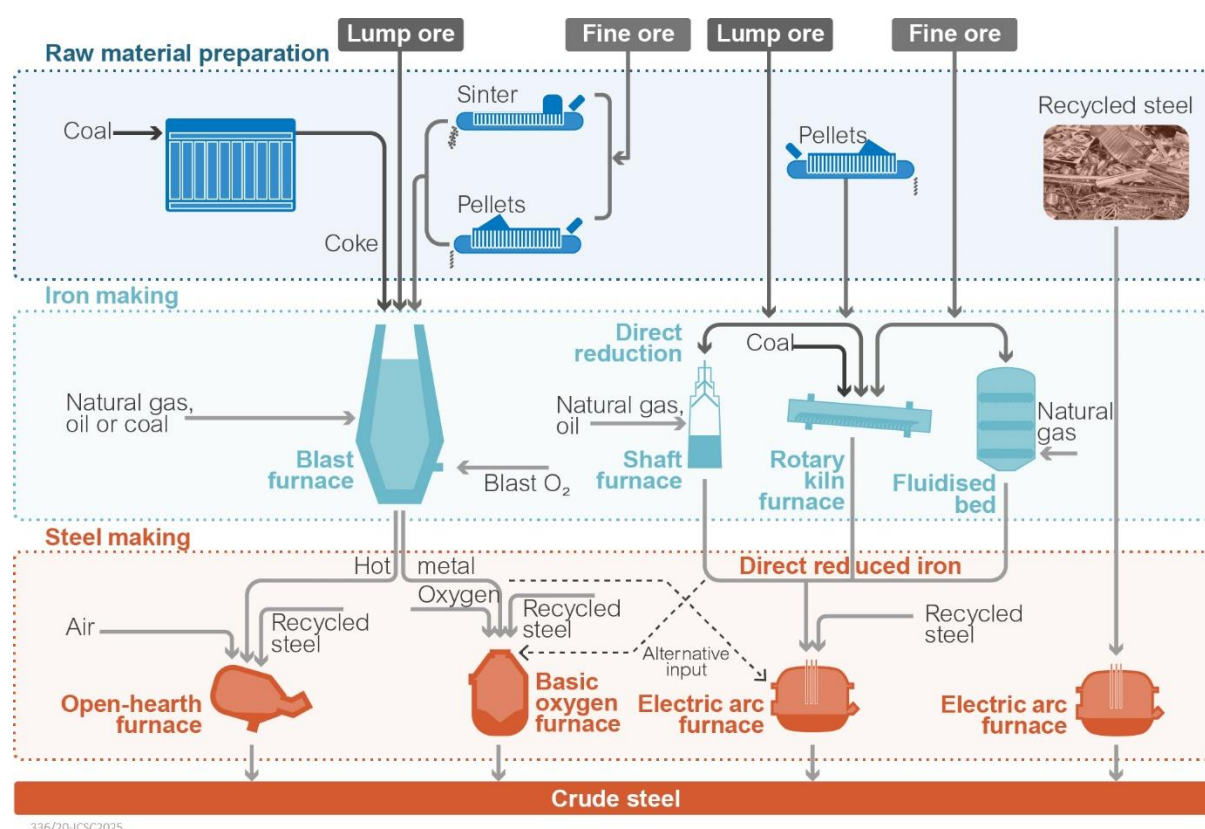


Figure 20 Primary steel production methods (adapted from Kelsall, 2023)

TABLE 6 OVERVIEW OF IRON AND STEEL MAKING PROCESSES (ADAPTED FROM KIM AND OTHERS, 2022)		
Process	Subcomponents	Description
Raw material preparation	Sintering	A mixture of iron ore fines, iron-containing wastes, coke breeze, and limestone are burned and sintered into agglomerates for the BF
	Pelletising	Iron ore fines are purified and converted to pellets for transportation from the mine and for use in the BF
	Coke making	Coking coal is heated slowly in slot ovens and carbonised to form coke for use in the BF. Off gases also pass to the BF in an integrated plant
Iron making	Blast furnace (BF)	Iron ore, sinter, fluxing material, and coke are charged in alternating layers in an enormous shaft furnace. Heat is provided by pulverised coal combustion through injection with air at the BF base. This leads to the generation of reducing gases from coke gasification also. Iron ore is gradually reduced and then melted as it travels down the furnace. The molten pig iron produced is tapped and passed to the BOF
	Direct reduction (DR)	Iron ore and/or pellets are reduced to direct reduced iron (DRI) in the solid-state using syngas as a reductant. Syngas is from natural gas reforming or from coal gasification
	Smelting reduction (SR)	An alternative to the BF, it produces smelting-reduced iron (SRI). Generally, fines, ore and/or pellets are pre-reduced by hot syngas from an oxygen-fired slagging gasifier before passing to the gasifier for further reduction. Molten SRI is tapped at the bottom of the coal gasifier
Steel making	Basic oxygen furnace (BOF)	Hot metal from the BF is converted to steel by high-temperature combustion of residual carbon with oxygen, and concurrent removal of impurities in the slag
	Electric arc furnace (EAF)	Usually used for scrap metal, DRI or pig iron. Carbon is also added to the load (coal or coke) and via oxyfuel burners (natural gas or coal). The load is heated by both electrical arcs and by chemical energy released in combustion. Crude steel is tapped from the hot liquid
Casting, rolling, finishing		Crude, molten steel from BOFs or EAFs is passed to rolling or finishing mills in a continuous caster to produce semi-finished steel. This is then processed into final steel products, such as coil, sheets, or strips

Table 7 compares the energy consumption and typical CO₂ emissions of the different routes. This Chapter provides an overview of the main manufacturing routes (Sections 4.1–4.3) and summarises some of the opportunities for carbon reduction. Carbon capture is an important route under consideration for decarbonising the sector, and in the IEA NZE scenarios, it provides more than 50% of the reductions. This topic has been reviewed in detail for the ICSC by Kelsall (2023), so is not considered here. Other routes include energy efficiency, technology changes and the utilisation of biomass and waste. These routes are summarised in this Chapter (Sections 4.4 and 4.5) and the opportunities for biomass are discussed in more detail in Chapter 6.

TABLE 7 ENERGY CONSUMPTION FOR THE DIFFERENT IRONMAKING ROUTES (CAVALIERE, 2019; MOUSA AND OTHERS, 2016; LING AND OTHERS, 2024; ECHTERHOF, 2021)

Process	Energy consumption, Gt/t hot metal	Direct CO ₂ emissions, tCO ₂ /t hot steel
Blast furnace (BF)	12.7–18.6	1.2
Direct reduced iron (DRI)	10.9–16.9	0.6–1.0
Basic oxygen furnace (BOF)	0.7–1.0	0.06–0.2
Electric arc furnace (EAF)	4.0–6.5	0.24

4.2 THE INTEGRATED BLAST FURNACE-BASIC OXYGEN FURNACE FOR STEEL MAKING

BF operation is described in Kelsall (2023) and a schematic of an integrated plant is shown by the processes in Figure 17a. In summary, inputs into the BF are sintered iron ore agglomerates, lump iron ore, coke, coal, limestone (a fluxing material which helps to remove impurities), and air. The coking process is described in Section 5.3. It produces high-grade metallurgical coke in several sized fractions: lump or ‘bell coke’ (40–80 mm), nut coke (10–30 mm) and in fines (<12 mm) known as coke breeze (Babich and Senk, 2015). The lump (bell) coke and nut coke are used in the BF and added in alternating layers. Nut coke improves the permeability of the charge in the furnace and decreases the pressure drop. This greatly enhances the productivity of the BF (Babich and Senk, 2015).

4.2.1 The sinter plant

Coke breeze is used in the sinter plant which takes pelleted iron ore fines (produced upstream close to the mine site, about 8 mm in size), recycled iron-based material, fluxing agent (limestone or dolomite) and sometimes binders. The first step produces granules through crushing, blending and mixing with the addition of moisture. They are passed to the sinter bed on a travelling grate combustor (Cavaliere, 2019). Burning on this bed achieves temperatures of 1200–1300°C and results in a sinter cake. The cake is then crushed and sized to yield larger agglomerates (up to 50 mm) with the physical and metallurgical characteristics and gas permeability required for efficient use in the BF operation. The coke breeze material acts as both a bonding agent in the initial agglomeration step and as a heat source, as it combusts in the sintering process (Lu and Ishiyama, 2015). It also calcines the limestone and provides some partial reduction of the iron ore which sinters with the added fluxes (and silica in the coke ash). The product from the sinter is lumps of clinker-like material that are fed into the BF. The combustion characteristics of the coke breeze material mean that a narrow, high-temperature sintering zone is generated in the sinter plant which improves energy and heat transfer efficiency in the sinter bed. The thermal and reducing properties of the coke breeze also generate sinter with the required qualities for the BF (Cavaliere, 2019).

4.2.2 The blast furnace

The BF is based on a counter-current moving bed reactor, whereby solids (and further down, molten liquids) move down the reactor while heat and gases travel up the reactor (*see* Figure 21). Solids are charged in alternating layers and move downwards by gravity. BFs can be over 100 m in height, producing 11,000–13,000 t/d of molten metal, and it can take 5–8 hours for the material to move to the bottom of the furnace (Babich and Senk, 2015). In the BF iron oxides are reduced using carbon-based reducing agents, and heat is provided by combustion of injected pulverised solid fuel, usually coal (as pulverised coal injection, PCI), natural gas, or oil, in the lower part of the furnace. Therefore, the furnace has a temperature gradient increasing from top to bottom, and oxidising and reducing zones, much like a counter-current gasifier. The hottest temperature of over 2000°C is experienced in the high-velocity injection area, the raceway zones, where air and pulverised coal or gas are injected via tuyeres near the bottom of the furnace and undergo exothermic combustion. Above this zone, gasification of coke (as well as combustion and gasification of added PCI or other supplementary heating fuel) takes place at elevated rates and generates the reducing gases (carbon monoxide and hydrogen). The carbon monoxide and hydrogen reduce iron ore to produce molten iron and slag that exits the BF at the bottom. The gas continues to move upwards, exchanging heat and reacting with the solids as it does so in a series of exothermic and endothermic reactions, until it leaves the furnace at a temperature of 100–200°C. Many of the reduction reactions are reversible and related to temperature, and the ratio of CO/CO₂ needs to be >stoichiometric to ensure efficient operation (Babich and Senk, 2015). Hydrogen is thermodynamically the more powerful reductant at temperatures above 810°C. Further details of the intricate tuning required in BF operation and the detailed chemistry and physics of the system are given in the excellent reviews by Babich and Senk (2015) and Cavaliere (2019).

The role of coke is critical in the physics and chemistry of steel making in the BF. It not only acts to support the burden of solids as they move down the furnace, but also needs appropriate permeability for gas flow, and reactivity to survive to the ‘active coke zone’ where temperatures are in excess of 1400°C.

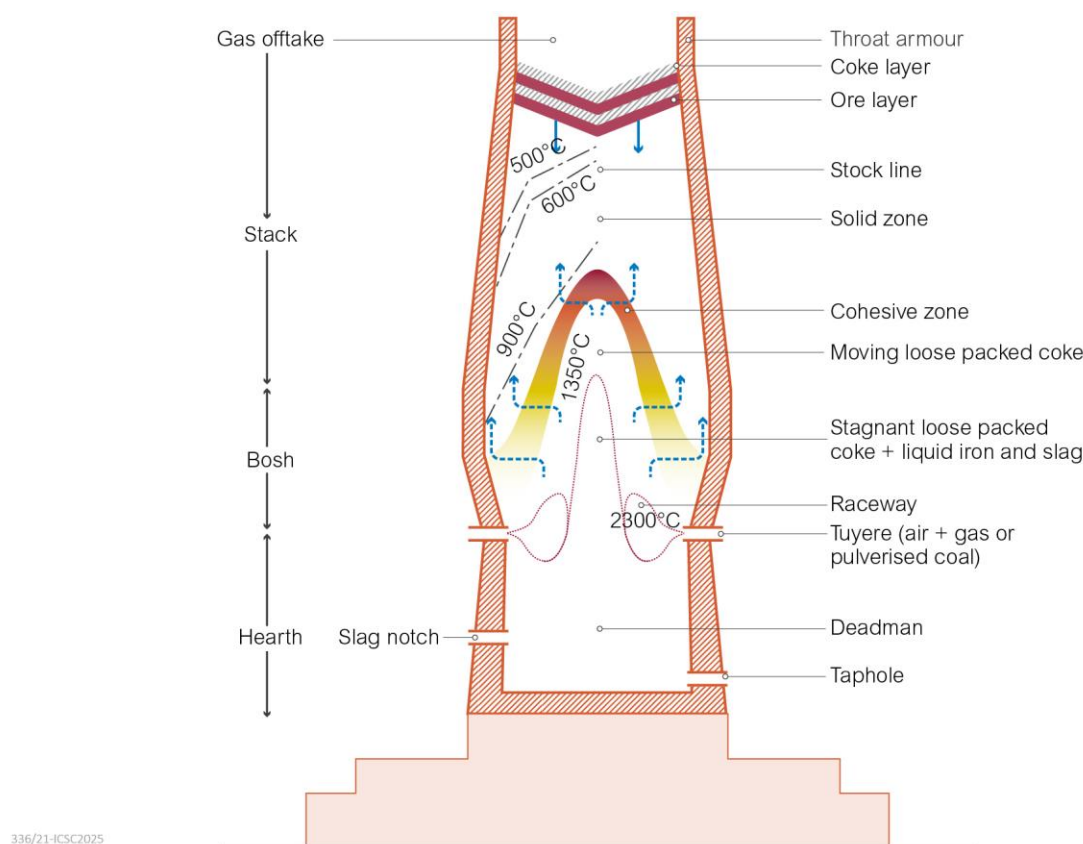


Figure 21 Blast furnace cross section (from Couch, 2001)

4.2.3 The basic oxygen furnace

From the BF the molten pig iron moves into the basic oxygen furnace (BOF), a pear-shaped vessel where it is converted into crude steel. Here, residual carbon content is decreased from 4% to approximately 1% by its reaction with a jet of high-purity oxygen in intense exothermic processes generating temperatures in the ideal range of 1600–1700°C (Lotfy and others, 2014). Scrap steel can also be recycled in the BOF and its addition acts as a coolant. In the hottest region (near the base of the furnace), residual carbon in the melt is oxidised to CO and complex chemistry between metal and slag species takes place which removes other impurities, such as phosphorus and sulphur, from the metal, and dissolves them in the basic slag. The output from the BOF is crude steel with the required composition, which is subsequently cast into different steel products in downstream casting and rolling processes (Kelsall, 2023).

The whole of the BF-BOF route is integrated, whereby waste gases from the coke oven, BF and BOF are recovered and reused as fuel or to provide process heat or fired in the on-site electricity plant. There have been many innovations in BF operation to improve performance and productivity as well as to reduce carbon emissions. Some of these approaches are discussed in Section 4.4.

4.3 THE DIRECT REDUCTION-ELECTRIC ARC FURNACE

The main alternative to the BF-BOF route for steel making uses the EAF. Depending on the steel mill, inputs to the furnace consist of a mix of scrap metal, additives (alloying elements, slag formers), directly reduced iron (DRI), and/or pig iron (from the BF). The preheated charge is added through the top of the furnace and after resealing, the whole load is heated in stages via electric arcs generated between graphite electrodes. Additional charges may be added before tapping, and the tap-to-tap cycle time is of the order of 40 minutes (Cavaliere, 2019). Chemical energy also plays an important part, usually introduced by oxyfuel lance burners but also from other contaminants introduced with the scrap (such as from paint, oil or grease) or from carbon directly added in some form, so-called charge carbon (Echterhof, 2021). The output is liquid steel which is tapped and passed to downstream processes. Despite the high electricity demand, the carbon emissions are much lower than from the integrated BF/BOF mills, but this depends on the amount of DRI added in the process (Table 3).

4.3.1 Direct reduced iron

Direct reduced iron (DRI) or sponge iron is added to the EAF as a substitute for premium scrap metal and pig iron and enables cheaper, low-quality grade scrap to be used, thereby lowering overall raw material cost. Direct reduction is the removal of oxygen from the iron ore without the need for melt forming – that is, in the solid state. The normal reductants used are natural gas or coal, and the DRI produced is highly porous with a metallisation degree of 85–95% and a carbon content of 0.5–4.0% (Cavaliere, 2019). The high porosity makes it extremely reactive to oxidation and so hot briquetting of the iron happens after the DRI process to help inhibit this reaction. There are many commercial processes, and the small-scale and low capital investment requirements of the plant means that the number is growing worldwide. Some of the commercial processes are indicated in Figure 22. The processes use different reactors including rotary kiln, rotary hearths, fluidised bed or shaft furnace and the maximum capacity per module is <0.5 Mt/y rotary kiln, ~0.5 Mt/y rotary hearth and fluidised bed, 1.5–2.5 Mt/y shaft furnace, compared to over 5 Mt/y for the BF. The process times vary from minutes to several hours depending on the technology. The Midrex® and Hyl-Energiron processes accounted for over 90% of global DRI in 2019 (Cavaliere, 2019). Both these processes use syngas as the reductant for iron ore pellets in a counter-current shaft reactor. The syngas can either be from natural gas reforming and/or for added flexibility from oxygen-fired coal gasification. Using cleaned syngas means that the DRI is free from tramp elements. The reduced iron from the direct reduction process is then converted to steel in the EAF.

4.3.2 Electric arc furnace

According to Echterhof (2021), the charge carbon is responsible for 40–70% of the direct emissions from the EAF. As noted in Kelsall (2023), the charge carbon is often coal or coke and its role is to improve energy efficiency and help with the carburisation (where carbon is absorbed in the metal) and slag foaming processes. If the main aim of the charge carbon is to release carbon monoxide which dissolves in the melt for carburisation, then the reactivity needs to be slow enough to allow time for this to happen. If the main aim is for the release of chemical energy as heat, then the CV and quick energy release are important (Echterhof, 2021).

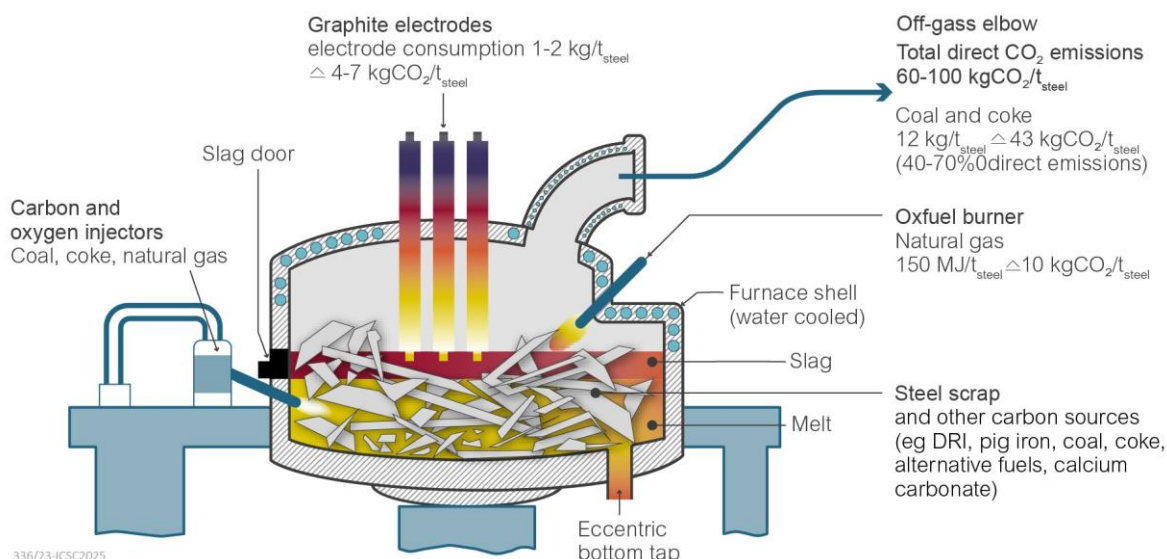


Figure 23 Direct CO₂ emissions from a typical EAF (adapted from Echterhof, 2021; Hay and others, 2021)

The injected carbon plays an important part in the furnace chemistry. Its role is to encourage slag foaming through the release of carbon monoxide and CO₂ gas bubbles in reaction with iron oxide, which recovers iron from the slag, or via the C-CO₂ reaction. Hydrogen in the injected fuel also contributes, both in the foaming process and in reduction reactions of iron oxide. Foaming increases the energy transfer efficiency of the slag, reduces heat losses and protects the refractories, among other things (Echterhof, 2021). Fast reaction is the main requirement for the carbon source for the burners, together with high carbon content and low ash content; normally natural gas or coal is used. If coal is used, then the small particle size enables the pulverised fuel to be conveyed pneumatically into the oxyfuel burners.

4.4 DECARBONISATION OPTIONS FOR THE IRON AND STEEL SECTOR

The demand for crude steel has been estimated to increase by 30–60% in 2050 under a BAU projection (Kelsall, 2023). The adoption of commercially available BAT to improve operational efficiency and waste energy recovery are some of the measures that are considered to result in incremental energy savings and emission reductions in the IEA I&S Roadmap (IEA, 2020). Table 8 lists the main decarbonisation options considered for the I&S sector (Kelsall, 2023). Decarbonisation rates depend on many factors including the age and nature of the existing fleet; for example, the BF fleet dominates in Asia and is relatively young (Brooks and others, 2023).

The electrification of the steel (and cement) industries is considered critical in the IEA NZE Scenario, although will have a smaller role by 2030 due to time requirements for the development and commercialisation of the technologies needed (IEA, 2023b). Overall, electricity consumption by the industrial sector is expected to grow from 23% in 2022 to 49% in 2050 (IEA, 2023b). In the scenario, hydrogen for high-temperature heat is expected to make a significant contribution to the

decarbonisation of this sector, with 80% of the low-emissions hydrogen produced in 2050 coming from electrolysis (IEA, 2023b). According to the IEA (2023b), the installation of electrolyzers for hydrogen reached a capacity of nearly 700 MW in 2022, which is more than double that of the two previous years. There has been progress in the I&S sector too, with an increasing number of hydrogen-based DRI projects announced since 2021. Notably, the updated 2023 IEA NZE Scenario (IEA, 2023b) expects CCUS to play a smaller role in the decarbonisation of the I&S industry than that anticipated in the 2021 Scenario due to the slow progress of CCUS in this sector. The use of biomass as an alternative to fossil fuels is considered to play a small role in the IEA's I&S Roadmap (IEA, 2020), with the share of bioenergy increasing from <1% to 5% in 2050 in the sector's total energy input mix in their Sustainable Development Scenario. Although biomass injection in the form of charcoal into BF's is already used commercially at a small scale in Brazil, its wider use presents several challenges, not only because of the limited availability of sustainable biomass but also due to the specific chemical and physical properties required. Thus, further development of the charcoal production process may be needed, as discussed in more detail in Chapter 5. For each I&S plant the optimum solution will depend on location, available natural resources, infrastructure, and policy incentives which all have a large impact on the economics (Fan and Friedmann, 2021).

TABLE 8 MAIN DECARBONISATION LEVERS FOR IRON AND STEEL MANUFACTURING CONSIDERED IN NZE 2050 SCENARIOS (KELSALL, 2023; IEA, 2021B; MPP, 2021; CAVALIERE, 2019; KIM AND OTHERS, 2022)

Decarbonisation lever	Some examples of approaches	Requirements or assumptions	Potential reductions
Reduction of demand	Changes in design (lightweight vehicles, more durable products), manufacturing methods (improved metallurgy, improved yields/ reducing scrap in product manufacturing), construction practices (substitution of steel, higher efficiency in building construction)	Cross-sector strategies and significant societal behavioural change	Global reduction demand for steel in 2050 ~12% higher than current levels
Incremental improvements	Use of BAT: Improvements in energy efficiency, heat recovery and using drop-in fuels, including biomass based	Improved burners, furnaces, compressors, efficient ladle preheating, waste heat recovery, waste gas recovery and use, coke dry quenching	Approximately 16% reduction in emissions by 2050 from improved efficiency and use of biomass and waste fuels.
Increasing scrap steel recycling – secondary steel production	Shifting from BF-BOF to EAF processing for ~75% reduction in both emissions and energy consumption – with potentially higher reductions when moving to low-carbon and renewable electricity. 'Post-consumer scrap' recycling (design for end-of-life and reuse) 'Pre-consumer scrap' recycling	Material recirculation strategies to increase collection of end-of-life steel and improve recycling (better systems for collection, separation and to minimise contamination and downgrading of steel)	Both reduced demand and increased recycling of scrap when maximised are estimated to achieve up to a 40% reduction in global steel demand in 2050 compared with the business-as-usual projection
Adoption of innovative technologies for low-carbon iron and steel making	There are around 17 potential transitional and NZE technologies identified, including hydrogen-based DRI, iron ore electrolysis, and CCUS-based technologies, including those integrated with smelting reduction, natural gas-based DRI technologies, and innovative blast furnace retrofit arrangements for young fleet plants with access to low-cost fossil fuels and CO ₂ storage	CCSU-based technologies account for 45–53% of primary steel production in 2050, and 90% carbon capture is assumed (considered a low value) Gradual replacement of natural gas with low emissions hydrogen in DRI-EAF and DRI-Melt-BOF technologies for ~40% of primary steel production in 2050 Electrolyser technologies coupled with EAFs adopted in regions with access to low-cost, low-emissions electricity - producing 15% of steel in 2050	Most of the emissions reduction after 2030 are expected to come from innovative technologies. Steel production technologies utilising CCUS are foreseen to provide reductions of ~650–670 MtCO ₂ /y by 2050

4.5 OPPORTUNITIES FOR BIOMASS

Figure 24 illustrates the uses of coal and coal products in the fabrication of steel and therefore represents possible opportunities for the substitution of coal and its products by biomass-derived products (Suopajärvi and others, 2017). The boxes outlined in red in Figure 24 indicate opportunities for biomass, including fuel for providing heat requirements in the Tuyere injection, and as a chemical reductant of iron, for example, by partial substitution of coal/coke in the lump coke or the coke breeze by biomass-derived products. Raw biomass cannot be used as a direct substitute due to its lower carbon content, CV, and potentially high moisture content. Thus, some form of thermal processing is necessary, which could include torrefaction (temperatures of around 300°C), biochar production (temperatures of around 400°C) or charcoal production (500–800°C). Substitution by charcoal has received the most attention.

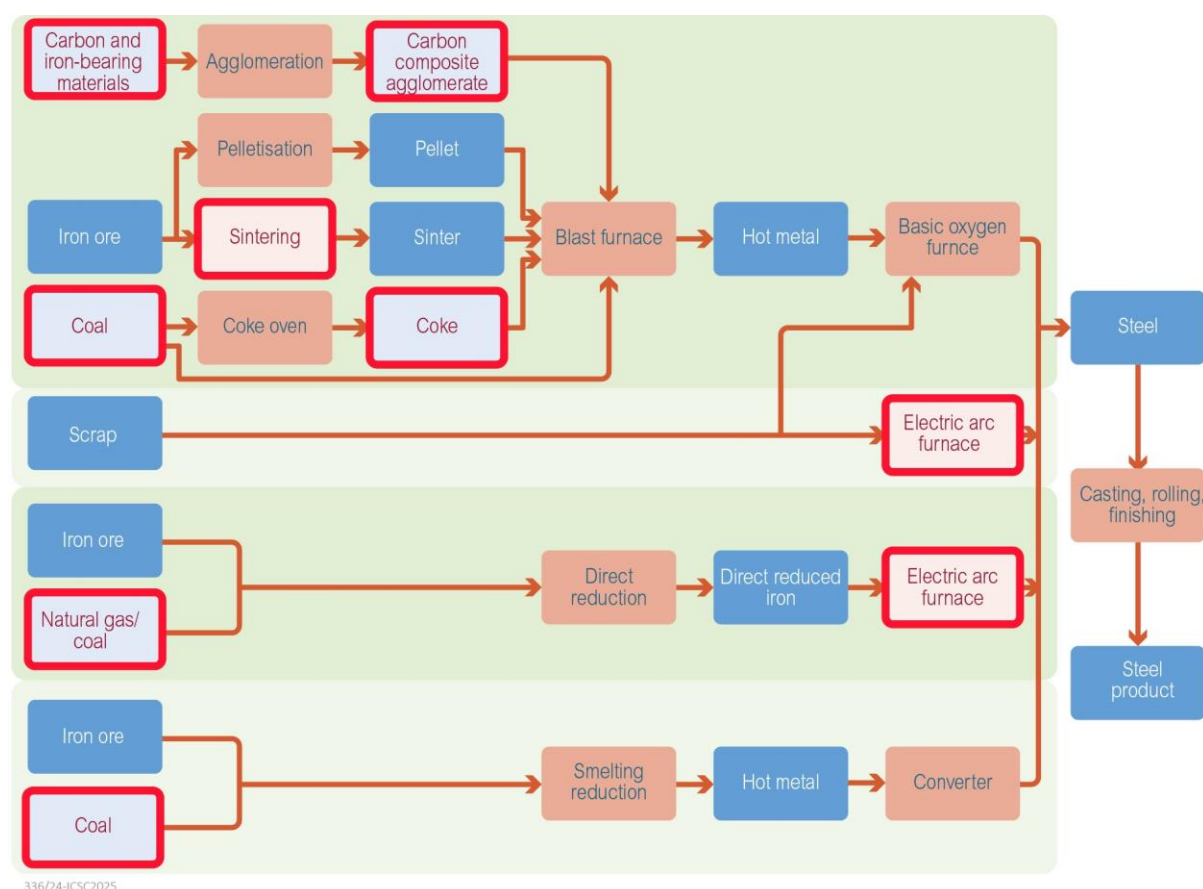


Figure 24 Steel production routes (adapted from Suopajärvi and others, 2017)

Some key properties necessary for coal-derived products in steel making are given in Table 9. There are strict specifications for efficient operation, and high carbon content, low moisture, ash and sulphur (and therefore high CV) are the general requirements, in addition to the size and strength of the material. In theory, it may be possible to produce some products from biomass with similar properties to the conventional materials used. However, there are limitations, due to economics, and fundamental thermal behaviour and carbon science in the production and properties of products from coking coals

versus biomass. This aspect is reviewed in Chapter 5. Chapter 6 revisits this topic when considering the current status of substitution of coal and its products by biomass-derived products.

TABLE 9 FUEL AND REDUCING AGENT QUALITY REQUIREMENTS (PROXIMATE ANALYSIS) FOR BF-BOF (ADAPTED FROM KOVERIA AND OTHERS, 2020)				
	Blast furnace	Iron ore sintering	Blast oxygen furnace pulverised fuel	Pulverised fuel
Grain size, mm	25-80	<3 (85–90%)	6–25	0.1–0.07
Moisture, % (as-received)	<5 (wet) <0.3 (dry quenching)	<15	<4	0.5–1
Ash, % (dry basis)	<9.0	<16.0	<12	<9.0 for coke <8.5 for coal
Total sulphur, % (dry basis)	>0.6	<2	<0.6	<1 for coke <0.5 for coal
Volatile matter, % (dry basis)	>0.5	>2.5	<12 if fuel is blown in, or <30	~20%
Fixed carbon, % (dry basis)	>90	>76	>70	–
Blast oxygen furnace is next generation technology from the BF using oxygen-enriched blast rather than air. Integrating with top gas recycling (and potentially CCS) offers substantial carbon emission reduction and enhanced efficiency in production (see Zhang and others, 2024 for a detailed review)				

4.6 COMMENTS

Two main technologies dominate I&S production, the integrated BF-BOF plant and the DRI-EAF plant which have inherently different carbon intensities, although this also depends on the age of the fleet and what BATs have been installed. Both routes currently use substantial coal-based fuels to provide process heat and/or reducing ability. Road maps for decarbonisation assume that electrification and renewable hydrogen, combined with CCS, will become long-term options for decreasing the carbon intensity of this hard-to-abate sector. In the near term, there are opportunities for incremental improvements in efficiency and emissions through the adoption of BAT, but also through the use of drop-in biogenic fuels. The immediate challenge for the industry to increase its use of sustainable biogenic fuels is the development of drop-in fuels with properties that match those provided by coal and coke.

BF-BOF AND DRI-EAF ARE THE DOMINANT
TECHNOLOGIES IN I&S MANUFACTURE; BOTH ARE
HEAVILY RELIANT ON COAL AND COKE.
OPPORTUNITIES FOR PARTIAL SUBSTITUTION BY
BIOMASS INCLUDE COKE MANUFACTURE, SINTERING,
DRI AND INJECTED AND CHARGE CARBON IN THE BF
AND EAF.

5 CARBON SCIENCE

Most attention in decarbonising the steel industry has been paid to process innovations, modifications to the BF, or retrofitting CCS (Kelsall, 2023). An alternative approach is to displace some fossil fuel using biomass-derived products, with the possible opportunities shown in Figure 24 (Chapter 4). The advantage of biomass is its short carbon production cycle. This means that if it is produced with maximum sustainability and minimum CO₂ emissions, its substitution for coal products will displace the CO₂ emissions from the long-carbon fossil fuel cycle. Another advantage is that using biomass may require minimal modification to existing plant and so a lower Capex. This Chapter uses fundamental carbon science to explain the challenges and limitations of substituting coal products with biomass products.

5.1 ISOTROPIC AND ANISOTROPIC CARBONS

Carbonisation is the process of producing material with increasing carbon content through heating (such as pyrolysis/devolatilisation). The resulting solids produced have a complex chemical structure. All carbons, except diamond, are based on fused 6-carbon atom ring (graphite) type structures which produce layer-planes, or lamellae. In graphite, the lamellae lie parallel to each other and the structure of carbons can be described in terms of the perfection of this stacking, known as isotropic and anisotropic (see Figure 25). The presence of heteroatoms (O, N, S), 5-membered rings, stacking faults or other defects, or bonding between layers, results in bending and twisting of the lamellae so that they cannot stack together perfectly. Thus, most carbons have localised regions where the structure resembles graphite – so-called crystallites – embedded in less-ordered areas (Marsh and Menendez, 1989). *Isotropic carbons* have random orientation of lamellae, meaning that measured properties are not a function of orientation. This arrangement of lamellae leads to extensive pore structure within the carbon structure and often high surface area characteristics, for example, 500–1500 m²/g.

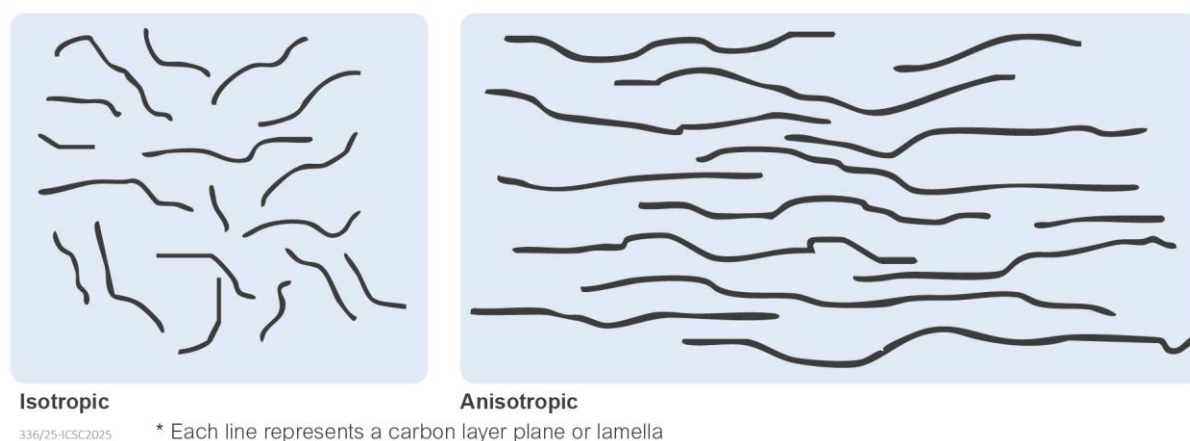


Figure 25 Representations of isotropic and anisotropic carbon structures (adapted from Marsh, 1989)

Anisotropic carbons have larger lamellae, fewer defects and heteroatoms, and the stacking arrangement is more aligned in parallel. Anisotropic carbons are either partially-graphitising or graphitising. This means that further heating will remove defects and heteroatoms and promote increasing alignment of the lamellae. For graphitising carbons, graphite can be produced if the carbon experiences a high enough temperature. These carbons would already be anisotropic when produced at temperatures of 1000°C for example, and because of better packing of the lamellae, the porosity is much lower (typically surface areas of $<10 \text{ m}^2/\text{g}$).

Figure 26 illustrates the progressive increase in order, through the removal of defects and impurities during heat treatment (annealing) of an anisotropic graphitising carbon (Marsh and Griffiths, 1982). In contrast, isotropic carbons are non-graphitising and isotropic upon preparation. The type of structure that is produced during the preparation of the carbon material is related to the precursor material used. Biomass and lignite coals produce isotropic carbons on heating. Generally, materials which pass through a fluid phase during carbonisation yield anisotropic carbons; this includes pitch, PVC, coal tar pitch, and coking coals. Char is the generic name for carbons produced from coal, but anisotropic graphitisable carbons produced from the carbonisation of coal are known as coke. For use in the I&S industry, they will have experienced temperatures of up to 1100°C to produce an anisotropic material of high strength and low porosity.

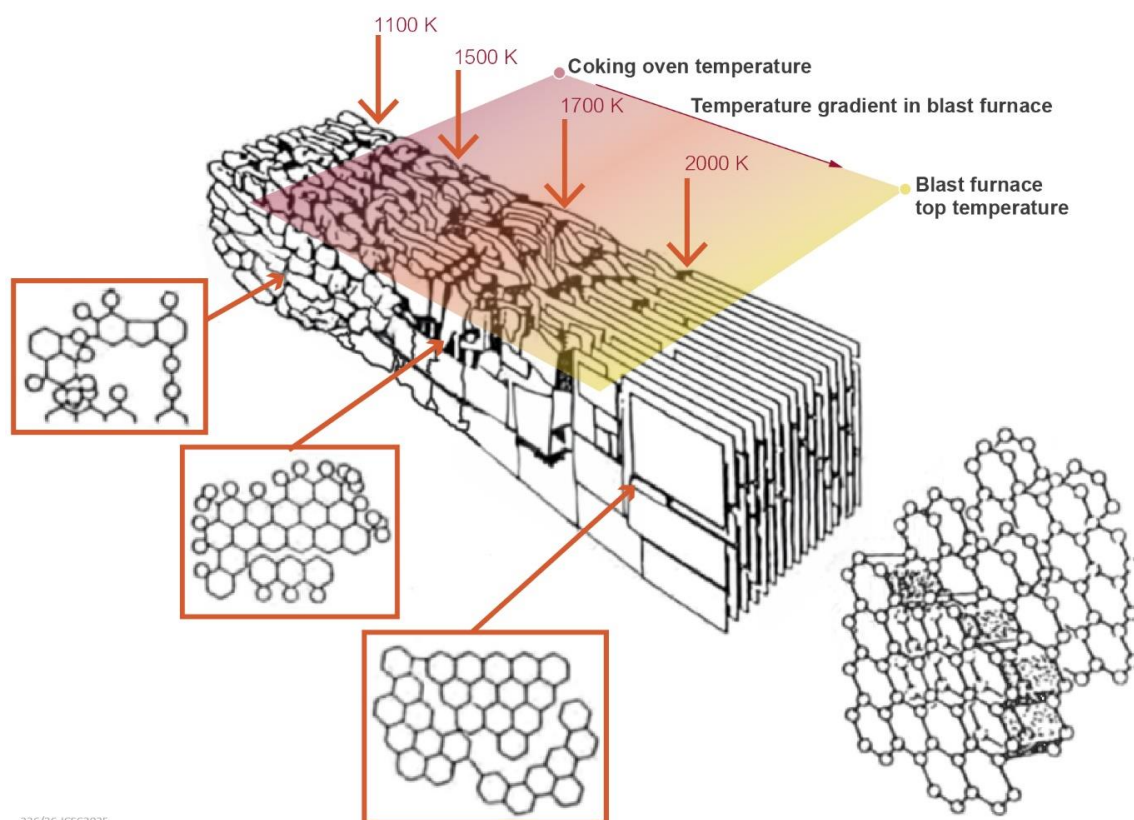


Figure 26 Changes in structure as non-graphitic, anisotropic carbon is converted by heat treatment to graphite (from Marsh and Griffiths, 1982)

5.2 CARBONISATION OF COKING COALS

Coke acts as both a fuel and a reactant in the BF, as well as a structural support for the heavy burden of materials. It also provides permeability for gas flow through the solid bed and has slow enough reactivity with the gases in the furnace to survive and provide a coke bed at the bottom of the furnace where temperatures can be up to 2000°C. Coals with a narrow range of properties are used to make coke with these characteristics, shown in the proximate analysis indicated in Table 9, and with unique thermal processing properties such that they soften and produce a strong, anisotropic and graphitising material. Only coals of specific rank and maceral composition satisfy these requirements. Vitrinite macerals are derived from woody biomass and high vitrinite, medium-rank (bituminous) deposits generally deliver good coking coals. To appreciate the reason for this, it is useful to understand the structural features of coals and what happens as they are heated (see Sections 5.3.1 and 5.3.2.).

Most metallurgical coke is produced in a battery of slot ovens, each containing a charge of blended coal which is heated in the absence of air via externally-heated walls. The charge slowly heats over 12–30 hours to 1000–1100°C. During this time, it undergoes decomposition and carbonisation reactions to produce typically 750–800 kg of coke, 45–90 kg of coke breeze, and gas, tar and light oils (and ammonia) per tonne of coal (Couch, 2001).

5.2.1 The structure of coal

The structure of coal is extremely complex: on a microscopic level, individual macerals can be identified which are coalified remains of woody material (vitrinites), spores, shoots and stalks (exinite or liptinite) and carbonised wood (inertinite), among other things. At the molecular level, there is an extended polymeric coal matrix structure containing aromatic and aliphatic components together with nitrogen, sulphur and oxygen functional groups. Inorganic material is interspersed in the structure and there are also smaller ‘guest’ molecules loosely bound within the pores of the organic framework. Generally, with increasing rank, the size of the fused aromatic area increases, heteroatom functional groups decrease, and the ordering of lamellae increases.

5.2.2 Thermal decomposition of coal

Thermal decomposition of coals depends on many factors, particularly coal rank and maceral composition. Heating of coal results in the first distillation of some of the ‘guest species’ within its structure, such as water, methane and other low molecular weight organic molecules. Further heating to 350–450°C begins to cleave bonds within the molecular structure with the release of volatiles – a mix of gases and light organics from the functional groups and aliphatic regions, as well as many medium and heavy tar components. As these tars and oils migrate through the particle, pores develop. At the same time, the tars and oils begin to soften the rest of the reactive macerals in the solid and, for some coals, form a fluid mass. Then, at 400–600°C gases escape (and the particles swell for some coals) and the organic matrix reacts with both released volatiles and itself in repolymerisation, ring formation

or carbonisation reactions to produce a carbon-enriched solid. This solid is lower in hydrogen, oxygen, nitrogen, sulphur and others, has higher aromaticity and has larger lamellae than the original coal. Further heating results in the loss of hydrogen and methane as the lamellae anneal and become increasingly ordered. Very slow heating can promote the carbonisation reactions, which increases solid yields and, in the case of coking coals, prolongs the fluid phase which enhances the growth and stacking of the layer planes (see Section 5.4.3).

5.2.3 Coke formation mechanism

Early investigations of carbonisation of coking and non-coking coals recognised that the development of a graphitisable carbon from coal, essential for producing a strong coke, depended on the ability of the lamellae in the coal to rearrange and stack, which required a fluid (plastic) state. It was established that some coals swelled or became fluid on heating and standard test methods were developed to assess this, and so a coal's suitability for coke production (for example: ISO 502:2015; ISO 10329:2017; ISO 349:2020; ISO 23873:2010). A detailed understanding of the mechanism to produce anisotropic coke was not gained until the 1960s.

A discovery of a coal seam in Australia that had been exposed to temperatures greater than 1000°C by a magma flow was an important find for elucidating the mechanism (Taylor, 1961). The coal seam had experienced a very gradual temperature gradient and the entire transition of coal to coke could be followed by taking samples from different parts of the seam. It was found that as the coal decomposes and releases tars, the vitrinite macerals in the seam change from anisotropic to isotropic at temperatures approaching the onset of plasticity. This happens over a narrow temperature range (around 475°C). At a slightly higher temperature (480°C) tiny reflective, anisotropic spheres form in the isotropic mass, which gradually grows bigger with increasing temperature, at the expense of the isotropic fluid. Here, the lamellae are beginning to order themselves and begin aligning. By 490°C, no plastic vitrinite remained and the solidification of coke was complete. This fluid phase in which the anisotropic spheres appear is known as the mesophase. The mechanism is illustrated in Figure 27.

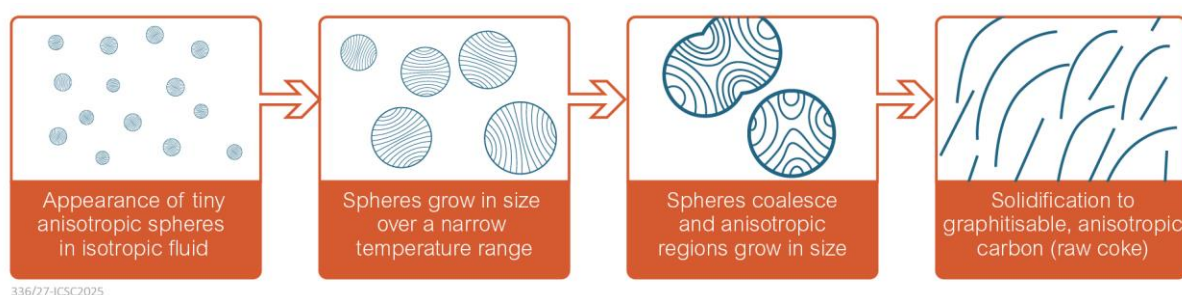


Figure 27 Development of the mesophase during carbonisation to form coke (adapted from Yuan and Cui, 2019)

During coking the blended coal mixture is heated in a slot oven where heat is transferred slowly from the oven walls to the centre of the coal charge. The slow heating moves from the walls to the centre of the charge, first producing volatiles followed by a plastic zone, which propagates through the charge.

As it heats further the charge resolidifies to ultimately form coke. Thus, coke production occurs over time, starting from the walls of the oven and moving through the coal charge until the centre of the charge also becomes coke. The fluidity of heated coal varies with its volatile matter, passing through a maximum of around 30–35% volatile matter (bituminous coals). Lowest rank coals (high volatile, brown coals and lignites) do not become very fluid because of extensive C-O-C cross-linking, similar to biomass (see Section 5.5). Highest-rank coals (anthracites, partially graphitising) do not become very fluid because there is carbon-carbon cross-linking between large polyaromatic molecules, and little tar is produced. Intermediate rank (coking) coals of approximately 22–24 wt% volatile matter have hydrogen-bonded aromatic structures which can become fluid on heating. The resultant solid from coke-making has a structure similar to that depicted in Figure 27, but it will transform in the BF, where there will be competing reactions of gasification to yield a more reactive carbon, and annealing to produce more ordered carbon.

5.3 CARBONISATION OF BIOMASS

Biomass behaves differently to coking coals on heating. Due to the different chemical structures of biomass, it does not pass through a fluid mesophase during carbonisation, and the results are isotropic, porous carbons.

5.3.1 The structure of biomass

The mass in the cell walls of biomass is composed of three main polymers, cellulose (40–50%), hemicellulose (up to 15–35%) and lignin (10–30%). The relative content of the three polymers depends on the nature of the biomass but the main component is always cellulose. The plant cell walls consist of microfibrils made up of a core of cellulose surrounded by hemicellulose and encrusted by lignin polymers (Brethauer and others, 2020). The chemical nature of lignin is reminiscent of young coals and there is cross-linking between substituted aromatic units to create large polymeric structures which have high thermal and chemical resistance.

The hemicellulose polymers contain crosslinked polysaccharide polymer chains. Cellulose is also a polysaccharide, made up of D-glucose monomers. The polysaccharides are very different chemically to lignin, have no aromaticity and very high oxygen content. This means that the gas, liquid and solids that result from heating biomass are different in nature and quantity from heating coal. The products vary with the heating rates, temperatures and vapour-solid residence time and the thermal behaviour is explained in Section 5.5.2.

Typical proximate and ultimate analysis is given in Table 10 compared with a bituminous coking coal. As biomass has a much higher oxygen-content, this partially oxidised solid produces large amounts of light-to-medium volatile oxygenated products during heating and only limited solid material. Poor carbon yield is one of the economic limitations when seeking to substitute coal products with biomass products in I&S manufacturing.

TABLE 10 ILLUSTRATIVE COMPOSITIONS OF WOODY AND HERBACEOUS BIOMASS COMPARED TO CELLULOSE AND BITUMINOUS COAL (AUTHORS' WORK)

	Pure cellulose	Woody biomass	Herbaceous biomass	Bituminous coal
Ultimate analysis (wt% dry)				
Carbon	44.44	~50	46–50	69
Hydrogen	6.22	~6	5–6	5–6
Oxygen	49.34	~44	~40	14
Nitrogen	0	0.1–0.6	0.3–0.7	1.6
Sulphur	0	<0.1	<0.2	1.0
Proximate analysis (wt%)				
Moisture (as-received)		Variable	Variable	3
Volatiles, VM (dry basis)		81	75–82	33
Fixed carbon, FC (dry basis)		17.5	15–18	54
Ash (dry basis)	0	1.5	5–9	10

5.3.2 Thermal decomposition of biomass

When biomass is heated it produces a complex mix of gases, vapours (tar or bio-oil) and char. The main reactions are fragmentation, depolymerisation and char formation (condensation) (see Figure 28).

The uncatalysed cellulose decomposition reaction occurs between 300–390°C (Collard and Blin, 2014). Major primary products include various sugars from depolymerisation. Other concurrent reactions help to cross-link polymer chains, pinning them in place, and releasing reaction water, carbon monoxide and CO₂. These reactions are relevant to charcoal production since they generate a small amount of residual isotropic char which becomes more aromatic with increasing temperature. Other reactions including ring opening, further decarboxylation and dehydration, and further condensation reactions are in competition with primary reactions. Similar chemistry occurs during pyrolysis of hemicellulose, but hemicelluloses are more reactive than cellulose, and conversion occurs over the range 200–350°C (Collard and Blin, 2014; Zhou and others, 2018). Like cellulose, a small quantity of isotropic char residue is generated via cross-linking, condensation and aromatisation reactions, and this becomes more aromatic as temperature increases.

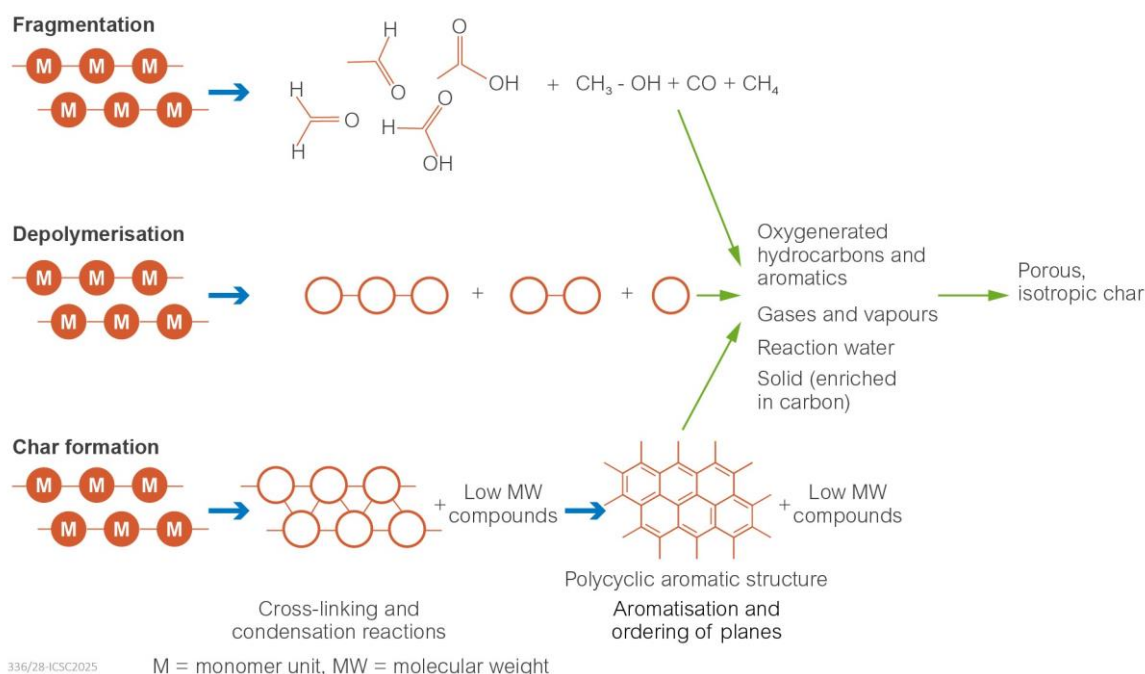


Figure 28 Main pathways in the decomposition of lignocellulosic biomass (adapted from Collard and Blin, 2014)

The range of functional groups and polymeric unit sizes within lignin means that its thermal conversion happens over a broad temperature range (200–450°C). A vast array of light and medium volatile aromatics is formed with oxygenated side chains which can undergo further secondary reactions (*see*, for example, Wang and others, 2017). Rearrangement and cross-linking/condensation of the residual polymer framework pins the structure further, so no fluidisation is possible. The solid phase reactions are aromatisation and growth of layer planes to form the major contribution to the char from biomass. Heating above 450°C results in loss of oxygen-functionality from the young char and it becomes more carbon-rich (Collard and Blin, 2014).

While slow heating can promote carbonisation reactions, they are limited because of the high oxygen content and structural features of lignocellulosic biomass compared to coal. The reactions that result in gases and vapours are fast and dominant, which accounts for the high volatile matter and low fixed carbon (low char yield) of biomass compared to coal (*see* Table 9).

Torrefied biomass, biochar and charcoal

Torrefaction is a mild pyrolysis process in an oxygen-depleted environment (typically, 200–320°C, less than 6% oxygen and a residence time of 10–30 min) (Jones and others, 2024). This process targets the decomposition of the hemicelluloses present in the lignocellulosic biomass. CO₂ and reaction water are major gaseous products and the preferential loss of oxygen (over carbon) means that the resultant solid is carbon enriched. Solid yields of 70–80% are typical and the carbon content increases from approximately 49% dry ash free (daf) to 55–65 % (daf) (Bridgeman and others, 2010; Park and others, 2013). When the hemicellulose is decomposed the material becomes more friable (easier to mill), enabling the manufacture of high-energy density pellets (*see* Section 5.4.1). Furthermore, the loss of

hydroxyl groups in the chemical structure results in some hydrophobicity and resistance to fungal attack. These are the main advantages of torrefied biomass: improved energy density, hydrophobicity, friability and resistance to fungal attack. From a structural point of view, carbohydrate groups decrease, and aromaticity and ketone groups increase. Lignin concentrates in the solid residue. Upon torrefaction, the aromatic carbon content increases from 36% to 60%, depending on the severity of reaction conditions. In addition, the aromatic layer planes are growing from one ring (in lignin) to larger fused ring structures (Park and others, 2013).

Heating biomass above 300°C means that the rate of cellulose decomposition becomes appreciable and temperatures above 400°C enhance the rate of lignin decomposition. *Biochar* is the generic name given to carbons produced in thermal treatment in an oxygen-depleted atmosphere, usually at temperatures exceeding 400°C (International Biochar Initiative, 2015). However, the term is commonly applied to carbons, usually non-woody, produced specifically for soil amendment purposes (International Biochar Initiative, 2024).

The term *charcoal* is more commonly applied to carbon produced from the thermal treatment of *woody* biomass in oxygen-depleted environments to temperatures exceeding 400°C. Charcoal is most relevant for I&S manufacturing and its production is described in Section 5.4.3. Once pyrolysis temperatures exceed the lignin decomposition temperature, the resultant carbon becomes almost completely aromatic in nature (Park and others, 2013). This indicates that layer planes have grown and dominate in the structure in the form of crystallites which are orientated in a random manner forming a porous isotropic carbon (Wood and others, 2024). In scientific literature, biochar has been used interchangeably with charcoal regardless of the biomass precursor used.

Hydrothermal carbonisation

Hydrothermal carbonisation (HTC) involves the heating of biomass to a temperature between 180–250°C, in water and under pressure (1–4 MPa), with a reaction time between 1 minute to several hours (Jones and others, 2024). Under HTC conditions (subcritical water) the lignocellulosic components of the biomass decompose at lower temperatures than they would under normal thermal conditions. Similar to torrefaction, the hemicelluloses undergo dehydration and decarboxylation producing a more brittle, hydrophobic and microbe-resistant solid. At around 200°C, the cellulose also degrades, together with some limited reaction of lignin. Solid yields of up to 70% have been demonstrated with carbon-contents of up to 55% (both on a dry basis) (Smith, 2018). A higher carbon-content is possible by operating at a higher temperature at the sacrifice of substantial solid yield (Smith, 2018). The structure of the so-called pristine hydrochar is reported to have low porosity and to resemble a low-rank coal in its chemical analysis. However, HTC is versatile and there is a research effort in producing fine-tuned carbons, including carbons with ordered structures, for different applications. Some cited applications of hydrochars include energy storage, electrocatalysis, gas storage, heterogeneous catalysis, and water treatment (Nicolae and others, 2020). Brooks and others (2023) cite HTC as a promising pre-treatment for using biomass in coke making due to its low alkali

content and chemical properties, and some studies to assess this are appearing in the literature as a substitute for coal and coke or as an injectant (Wang and others, 2023). Because of HTC's ability to decrease some ash components, it may be a suitable pretreatment for upgrading agricultural residues and wastes (Cardarelli and Barbanera, 2023; Munir and others, 2023; An and others, 2024).

Other methods of carbon production from biomass

Table 11 compares the thermal processing methods described with other methods, including charcoal production (slow pyrolysis) and chars produced from gasification or from microwave or plasma-enhanced pyrolysis. All these approaches produce carbons with different properties (see Section 5.5) which dictates where they can be more useful for fuel switching in the I&S industry. Consequently, many of these routes have the potential to deliver useful products. Charcoal may be the most promising and its production and nature are described in Section 5.4.3.

TABLE 11 COMPARISON OF DIFFERENT METHODS FOR MANUFACTURING CARBON MATERIALS FROM BIOMASS (ADAPTED FROM IBITOYE AND OTHERS, 2024; ANTAL AND GRONLI, 2003; ROY AND OTHERS, 2024)				
Technology	Description	Yields, %	Advantages	Disadvantages
Slow pyrolysis	Oxygen-depleted atmosphere, 300–600°C	10–38	Can approach thermodynamic limit on charcoal yield with modern technology High fixed carbon content Variable quality for different applications Scalable and commercial	Long processing time Traditional kilns are very polluting and give low yields High to moderate energy consumption
Gasification	Partial combustion/gasification of feedstock 600–1200°C	5–15	Co-product from syngas production Low emissions Commercial scale	High energy consumption
Hydrothermal carbonisation	Oxygen-depleted atmosphere, subcritical water (1–4 MPa) 180–250°C	30–90	Faster than traditional slow pyrolysis. Suitable for wet feedstocks Partial removal of potassium and chlorine if followed by rinsing step	High energy and pressure requirements Limited feedstock options Hydrochar stability varies
Microwave and plasma pyrolysis	Pyrolysis in the presence of microwave or plasma; Oxygen-depleted atmosphere, 300–800°C (microwave), higher temperature for plasma	40–80	Faster heating rates Control of reaction conditions Good energy efficiency	Specialised equipment and energy requirements Complexity in operation Lower technology readiness levels (TRLs) (limited commercial applications)
Torrefaction	Oxygen-depleted atmosphere, 200–320°C	60–90	Flexibility for fine-tuning product characteristics Grindability Demonstrated at commercial scale	Optimisation required for new feedstocks Autothermal operation can be a challenge
Steam explosion	140–260°C for 5–10 min, using high-pressure steam (1–3 MPa), followed by rapid depressurisation	70–95	Co-production of soluble products for fermentation or other processes. Partial removal of potassium and chlorine if followed by rinsing step Demonstrated commercially	Requires drying step Limits on FC content achieved – carbonisation step may be required Water treatment

5.3.3 Charcoal production

Charcoal production dates back to ancient times. The most basic process involves igniting a covered pile of wood billets at its base and allowing it to combust in a starved oxygen environment. After the pyrolysis/combustion dies down (when the smoke production stops) the residue is charred woody material known as charcoal. Modern production uses brick or cement kilns which are loaded with dried wood, and have sealable air vents and recirculation of gases, vapours and heat to improve efficiency and reduce pollution (Kajina and others, 2019). Some of the wood is sacrificed through combustion to generate the necessary heat to drive the pyrolysis and carbonisation of the remaining wood. The quality and yield of charcoal produced are temperature dependent (Antal and Gronli, 2003). Up to 78% of global charcoal production (51.2 Mt in 2017) comes from Africa and South America, with Brazil producing the most (Rodrigues and Braghini Jr, 2019; Nabukalu and Giere, 2019). Most of the charcoal is produced from low-technology kilns with low yield, which may be below 20%, and is used for domestic use (heating and cooking) in the developing world. Usually, for domestic use, volatile matter is typically 20–30% (maximum of 40%) (Antal Jr and Gronli, 2003). In contrast, charcoal for substitution in I&S manufacturing requires both good yield for economic and environmental considerations, and good process control to deliver consistent material with the necessary physical and chemical characteristics. Typically, it contains 10–15% volatile matter (or less), has an ash content of <5% and a CV of 28–33 MJ/kg. It can substitute for coal and coal-derived products in several ways in the I&S sector and the properties required depend on where it is being used (*see* Chapter 6).

Due to the high oxygen content of biomass, the maximum theoretical charcoal yield is limited to around 37% for hardwood (Antal Jr and Gronli, 2003). The fixed carbon content will increase with carbonisation, as oxygen and hydrogen contents decrease, but the yield will approach an asymptotic value. This yield depends on biomass type, but the theoretical maximum is rarely achieved because much carbon-containing volatile matter is lost during manufacture. Different biomass types have different quantities and natures of cellulose, hemicellulose and lignin, as well as different starting physical properties, such as density (Antal Jr and others, 2000). Shells and pits and hard, tropical woods have been reported to give the highest yields of good quality charcoal, and resinous hardwoods produce denser and more durable charcoal than softwoods (Antal Jr and others, 2000). Inherent ash also influences charcoal yield. Alkaline earth and alkali metals (potassium in particular), catalyse the pyrolysis mechanisms and promote char-forming reactions, so that more carbon is fixed in the resultant char, rather than lost in the tars (*see* Nowakowski and Jones, 2008; Nowakowski and others, 2007; Hu and others, 2015).

5.4 BIOMASS CHARS COMPARED WITH COKE

Figure 29 captures the main features of the carbon structures of the various carbon sources used in the I&S industry in a Van Krevelen diagram. It illustrates how the molecular make up of coals and biomass differ, and how this impacts the structural features of the carbonaceous materials that develop as these

carbon sources are heat-treated. The consequence of the different structures at a molecular level are different physical and chemical characteristics, summarised in this section.

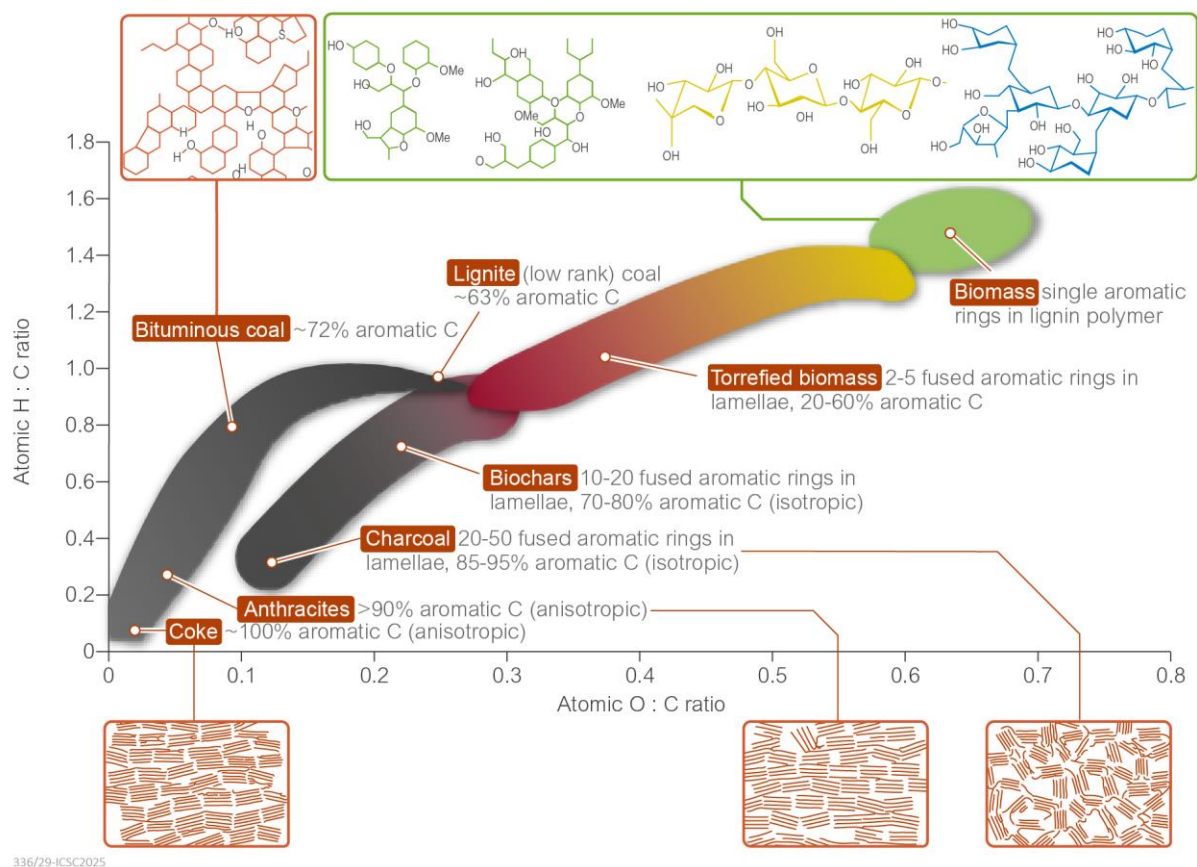


Figure 29 Van Krevelen diagram illustrating the different molecular structures during the carbonisation of biomass and coking coal (structural descriptions are estimations from Wood and others, 2024; Smith and others, 1994 and are illustrative only)

5.4.1 Porosity, reactivity and mechanical strength

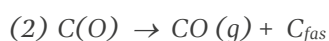
The molecular nature of the materials shown in Figure 29 generates pores within their structures. They are defined based on their size:

- Macropores – pore width >50 nm;
- Mesopores – pore width between 2–50 nm;
- Micropores – pore width <2 nm.

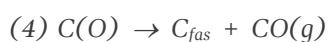
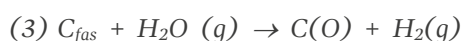
Most carbons have a distribution of all these pore sizes; those with a high fraction of micropores will have a high surface area. Isotropic carbons such as charcoal are inherently microporous because the lamellae cannot form extended close-packed layers, and surface areas may be 500–1500 m²/g (Marsh and Menendez, 1989). In contrast, anisotropic carbons such as coke have more extended lamellae that can pack closely; they have low microporosity and typical surface areas are <10 m²/g.

Within the BF, the coke eventually reacts with CO₂ and water vapour in gasification reactions to form carbon monoxide and hydrogen which are the main reductants for the iron ore. As noted previously,

the coke bed needs both good permeability to allow gases to pass through it, but also slow reactivity with CO₂ so that it survives long enough in the BF to provide the necessary mechanical support. The reactivity of a carbon to any oxidising gas can be described by active site theory. This assumes that certain sites in the carbon structure can adsorb the reacting gas. The adsorbed gas undergoes a surface reaction and then desorbs. These reactions are illustrated in equations 1–4, where C_{fas} corresponds to a free active site on the carbon, and C(O) represents an adsorbed atomic oxygen. Note that the active site is regenerated after desorption of the CO molecule so that reaction with carbon active sites gradually gasifies the carbon.



Or with water vapour:



The active sites within the carbon structure are carbon edges (edges of aromatic lamellae), defect sites, heteroatom sites, or inorganic impurities. Heat treatment eliminates heteroatoms and defects in a carbon structure and so, in general, the higher the temperature it has experienced, the fewer the active sites (and the lower its reactivity). In addition, isotropic carbons have inherently more edge sites than anisotropic carbons. Thus, coke is expected to have a lower reactivity (reaction rate) with CO₂ than charcoal, when both have been produced at similar carbonisation temperatures. Generally, the number of active sites correlates with surface area but not always, since other factors, such as the presence of inorganics and catalytic effects, also influence the reactivity.

An important measure of the chemical quality of a coke for BF use is the coke reactivity index (CRI) which is a standard test method (ISO 18894:2018). It uses a 19–22.4 mm size fraction and measures the reactivity (per cent mass loss) when reacting with CO₂ gas at 1100°C. It is combined with a tumbling test of the resulting coke to assess its mechanical strength after reaction (coke strength after reaction, CSR), which is % >10 mm remaining after 30 minutes of tumbling. Porosity develops further on reaction with CO₂ and porous solids have lower mechanical strength than non-porous carbons. According to Koveria and others (2021), recommended values are CRI ~<23, and CSR ~>65 for use in iron-making BF's, although these are country-specific (Mousa and others, 2016).

5.4.2 Chemical and physical characteristics

Table 12 lists some typical chemical and physical characteristics of different carbonaceous materials. The data for charcoal is for a top-quality product and that for coke is for the coke lump. Producing charcoal that meets the requirements for coke lump is challenging, but co-charging with small amounts has been examined (Babich and Senk, 2015). The main approaches under consideration for utilising

biomass-based carbons are discussed in Chapter 6 and include the displacement of pulverised coal for injection in the raceway region of the BF.

TABLE 12 COMPARISON OF PROPERTIES OF SOME SOLID FUELS (SUOPAJÄRVI AND OTHERS, 2017; KOVERIA, AND OTHERS, 2021; YE AND OTHERS, 2019; DORNIG AND OTHERS, 2024; MONSEN AND OTHERS, 2004; MOUSA AND OTHERS, 2016)

As-received	Coke lump (for blast furnace)	Charcoal (high quality)	Pelleted torrefied wood	Wood pellet
Moisture, wt%	1–5	1–5	1–5	7–10
Fixed carbon, wt%	85–88	85–87	22–35	16–25
Volatile matter, wt%	1.0–1.5	10–12	55–65	75–84
Ash, wt%	8–12	1–3	1–2	0.2–1.0
Bulk density, kg/m ³	400–500	180–240	650–800	550–650
Low calorific value, MJ/kg	~30	~30	18–24	15–17
Coke reactivity index (CRI)	~<23	43–53	high	highest
Coke strength after reaction (CSR)	~>65	–	–	–
Compressive strength kg/cm ²	130–160	10–80	13–50*	48–75
Typical % yield	75–80	~30	61–84	n/a
n/a – not applicable * when torrefying wood pellets				

5.5 COMMENTS

The properties of carbon sources used in I&S manufacture are intricately linked to their molecular structure. Certain ranks of coal produce a quantity and quality of tar during carbonisation that can act as a liquid medium for the maceral components so that they pass through a fluid stage. Further heating produces a mesophase where the aromatic layers in the structure (lamellae) begin to align and eventually carbonise into an anisotropic solid, which becomes a low porosity, high strength coke. Carbonisation of a biomass precursor always produces a porous, isotropic solid (charcoal or biochar) because the starting ‘template’ polymers in biomass are already pinned in place, and do not produce a mesophase. The high porosity of isotropic carbons means that they are inherently more reactive than coke and have lower mechanical strength. This dictates their suitability for different applications in I&S manufacturing.

THE PRECURSOR USED IN CARBONISATION DIRECTS WHETHER THE RESULTING CARBON WILL BE ANISOTROPIC COKE OR ISOTROPIC CHARCOAL. THE INHERENT POROSITY AND REACTIVITY OF CHARCOAL AND BIOCHAR DICTATE THEIR POSSIBLE USES IN IRON AND STEEL MANUFACTURING.

6 CHALLENGES AND OPPORTUNITIES FOR BIOMASS IN IRON AND STEEL PRODUCTION

6.1 BIOMASS IN THE INTEGRATED BF-BOF PLANT

The main carbon sources in the integrated BF-BOF plant are coke lump, nut coke, coke breeze, and PCI. The key chemical properties required for these sources are given in Table 8 (see Chapter 4). The BF is the highest emitter of CO₂ in the integrated plant and consequently, displacement of coal and coke by biomass-derived products has been researched intensively. The World Steel Association cites biomass as an option in a portfolio of strategies for producing low-carbon steel for areas where biomass resources can be mobilised. This includes Australia and Brazil (WSA, 2021). In October 2021, BlueScope and Rio Tinto signed a Memorandum of Understanding (MoU) to explore low emission steel making at Port Kembla Steelworks in New South Wales, Australia. As well as exploring the use of hydrogen as a reductant, the industry is examining the “*potential use of charcoal from forestry and construction waste to replace coal and other carbon sources in a blast furnace*” (BlueScope, 2021). There have been other initiatives and coordinated projects for biomass substitution. For example, ArcelorMittal developed mini-BF technology in Brazil which has potential for nearer carbon-neutral operation. This technology is a promising competition to commercial-scale iron making – it has lower investment costs and is more amenable to increases in efficiency (Brooks and others, 2023).

Charcoal (or biochar) has received the most attention for meeting the requirements given in Table 9 and some of the advantages and disadvantages of its use are given in Table 13. Brazil uses substantial amounts of charcoal in its I&S manufacturing as shown in Box 2, but the supply chain development has had problems. In addition, torrefied biomass, steam exploded biomass, and lignin have all been considered for partial substitution in coke making, sinter plant or BF, either as a reducing agent or as a fuel (Mousa and others, 2016; Suopajarvi and others, 2017). The coke introduced at the top of the BF should have good permeability, high mechanical strength, and a low reaction rate to CO₂. Operation of the most efficient modern BFs has evolved to use lower coke addition rates combined with higher PCI, such that high productivity over prolonged periods is only achieved with coke of the highest quality (Mousa and others, 2016).

As discussed in Chapter 5 and summarised in Table 13, charcoal is inherently porous with a high surface area. This impacts both its mechanical strength, which is low, and reactivity to both combustion and reaction with CO₂, which are high. Small BFs, such as those used in Brazil, can operate with granular charcoal displacing coke (Khasraw and others, 2024). For large BFs, these factors limit the substitution rate of charcoal in the carbon charge but are actually advantageous for other applications, such as milling and fast combustion rates in charcoal powder injections (CPI) in the BF. The PCI should be low sulphur and phosphorus, with a specified volatile matter content and lower CV ranges (Suopajarvi and others, 2017). In addition, alkali content needs to be low. The volatile alkali species (from potassium oxide and sodium oxide) tend to accumulate and circulate within the BF,

vaporising in the high-temperature zones of the furnace and travelling upwards before condensing at the lower temperatures and gradually moving back down the furnace with the solids. They progressively attack the refractory lining of the furnace (Suopajärvi and others, 2017). Generally, alkali contents are acceptable for charcoal made from wood but this needs to be considered when sourcing biomass (Mathieson and others, 2015).

Other considerations concern the handling and transportation of coal and coke. The bulk density and hydrophobicity impact the volume of solids required for the process, and also how the material is transported, stored and conveyed. The material's hardness affects its grindability for PCI. Charcoal and thermally treated biomass are more hydrophilic than coke and many coals and so may require modified storage and conveying; however, they have good grindability properties.

TABLE 13 CHARCOAL PROPERTIES FOR IRONMAKING APPLICATIONS (ADAPTED FROM MATHIESON AND OTHERS, 2015)		
Charcoal property	Advantages	Disadvantages
Ash, sulphur, nitrogen contents	Low, and so can be a high-value product. Pollutant reduction. Also appears to give lower dioxin formation	
Ash composition	Calcium content of the ash in charcoal from wood may enable lower quantities of added flux material	Alkali (K_2O and Na_2O) content is usually acceptable but might approach BF limits in some circumstances. Biomass sourcing is therefore important; alternatively, a blend for charcoal injection (charcoal powder injection, CPI) might be necessary
Volatile matter (VM)	This can be controlled by the pyrolysis conditions, so a range of properties is possible (much like coal and coke types)	
Combustibility	This is higher than coal for the same VM and can give improved heat balance as a BF injectant	Probably too high for full coke substitution in sintering without some type of modification
Reactivity to CO_2	This is higher than coke in the BF and enables lower temperature in the thermal reserve zone – the zone that generates CO by the C- CO_2 reaction	Could result in the weakening of the coke in the BF if used as a coking component
Mechanical strength	Easier to mill to a fine powder for some applications such as CPI	Lower mechanical strength means charcoal cannot be used as a drop-in replacement for coke in large BFs and limits the per cent that can be blended with the coke. Durable pellets aid in handling and transportation
Density		Lower density than coal or coke so there are higher volumes for transporting and handling. High density pellets are desirable
Moisture absorption		This is higher so covered storage or airtight bags may be necessary. Also, difficult to dry if saturated
Contamination		The high surface area and high porosity of charcoal makes it susceptible to acquiring contaminants such as dust and soil

Typical or proposed substitution rates for biomass-derived products are given in Table 14. The figures shown assume direct material substitution and are based on a median value of total GHG emissions of 2.2 tCO₂/tcs for the BF-BOF process (Fan and Friedmann, 2021). However, emissions from the production of the charcoal are assumed to be net zero, and no efficiency losses are considered. Therefore, the possible CO₂ reduction given in Table 9 represents an ideal maximum value. The limits of the substitution rates are a result of the different properties of biomass or biochar compared to coal or coke. Some of the relevant research is considered in the following sections.

TABLE 14 PROPOSED APPLICATIONS AND SUBSTITUTION POSSIBILITIES FOR BIOMASS-DERIVED CHARs IN IRON MAKING IN THE INTEGRATED BF-BOF PROCESS (MANDOVA AND OTHERS, 2018; MATHIESON AND OTHERS, 2015; MOUSA AND OTHERS, 2016; WANG AND OTHERS, 2015; SUOPAJÄRVI AND OTHERS, 2017; KHASRAW AND OTHERS, 2024)						
Application	Fossil fuel substituted	Possible biomass product	Proposed substitution, %	Proposed rate, kg/tHM	Net emission reduction, tCO₂/tcs	Net emission reduction, % CO₂ emissions
Coke making blend component	Coking coal at 300–350 kg coke/tHM	Charcoal or biomass	2–10	6–35	0.02–0.11	1–5
BF coke charge	Lump coke at 300–350 kg coke/tHM	Charcoal	2–10	6–35	0.02–0.11	1–5
BF coke charge	Nut coke at 45 kg nut coke/tHM	Charcoal	50–100	22–45	0.08–0.16	3–7
BF tuyere injection	Coal at 150–200 kg coal/tHM	Charcoal	Up to 100	Up to 200	0.41–0.55	19–25
BF tuyere injection	Coal at 150–200 kg coal/tHM	Wood pellets	Up to 20	30–40	0.06–0.11	3–5
BF tuyere injection	Coal at 150–200 kg coal/tHM	Torrefied wood	Up to 23	34–46	0.07–0.13	3–6
Sinter plant	Coke breeze or anthracite at 45–60 kg/t sinter (1.7 t sinter/tHM)	Charcoal	Up to 40	22–30	0.13	4
TOTALS	Coal and coke	Charcoal	maximum	Up to 345	Up to 1.06	Up to 46
tHM – tonnes of hot metal; tcs – tonnes of crude steel; PCI coal assumed as 75% carbon; coke, coke breeze, anthracite assumed as 85% carbon						

BOX 2: CHARCOAL USE IN BRAZIL'S IRON AND STEEL INDUSTRY

The Brazilian I&S industry has a long history of using charcoal in its integrated BF plant as well as in pig iron production, but nevertheless, two-thirds of operating plant rely on coal-based technology. The BFs are relatively new and will continue to operate well into the 2030s. Brazil's steel production was 32 Mt in 2023 across 21 steel plants and it is ranked 9th in the world (WSA, 2024). The main energy sources in 2021 were coal (57%), charcoal (18%) and electricity (10%) (Hebeda and others, 2023). Charcoal use has been developed in seven I&S plant but has declined over the past decade, mainly due to a lack of competitiveness with coal but also because of inefficiencies in production (Hebeda and others, 2023). Historically, there was a lack of planning for wood supplies plan which caused pressure on native forests. Coupled with production in inefficient traditional kilns, this led to largescale deforestation in some areas (Global Energy Monitor, 2024) and emissions of pollutants and GHGs (Pereira and others, 2017). Reforestation via eucalyptus plantations, good forest management, and the development of efficient carbonisation methods have helped to deliver more sustainable credentials, and three cases are given in Table 15 (Global Energy Monitor, 2024): Aperam BioEnergia's forest management at Minas Gerais is under Forest Stewardship Council (FSC®) certification. Charcoal production technology uses gas and vapour recirculation and waste heat for wood drying which helps to improve the environmental performance as well as charcoal yield (Aperam Bioenergia, 2024). However, the charcoal is transported 350 km to the I&S works which illustrates the logistical challenge that limits its availability. The charcoal route in Brazil represents good potential for helping to decarbonise its I&S sector but assessing the carbon footprint of its manufacture is complex and often controversial. The I&S sector therefore needs to balance financial, environmental and societal issues, which includes certification of the sustainability of its forests for biochar production.

TABLE 15 EXAMPLES OF BRAZILIAN I&S PLANTS USING BIOCHAR IN BF (GLOBAL ENERGY MONITOR, 2024; APERAM BIOENERGIA, 2024)

Plant name	Production, 2022	Biochar plantation, kha	Biochar division	Certification	Comments
Aperam Timóteo	475 kt/y BF (crude iron) 691 kt/y EAF (crude steel)	134	Aperam BioEnergia	SGS, FSC, ResponsibleSteel™	Biomass from eucalyptus plantations; improved efficiency measures implemented at the carbonisation plant; charcoal is transported 350 km to the plat in Timoteo, which uses BF-EAF technology
ArcelorMittal Juiz de Fora	369 kt/y BF (crude iron) 950 kt/y EAF (crude steel)	100	ArcelorMittal BioFlorestas	FSC, ResponsibleSteel™	Produce and distribute charcoal from eucalyptus forests.
Gerdau Divinópolis	367 kt/y BF (crude iron) 428 kt/y BOF (crude steel)	250		CDP	World's largest charcoal producer. Divinopolis plant uses BF-BOF technology
SGS – Societe Generale de Surveillance, FSC – Forest Stewardship Council, CDP – Carbon Disclosure Project					

6.1.1 Biomass in coke making

Blending of biomass during coke manufacture has been thoroughly researched over the past decade or so, looking at its impact on fluidity during coking, the resultant coke strength, the reactivity of the material produced, and compositional and textural analysis (Suopajarvi and others, 2017; Brooks and others, 2023). A range of material types have been studied including raw biomass, torrefied biomass, charcoal, bio-oil, and Kraft lignin from the pulp and paper sector. Biocoke can be produced with ultimate analysis, proximate analysis and CV that match the properties of the industrial coke breeze (Kieush and others, 2022), but the actual mechanical and chemical properties can differ enormously. Thus, the production of a suitable coke from a coal-biomass blend remains a challenge, and some of the key reasons and findings are summarised here.

Fluidity

The plastic stage in coke production is essential to allow long-range ordering in the carbon structure, which is the main basis for the mechanical strength of the resultant solid, its low porosity and low reactivity. The temperature range for fluidity and the maximum degree of fluidity can be measured using a Gieseler plastometer (ISO 10329:2017). Fluidity passes through a maximum with coal rank and, for a good coke, a blend of coals is used to give optimum fluidity of around 400–1000 ddpm (dial divisions per minute) (Suopajarvi and others, 2017 and references therein).

Some generalisations can be made based on extensive studies. It is widely accepted that any biomass material has the effect of decreasing the maximum fluidity (*see* Figure 30) because its decomposition mechanism does not allow for the necessary plastic stage. The plastic range during coke making is 400–500°C, and raw biomass will have undergone substantial decomposition before the onset of coal fluidity is reached (*see* Section 5.4.2). Meanwhile, charcoal decomposition will overlap towards the end of this fluid temperature range (Diez and others, 2012). However, as demonstrated in Figure 30, different behaviours are observed depending on biomass constituents (xylan, cellulose, lignin) and charcoal compared to virgin biomass. This supports the suggestion from Zhang and others (2022) that thermally pretreated biomass is better suited to blending in coking as there are fewer volatiles to interfere with the coal-to-coke process. While the actual mechanism is still under study, the resultant effect is that even small amounts of biomass produce a marked drop in fluidity. Although dependent on biomass type, only between 2–10 wt% biomass can be added to retain acceptable coke properties.

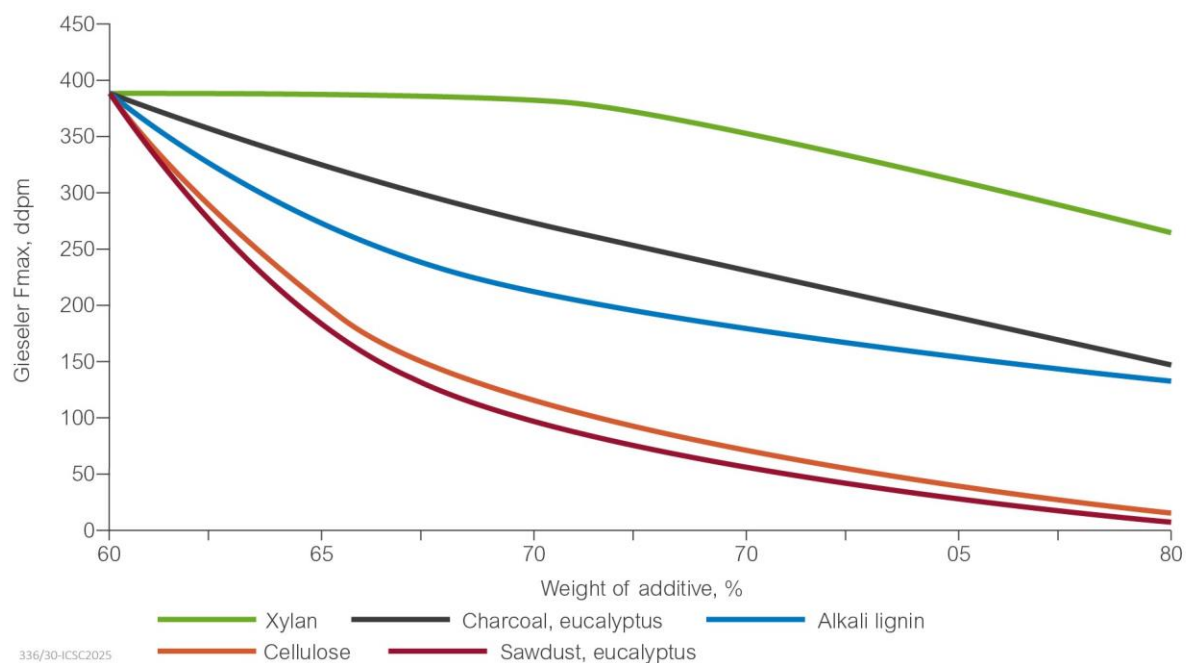


Figure 30 Maximum fluidity measured by Gieseler plastometer of a coking coal blended with different biomass-based additives (adapted from Diez and others, 2012)

Mechanical strength and reactivity

The coke strength after reaction index (CSR) and the coke reactivity index (CRI) are also key measures of coke behaviour in the BF. Various evidence for the impact of biomass blending is summarised in Table 16. CRI and CSR are both impacted negatively when biomass or charcoal is added during coking. This is due to their higher oxygen-content which reduces the coking ability of coal (Mathieson and others, 2015; Brooks and others, 2023); their inability to be properly incorporated into long-range order in the coke; and their higher porosity which affects both mechanical strength, bulk density, and reactivity, together with the possibility of a catalytic effect of some wood inorganics (such as calcium) in the reaction with CO₂. While the compiled results are hard to compare directly, it appears that charcoal affects the resultant coke more than biomass addition. The higher fixed carbon content of charcoal may be a contributing factor to this, so in essence, more additive is present in the coke when charcoal is used rather than biomass. The results also agree with the hypothesis that biomass decomposition does not interfere as much with the coking process, because its decomposition range is at a much lower temperature than mesophase formation. A general conclusion was that a 5% sawdust addition during coking could produce a coke with acceptable properties. Acceptable coke is also produced with modest charcoal addition (<5%) but further research in the understanding of the influence of coal blends, charcoal particle size, and mineral matter may enable higher substitutions (for example up to 10%) (Mathieson and others, 2015). HTC char is reported to have superior properties in coke blends compared to torrefied materials, with the added advantage of lower inorganic elements including potassium and sodium (Brooks and others, 2023).

TABLE 16 IMPACT OF BIOMASS AND CHARCOAL ADDITION DURING COKE PRODUCTION ON ITS REACTIVITY AND STRENGTH AFTER REACTION WITH CO₂ (FROM SUOPAJÄRVI AND OTHERS, 2017; MATHIESON AND OTHERS, 2015)

Biomass type	wt% added during coking	Coke reactivity index (CRI), %	Coke strength after reaction (CSR), %
Charcoal	0	30–34	48–62
	2	34–36	42–52
	5	42–44	30–52
	10	47–49	18–42
Wood sawdust	0	24–34	60–63
	2	27–30	57–60
	5	29–33	50–55
	10	40	40
The range in values is due to different carbonisation degree and also particle sizes used – CRI ≤30 and CSR ≥55 is acceptable			

6.1.2 Biomass in iron ore sintering

Sintering involves the production of an agglomerated, partially reduced, porous sintered iron material from iron ore fines, coke breeze, limestone and calcium oxide (Kieush and others, 2022) (see Section 4.1.1.) and consumes 9–12% of the total energy required to make hot metal (Zhang and others, 2022). The sinter is similar to lump iron ore and makes up typically 40–60% of the iron charge in the BF (Kieush and others, 2022) but can be higher. To reduce the environmental impact, the substitution of coke breeze with biomass-based alternatives, mainly charcoal, has been studied for more than a decade (see for example, Kieush and others, 2022; Mohammad and others, 2023). Coke breeze is considered the best fuel for sintering, but there can be a shortage of this material – another driver for finding substitutes – and anthracite or petroleum coke have been used (Cavaliere, 2019). Reductant (fuel) cost is another consideration since this represents 17–20% of the total cost in the sintering process (Mohammad and others, 2023). The main thrust of the research for biomass products has been to find an optimum ratio which gives an acceptable strength sinter and minimises costs and environmental impacts. Some of the challenges of using biomass directly include its fast rate of combustion and its low fixed carbon content. Early studies by Corus and Commonwealth, Scientific and Industrial Research Organisation (CSIRO) reported in Cavaliere (2019) identified shells, hulls and pits as biomass worth investigating. However, the direct use of materials such as olive residues, sunflower husks and bagasse pellets at 25% biomass addition (on a carbon content basis) resulted in a lower peak sintering temperature (>1300°C is required). In addition, the combustion and sintering zones become narrower because the fuel burns too rapidly. The resultant sinter is weaker because of insufficient melt produced during the sintering process, making it more porous.

The use of charcoal can improve this situation. Figure 31 shows the findings for the substitution of coke breeze by charcoal (reported in Cavaliere, 2019). While charcoal is less reactive than its parent biomass, it still ignites at a lower temperature and burns quicker than coke which accelerates the sintering speed, giving a positive effect at addition rates below 40%. However, if too much biochar is added then the combustion parameters change significantly, and the process becomes inefficient. An additional benefit is a decrease in NO_x and SO_x emissions due to lower levels of nitrogen and sulphur in the charcoal fuel.

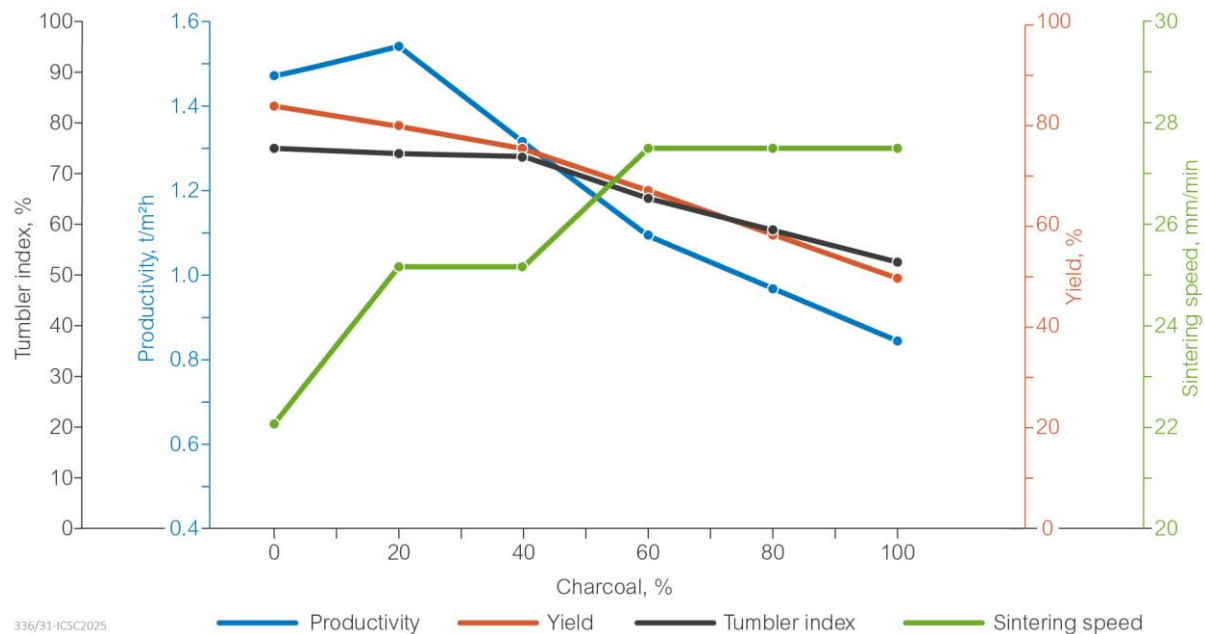


Figure 31 Effects of replacing coke breeze with biochar on yield and quality of sinter (reported in Cavaliere, 2019)

Kieush and others (2022) produced sinter in a laboratory study using biocoke – a blend of wood pellets and coke that had been carbonised – to produce a composite material of charcoal and coke. They then assessed the impact strength and abrasion resistance of the resultant sinter. They found that impact strength was unaffected with up to 15% biomass addition but then decreased with the addition of more than 30% wood pellets. Also measured were the permeability of the sinter bed before and after ignition and the reducibility of the sinter. This and other work (Cavaliere, 2019) demonstrated that the reaction performance can improve with some charcoal addition because its more porous structure increases the number of active sites for combustion/gasification reactions during sintering. However, there is an upper limit because the faster combustion rate of charcoal affects the temperature profile in the sinter bed, the degree of sintering that takes place, and therefore the performance of the resulting sinter. Zhao and others (2018) found that 20% charcoal could be employed in the sinter bed without impacting sintering rates and gas concentrations, and in fact, could improve yield and productivity by up to 8% under typical sintering conditions (Cavaliere, 2019).

6.1.3 Biomass in nut coke replacement

Nut coke is typically 10–30 mm and improves the permeability of the iron ore layers in the BF. It is usually added at around 45 kg/t hot metal, (tHM) (*see* Table 14). The nut coke is not load-bearing so substitution by charcoal could provide a renewable portion of reductant/fuel. Aperam in Brazil has reported that it gives good operation with improved permeability and reduced heat losses (Gonçalves and others, 2012).

6.1.4 Biomass in iron-carbon composite agglomerates

Iron-carbon composite agglomerates (CCA) are cold-bonded pellets, and hot or coal-bonded briquettes produced from fine iron ore, and fine coke, coal or charcoal. Their use in the BF results in faster reduction and gasification reactions of the iron ore because of the intimate contact between the ore and carbon particles; essentially, they have a high propensity to self-reduce. They provide a route to recycling waste streams in the integrated BF-BOF plant and lower costs by using cheaper materials. This includes fines from coke making and fines from the sinter plant (Chen and others, 2024). CCA are also of interest in EAF steel making and in DRI processes (Suopajarvi and others, 2017). A main drawback to their use in the BF is their low mechanical strength. Various types of biomass have been studied in the production of CCA including charcoal, sawdust, straw and biochars from bamboo and rice husks (Suopajarvi and others, 2017). Results are promising for very low levels of addition (2%), and are particularly suited to small BFs, especially when optimised such as through the addition of binders, such as bentonite, to improve mechanical strength (Chen and others, 2024 and references therein). Addition rates are higher for agglomerates for DRI.

6.1.5 Biomass as an injectant in the blast furnace

This is one of the key areas for fuel substitution in the BF plant. Both charcoal and torrefied biomass have promise, and the sector is embracing this technology. For example, ArcelorMittal is building two 40,000 t/y torrefaction plants in their Tolero project, to provide fuel to their steelworks in Ghent, Belgium, which would deliver an anticipated CO₂ emissions reduction of 225 Mt/y when in full operation (ArcelorMittal, 2024). The benefit of injecting pulverised reducing agent into the tuyeres of the BF is that less top-charged coke can be used (which is expensive). It also helps in control of the BF operation (Carpenter, 2006). Typical rates of pulverised coal are 150–200 kg/tHM (*see* Table 11) and it acts as both a fuel and a reductant. Other materials including plastics, oil and natural gas can also be used (Carpenter, 2010), but biomass-derived material is attractive due to the possible carbon emission savings. Liquid fuels (bio-oil) and gaseous fuels (syngas) also present opportunities for displacing some coal use (Suopajarvi and others, 2017). Important properties of solid biomass-derived products for this application include grindability (and particle size and distribution produced), ignition and reactivity, as well as chemical composition. Sawdust, torrefied biomass and charcoal have all been studied, as well as Kraft lignin, and rates of up to 20% for sawdust, 23% torrefied wood and up to 100% charcoal were demonstrated in advanced BF modelling (Wang and others, 2015). Agricultural residues

or biochars derived from non-woody residues are less attractive because of their high ash content and high amounts of undesirable elements (*see* Section 6.4). It is well known that charcoal and torrefied biomass have good grindability compared to biomass, but many of these studies are for pulverised combustion applications. There have been few studies on milling behaviour in vertical roller mills, which are the ones employed in many steel plants using coal. In addition, given the higher reactivity of biomass-based fuels, it may be possible to use larger particle sizes for comparable performance to pulverised coal – another area for future research (Suopajarvi and others, 2018).

The fuels are injected with oxygen-enriched hot air and the char burnout time is approximately 20–30 ms (Khasraw and others, 2024). The particles heat rapidly and undergo combustion and gasification reactions generating the high temperature required to melt the burden and produce reducing gases. For pulverised fuel injection mechanical strength is not an issue, but the impact on the raceway adiabatic flame temperature, distribution and composition of reducing gases, and particle burnout in the raceway are all important factors (Suopajarvi and others, 2018). Lowering the temperature in the thermal reserve zone of the BF gives the advantage of a lower rate of carbon consumption. This has been demonstrated in Brazilian plants (Cavaliere, 2019).

The reactivities of biomass and charcoal are much higher than pulverised coal due to their structure and higher porosity, which give rise to higher surface area, 60–350 times higher in charcoal than in pulverised coal (Cavaliere, 2019) and more active sites for reaction with oxygen or CO₂ (*see* Chapter 4). This can be advantageous as it leads to more complete burnout and therefore better fuel efficiency. Figure 32 shows the output from several BF modelling studies comparing the reducing agent consumption rates for the injection of different mixes of coal, coke, oil and biomass-based materials (Cavaliere, 2019; Suopajarvi and others, 2018). The figure indicates that charcoal gives the highest coke replacement ratios for the materials studied. In addition, charcoal with high carbon content can out-perform pulverised coal.

The main conclusions from the ongoing research effort are that (i) pretreatment is necessary to improve the CV and grindability of the biomass; (ii) conveying and injection of biomass at a high rate can be a challenge due to its lower density (compared to coal), and potentially higher explosion hazard; (iii) grinding can yield a wider size distribution (compared to pulverising coal) and sieving may be necessary for the appropriate particle size distribution for feeding; (iv) alkali metals need to be minimised before utilisation. Levels in most wood-based charcoals are acceptable.

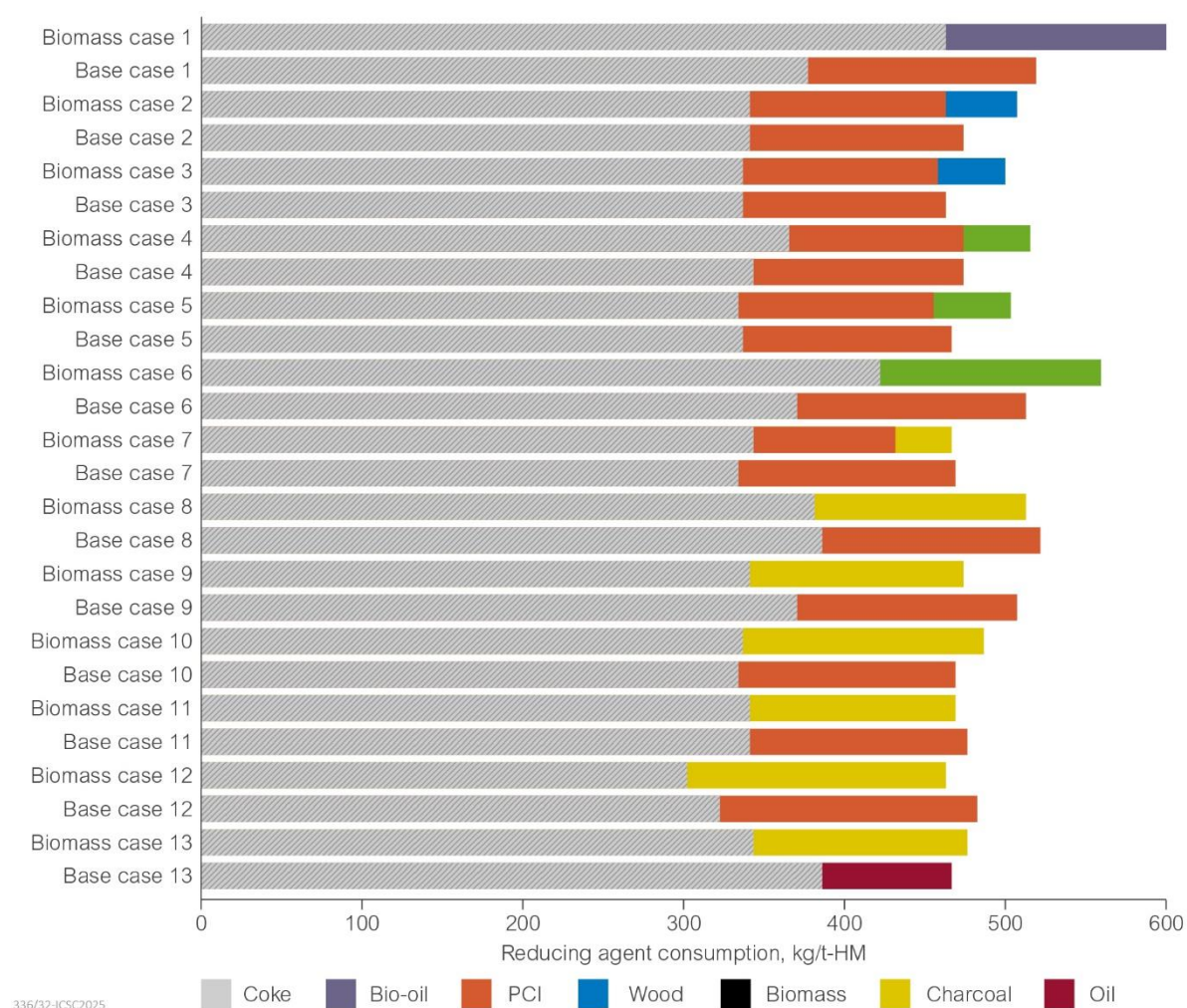


Figure 32 Modelling results showing consumption of reducing agents at different injection rates into the BF (adapted from Cavaliere, 2019; and Suopajarvi and others, 2018)

6.2 BIOMASS ADDITION IN THE EAF

As noted in Section 4.3.2 carbon addition into the EAF is either in the charge or injected in the oxyfuel lances. Coal, coke and at some sites, certain alternative fuels (such as rubber tyres) are standard practice (Echterhof, 2021). There is ongoing research into the addition of biomass, biochar or charcoal into the EAF and some of the progress is summarised in Table 15. Testing at industrial scale has progressed faster for EAF than for biomass as a BF reductant, probably because it is a batch system and easier to control (Suopajarvi and others, 2017). In addition, displacing fossil fuels with alternative wastes, such as waste plastics, tyres or automotive shredding residue has also been trialled by the industry, and some of these are at high technology readiness levels (TRLs). Both fundamental and applied research as well as industrial trials and demonstration projects have been conducted for a range of biomass and charcoal types. They have involved the partial substitution of coal or coke in either the pulverised fuel lances or in charge carbon. Results for virgin biomass appear promising and those for charge carbon have been demonstrated to reduce the specific energy consumption of the EAF by about 6% (Echterhof, 2021, and references therein). Briquetting or pelletising is necessary because of the low density, and this helps to

reduce the reactivity of the raw biomass so that there is more time for carburisation (Suopajarvi and others, 2017). Similarly, carbonised biomass materials also need to be briquetted when used as charge carbon and optimised to give combustion behaviour closer to that of coal. Research includes trials at industrial scale as shown in Table 17. When substituted in industrial trials no deviations from standard operating conditions were seen. The biochars appear to deliver faster carburisation reactions and satisfactory slag foaming when injected, although their fast reactivity remains a challenge (Suopajarvi and others, 2019). Biochar with at least 60 wt% volatile matter and ash content below 5% has been reported as ideal for achieving effective foaming of the slag (Kieush and Schenk, 2024).

TABLE 17 TECHNOLOGY READINESS LEVELS FOR PARTIAL SUBSTITUTION OF COAL OR COKE BY ALTERNATIVE CARBON SOURCES IN THE EAF (ECHTERHOF, 2021; SUOPAJÄRVI AND OTHERS, 2019)			
Carbon source	Application	Comments	TRL
Charcoal from different materials	Injected carbon	Laboratory trials. Foaming behaviour not fully understood. Transferring laboratory results to larger scale not fully understood	3
Different virgin biomass	Injected carbon	Laboratory trials. Foaming behaviour not fully understood. Transferring laboratory results to larger scale not fully understood	3
Polymer/coke blends	Injected carbon	Demonstrated at scale – shown to reduce electrical energy consumption	4–7
Rubber tyre/coke blends	Injected carbon	Standard practice for some steelworks, for example, OneSteel	4–9
Automotive shredding residue (ASR)	Charge carbon	Consists of plastics, rubber, textile and fibres – trialled as briquettes at industrial scale as partial substitute for coal – experienced gained on operating practice, benefits and limits. R&D needed to advance understanding of reaction processes.	2–5
Polymer/ coke briquettes	Charge carbon	Reports of better slag foaming, better reduction of iron oxide, better carburisation, slightly reduced energy consumption, reduced tap-to-tap time	4–5
Charcoal/biochar from different materials	Charge carbon	Provided ash content is low enough – ready to implement at demonstration stage. Chars from wastes and residues are of interest, eg after steam explosion or hydrothermal carbonisation.	4–5
Different virgin biomass	Charge carbon	Provided ash content is low enough then interest in high carbon materials such as woody biomass, and nut shells. Briquetting or pelletising is necessary because of low density. Has been demonstrated at scale for 1/3 substitution of anthracite by woody biomass briquettes. Appears to be ready for deployment but will need a secure and available supply, and economic incentives	4–6
Rubber tyres	Charge carbon	Standard practice for some steelworks. Demonstrated for substitution for charge coal or anthracite at a rate of 1.7 kg tyre/kg carbon up to 8–12 kg/t steel at steelworks in France, Belgium, Iran and others. Further research and experience required for optimum loading	2–9
TRL – Technology readiness level			

6.3 BIOMASS USE IN DRI MANUFACTURING

Carbon use differs in the various DRI processes summarised in Section 4.3. Some technologies require pellets of iron ore fines, steelmaking wastes, and coal. Displacing coal with biomass or charcoal substitution in shaft reactors has similar constraints in terms of mechanical strength as in the BF. Some technologies, such as the rotary hearth furnace, use carbon composite briquettes or pellets that could be candidates for substitution by biomass or charcoal (Yuan and others, 2017) (Section 6.1.4). Those technologies that use pulverised fuel injection into the gasifier can benefit from the partial substitution of biomass, with similar contenders as those used in the tuyere injection of the BF (Section 6.1.5). Biomass gasification is commercial although units tend to be smaller than coal gasifiers (Cavaliere, 2019), and biomass-derived syngas could, in principle, provide the necessary reducing atmosphere (Guo and others, 2017).

6.4 ASH AND CONTAMINANT ISSUES

Any contaminants introduced with biomass components used within the BF or other I&S manufacturing operations could impact the chemistry or process/furnace equipment. Some of the key elements that could be introduced by partial substitution of biomass include lead (Pb), phosphorus (P), potassium (K), sodium (Na) and sulphur (S). Typical concentrations are given in Table 18 in comparison to typical values for coke and coal. The potential impacts of these elements are also given in Table 18. It is important when considering sources of reducing agents or fuels that the burden of these elements is not increased. Note that carbonisation will concentrate certain undesirable elements in the charcoal or biochar, although some, such as HTC, will reduce some of them (*see* Jones and others, 2024 for further details).

In the EAF, fast formation of liquid slag with appropriate viscosity is important in protecting the melt from contact with the air and to draw impurities, especially sulphur, out of the molten iron. Composition impacts the foaming ability of the molten slag layer on injection of carbon. The ability to remove impurities is also related to the basicity of the molten slag which depends on the chemical composition of the ash components in the charge and injected materials. Usually, the required basicity is delivered from the blend of charge materials used (pig iron, recycled steel, charge carbon ash components, fluxing materials) (DiGiovanni and others, 2024). Biomass-derived carbon sources have different ash compositions compared to the conventional coal and coke sources used. Research into the impact of this on different rates of charcoal substitution in the EAF is ongoing with the focus being on the foaming behaviour (Kieush and Schenk, 2023).

TABLE 18 POSSIBLE IMPACTS OF HARMFUL ELEMENTS IN THE BLAST FURNACE (SUOPAJÄRVI AND OTHERS, 2018; ISO 17225-2; ISO 17225-6; NIU AND OTHERS, 2024)

Element	Effect on BF	Input into BF	Output from BF
Lead (Pb) ≤10 ppm ISO standard biomass	Lead migrates under metal components in the hearth and actively penetrates the lining ultimately leading to structural damage	Is present in the iron ore or limestone in the burden, and also is recycled to the BF with the BOF sludge used in sintering	Volatile – partitions into vapour, liquid and solid phases (dust). Molten lead only weakly dissolves in hot metal
Phosphorus (P) Variable in biomass. Typically, less than 1000 ppm in both biomass and met coke and PCI coal	Reduces the value and mechanical properties of manufactured steel. Needs to be kept as low as possible	Most comes from the coal and coke; some is present from the flux and iron ore components	Most (90–98%) ends up in the hot metal
Alkali metals, potassium (K) and sodium (Na) Variable in biomass but comparable. Typically, 2000 ppm in met coke and PCI coal	Increases CRI and reduces CSR. Increase coke consumption	Added via the coal, coke and iron ore. In EU BF the alkali input is about 1.5–5.0 kg/tHM and in China BF is about 2.0–12.0 kg/tHM	Potassium and sodium both reflux in the BF and can concentrate there. It is partly removed in off-gases and partly in the slag
Sulphur (S) Typically, <0.05% in biomass. <1 wt% for coal and coke	Detrimental in steel properties and so needs to have been removed via BF operations	80–90% is added from the coke and pulverised coal. The rest is in the other burden materials	High amount dissolves in the BF slag
Zinc (Zn) ≤100 ppm ISO standard biomass	Increased wear on BF refractory lining. Increases CRI and decreases CSR. Increases coke consumption	Present mainly in iron ore and reducing agent components – particularly the sinter. Much comes from the BOF sludge that is recycled via sintering back to the BF	Can concentrate up to 80 times on surfaces of charge material. Most loss is in the vapour phase (with the dust). About 10% is captured in the slag and hot metal
All element concentrations are on a dry basis; ppm = mg/kg			

6.5 BIOENERGY PROJECT EXAMPLES

Table 19 lists some projects at different TRLs in various parts of the world. The ArcelorMittal development of injection of ‘biocoal’ is described in more detail in Box 3. In all cases, only partial substitution of coal (or coke) is possible, with the exception of some of the small blast furnaces in Brazil which can in principle use 100% substitution (see Box 2).

TABLE 19 **EXAMPLES OF IRON AND STEEL PRODUCTION PROJECTS USING BIOMASS (WSA, 2021B; GLOBAL ENERGY MONITOR, 2024; ARCELOR MITTAL, 2023; RIO TINTO, 2022; (BIASUTTI AND OTHERS, 2023) (BHUBANESWAR, 2024)**

Company	Country	Biomass substitution in the iron and/or steel-making process	Trials
Aperam	Brazil	Charcoal from eucalyptus plantations – see Box 2	Timóteo
ArcelorMittal			Juiz de Fora
Gerdau			Divinópolis
ArcelorMittal (Gent)	Belgium	Arcelor Mittal has constructed an industrial-sized demonstration plant (Torero) to produce biocoal from waste wood which would then be used in the blast furnace in their steelmaking plant in Gent	The plant was commissioned in 2023 and consists of two reactors, each with a production capacity of 37.500 t/y which is expected to increase to 50,000 t/y by 2025 and is expected to reduce CO ₂ emissions in 2030 by 35% compared to 2018 levels
Rio Tinto (Iron ore production)	Australia	Biolron Process uses raw biomass instead of metallurgical coal as a reductant and microwave energy to convert Pilbara iron ore to metallic iron in the steelmaking process	Small-scale pilot plant has been conducted for 18 months by Mesto Outotec and the University of Nottingham's Microwave Process Engineering Group Development in Germany which was successful. The trials were carried out using batches of 1000 golf ball-sized iron ore and biomass briquettes. There are plans to carry out trials on a large-scale pilot plant. The biomass used is agricultural by-products like straws and bagasse and some purpose-grown energy crops. The technology when combined with renewable energy can reduce CO ₂ emissions by 95% compared to the conventional blast furnace method
Port Kembla Steelworks (PKSW)	Australia	Industrial trials were carried out to substitute coal with biochar for PCI in blast furnaces for two months in 2023. Substitution ranges of 5–30% biochar were trialled	The trials concluded that a 20% substitution rate of biochar is optimum, however, Australia does not have enough supply of biochar to make it commercial
Tata Steel (Athagarh ferro-chrome plant)	India	Substitution of conventional fuels with biomass (charcoal) to produce ferrochrome. Ferrochrome is an important alloying element in stainless steel production	Trials were carried out at the Athagarh plant where 5% charcoal substitution was done to produce the ferrochrome. The achieved a CO ₂ reduction of 0.08 t CO ₂ /t of ferrochrome, which is 6% of the plant's CO ₂ emissions. Further trials will be carried out to increase the substitution rate of charcoal

BOX 3 ARCELORMITTAL TORERO PROJECT

ArcelorMittal is one of the top steel producers in the world with production of 59 Mt in 2022. The company has committed to reduce its CO₂ emissions in European operations by 35% by 2030. It has several low-carbon steel initiatives underway including reducing emissions from its BF operations and innovation in DRI.

The Torero project concerns the injection of 'biocoal' into their BF at the plant in Ghent, Belgium. To achieve this, they are installing two industrial scale torrefaction reactors which use Perpetual Next's C-Vertr technology. This €55 million first-of-a-kind demonstration began construction in 2018, and construction of the second €35 million reactor is currently underway (November 2024). The process converts 112.5 kt/y of locally-sourced waste wood into carbonised material – producing 40 kt/y biocoal. The biocoal is then transported across the site to the BF where it is milled and injected with the PCI into the tuyere injection system. The offset in fossil fuel emissions is estimated at 112.5 ktCO₂/y.

In an added innovation, the off gases are converted to ethanol in their Steelanol CCU facility. This uses LanzaTech's carbon biorecycling process which takes the carbon-rich gas from steel production at the Ghent plant and biologically converts it to ethanol. The plant was officially inaugurated in December 2022, and the first reactor began industrial-scale production in November 2023. The capacity, when all four reactors are commissioned, is 80 million litres per year with an emission reduction from the steel plant of 125 ktCO₂/y.



Figure 33 Torero biocoal project (image ©ArcelorMittal)
[\(https://belgium.arcelormittal.com/en/torero-officially-commissioned/\)](https://belgium.arcelormittal.com/en/torero-officially-commissioned/)

6.6 SUSTAINABILITY, STRATEGIES AND INCENTIVES

Historically, charcoal was the main reductant in iron making before its replacement by coal and coke during the 1880s. Some countries made its use illegal due to increasing environmental concerns (Brooks and others, 2023). Poor efficiency charcoal kilns and unsustainable wood use are some of the dangers that charcoal (or biomass) face in its re-emergence as a decarbonisation option. Some of the key challenges in using biomass at large scale are the uneven distribution of the resources, competition from other markets and a lack of infrastructure. Based on 2022 figures, the quantities of charcoal required to substitute just 5% of annual met coal and coke is estimated at 55 Mt assuming 1–1 substitution of charcoal for coal. However, the integration of bioenergy into I&S manufacturing is highly plant-dependent, considering geographic location and availability of supply (Mandova and others, 2018; Lei and others, 2023). This will dictate the associated life cycle CO₂ emissions and thus actual emission reductions in replacing coal with biomass or charcoal. Cultivation practices, land use change, conversion efficiency and transport infrastructure impact the life cycle emissions; some of this debate is summarised in Jones and others (2023, 2024). Local sourcing of well-managed forest supplies or waste residues helps to mitigate some of these concerns. Consequently, biomass use has both a regional and plant-specific dependency.

Price is another important factor. Prices in 2021 were reported at 200 \$/t for coke compared to 295–525 \$/t for charcoal (Fan and Friedmann, 2021). In 2021, Brazil produced 9 Mt of charcoal, followed by India (1.7 Mt), the USA (0.94 Mt) and China (0.12 Mt) (Fan and Friedmann, 2021) and so charcoal could supply a fraction of their steel industries. However, the EU is a net importer of charcoal, mostly from Africa, and this generates concerns about possible deforestation, loss of biodiversity and societal impacts at the point of production. Mandova and others (2018) mapped the potential for indigenous bioenergy across the EU to supply its I&S plant and showed that, while a sufficient bioresource exists, integrated plants in Belgium, Germany, Spain, Italy, Netherlands and the UK would be reliant on imported biomass from other EU countries. Furthermore, the economics are unappealing although the implementation of organic wastes would improve both carbon saving projections and cost.

Early retrofitting of all carbon-reducing measures is the key to having the largest benefit for limiting global warming (Lei and others, 2023), but the I&S industry will require significant initial investment to achieve this (Kim and others, 2022). Any improvement in efficiency will result in financial savings for the industry, but decarbonisation projects require large, upfront capital costs. Carbon taxes and regulatory standards can be an effective incentive, and border adjustment mechanisms can help to reduce the risks of leakage (Kim and others, 2022). There are wider environmental (and societal) co-benefits from improved efficiency and decarbonisation measures which could include improvement in air quality, reduction in water used, minimisation of waste, extending plant lifetime and maintaining and expanding workforce employment opportunities.

6.7 COMMENTS

The physical, chemical, mechanical and thermal properties of biomass limit its use in coke and I&S manufacturing. Pretreated biomass including charcoal and torrefied materials have superior properties in terms of volatile matter content, oxygen-content, CV, better grindability and lower moisture content. This means they are better suited for both injection into the BF or EAF in pulverised form or for use in agglomerates as charge carbons or as supplements to coking blends. The utilisation of biomass products in these ways has been demonstrated at high TRL, albeit often at low substitution rates. In principle, injection in the tuyeres of the BF can be up to 100% charcoal, 23% torrefied wood, or 20% sawdust, where the limit is related to the throughput of the required heat content and safety issues around handling and conveying the more reactive fuel. In large BF, substituting coke with charcoal is limited by its mechanical and chemical properties to less than 10%; this can be much higher in the smaller BFs such as those used in Brazil. Blending of biomass or charcoal in coke making is limited to less than 10% and even small additions negatively impact the plastic behaviour, and thus the properties of the resultant coke. However, this area of research is seeing renewed research and optimism. Low levels of biomass-based alternatives have also been successfully employed in sintering trials, again at low levels of less than 20% substitution of the coke breeze). Substitution of injected carbon in the EAF by charcoal and biomass is at lower TRLs (3–5) but research indicates that satisfactory slag-foaming behaviour can be achieved for the right level of addition. Generally, there are no issues related to contaminants introduced by biomass/charcoal substitution, and some benefits – for example, lower sulphur levels. Some of the key issues in utilising biomass and charcoal in I&S manufacturing include economics versus sustainability credentials. Local sourcing of well-managed forest supplies or waste residues helps to mitigate some of the concerns. Carbon taxes and regulatory standards will be required as effective incentives for wider adoption.

THERMALLY PRETREATED BIOMASS AND CHARCOAL ARE ABLE TO SUBSTITUTE FOR COAL AND COKE AT VARYING LEVELS IN DIFFERENT OPERATIONS IN THE INTEGRATED PLANT. THIS NEAR-TERM STRATEGY WILL REQUIRE INCENTIVES AND REGULATORY STANDARDS FOR WIDER ADOPTION.

7 CONCLUSIONS

Cement, concrete, iron and steel are essential to modern life and linked to growth in population, economies and urbanisation and industrialisation (Kim and others, 2022). Consequently, demand for these products is forecast to increase substantially to 2050. Both manufacturing sectors are energy intensive and reliant on coal as their traditional fuel for process heat, and in the case of I&S, to produce coke for use as a reductant and fuel. Consequently, the global averages of carbon emissions are high, and the two sectors were responsible for 12% of all CO₂ emissions in 2021. For both industries, decarbonisation options are related to energy saving through efficiency improvements and the deployment of BAT, but these are often capital-intensive to deploy. Consequently, neither sector is on track globally to meet its decarbonisation targets.

Policy efforts will be necessary to promote global decarbonisation of these sectors. Some of the recommendations from the World Economic Forum (WEF, 2023) include:

- Infrastructure development – mechanisms to support the development of low-carbon power generation and electrolytic hydrogen production.
- RD&D support to accelerate low-emission steel technologies and progress them through the TRLs.
- RD&D support for CCS/CCUS projects.
- Introduction of mechanisms to incentivise demand for low emissions steel and concrete, such as through public procurement practices.
- Border adjustment tariffs complemented by fair and transparent carbon-accounting practices.

The EU leads the way in policy development. Examples include the review of its CBAM in 2025, the \$1.7 billion EU Clean Steel Partnership, the \$800 million EU innovation fund for CCUS projects in cement plants, and its direct funding incentives. However, decarbonisation ambitions vary greatly in different parts of the World, which leads to undercutting from cheaper imports. For example, steel producers in Europe are under pressure to cut their emissions and remain profitable against cheaper competition, notably from China. Consequently, improvements in efficiency or decreased production in I&S manufacturing in developed regions, are being offset by increased production in countries with high carbon intensity technology. This has led to stagnation of emissions which threatens emission reduction pathways (Wang and others, 2021). The required policy, technology and market requirements are not progressing fast enough globally to attract the necessary investment and so EU companies are postponing implementing their decarbonisation plans.

Decarbonisation options for the cement sector include the substitution of clinker material, CCUS, implementing kiln efficiency measures, and using alternative fuels. It has been estimated that deployment of all these measures could reduce CO_{2-eq} emissions by 88% by 2050 compared to 2020

levels (Georgiades and others, 2023). The dry kiln process for manufacturing cement has mostly displaced the much less efficient wet-kiln process. During the process, CO₂ is emitted from both calcination of calcium carbonate to calcium oxide, and from combustion of fuel to provide process heat. This process is amenable to the substitution of fossil fuels by alternative fuels- non-biogenic wastes (such as tyres or waste plastics) and biogenic wastes (such as RDF, textiles, sewage sludge, animal meat and bonemeal, paper fibre residues). Depending on the nature of the fuel, it may be added in the calciner or in the primary and secondary firing zones of the kiln. The high temperature and long residence time in the kiln delivers flexibility for alternative fuels where routes to the synthesis of dioxins and furans are avoided. Nevertheless, alternative fuels may contain elevated concentrations of undesirable elements that impact cement quality and plant emissions, so their selection and their firing strategy need careful consideration.

Use of alternative fuels is standard practice across much of the globe, although at different substitution rates. The global average for AF substitution is 23.25% (GCCA GNR, 2024) and this number is rising steadily. Regions with more advanced waste management systems have higher rates of substitution and the 2021 average in the EU was 53%. The EU sees no technical impediment to increasing this to 60% by 2030 (Cembureau, 2024a) and higher substitution rates are feasible if suitable pretreatment of waste streams to improve CV become economic. Some plants are already substituting more than 94% of fossil fuels with alternative fuels (Schwenk, 2023). The higher the biogenic content the greater the CO₂ savings, and transparent carbon accounting mechanisms are needed. Waste materials have co-benefits of avoiding potential emissions from landfill and are also less controversial than biomass crops or wood fuels. The effectiveness and uptake of alternative fuel use is influenced by regional factors, such as availability, economics, and policies and regulations that support effective management of waste streams. Policy measures or incentives that promote the use of alternative fuels over fossil fuels would support this decarbonisation lever.

The two dominant technologies in I&S manufacturing are BF-BOF and DRI-EAF, between them responsible for 90% of all steel production. BF manufacturing is the most carbon-intensive but will remain relevant into the near future because (i) the BF route to iron making remains the cheapest and most efficient process on a commercial scale (Brooks and others, 2023), (ii) the BF fleet in Asia is relatively young (around 10 years old) and the availability of scrap steel for the scrap-EAF route is low. Thus, substantial measures to reduce the carbon intensity of the integrated BF-BOF route are required to meet the goal of carbon neutrality.

Approaches to reduce carbon intensity include electrolysed hydrogen substitution for coal, CCS and sustainable biomass (Brooks and others, 2023). Biomass-derived carbon materials are structurally different from coke which makes them more porous, with higher reactivity and lower mechanical strength. This limits their use in the I&S industry and they cannot be used as 100% drop-in fuels for coke. Smaller BF, such as those used in Brazil can run exclusively on charcoal but for large BF only

partial substitution is possible. Most R&D has focused on maximising the substitution rate while maintaining satisfactory performance. Injection of charcoal or torrefied biomass into the BF to displace a portion of PCI has the highest TRL. Other avenues of research include blending of biomass/charcoal with coal during coking, substitution of nut coke, partial substitution of coal in the sintering plant, and carbon composite agglomerates for the BF or in DRI production. Possible substitution rates depend on the application and estimates of this with the associated TRL are given in Figure 34. Plant-by-plant consideration is necessary for implementing bioenergy. Modelling, such as GIS mapping linked to detailed plant data – age and technology – together with the availability of a sustainable and economic supply chain, can provide excellent guidance (Lei and others, 2023; Xu and others, 2023; Mandova, 2018).

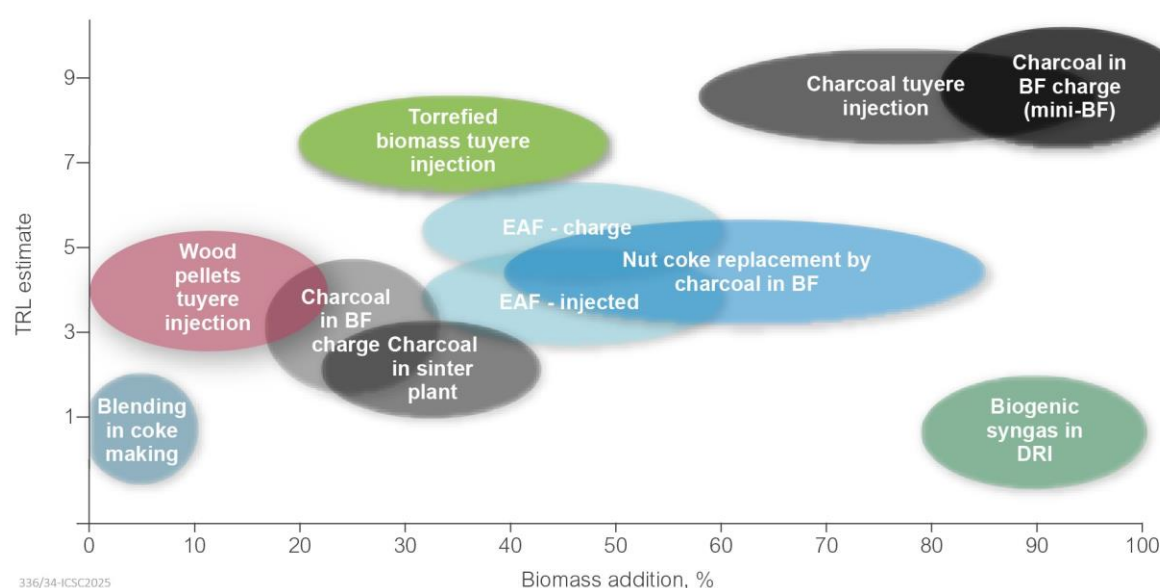


Figure 34 Estimated TRLs of different strategies for biomass addition in I&S manufacturing, and approximate substitution rates achieved (authors' work)

Apart from the technical challenges of substituting charcoal for coal and coke, there are concerns about its availability, production and the carbon savings afforded (Silva and others, 2022). Circular processes, such as recirculating and using liquid and gaseous products in charcoal manufacturing help to minimise emissions and enhance the economics of its production. The biomass supply chain itself must comply with sustainability criteria such that carbon savings are maximised and undesirable ecological or social impacts are eliminated (Jones and others, 2023). The co-benefits can be substantial and can deliver most of the SDGs either directly or indirectly. For example, good health and well-being through improved environmental impact (SDG3); decent work and economic growth (SDG8); industry innovation and infrastructure (SDG9); sustainable cities and communities (SDG11); responsible consumption and production (SDG12); climate action (SDG13); life on land (SDG15).

Technology roadmaps for decarbonising both heavy industries include major roles for CCUS, renewable hydrogen and electrification. The infrastructure development to support this should progress hand in hand with implementation of technology innovation to deliver the earliest deployment and the greatest benefits for limiting climate change. This requires collaboration and organisation on national and international levels. Benefits include energy savings, financial savings and delivery of SDGs. Understanding this is key to unlocking the organisational and policy framework to attract necessary investment and make it happen.

DECARBONISATION OF HEAVY INDUSTRY IS AN OPPORTUNITY FOR ENERGY SAVINGS, FINANCIAL SAVINGS AND ENVIRONMENTAL AND SOCIETAL BENEFITS. BIOENERGY IS AMONG A SUITE OF OPTIONS FOR RETROFIT IN EXISTING PLANT AND WILL PROVIDE A NEAR-TERM CONTRIBUTION.

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