UK Parliament POST

POSTNOTE

Number 672 May 2022

# Green steel

Greenhouse gas (GHG) emissions from the iron and steel industry make up 14% of industrial emissions in the UK. Decarbonisation of the steel industry is needed if the UK is to meet its 2050 net zero GHG emissions target. This POSTnote outlines current steelmaking processes in the UK, $CO_2$ emission reduction technologies and measures, and the supporting infrastructure and policies that could enable a 'green steel' industry in the UK.

## Overview

- Iron and steelmaking are responsible for around 7% of global $CO_2$ emissions.
- UK steel industry emissions need significant reductions to meet UK net zero targets.
- Strategies that could be rapidly implemented include improvements to energy efficiency and reducing the amount of steel used to make products.
- The three main technology pathways to net zero for UK steelmaking are: greater use of electric arc furnaces and recycled (scrap) steel; direct reduced iron using green hydrogen; and carbon capture, utilisation and storage (CCUS).
- Challenges to decarbonising the steel industry include high investment costs for technology, rising electricity prices, and the need for hydrogen and CCUS networks.
- There have been calls for a clearer policy framework for UK green steel production.

## Background

Steel is an alloy of iron, carbon and other elements depending on the desired material properties. Steel is the third most abundant synthetic material on Earth,[1] and the second most traded global commodity (after crude oil).[2] The strength, durability and recyclability of steel make it an essential material for construction, transport, machinery and consumer goods.[1] Iron and steel production is carbon-intensive, responsible for around 7% of global $CO_2$ emissions.[3] Globally, on average, 1.85 tonnes of $CO_2$ are emitted for each tonne of steel produced.[4]

Iron and steelmaking account for 14% of industrial GHG emissions in the UK,[5,6] equivalent to around 2% of total UK emissions.[7] The UK produced 7.2 million tonnes of steel in 2021 (0.4% of global annual steel production),[8] directly contributing £2.4 billion to the UK economy.[9] In comparison, China produced 1,033 million tonnes of steel in 2021.[8] Over half (54%) of UK steel demand in 2021 was met through imports, including in final consumer products.[9] Steel will be a critical material to support the UK's transition to net zero, through its use in wind turbines, electric vehicles, infrastructure and the energy sector,[10] making decarbonisation of steelmaking essential to the overall decarbonisation of UK industry.[11]

The UK has committed to achieving net zero GHG emissions by 2050,[12] with an interim target of reducing industrial emissions by two thirds by 2035.[11] The Climate Change Committee has recommended that steelmaking reaches near-zero emissions by 2035.[13] The UK has not yet piloted any new 'green' steelmaking technologies on a large scale, nor set any specific policy framework.[14] In this POSTnote, green steel refers to steel which is produced with low (near-zero) $CO_2$ emissions.[15]

## Current steelmaking processes in the UK

### Blast Furnace–Basic Oxygen Furnace (BF-BOF)

Conventional steelmaking involves the reduction of iron ore in a blast furnace (BF) to create hot iron-rich metal, which is then converted to steel in a basic oxygen furnace (BOF).[16,17] The product is known as primary or virgin steel. The UK imports most of its iron ore from Canada, Brazil, Sweden and Russia.[18] Iron ore and coke (made from coal) are loaded into the blast furnace, and coal is injected through pipes. The coke and coal are used as both fuel for heating the furnace and to generate reducing gases for the ore. Coke is critical to the blast furnace because its mechanical properties allow for permeable support of the iron ore and gas distribution through the furnace. As the iron ore is melted and reduced, chemical reactions within the furnace produce $CO_2$. The liquid metal is transferred to the BOF, and up to 25% recycled scrap steel can be added. Oxygen is injected and reacts with carbon in the liquid metal to produce additional $CO_2$. This decreases the carbon content to the required level for steel (<0.8% and typically much lower). The chemistry of the steel can be further altered by adding elements like silicon, manganese and chromium.

The UK has two integrated BF-BOF sites, in Scunthorpe[19] and Port Talbot,[20] which together produce 5.9 million tonnes of steel per year (82% of UK steel production).[9] These two sites are responsible for 95% of emissions from steelmaking in the UK.[22] Average global emissions from BF-BOF steelmaking are around 2 tonnes of $CO_2$ per tonne of steel produced.[1,23]

### Electric Arc Furnaces

Steel can also be made in an electric arc furnace (EAF) that uses electricity to melt and recycle scrap steel. Up to 100% scrap steel can be used in an EAF.[24] As scrap often comes from end-of-life products, the steel can be contaminated with other materials that contain undesirable elements like copper.[25] Iron from a blast furnace or direct reduced iron (see below) can be added to the EAF to dilute these elements and improve the steel quality, or high quality scrap must be used. $CO_2$ emissions from an EAF depend primarily on the carbon intensity of the electricity used, but EAFs in the UK can be over 80% less carbon-intensive than the BF-BOF route.[26] EAFs produce 18% of UK steel per year.[9] In contrast, the US produces over 70% of its domestic steel from EAFs.[27]

## Improvements to existing processes

### Energy efficiency

Existing BF-BOF sites can be retrofitted with the 'best available technologies', which make incremental improvements to the energy efficiency of the site.[28–31] This could reduce $CO_2$ emissions in the near term, however there may be limited potential to improve energy efficiency in the long term due to the maturity of current BF-BOF technology.[29,32,33]

### Biomass

Biomass (organic matter) absorbs atmospheric $CO_2$ during growth and releases $CO_2$ during burning. The Government considers biomass to be a low-carbon renewable fuel,[34] though there are issues regarding its sustainability.[35] Biomass can partially replace fossil fuels in several stages of the BF-BOF process,[36] such as in the production of coke[37] or as fuel within the BF itself.[38,39] Biomass use is prevalent in small BFs in Brazil, but the mechanical properties of coke are essential to the operation of larger furnaces in Europe, thus limiting the use of biomass.[40] The UK also has limited biomass availability and would be reliant on imports.[40] Biomass can be combined with carbon capture and storage to create a 'negative emissions' technology (BECCS; PN 618), where the $CO_2$ released from the biomass is permanently captured, but there are currently no commercialised applications of BECCS for the steel industry.[41,42]

### Hydrogen injection

Hydrogen gas can be injected directly into a blast furnace to act as an additional reducing agent for iron ore, which produces water instead of $CO_2$ and reduces the amount of coke and coal needed.[43,44] This method could reduce $CO_2$ emissions from the furnace by up to 21%,[43] but it may only be a transitional technology while other hydrogen technologies with lower $CO_2$ emissions develop.[45,46] German steelmakers Thyssenkrupp have completed the first phase of hydrogen injection tests in Duisberg, Germany,[47] with further trials planned for 2022.[48]

### Material Efficiency

Increasing material efficiency means providing the same service or product using less material input.[49] Improvements to material efficiency could decrease the need for primary steel production across the EU by more than 50%.[50] Strategies for the steel industry could include:

- using higher strength, thinner steel sections;[51]
- creating smaller products, such as reducing car size;[52]
- designing products with longer life spans;[53]
- developing service-based and sharing business models, such as car-sharing schemes;[54]
- reusing steel instead of scrapping and recycling products.[55,56]

## Low-carbon technology pathways

For the steel industry to reach net zero, disruptive long-term strategies are needed to achieve significant $CO_2$ reductions.[1,4] It is unlikely there will be one optimal solution from the range of low-carbon emission iron and steelmaking technologies that are being developed.[1,4,57] The UK Government's Industrial Decarbonisation Strategy[11] (Box 2) takes a 'technology-neutral' approach, allowing for the prospect of future innovation. As described below, there are likely to be three main technological pathways to decarbonise steelmaking in the UK.

### Direct reduced iron using hydrogen

In contrast to a blast furnace, direct reduced iron (DRI) is made by converting iron ore to iron in the solid-state, without melting any components.[58] The iron is then converted to steel in an EAF. Commercialised technologies such as MIDREX[59] or HYL/Energiron[60] reform natural gas into hydrogen and carbon monoxide, which are then used as the reducing agents.[58] DRI-EAF production using natural gas emits around 1 tonne of $CO_2$ per tonne of steel.[1,23] No UK companies use direct reduction technology at present,[9] though India and Iran each produce more than 30 million tonnes of DRI per year.[61]

Recent attention has turned to the use of hydrogen as both the fuel and the reductant for DRI, as a low-carbon alternative to natural gas.[31,62–64] This would produce water instead of $CO_2$. Hydrogen-DRI is not yet commercialised, but would require little modification to existing natural gas-DRI processes.[65,66] DRI presents a route to primary steel that doesn't involve carbon-intensive BF-BOFs. Emissions from hydrogen-DRI can be reduced further if the hydrogen is produced via electrolysis of water, using electricity from renewable energy sources ('green hydrogen'; PN 645). A DRI-EAF production route using green hydrogen could emit as little as 0.1 tonnes of $CO_2$ per tonne of steel.[57] However, if the UK's blast furnace capacity was converted to green hydrogen-DRI, the technology could demand up to 17% of the UK's current renewable electricity.[67]

### Increasing use of EAFs and recycling

EAFs are an established technology used by Celsa, Liberty Steel Rotherham, Outokumpu, and Sheffield Forgemasters in the UK.[68] The carbon intensity of the GB electricity system is steadily decreasing due to the growth of renewable energy sources.[69] EAFs are already a low-carbon technology and $CO_2$ emissions from EAFs will decrease further in the future, allowing EAFs to become a near-zero technology.[57] Phasing out BF-BOF use and replacing production capacity with EAFs would allow for large domestic $CO_2$ reductions in the steel sector.[11,70]

The UK produces 11 million tonnes of scrap steel per year, but only 23% of this scrap is recycled and used in domestic steelmaking, while the remainder is exported.[77] There are opportunities for the UK to increase scrap use without significant changes to existing infrastructure, as the maximum capacity for scrap use in current UK integrated BF-BOF and EAF facilities is 6.1 m tonnes.[77] Increased recycling would contribute towards a circular economy (PN 646), in which greater focus is placed on the reuse and recycling of steel products.[78]

### Carbon capture, utilisation and storage (CCUS)

CCUS describes a range of processes that capture waste $CO_2$ emissions and either use the $CO_2$ in a commercially productive way (PB 30) or permanently store the $CO_2$ in a geological formation.[79] $CO_2$ is produced at many stages of the BF-BOF process, thus CCUS could be added to a BF-BOF site to capture residual emissions.[80] The Industrial Decarbonisation Strategy outlines one option for decarbonising steelmaking as retaining the use of coke in integrated steel sites and using CCUS to utilise or sequester the $CO_2$ emissions.[11]

### Other low-carbon technologies

*Hydrogen plasma smelting reduction*

Hydrogen plasma can reduce iron ore in a process similar to hydrogen-DRI.[81,82] This process may have greater energy efficiency than hydrogen-DRI and would produce only a small amount of $CO_2$ from the use of graphite electrodes.[45,83] This technology is at the pilot stage (Box 1).

*Direct electrolysis*

Direct electrolysis involves passing an electric current through molten iron ore or an iron ore solution, which splits the iron and oxygen atoms.[30] Electrolysis produces no $CO_2$ and could be a low-carbon technology if renewable and decarbonised electricity is used. This technology is still at the laboratory stage.[84,85]

*Fuel switching in steelmaking*

Steel processing facilities which cast, roll and forge steel often use natural gas to heat the furnaces, but research is being done into the use of hydrogen as a low-carbon alternative.[86] Some metal recyclers are also working to switch diesel-powered material handlers to electric machinery in their scrap yards.[87]

## Benefits of a domestic green steel market

Decarbonising the steel industry could give the UK an opportunity to be a global leader in the production of green steel,[88] and to collaborate with other industries such as the automotive sector (Box 1).[89] Green steel will directly contribute to building a low-carbon economy[10] and could reduce the embodied $CO_2$ emissions of materials and finished products.[90] Greater reuse and recycling of scrap steel will contribute to industry circularity, as well as reducing $CO_2$ emissions.[53,67,91]

Steelmaking is considered a 'foundation industry' in the UK,[92,93] employing 34,500 people and a further 43,000 in the supply chain.[9] The industry generates well-paid, skilled jobs in traditionally disadvantaged regions of the UK.[9,94] The steel sector is highly localised in the UK, so decarbonisation is likely to affect specific areas.[95] Most options for decarbonisation result in increased productivity but a decreased workforce size,[67] however the Government has committed to helping industry to develop a skilled workforce and to generate jobs in new 'green' sectors.[92]

## Challenges for decarbonisation

### High electricity costs

Electricity prices for UK steel producers in 2020/21 were up to 82% higher than their nearest European competitors.[77,96] Rises in electricity prices during 2021/22[97] are only increasing this disparity. As many steel products are a commodity and are priced globally, the UK steel industry struggles to pass on these additional energy costs to the end-user, resulting in reduced profitability and competitiveness on the global market.[94] All low-carbon technology pathways for steelmaking will increase demand for electricity, meaning steel producers would continue to face high operating costs in the future.[94,96]

### Cost of investing in new technologies

As the UK steel industry operates with narrow profit margins, there are limited funds available to invest in new low-carbon technologies.[94] Investment decisions in the industry are typically long-lasting because of high capital costs and long blast furnace campaigns (the time between relining or refurbishing the furnace, often 20–25 years). There are limited investment cycles remaining before 2050 and steelmakers must soon decide whether to invest in new technologies or to refurbish existing capital, as such 'locking in' $CO_2$ emissions for decades to come.[57,63,67,98] Adding CCUS infrastructure to an existing BF-BOF site will also effectively lock in the BF-BOF capital, as CCUS is very expensive to install and operate.[67] Technology deployment must align with investment cycles or there is a risk of stranded assets, but many of the proposed low-carbon solutions for steelmaking are not fully commercialised. Because of this, steelmakers may invest in sub-optimal technology pathways simply because they are available and mature.[94] Some studies recommend developing short- and long-term timelines, focusing on retrofitting and material efficiency strategies in the short-term while developing

**Box 1. Green steel trials and pilot plants**

- HYBRIT[64,71] is a Swedish collaboration between steelmakers SSAB, mining company LKAB, and state energy company Vattenfall that seeks to produce steel without any fossil fuels, by using hydrogen-DRI, EAFs, and renewable electricity. A demonstration plant aims to bring green steel to the market by 2026. The venture could reduce Sweden's total $CO_2$ emissions by 10%.[72]
- In 2021, Volvo launched the world's first vehicle made of green steel, in partnership with SSAB in Sweden.[73] Small-scale production is planned for 2022.[74]
- The German government are providing €55 million to ArcelorMittal to help fund the construction of a new industrial-scale hydrogen-DRI plant. This is half of the expected capital expenditure.[75]
- Austrian steelmakers Voestalpine are developing a pilot hydrogen plasma smelting plant in Donawitz, Austria.[76]

**Box 2. Government strategies and funds relevant to decarbonisation of the steel industry**

- The **Net Zero Strategy** (2021)[92] outlines plans for four CCUS clusters that will capture 6 million tonnes of industrial $CO_2$ emissions per year, by 2030. The Government will also 'consider the implications of the recommendation of the Climate Change Committee to set targets for ore-based steelmaking to reach near-zero emissions by 2035, and the business environment necessary to support the transition'.
- The **Industrial Decarbonisation Strategy** (2021)[11] states that industrial emissions will need to reduce by at least two thirds by 2035 and by more than 90% by 2050. Key actions include developing funding mechanisms for CCUS and hydrogen infrastructure, supporting deployment of CCUS in industrial clusters, encouraging resource efficiency and material substitution within industry, and supporting innovation in fuel-switching technologies.
- The **UK Hydrogen Strategy** (2021)[102] sets out plans to deliver 1 GW of hydrogen by 2025, as well as providing £240m through the Net Zero Hydrogen Fund[104] for co-investment in early hydrogen production projects.
- The **Industrial Energy Transformation Fund**[105] was designed to help energy-intensive industries transition to low-carbon technologies. In 2020, Celsa was awarded £3m to install equipment which reduces steel melting time in an EAF, thus increasing energy efficiency.[106]
- The £250m **Clean Steel Fund** was announced in 2019[107] 'to provide a long-term signal of support to the steel sector and its decarbonisation efforts'. After an initial call for evidence, it was announced the fund would open in 2023, to allow time for technologies to develop.[94] The Climate Change Committee's 2021 progress report remarked that the Clean Steel Fund 'appears to have made no progress'.[13]

more disruptive technologies like hydrogen-DRI, which have greater potential for long-term $CO_2$ emissions reduction.[28,29] Pilot plants can provide confidence in moving to commercial deployment of new technologies.[57,94] There are at least 23 green steel pilot plants and trials currently planned across the EU, but none within the UK.[99,100] The UK's high energy prices make it a less favourable location to international companies looking to invest in new pilot plants.[96]

### Scrap steel supply and quality

Increasing the use of EAFs in the UK would require an increased supply of scrap steel. Unsegregated scrap can be easily sold overseas, which results in 77% of UK scrap steel being exported.[77] If the UK were to increase use of EAFs and recycled scrap steel (while phasing out BF-BOF production), domestic $CO_2$ emissions could be reduced.[11,70] However scrap is a finite resource, so this route could displace scrap-based steel production abroad, increasing the need for primary steel production and contributing to global $CO_2$ emissions.[101]

Current scrap sorting standards in the UK do not ensure that scrap received by steelmakers is of the quality and consistency needed for high-grade steel.[77] Improving the design and disassembly of products, developing better scrap-sorting technologies, and incentivising metal recyclers to invest in this technology would improve the quality of scrap steel available to UK steelmakers, reducing the need for additional carbon-intensive iron in the EAF.[53,77] EAFs produce a wide range of steels but cannot currently produce all the highest steel grades at competitive costs.[67] The UK may still need some primary steel supply (from DRI or BF-BOFs) in the future, and the Government is keen to retain some domestic primary steelmaking capacity to avoid reliance on imports.[94,99]

### Hydrogen and CCUS infrastructure

The optimum pathway for decarbonisation may depend on a steel plant's access to hydrogen or CCUS infrastructure.[4] However, as discussed in PN 645, there are issues with developing hydrogen demand sources and low-carbon hydrogen supply at the same pace. There are currently no large-scale hydrogen networks in the UK, and there are risks associated with committing to a hydrogen-technology pathway without the necessary infrastructure in place.[95] If the UK were to maintain current steel production capacity but convert to hydrogen-DRI and EAFs, the production could demand up to 1.4 GW of hydrogen[63]; the Government has pledged to deliver 1 GW of hydrogen by 2025[102] and 10 GW by 2030,[103] thus steel would be competing for a high proportion of this supply.

Developing and running a CCUS network is beyond the means of a single company,[67] but the Government's Net Zero Strategy and Industrial Decarbonisation Strategy outline plans to deploy CCUS networks in four industrial clusters by 2030 (Box 2).[11,92] Industrial clusters can link individual $CO_2$ sources to a common CCUS network, allowing multiple energy-intensive companies to share infrastructure and access to offshore $CO_2$ storage sites.[108,109] $CO_2$ storage may not be feasible for all UK clusters: British Steel's Scunthorpe site is part of the Humber Cluster, which can sequester $CO_2$ under the North Sea. However the South Wales cluster, which includes Tata Steel's Port Talbot site, is not geologically suitable for $CO_2$ storage and would have to transport the captured $CO_2$ to Merseyside or another suitable cluster, incurring additional costs.[11,110,111]

## Supporting a domestic green steel market

Stakeholders have called for the Government to set a clearer policy framework for UK green steel production, including targets, to provide financial certainty.[94] Stakeholders have suggested various ways the Government could encourage decarbonisation and support a UK green steel market:

- Addressing rising energy costs and levelling electricity prices in line with the UK's nearest competitors would help industry to invest in low-carbon but energy-intensive technologies.[96]
- The Environmental Audit Committee recommended the Government introduce a scheme similar to the EU's proposed Carbon Border Adjustment Mechanism,[112] which will affect the cost of steel imports into the EU from 2026.[113]
- Contributing to investment in new technologies, such as developing the Clean Steel Fund (Box 2).
- Public procurement policies, future purchase commitments, or direct demand signals could promote the green steel market and provide steel producers with the confidence to invest in new technologies.[95,114] The creation of a green steel product market may itself be a viable means of generating a revenue stream to support greener steel production.[89,115,116]
- Research and development should continue to be supported, to develop key technologies at the pace required.[49,117]
- Standards could be created for the reuse of steel, e.g. incorporating scrap steel into public infrastructure.[118,119]

POST is an office of both Houses of Parliament, charged with providing independent and balanced analysis of policy issues that have a basis in science and technology. POST is grateful to Lizzie Knight for researching this briefing, to NERC for funding her parliamentary fellowship, and to all contributors and reviewers. For further information on this subject, please contact the co-author, Dr. Alan Walker. 

**References:**


1. IEA (2020). Iron and Steel Technology Roadmap - Towards more sustainable steelmaking.
2. World Steel Association (2021). Steel and raw materials factsheet.
3. Philbert (2017). Renewable Energy for Industry.
4. World Steel Association (2021). Climate change and the production of iron and steel.
5. National Atmospheric Emissions Inventory (2021). Greenhouse Gas Emissions Reports.
6. ONS (2021). Atmospheric emissions: greenhouse gases by industry and gas.
7. BEIS (2021). Final UK greenhouse gas emissions national statistics: 1990 to 2019.
8. World Steel Association (2022). December 2021 crude steel production and 2021 global crude steel production totals.
9. UK Steel (2022). Key Statistics Guide April 2022.
10. House of Commons Library (2021). UK Steel Industry: Statistics and policy.
11. BEIS (2021). Industrial Decarbonisation Strategy.
12. HM Government (2019). The Climate Change Act 2008 (2050 Target Amendment) Order 2019.
13. CCC (2021). 2021 Progress Report to Parliament.
14. Environmental Audit Committee (2022). Call for Evidence - Technological Innovations and Climate Change: Green Steel.
15. The term 'green steel' is becoming widely used in academia and industry, though there is no generally accepted definition. In this POSTnote, we use 'green steel' as a broad term to refer to steel which generates near-zero carbon emissions during its production. We note that the term 'low-carbon steel' is potentially confusing, as it could refer to steel with low carbon emissions or to a steel alloy with low carbon content.
16. Yang, Y. *et al.* (2014). Chapter 1.1 - Ironmaking. in *Treatise on Process Metallurgy*.
17. Jalkanen, H. *et al.* (2014). Chapter 1.4 - Converter Steelmaking. in *Treatise on Process Metallurgy*.
18. UK Trade Info (2022). Overseas trade data table.
19. British Steel How we make steel.
20. Tata Steel Port Talbot. *Tata Steel in Europe*.
21. UK Steel (2021). UK Steel Key Statistics Guide 2021.
22. BEIS analysis (2021). Net Zero Industry Pathway (N-ZIP) model.
23. Sohn, H. Y. (2020). Energy Consumption and CO2 Emissions in Ironmaking and Development of a Novel Flash Technology. *Metals*, Vol 10,
24. Madias, J. (2014). Chapter 1.5 - Electric Furnace Steelmaking. in *Treatise on Process Metallurgy*.
25. Daehn, K. E. *et al.* (2017). How Will Copper Contamination Constrain Future Global Steel Recycling? *Environ. Sci. Technol.*, Vol 51, 8.
26. CELSA Manufacturing (UK) Limited (2021). Sustainability Statement 2021.
27. World Steel Association (2021). World Steel in Figures.
28. Griffin, P. W. *et al.* (2019). Industrial energy use and carbon emissions reduction in the iron and steel sector: A UK perspective. *Applied Energy*, Vol 249, 109–125.
29. Garvey, A. *et al.* (2022). Technology and material efficiency scenarios for net zero emissions in the UK steel sector. *Journal of Cleaner Production*, Vol 333, 130216.
30. Cavaliere, P. (2019). Clean Ironmaking and Steelmaking Processes: Efficient Technologies for Greenhouse Emissions Abatement.
31. Holappa, L. (2020). A General Vision for Reduction of Energy Consumption and CO2 Emissions from the Steel Industry. *Metals*, Vol 10, 1117.
32. Pardo, N. *et al.* (2013). Prospective scenarios on energy efficiency and CO2 emissions in the European Iron & Steel industry. *Energy*, Vol 54, 113–128.
33. Rechberger *et al.* (2020). Green Hydrogen-Based Direct Reduction for Low-Carbon Steelmaking.
34. BEIS (2021). Biomass policy statement.
35. IPCC (2020). Special Report on Climate Change and Land.
36. Mandova *et al.* (2018). Global assessment of biomass suitability for ironmaking–Opportunities for co-location of sustainable biomass, iron and steel production and supportive policies. *Sustainable Energy Technologies and Assessments*, Vol 27, 23–39.
37. Matsumura, T. *et al.* (2008). Carbonization Behaviour of Woody Biomass and Resulting Metallurgical Coke Properties. *ISIJ International*, Vol 48, 572–577.
38. Babich, A. *et al.* (2010). Charcoal Behaviour by Its Injection into the Modern Blast Furnace. *ISIJ International*, Vol 50, 81–88.
39. Feliciano-Bruzual, C. (2014). Charcoal injection in blast furnaces (Bio-PCI): CO2 reduction potential and economic prospects. *Journal of Materials Research and Technology*, Vol 3, 233–243.
40. Mandova, H. *et al.* (2018). Possibilities for CO2 emission reduction using biomass in European integrated steel plants. *Biomass and Bioenergy*, Vol 115, 231–243.
41. Mandova, H. *et al.* (2019). Achieving carbon-neutral iron and steelmaking in Europe through the deployment of bioenergy with carbon capture and storage. *Journal of Cleaner Production*, Vol 218, 118–129.
42. Tanzer, S. E. *et al.* (2020). Can bioenergy with carbon capture and storage result in carbon negative steel? *International Journal of Greenhouse Gas Control*, Vol 100, 15.
43. Yilmaz, C. *et al.* (2017). Modeling and simulation of hydrogen injection into a blast furnace to reduce carbon dioxide emissions. *Journal of Cleaner Production*, Vol 154, 488–501.
44. Zhuo *et al.* (2021). CFD study of hydrogen injection through tuyeres into ironmaking blast furnaces. *Fuel*, Vol 302, 10.
45. Souza Filho, I. R. *et al.* (2021). Sustainable steel through hydrogen plasma reduction of iron ore: Process, kinetics, microstructure, chemistry. *Acta Materialia*, Vol 213, 16.
46. Pimm *et al.* (2021). Cumbria mine: is there a technical need for new coal mines in the UK?
47. Thyssenkrupp (2021). Injection of hydrogen into blast furnace: thyssenkrupp Steel concludes first test phase successfully.
48. Thyssenkrupp (2021). Green steel: Review of phase 1 of the injection trials.
49. Stevens *et al.* (2021). Policy options for a net zero emissions UK steel sector.
50. Vogl, V. *et al.* (2021). The making of green steel in the EU: a policy evaluation for the early commercialization phase. *Climate Policy*, Vol 21, 78–92.
51. Tisza, M. *et al.* (2018). Comparative study of the application of steels and aluminium in lightweight production of automotive parts. *International Journal of Lightweight Materials and Manufacture*, Vol 1, 229–238.
52. González Palencia, J. C. *et al.* (2016). Energy, environmental and economic impact of mini-sized and zero-emission vehicle diffusion on a light-duty vehicle fleet. *Applied Energy*, Vol 181, 96–109.
53. Allwood, J. M. *et al.* (2019). Steel Arising: Opportunities for the UK in a transforming global steel industry.
54. Energy Transitions Commission (2018). Mission Possible: Reaching net-zero carbon emissions from harder-to-abate sectors.

55. Allwood *et al.* (2010). Conserving our metal energy: avoiding melting steel and aluminium scrap to save energy and carbon.
56. Lane, L. (2021). Steeling ourselves for climate change.
57. Mission Possible Partnership (2021). The Net Zero Steel Sector Transition Strategy.
58. Battle, T. *et al.* (2014). Chapter 1.2 - The Direct Reduction of Iron. in *Treatise on Process Metallurgy*. 89–176. Elsevier.
59. MIDREX (2018). The MIDREX® Process - The world's most reliable and productive Direct Reduction Technology.
60. Duarte, P. *et al.* (2008). ENERGIRON Direct Reduction Technology - Economical, Flexible, Environmentally Friendly.
61. MIDREX (2021). World direct reduction statistics 2020.
62. Vogl, V. *et al.* (2018). Assessment of hydrogen direct reduction for fossil-free steelmaking. *Journal of Cleaner Production*, Vol 203, 736–745.
63. Pimm, A. J. *et al.* (2021). Energy system requirements of fossil-free steelmaking using hydrogen direct reduction. *Journal of Cleaner Production*, Vol 312, 127665.
64. Pei, M. *et al.* (2020). Toward a Fossil Free Future with HYBRIT: Development of Iron and Steelmaking Technology in Sweden and Finland. *Metals*, Vol 10, 972.
65. MIDREX, S. C. (2021). Direct from MIDREX. 17.
66. MIDREX MIDREX $H_2$. *Midrex Technologies, Inc.*
67. MPI (2021). Decarbonisation of the Steel Industry in the UK.
68. UK Steel (2018). UK Steel Sites and Statistics 2nd Edition.
69. BEIS (2021). UK Energy in Brief 2021. 52.
70. Griffin, P. W. *et al.* (2021). The prospects for 'green steel' making in a net-zero economy: A UK perspective. *Global Transitions*, Vol 3, 72–86.
71. HYBRIT HYBRIT - Research project 1.
72. SSAB (2022). SSAB plans a new Nordic production system and to bring forward the green transition.
73. Volvo (2021). Volvo launches world's first vehicle using fossil-free steel.
74. SSAB (2021). Volvo Group and SSAB to collaborate on the world's first vehicles of fossil-free steel - SSAB.
75. ArcelorMittal (2021). German Federal Government commits its intention to provide €55 million of funding for ArcelorMittal's Hydrogen DRI plant.
76. Voestalpine Breakthrough technologies - SuSteel.
77. Hall, D. R. *et al.* (2021). Domestic Scrap Steel Recycling–Economic, Environmental and Social Opportunities. 45.
78. Material Economics (2018). The Circular Economy: A powerful force for climate mitigation.
79. Osman, A. I. (2021). Recent advances in carbon capture storage and utilisation technologies: a review. *Environmental Chemistry Letters*, 53.
80. IEA (2019). Transforming Industry through CCUS.
81. Naseri Seftejani, M. *et al.* (2018). Thermodynamic of Liquid Iron Ore Reduction by Hydrogen Thermal Plasma. *Metals*, Vol 8, 1051.
82. Naseri Seftejani, M. *et al.* (2019). Reduction of Haematite Using Hydrogen Thermal Plasma. *Materials*, Vol 12, 1608.
83. Naseri Seftejani, M. *et al.* (2020). Slag Formation during Reduction of Iron Oxide Using Hydrogen Plasma Smelting Reduction. *Materials*, Vol 13, 935.
84. Napp *et al.* (2017). A survey of key technological innovations for the low-carbon economy.
85. Abdul Quader, M. *et al.* (2016). Present needs, recent progress and future trends of energy-efficient Ultra-Low Carbon Dioxide (CO2) Steelmaking (ULCOS) program. *Renewable and Sustainable Energy Reviews*, Vol 55, 537–549.
86. SNAM *et al.* (2021). Snam, RINA and the GIVA Group: the world's first test with a 30% natural gas/hydrogen blend in steel forging.
87. EMR Decarbonising our business - Moving materials onsite.
88. Green Alliance (2021). Making the UK a world leader in the production of green steel.
89. Muslemani, H. *et al.* (2021). Opportunities and challenges for decarbonizing steel production by creating markets for 'green steel' products. *Journal of Cleaner Production*, Vol 315, 128127.
90. POST (2021). Reducing the whole life carbon impact of buildings.
91. Norman *et al.* (2021). Resource efficiency scenarios for the UK: A technical report.
92. BEIS (2021). Net Zero Strategy: Build Back Greener.
93. BIS Committee (2015). The UK steel industry: Government response to the crisis.
94. BEIS (2020). Summary of Responses to the Clean Steel Fund Call for Evidence.
95. BEIS Committee (2021). Liberty Steel and the Future of the UK Steel Industry.
96. UK Steel (2021). UK Steel Electricity Price Report.
97. House of Commons Library (2022). The energy price crunch.
98. IEA (2020). Clean energy innovation–Energy Technology Perspectives.
99. ECIU (2021). Stuck on the starting line: How the UK is falling behind Europe in the race to clean steel.
100. Vogl *et al.* (2021). Green Steel Tracker - Leadership Group for Industry Transition.
101. UK Steel (2022). Written evidence submission to Technological Innovations and Climate Change: Green Steel (GST0011).
102. HM Government (2021). UK Hydrogen Strategy.
103. HM Government British energy security strategy. *GOV.UK*.
104. BEIS (2021). Designing the Net Zero Hydrogen Fund - Consultation.
105. BEIS (2022). Industrial Energy Transformation Fund.
106. BEIS (2021). IETF Phase 1: Summer 2020 competition winners.
107. BEIS (2019). Clean Steel Fund: call for evidence.
108. Hammond, G. P. (2022). The UK industrial decarbonisation strategy revisited. Vol 175, 30–44.
109. BEIS (2017). Industrial Clusters in England.
110. Welsh Government, W. (2021). A Carbon Capture, Utilisation, and Storage Network for Wales.
111. Element Energy *et al.* (2020). Deep-Decarbonisation Pathways for UK Industry.
112. Environmental Audit Committee (2022). Greening imports: a UK carbon border approach.
113. European Commission (2021). Carbon Border Adjustment Mechanism.
114. Mission Possible Partnership (2021). Steeling Demand: Mobilising buyers to bring net-zero steel to market before 2030.
115. Muslemani, H. *et al.* (2020). Business Models for Carbon Capture, Utilization and Storage Technologies in the Steel Sector: A Qualitative Multi-Method Study. *Processes*, Vol 8, 576.
116. Element Energy *et al.* (2018). Industrial carbon capture business models.
117. Webb (2021). Forging the future: A vision for northern steel's net zero transformation.
118. Densley Tingley, D. *et al.* (2017). Understanding and overcoming the barriers to structural steel reuse, a UK perspective. *Journal of Cleaner Production*, Vol 148, 642–652.
119. Peake, L. *et al.* (2018). Creating effective UK markets for recovered resources.