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Technology and material efficiency scenarios for net zero emissions in the UK steel sector

Alice Garvey [*], Jonathan B. Norman, John Barrett

Sustainability Research Institute (SRI), School of Earth and Environment, University of Leeds, Leeds, LS2 9JT, United Kingdom

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ABSTRACT

With the UK's legislation of a 2050 net zero emissions target, there is urgent need for radical industrial decarbonisation. The steel sector represented 12% of UK industrial emissions in 2016 and is therefore a critical target for mitigation. Mainstream scenario analyses variously assume use of unproven Carbon Capture and Storage (CCS) or reductions to steel demand in order to reach a 1.5 °C compatible budget by 2050. This analysis aims to: a) assess the mitigation potential of current technology options (excluding CCS) towards a cumulative budget aligned to net zero and assuming constant steel demand; b) to evaluate the potential of material efficiency to close any mitigation gaps, (where material efficiency is providing the same useful 'service' with less input of energy-intensive materials); and c) to discuss the importance of sectoral budget assumptions and other uncertainties in estimating the scale of future mitigation required by the industry and the policy implications of this. We modelled four key technology scenarios including steel plant retrofit, replacement of steelmaking technologies to best practice standards, fuel shifts to greater Electric Arc Furnace (EAF) production, and implementation of selected novel technologies, under different ambition levels. Technology scenarios could reduce cumulative Greenhouse Gas (GHG) emissions (2016–2050) by as much as 44% against a constant baseline, whilst coupled technology and material efficiency scenarios could achieve reductions of as much as 53%. We also find that whilst grid electricity decarbonisation and earlier demand reduction can achieve additional mitigation, there may still be a need for some CCS capacity in the long-term to address residual emissions. In the most ambitious case, absolute GHG emissions from the steel sector reduced by 80% by 2050 against 2016 levels, assuming grid decarbonisation. We found that the most effective interventions were through established technologies, such as retrofit, replacement and EAF production, since they were immediately available, with the condition they are implemented faster than previously observed. Given the commercialisation constraints of novel technologies, structural shifts such as material efficiency and EAF production were considered highly important. However, structural changes are necessarily more complex to influence via policy, and there is little precedent for structural change by design in the UK. Our results show that only complementary scenarios combining material efficiency and technology options would achieve a level of mitigation near to net zero in the UK. We conclude that it is possible to achieve net zero emissions in the UK steel sector, but that this would require greater and earlier levels of material efficiency and some degree of CCS removal capacity.

1. Introduction

The 2015 Paris Agreement established a policy precedent to limit the rise in global average temperature to 'well below' 2 °C, whilst aiming for 1.5 °C, compared to pre-industrial levels; over 100 countries have set or are planning targets for carbon neutrality (van Soest, 2021). Industry is a critical target for these emissions reductions, representing 30% of global Greenhouse Gas (GHG) emissions (Rogelj et al., 2019). The emissions from the sector are increasing and larger than any other end-use sector (ibid), demanding concerted effort towards cleaner production and efficient consumption.

In June 2019 the UK Government passed legislation mandating the achievement of net zero GHG emissions by 2050 (Priestley, 2019).[1] This requires an unprecedented pace and scale of decarbonisation for the industrial sector which constituted 21% of the UK's GHG emissions in

* Corresponding author.
E-mail address: ee17amg@leeds.ac.uk (A. Garvey).

[1] 'Net zero' refers to the act of mitigating GHG emissions as close to near zero as possible, and using carbon removal techniques to offset the residual emissions. By contrast, 'carbon neutral' can be interpreted as the act of offsetting existing emissions rather than proactive attempts to decarbonise.

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Abbreviations

BAT	Best Available Techniques
BF-BOF	Blast Furnace Basic Oxygen Furnace
BCA	Border Carbon Adjustment
CCS	Carbon Capture and Storage
CDR	Carbon Dioxide Removals
CCC	Climate Change Committee
BEIS	Department for Business Energy and Industrial Strategy
EAF	Electric Arc Furnace
EU ETS	European Union Emissions Trading System
GHG	Greenhouse Gas
H-DR	Hydrogen Direct Reduction
IEA	International Energy Agency
NETs	Negative Emissions Technologies
UED	Useable Energy Database
WLCA	Whole Life Carbon Assessments
WSA	World Steel Association

2017 (p. 107, Climate Change Committee, 2019a). This scale of change has not been demonstrated before in the sector, and is complicated by the fact that much of the mitigation potential of energy efficiency, as ‘low-hanging fruit’, has already been captured.

In 2016 the UK iron and steel sector contributed 12% of industrial emissions (p. 108, ibid). However, the steel sector has been a key contributor to industrial mitigation in recent years, with 27% of reductions to final energy consumption by industry attributable to the iron and steel sector (p. 132, Hardt et al., 2018). Offshoring has been a significant driver of the reductions, and a challenge remains in driving action towards net zero through strategic decarbonisation rather than carbon leakage. The closure of the SSI Redcar blast furnace site in 2015, coupled with subsequent announcements of reductions in production capacity across the UK are key factors in reductions to date (Rhodes, 2018).

The steel sector is worth approximately £1.6bn to the UK economy, and represents over 32,000 jobs in the supply chain (Rhodes, 2018). The steel sector is arguably strategic given the likely future demand in supplying components of renewable energy and electricity distribution infrastructure. The recent Industrial Strategy white paper outlined an aim to ‘develop a commercially sustainable proposition in a competitive global market’ (p. 239, Department for Business Energy and Industrial Strategy, BEIS, 2018a), whilst the designation of a £250m Clean Steel Fund highlights a growing commitment to supporting decarbonisation in the sector as a strategic industry (BEIS,2019). This questions how sustained emissions reductions in the industry can be achieved, when the precedent for emissions reductions has been set mainly by unplanned reductions to production capacity.

Further imperative is given for decarbonisation of the sector given proposals by the European Union (EU) for a border carbon adjustment (BCA). Designed as complement to the EU Emissions Trading System (EU ETS), the BCA would protect against carbon leakage and competitiveness impacts from energy-intensive imports; under the proposed scheme the tariff would first apply to priority energy-intensive sectors such as steel. Therefore developing low-carbon steel could confer a key market advantage as many states look to increasingly ambitious climate policymaking (Burke et al., 2021).

This analysis therefore aims to evaluate the relative mitigation potential of a series of technology and coupled technology and material efficiency scenarios, in achieving sectoral carbon budgets aligned with net zero in the UK. Material efficiency is a form of demand-side action, which is broadly defined as: ‘[t]he pursuit of technical strategies, business models, consumer preferences and policy instruments that would lead to a substantial reduction in the production of high-volume, energy-intensive materials required to deliver human well-being; expressed as a ratio of the amount of product or service obtained by unit of material use’ (p. x, Hertwich et al., 2020). That is, the delivery of the same useful ‘service’ with less material input, acting within the steel production system (recovery, reuse, redesign) or on steel end-use as products (lifetime extension, product sharing).

The analysis contributes to the literature in considering how technology and demand-side action may perform in relation to explicit sectoral carbon budgets. Whilst previous research has considered whether mitigation strategies may achieve GHG emissions targets (Serrenho et al., 2016), our carbon budget perspective allows consideration of the cumulative impact of the various strategies and the implications of earlier or later action.

We develop a sector model, based on the UK Energy Research Centre Useable Energy Database (Griffin et al., 2013) to frame discussion of the role of technological and demand-side change in the iron and steel sector. The analysis addresses three core research objectives:

1. To assess the mitigation potential of a range of technology scenarios at varied levels of ambition towards achieving net zero aligned UK steel emissions.
2. To evaluate the potential of material efficiency in the UK to close any mitigation gaps towards net zero.
3. To discuss the importance of sectoral budget assumptions and other uncertainties in estimating the scale of future mitigation required by industry.

In this we use the phrase ‘net zero aligned’ emissions to account for the uncertainty in the prescription of carbon budgets at a sector level; for instance the budget level is contingent on the assumed capacity for Carbon Capture and Storage (CCS) removals by 2050.

In section 2 we conduct a literature review of existing decarbonisation scenario analyses for the sector, technological mitigation options, the potential for material efficiency in steel production and consumption, as well as discussion of sectoral carbon budget alternatives. In section 3 we outline the data and methods used to construct the sector model and develop the scenarios, before presenting and evaluating the results of the scenarios in section 4.

2. Mitigation scenarios for the UK iron and steel sector

2.1. Existing scenario analyses

The majority of work on the mitigation opportunities in the iron and steel sector are modelling studies, including stocks and flows (Serrenho et al., 2016), material flows (Milford et al., 2013), and global simulation models (van Ruijven et al., 2016). Few studies disaggregate to the UK, or set the industry in the context of global climate commitments. Demand reduction and mitigation technologies tend to be considered in isolation in these studies without assessments of possible complementarity between scenarios.

Serrenho et al. (2016) provide a framework for this analysis, in that they explore how UK demand for steel goods could be met under emissions allowances based on 4 energy pathways found in the 2011 Carbon Plan. In their scenarios demand which cannot be fulfilled by UK production under emissions constraints is met by offshored production. Our approach builds on this by considering whether steel technology and demand scenarios could be compatible with a more prescriptive sectoral carbon budget. They conclude that climate policy could be limited in reducing emissions in the sector on a global basis, without greater domestic production (via EAF/secondary processing) and consumption. Vögele et al. (2020) further explore the emissions effect of industrial relocation for the German steel industry. Griffin and Hammond (2019a) similarly assess the remaining potential for energy demand/emissions reductions in the subsector, concluding that the main opportunities are in the incremental energy efficiency improvements that can still be made. They conclude that continued energy efficiency has the most potential, but do not explicitly consider options such as EAF shifts – disruptive or novel options are viewed as highly uncertain, and do not frame the need for reductions in terms of the wider climate context.

2.2. Scenarios of future steel demand

Projections of future steel demand are affected by multiple uncertainties, and a sensitivity to the global economic outlook; as a result of recession following on from the coronavirus crisis demand for steel in developed states is estimated to reduce by about 17% during 2020 as a result of 'massive dislocations in spending, labour markets, and confidence' (World Steel Association, WSA, 2020a). However, in the long-term global demand for steel is projected to double by 2050 (Allwood et al., 2010; Milford et al., 2013), driven by demand in developing countries. An International Energy Agency (IEA) estimate suggests a potential increase in steel production of 50% by 2050 against 2010 demand (pp. 41–42, Science Based Targets Initiative, 2015). The UK could potentially be a key exporter of steel by mid-century, in order to meet greater global demand. As a producer of high quality steel goods, production could easily be expected to increase.

The recent *Future Capacities and Capabilities of the UK Steel Industry* report projects a 20% increase in demand for finished steel by 2030 against 2010 levels (p. 47, BEIS, 2017). The BEIS Updated Energy and Emissions Projections (BEIS, 2018b) provide projections of energy consumption in the iron and steel sector to 2035. However, this indicated an increase of only 1.4% in energy consumption from 2017 to 2035, in the Reference scenario. Since the projections are based on extrapolation of historically observed trends, it may be that demand reduction observed as a result of the recession has been forecast out to 2035. It is not clear what proportion of the reduction is anticipated from reduced production, efficiency gains or other technology improvements.

Serrenho et al. (2016), based on Pauliuk et al. (2013), project a saturation of demand for steel in the UK by 2030. But with projected growth in demand for steel goods globally, there is likely to be a continuing global market for UK products even if domestic demand remains stagnant. Since 2001, the UK has become a net importer of steel across most product categories (p. 27, BEIS, 2017). Whilst apparent steel use per capita has recovered since the recession, a greater share of final demand is being met by imported products, with only 27% of true steel demand being delivered by the UK steel industry (ibid). In 2017, the UK's net imports totalled 3.1 Mt (WSA, 2018). In 2015, two thirds of imports originated in the EU (Rhodes, 2020); by contrast, in the same year, 52% of UK steel exports were to the EU. There is therefore potential to both expand the share of UK demand being met by domestic production and to improve the net balance of trade by increasing exports of steel.

For further comparison of projections of steel demand in the literature see Table S1 (Supplementary Information).

2.3. Mitigation technologies

A number of modelling studies consider the remaining potential of retrofit to Best Available Techniques (BAT) in the steel sector. Many of these analyses are constrained by cost-effectiveness assumptions, that is, implementation rate is determined endogenously by the payback period of the designated BAT (Moya and Pardo, 2013). There is considerable variation in the potential energy demand and emissions reductions available from implementation of retrofit and upgrade technologies, which may in part derive from the diverse modelling methodologies.

There is some consensus that BATs, retrofit and upgrade offers the most promising short-term potential (Arens et al., 2017; Griffin and Hammond, 2019b; Oda et al., 2007), whilst presenting limited further potential in the long-term. There is also some indication that larger structural change such as grid electricity decarbonisation (Oda et al., 2007) and reduced production (Arens et al., 2017) are the largest contributors to achieving emissions targets. Pardo and Moya (2013) similarly suggest that there is limited potential for mitigation via BATs in the integrated route given the maturity of this production route. The findings may be influenced by the share of integrated production in the EU however, which was 59% in 2017, as opposed to 80% in the UK in 2017 (WSA, 2018).

There is a key distinction to be drawn between retrofit and upgrade or replacement. For instance Worrell and Biermans (2005) note that whilst stock turnover improved specific energy consumption by 0.7% per annum, retrofit achieved 0.5% pa.

There is general consensus that novel technologies will be less significant in reaching medium-term emissions targets given their commercialisation requirements and the intersections of this with the long investment cycles of the steel industry. However, it also important to note that there has been a recent increase in declared investments in low-carbon steelmaking technologies and demonstration projects. The recently launched Green Steel Tracker provides a comprehensive overview of planned projects on a site basis (Vogl et al., 2021). Therefore the assumptions of novel technology implementation in the UK are on the basis of available evidence from the Useable Energy Database (Griffin et al., 2013), and could be updated through consultation with industry.

The shift to greater EAF production is widely considered a mitigation option, since it reduces the requirement for carbon-intensive feedstocks such as coking coal, and instead makes use of scrap as primary feedstock. Secondary steelmaking has been estimated as twice as resource efficient as primary production (Gonzalez Hernandez et al., 2018). Similarly, the electrification of heating processes means that there is greater scope for decarbonisation of heat. Scrap availability and the difficulty of shifting to greater EAF capacity, for instance with locked-in integrated infrastructure, are viewed as constraints to EAF as a mitigation option. However, Moya and Pardo (2013) identify that constrained availability of raw materials to 2030 will prioritise the development of secondary production techniques. Blast furnace blast oxygen furnace (BF-BOF) is typically used in making flat products, whilst EAF is used for long products, but in Germany EAF is beginning to be used to produce high quality flat products (Arens et al., 2017), suggesting the future potential of more EAF production.

The potential for EAF production to meet total true steel demand will be dependent on both the composition of products making up this demand, and the availability of scrap and its quality (Serrenho et al., 2016). However, the UK is in a position of comparative advantage regarding scrap, with high levels of annual arisings (Allwood et al., 2019). For instance, in 2017 the UK exported 9.4 Mt of ferrous scrap (WSA, 2018). Global scrap prices will ultimately determine the economic viability of scrap recovery and use in secondary production, but improved linkages between recycling facilities and the scrap supply chain could support developing secondary steel production in the UK (Allwood et al., 2019).

2.4. Material efficiency: the sooner the better

Given the outlined potential for significant increases in demand for steel towards 2050, material efficiency or 'material productivity' should feature as a critical strategy for mitigation in the sector (Scott et al., 2018a). Allwood et al. (p. 12, 2019) note that steel demand could be met with an eighth of the steel currently used, citing that only 75% of the steel produced ends up in a product. They identify four key material efficiency strategies, namely: 'avoiding scrap' and 'over-design', and in producing 'smaller goods' with longer lifetimes (p. 13, ibid).

In this analysis we consider material efficiency strategies for both steel production and consumption, that is, the production of steel within the manufacturing value chain and the consumption of final goods. Production-based strategies involve light-weighting, improving fabrication yields, scrap recovery and reuse, optimised design, and material substitution. That is, options for improving the efficiency of steel use within the manufacturing value chain.

Consumption strategies involve extended product lifetimes, encouraging the shared use of steel-based products, increasing product reparability and remanufacturing, and substituting services for products (Scott et al., 2018a). Strategies to change the consumption of steel often involve 'avoided use' and act on how steel is used at the stage of final demand.

In this analysis we estimate the impact of material efficiency on steel sector emissions when combined with technology scenarios. This is achieved by using three literature-based estimates of the steel demand reduction which may occur from pursuing material efficiency strategies (without making explicit assumptions about whether the reductions are achieved through production or consumption sided material efficiency). These top-down estimates are applied at an aggregate level across the sector rather than considering specific aspects of the supply chain, and therefore only present a high-level estimate of the potential without identifying which individual strategies may be most effective. Pauliuk and Heeren (2020) provide a detailed scenario analysis of the contribution of individual material efficiency strategies to decarbonisation of the German economy. Much of the potential is reflected in recent proposals to extend the EU Ecodesign Directive to encompass 'Right to Repair', and in calls to include embodied carbon standards in the legislation (Scott et al., 2018b).

Material efficiency reduces final demand for steel and therefore provides an effective industrial decarbonisation strategy. Material efficiency reduces the required pace and scale of technology development and dependence on less proven technologies (such as hydrogen or CCS) (Grübler et al., 2018). Analysis by the Energy Transition Commission states that 'decarbonizing the harder-to-abate sectors would cost significantly less if pursuing energy efficiency improvement and demand management opportunities' (p. 92, 2018). Demand reduction via material efficiency would reduce the pressure to install costly decarbonising technologies rapidly. Similarly, implementing technology interventions alongside material efficiency strategies would reduce the costs and required ambition levels for both. There is further potential that greater demand reduction in the UK would also reduce demand for carbon-intensive imported goods (Milford et al., 2013), acting to mitigate the UK's consumption-based emissions account. As part of a wider movement recognising the embodied impact of goods consumed domestically, Liu et al. (2020) highlight that there is a need for shared responsibility in the environmental and economic impacts associated with the import of steel.

Various scenario analyses highlight the mitigation potential of changing final demand for steel as a result of material efficiency. The low energy demand (LED) scenario already assumes a 15% reduction in demand for industrial commodities by 2050 from dematerialisation and material efficiency actions (p. 518, Grübler et al., 2018). Dunant et al. (2019) suggest a possible 12% reduction in demand for UK steel goods. The Energy Transitions Commission estimate that circular economy schemes could reduce global virgin steel demand by 38% by 2050 (ETC, 2018). Meanwhile in the IEA World Energy Outlook (WEO) 2015, their 'Material Efficiency Scenario' estimates that energy demand would reduce by 21% in 2040 and emissions by 28% (IEA, 2015). Demand for steel goods would also fall 26% (all against the New Policies Scenario; ibid). Fischedick et al. (2014a,b) suggest that without global demand reduction for steel, only novel technologies would be able to deliver emissions targets for the sector, therefore this is an important aspect to consider.

There is also a critical argument to test the temporality of material efficiency, since Milford et al. (p. 3459, 2013) indicate the impact of delays to material efficiency strategy on achieving cumulative carbon budgets. Theoretically, earlier demand-side action could be disproportionately effective in reducing emissions when sectoral carbon intensity is at its highest.

In essence, the degree of material efficiency required is inversely proportional to the need for novel technologies, technological breakthrough and implementation of significant CCS removal capacity in the sector. However, in practice material efficiency could disincentivise investment in decarbonisation by reducing aggregate demand for products and associated profit margins. There could be a lack of direct economic benefit unless the manufacturer is a producer of final goods. In reality, though material efficiency could significantly de-risk the dependence on technologies to achieve net zero steel, it is a strategy required in co-existence with technological change.

2.5. The role of CCS and hydrogen in steel

Hydrogen and CCS are commonly cited technologies with applications for low carbon steelmaking. However, modelling the mitigation potential of these options is beyond the scope of this analysis given: a) the complexity of accurately representing these routes; b) the speculative nature of their demonstration and deployment, particularly in a UK context. See Pimm et al. (2021) for comprehensive discussion of the applications of hydrogen to the UK steel industry.

As Oda et al. (p. 156, 2009) note 'for deep emissions cuts in the BF-BOF route, CCS is one of the key technologies because a certain amount of coke is indispensable for a role of structural material in the blast furnace.' Therefore, depending on the share of BF-BOF in future UK steel production, CCS could be a requisite part of new steel infrastructure. The potential for application of CCS to steel production facilities is a critical research area, as highlighted by a number of recent analyses (Chisalita et al., 2019; Garcia and Berghout, 2019; Mandova et al., 2019; D'Amore et al., 2021).

However, as Wiley et al. (2011) suggest, capture at power plants may be more effective than at blast furnace sites, given the reuse of flue gas onsite and the potential of CCS to change the composition of the gas. There is a sense in the literature that energy efficiency improvement alongside CCS could be a viable route towards decarbonisation (Griffin and Hammond, 2019b; Morfeldt et al., 2015). However, as discussed, parallel implementation of material efficiency strategies would reduce pressure on technologies to deliver the reductions.

Hydrogen used as a reducing agent in the Hydrogen-Direct Reduction (H-DR) process is a novel technology with significant estimated savings compared to the integrated production route (Vogl et al., 2018). BEIS commissioned research found that fuel switching to hydrogen could occur for approximately half of all fossil fuel use in manufacturing (CCC, 2018). There are some H-DR plants in operation, as highlighted in the Green Steel Tracker (Vogl et al., 2021), and ThyssenKrupp are trialling the use of green hydrogen in blast furnaces (Winter, 2020; Pimm et al., 2021a). However, some demonstration projects indicate they will require 20 years before full commercialisation (Åhman et al., 2019). Whilst 23 hydrogen steelmaking projects are being demonstrated in Europe, there are no clear proposals for comparable projects in the UK (ECIU, 2021).

In the LED database, the share of hydrogen in final industrial energy demand in the global north was 0 in 2050 (IIASA, 2018). Furthermore, the sustainability and carbon intensity of hydrogen production is highly contingent; the majority of hydrogen currently available is produced from natural gas (grey), but cleaner versions using CCS (blue hydrogen) and generation from renewable sources (green hydrogen) pose cleaner options for future production. Hydrogen steelmaking was not included in this analysis given the commercialisation constraint and the dependence on the future availability of clean hydrogen in the UK (infrastructure for which is in only the early stages of development). Fischedick et al. (2014a,b) indicate that HDR could have most benefit after 2050. There is also likely to be competing future demand from different economic sectors for the use of CCS and hydrogen, which could complicate how accessible such resources are for UK steelmaking. Hydrogen steelmaking plants require large scale capital investments which are beyond the economic scope of single sites in the UK, requiring substantive new policy supports and business models to drive deployment for long-term decarbonisation (Karakaya et al., 2018; Kushnir et al., 2020).

2.6. Sectoral carbon budgets

The Climate Change Committee's (CCC) Net Zero report and subsequent 2020 Progress Report (CCC, 2020a; 2019b) disaggregate net zero aligned GHG emissions budgets to the sector level, indicating a steel budget consistent with the target in two scenarios in 2050 (the 9th carbon budget period). UK steel sector emissions in 2016 stood at 12.5 $MtCO_2e$; in the 'core' scenario residual emissions in the UK steel sector in 2050 are 6.1 $MtCO_2e$, and in the 'further' ambition case are 0.7 $MtCO_2e$ (CCC, 2019b). The residual budgets presuppose linear reductions in the emissions of the sector from 2018 to 2050.

However, the budgets do not represent a continuation of the current sectoral share of industrial emissions. That is, whilst steel emissions currently represent 12% of industry emissions, in the core scenario the share reduces to 11%, and in the further ambition scenario to 8%. This reflects a prioritisation of harder-to-abate sectors with higher process emissions, given an increase in the share of industrial emissions from 2% in 2016 to 4% (core) and 12% (further ambition). The allocation of budgetary share in 2050 is a reflection of the assumption of CCS removals capacity in each scenario. Fig. 1 indicates the difference in the absolute emissions time series when assuming either the core or further ambition scenarios, with either an assumption of prioritisation of process emission sectors or continued sectoral share of industrial emissions (e.g. maintained at 12% to 2050).

Fig. 1 also indicates the abatement pathway for the sector put forward by the CCC in their recent 6th Carbon Budget advice (CCC, 2020b). Whilst the residual emissions in the new scenario are almost the same as in the further ambition case, the critical difference in this new mitigation profile is the assumption of a more logistic, or s-shaped, rate of decarbonisation, with particularly rapid acceleration in the 2030s. This has direct implications for the cumulative carbon budget of the steel sector, which is approximately 18.9 $MtCO_2e$ lower than in the most ambitious linear reduction scenario of the previous analyses. In this analysis we compare our technological and material efficiency mitigation scenarios to the budgets set out by the net zero report to avoid making further, and potentially conflicting, assumptions about the rate of deployment of the various abatement measures.

The core and further ambition scenarios are differentiated by the assumed abatement cost and proportion of CCS deployed in industry and that would be available to each sector. The core scenario denotes low cost and 'low-regrets' options, whilst the further ambition case involves rapid deployment beyond typical industrial turnover rates (CCC, 2019b). Large scale implementation of CCS is assumed, with capacity of between 75 and 175 $MtCO_2$ per annum by 2050 (ibid).

In contrast, Grübler et al. (2018) indicate the potential of a low energy demand (LED) scenario without dependence on CCS or negative emission technologies (NETs) to achieve residual emissions compatible with 1.5 °C by mid-century. Similarly, the recent IPCC Special Report provided 4 illustrative pathway archetypes, with varying dependence on carbon dioxide removal (CDR) methods (p. 112, Rogelj et al., 2019). Both highlight the trade-off between the degree of demand reduction and reliance on unproven CCS/NETs/CDR.

Other precedent for setting sector-level budgets is in terms of corporate target-setting practice, namely the Science-Based Targets Initiative (SBTi) which applies the sectoral decarbonisation approach (SDA) to derive company-specific targets in line with global 1.5 pathways (CDP et al., 2019). Other methodologies for deriving sector budgets include the 'flat' application of industry-level reduction targets to the specific subsector, as in Arens et al. (2017), where reduction targets are equal and proportional across sectors. This is equivalent to assuming the same sectoral share in industrial emissions. Whilst policy for specific sectors is set at the national level, given the global interest in mitigation and the international trade in basic materials, there is a need for a coordinated global strategy on industrial decarbonisation.

In this analysis we adopt the CCC sectoral budgets as a UK specific estimate, though we consider the further ambition residuals as the upper bound of reduction potential without using CCS.

3. Methods

3.1. Constructing a steel sector model

A top-down iron and steel sector model was developed to evaluate the mitigation potential of four technology scenarios and combined

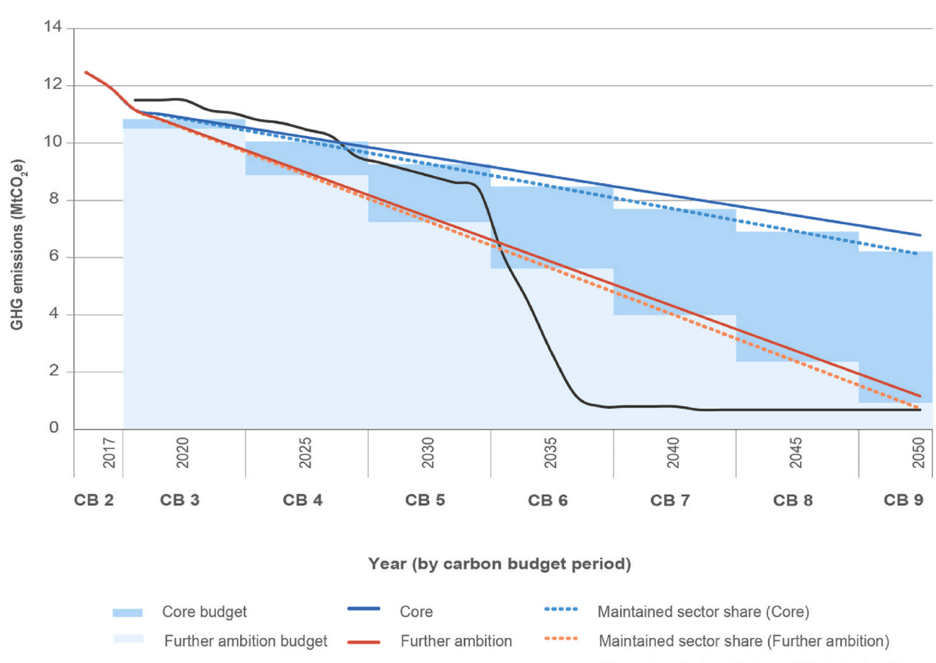

Fig. 1. Comparison of sectoral carbon budget time series when assuming different levels of economy-wide ambition, and allocation of share of industrial emissions in 2050.

technology and material efficiency scenarios to 2050 (Fig. 2). The model produced time series of GHG emissions between 2017 and 2050 on a territorial basis. This analysis aggregates production routes to integrated (BF-BOF) and electric arc furnace (EAF), rather than the conventional primary/secondary split, adopting the same broad approach as Moya and Pardo (2013). This also follows the split of 'site types' in the UED (Griffin et al., 2013). Since EAF production has a very small component of primary processing, mainly using scrap, it is synonymous with secondary production in the literature.

2017 is taken as the base year for the scenarios, as the most recent year for which baseline data was available at the time of analysis, namely production data. It is assumed that implementation of the scenarios can start at the earliest in 2022. This assumption is constant across the scenarios. 2050 is taken as the lead time corresponding with the UK's legislated net zero climate commitment. The CCC carbon budget period including 2050 (period 9), spans 2048 to 2052; in our scenarios we assume that the emissions achieved in 2050 in each case are held constant to 2052 for purposes of calculating carbon budget alignment. Many studies in the literature only consider 2030 as a lead time (Oda et al., 2007), and there is necessarily increased uncertainty in projecting over longer lead times. The Industrial Decarbonisation and Energy Efficiency Roadmaps (Department of Energy and Climate Change and the Department for Business Innovation and Skills, 2015) suggest that with typical investment cycles of 25–40 years, the iron and steel sector has only 1–2 investment cycles remaining to 2050. Taking a target year of about 2050 allows for possibly 2 investment cycles, and this assumption has been used to inform the implementation rates of the technology scenarios.

The UED assumes a share of approximately 70% BF-BOF and 30% EAF production (Griffin et al., 2013). The current share of production was derived from WSA production data (WSA, 2018), where 80.1% of UK production is via the integrated route, 19.9% through EAF. In all scenarios but that considering shifts to further EAF production, we assume a constant split between the share of BF-BOF to EAF production. Emissions factors were taken from the UED as providing the most internally consistent source of data for all sector-specific energy inputs/outputs. Emissions factors for the carbon intensity of grid electricity were updated however, they reduced by 56% between 2010 and 2020 (BEIS, 2018c). Emissions factors were applied against the energy intensity profiles for each technology scenario. Given the inherent uncertainty in projecting the UK's future crude steel demand, we assume that demand in the UK remains constant from 2018 levels to 2052, taking a trade-neutral approach. The WSA (2020b) provided production data for the years 2017 and 2018. Production in 2018 was 7268 kilotonnes crude steel (ktcs), and 7491 ktcs in 2017 (ibid).

3.2. Modelling technological mitigation options

The subsector model is based around 4 technology scenarios (Table 1). The impact of technology changes on the energy inputs and outputs of both production routes was modelled in each scenario, resulting in time series of changing energy intensity for each production routes. This was applied against the final demand baseline, the emissions factors, and assumptions of the share of each route as fraction of total production, as outlined in equation (1).

$$E_y = \sum_f \sum_r \left(I_{rf} \cdot P_r \cdot C_f\right) \cdot D \quad (1)$$

The total emissions (**E**; $MtCO_2$) from a scenario in any given year in the time series (**y**), is the sum for each production route (**r**) and fuel (**f**) of the product of the final energy intensity of production for the given production route and fuel (**I_{rf}**; GJ/tcs) the percentage of production fulfilled by each route (**P_r**), the emissions factor of the fuel (**C_f**; tCO_2/GJ) and the UK final demand for steel (**D**; tcs).

Equation (1) indicates the intervention points for reducing emissions: by changing the intensity of production of a particular route and fuel (e.g. retrofitting efficiency technologies), changing the proportion of production filled by each route (e.g. switching to new technologies, or increased EAF production), changing the carbon intensity of fuels (less applicable here, but improvements in the carbon intensity of electricity

Table 1
Overview of technology scenarios.

Scenario ref.	Description
A: Retrofit	Implementation of retrofit efficiency technologies derived from the Useable Energy Database (for further detail see the Supplementary Information, Sections 2-3).
B: Replacement	Updating existing equipment stock to new, current best practice efficiency technologies.
C: Fuel shift	Moving to a greater share of EAF production, with a reduction in production by BF-BOF.
D: Novel technologies	Adoption of technologies which are not yet commercialised, or proven at scale, but which offer radical process changes and emissions reductions.

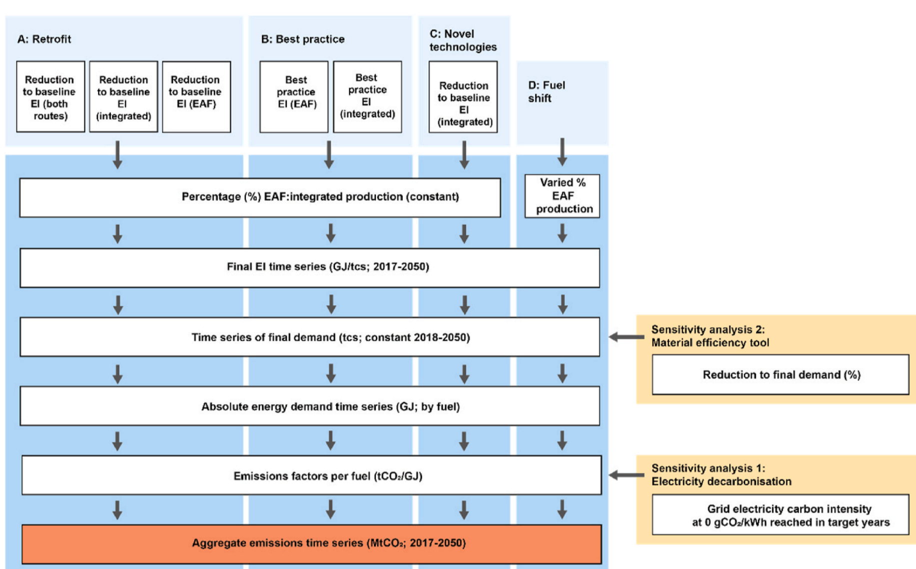

Fig. 2. Simplified schematic of the iron and steel model. EI stands for energy intensity.

favour EAF production) and changing total demand for steel.

The UED provides data on the energy demand reductions (GJ per tcs) to each energy input/output per mitigation technology. For each scenario a time series of reductions in energy intensities with technology implementation was developed. This was subtracted from the reference case fuel balance. This was then transposed onto the baseline energy intensity for the subsector, or, if a technology was route-specific, to the baseline energy intensity for either the integrated or EAF route. This produced time series of energy intensities for each scenario (GJ/tcs). Multiplication of these values by the final demand values per production route resulted in absolute energy demand values (GJ). Emissions factors were then applied to create emissions times series from 2017 to 2050. All technology scenarios assume linear implementation between the specified target years, according to the assumptions of the ambition levels for each technology (Table 2).

3.2.1. Retrofit

The retrofit scenario represents incremental improvements to energy efficiency in the sector, which more or less reflects the trajectory it has been following to date. Continuous retrofit appears to be a key approach in the sector, as a means of minimising energy costs. Given the length of investment cycles in the sector, it was assumed that a central scenario would mean 100% implementation of all technologies by 2050. Since investment cycles are typically 25–40 years in the sector (DECC/BIS, 2015), this represents a median value for the investment period in-keeping with the idea that many sites will already have implemented these technologies since the creation of the UED. At least 3 of the 6 UK steel sites (2 integrated, 4 EAF) have recently undergone major upgrades. Sheffield Forgemasters reported an EAF refit in 2017, Tata Steel at Port Talbot a 2019 refit of a blast furnace, and British Steel announced an upgrade at Scunthorpe in 2018 (BBC News, 2018; 2019). Therefore it is assumed that major investments have just been made, making c. 2020 the start of a new investment period. The variation in estimates of both plant lifetimes and investment periods in the literature, are used as bounds for the low and high ambition scenarios (see Tables S3–5 for detail on ambition level assumptions). The recency of these upgrades however (i.e. in 2017, 2018, 2019 etc.) could mean that the technologies modelled from UED data could already have been implemented.

To model the effect of implementing the technologies associated with energy efficiency the total reductions in energy use achieved by 100% implementation of all options were calculated. The following implementation rate variables were also accounted for: existing level of implementation, maximum theoretical implementation, application of the technology to integrated, EAF, or both routes, commercialisation year, and conflict between technologies. For a list of the technologies included see section 3 of the Supplementary Information.

3.2.2. Best practice

This scenario assumed implementation of best practice energy intensity for the sector, derived from Worrell et al. (2008). This models a 'faster' attainment of best practice values than incremental efficiency improvements. It is assumed that best practice represents the potential of entirely new equipment, that is, the 'replacement' of current stock to best practice. The best practice ambition levels follow the same rationale as the retrofit scenario.

3.2.3. Fuel shift

In this case, the dependent variable was the percentage share of total production by each route. The scenario was implemented by using the baseline fuel inputs and outputs for each route, and varying the proportion of each as a time series. This assumed linear interpolation to grow the use of EAF to the percentage share specified to be reached in 2050.

3.2.4. Novel technologies

The same approach used to implement the retrofit technologies was adopted here, but in this case the variable was implementation rate by 2050 rather than the year in which 100% implementation was achieved. In this scenario, options in the UED which use CCS were purposely excluded given the uncertain effectiveness and potential for competing demand for this technology by 2050.

Given the earlier availability of Midrex and TGR-BF (relative to other novel technologies, see Table 3), these options were modelled with varying levels of implementation by 2035 and 2050. The novel technologies tended to conflict with others in this category, that is, the technologies are to a degree mutually exclusive; the assumption made in the UED is adopted here, where when implemented in parallel these technologies can only be applied to 50% of the 'baseline output'. The technologies are implemented to their 'expected' value for 2050 (as derived from the UED), before the conflict assumption has been taken into account. The model allows implementation of a maximum of two novel technologies at a time. Since the expected levels of implementation are so low in 2050, it was seen that combining more than two options would not be realistic. Similarly, in reality the commercialisation process would not follow a 'curve' in the UK given the small number of sites.

3.2.5. Sensitivity analysis: electricity decarbonisation

A sensitivity analysis was carried out on the effect of grid electricity decarbonisation on the technology scenarios. This is to reflect both the

Table 2
Overview of assumptions in technology scenarios, by level of ambition.

		Ambition level		
		Low	Central	High
Scenario	A: Retrofit	75% of mitigation potential realised in 2050	100% of mitigation potential realised in 2050	100% of mitigation potential realised in 2050
	B: Replacement	Best practice in 2060	Best practice in 2050	Best practice in 2035
	C: Fuel shift	25% EAF production in 2050	50% EAF production in 2050	75% EAF production in 2050
	D: Novel technologies	MIDREX only implemented (to expected levels of implementation, see Table 3)	TGR-BF and MIDREX implemented (to expected levels of implementation, see Table 3)	TGR-BF and MIDREX implemented (100% implementation)

Table 3
Overview of novel technologies in the UED (Griffin et al., 2013).

Technology	Estimated commercialisation year	Maturity/readiness level	Type of technology change	Estimated 2030 adoption	Estimated 2050 adoption
TGR-BF without CCS	2025	Demonstration	Major	33%	100%
HISarna	2030	Demonstration	Major	N/A	66%
MIDREX	Present -	Commercial	Radical	N/A	20%
ULCOWIN	2040	R&D	Radical	N/A	10%

certainty of future grid decarbonisation in the UK (as outlined in the recent Energy White Paper; BEIS, 2020a), as well as the uncertainties of when this might be achieved and through what energy mix. To implement this sensitivity, the emissions factors associated with imported electricity inputs (that is electricity not auto-generated by the steel plant) were varied. Dynamic linear interpolation allowed selection of the year in which emissions from electricity generation reached net zero.

Emissions factors for grid electricity in the years 2017–2020 were derived from the BEIS Conversion Factors (2018c; see SI, Table S8). For year 2021, the values from 2020 were held constant, and any assumed changes to emissions intensity occurred from 2022 onwards. The effects of reaching low carbon grid electricity by 2040, 2050, and 2060 were tested. The IEA's 2° scenario (2DS) assumes a global average carbon intensity of electricity of 0 by 2060, whilst the beyond 2° scenario (B2DS) suggests 0 by 2050 and -10 (gCO_2/kWh) by 2060 (International Energy Agency, 2017). Therefore our assumption of 0 gCO_2/kWh as indicative of 'net zero' electricity is broadly in-keeping with the literature, and consistent with our assumption of minimal CCS implementation.

3.3. Modelling material efficiency

The impact of changing final demand for steel produced in the UK as a result of domestic action on material efficiency was evaluated. Based on the literature review conducted in section 2.4, three high-level estimates of the potential for demand reduction in the steel sector via material efficiency were tested (Table 4). This indicates aggregate potential at a sector level, rather than the potential from individual material efficiency strategies (such as lightweighting), or action taken in specific subsectors of the supply chain (e.g. the construction or automotive industries). It is important to note however, that only the estimate provided by Dunant et al. (2019) is specific to the UK, with the other estimates suggesting the global potential of material efficiency.

Table 4
Summary of high-level material efficiency estimates adopted in the analysis.

Material efficiency scenarios	Percentage demand reduction through material efficiency by target year (%)		
	2030	2040	2050
Energy Transitions Commission (2018)	12	25	38
IEA (2015)	8	17	26
Dunant et al. (2019)	4	8	12

Material efficiency was modelled by using reduced steel demand over the 2017–2050 time series as a proxy for the effect of the material efficiency strategies. The point at which material efficiency was integrated to the sector model is indicated in the model schematic (Fig. 2).

3.3.1. Sensitivity analysis: demand reduction profiles

Logically, earlier demand reduction via material efficiency should have larger cumulative mitigation potential than later action, since energy intensity is likely to be higher in the near-term. Therefore a sensitivity analysis was carried out on the effect of changing the assumed rate of demand reduction via material efficiency. The high-level material efficiency estimates from section 3.3 were input both linearly and logistically. In the logistic cases, the midpoint year was varied to test the effect of earlier or later demand reduction; the years tested were 2030, 2035, 2040, and 2045. Fig. 3 indicates the resulting demand profiles from the varied assumptions of the timing of material efficiency.

3.4. Limitations and boundaries of the analysis

In reality, technology scenarios would likely be implemented in parallel (e.g. EAF retrofit alongside greater conversion to EAF), similarly retrofit and achieving best practice energy intensity are not mutually exclusive actions. Therefore, considering potential pathways of combined technology scenarios, without incurring double counting, could be a further valuable step beyond the scope of this analysis. This analysis does not intend to identify an 'optimal' route, but to outline the relative potential of the available options.

Hidalgo et al. (2005) consider a 'homogenous steel product' in their global model due to a lack of data, and as a way of reducing complexity. However, testing the implications of shifting to a greater share of EAF production for scrap would be a further useful extension to this work. Indeed, scrap availability is used as a constraint in many modelling scenarios of the sector (Serrenho et al., 2016).

Approaches such as that of Moya and Pardo (2013) make assumptions of implementation rate on the basis of payback periods per technology. An assessment of costs could be valuable to the analysis, as this is often considered the primary limitation on the rate of upgrade.

A critical limitation may be in the top-down modelling approach, which as noted by Griffin and Hammond (p. 3918, 2019a) 'has the advantage of covering a large proportion of energy demand, but it is limited by the level of disaggregation available from industry-wide statistical sources. Thus, the conclusions that can be drawn from such top-down studies are often only 'indicative' in nature'. Given the aim of

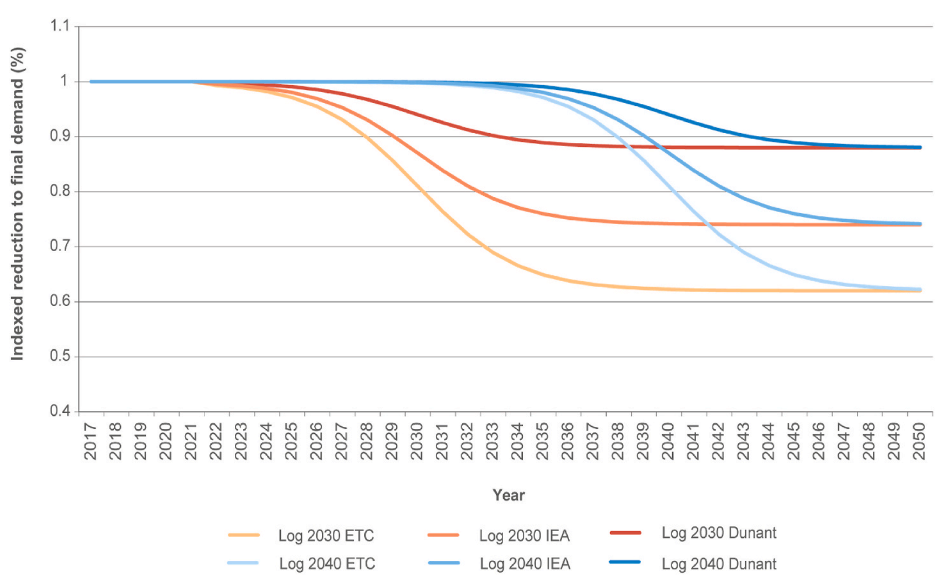

Fig. 3. Demand reduction profiles in the material efficiency sensitivity analysis. The logistic reductions with 2030 and 2040 midpoint years are shown for simplicity.

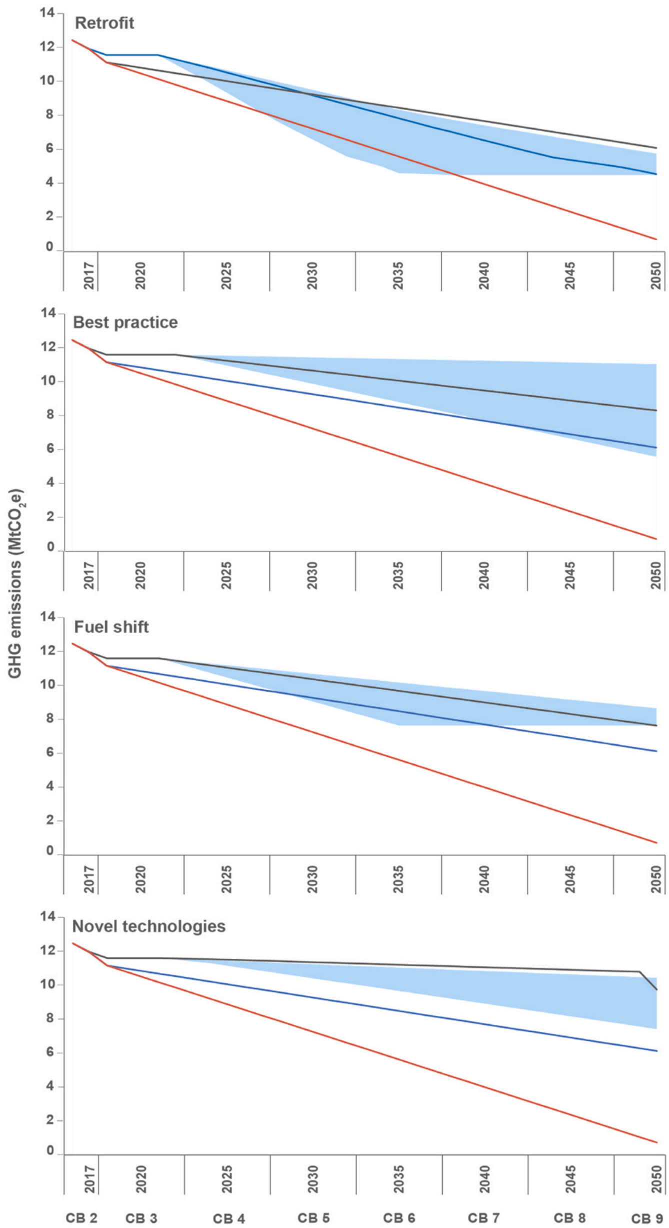

Fig. 4. Time series results of technology scenario mitigation potentials. Shaded areas represent the range between the high and low ambition scenarios.

this work to assess illustrative potentials of various mitigation options, the top-down approach was judged sufficient for the purposes of the analysis.

Further insight into the existing technological baseline (i.e. which retrofit technologies are already in place) would improve the analysis, as public data on implemented retrofit technologies is severely limited. A future extension of the work could involve consultation with expert stakeholders, as in the approach of Lechtenböhmer et al. (2015), to determine which technologies are already in place, and which would be most feasible.

4. Results and discussion

4.1. Technology scenarios

The results of the four technology scenarios (Fig. 4) indicate that the retrofit scenario has most potential to 2050, in reducing absolute emissions from the sector by between 54 and 64% according to ambition level between 2016 and 2050. The best practice scenario suggests a reduction potential of between 31 and 39%, whilst the fuel shift scenario indicates potential reductions of between 11 and 55%. In the novel technology scenario a range of between 16 and 41% is indicated, although according to the time series trend the largest reduction is achieved towards 2050, therefore assessment of the cumulative emissions per scenario may be more valuable. Novel technologies could prove to be valuable if considering time horizons beyond 2050. In any case, the technology scenarios only achieve reductions in line with the Core CCC budget in some cases; for instance, the retrofit scenario, and in the high ambition EAF scenario. In the central ambition case only the retrofit scenario has potential to achieve the core budget; Fig. 5 indicates the scale of the challenge in realising reductions aligned with the budgets with technologies alone.

4.1.1. Sensitivity 1: grid decarbonisation

Table 5 summarises the results of the grid decarbonisation sensitivity analysis, in which the carbon intensity of electricity is in line with net zero (at 0 gCO_2/kWh) in alternately 2040, 2050 or 2060.

This system-wide decarbonisation represents between −3 and −9% reductions in the cumulative emissions of the scenarios against assuming constant carbon intensity. It might be expected that the effect would be particularly pronounced in the fuel shift scenario, which involves a significant degree of electrification. Although there is relatively greater influence from grid decarbonisation on the fuel shift scenario (Fig. 6), this difference is marginal, perhaps due to the timescales over which the transition to greater EAF production occurs in each ambition case and how this intersects with grid decarbonisation.

4.2. Material efficiency towards mitigation gaps

Table 6 indicates the potential of applying the high-level material efficiency estimates to the technology scenarios. Comparing the cumulative emissions results to the budgets described in section 2.5, only the high ambition retrofit scenario coupled with material efficiency action achieves the most stringent CCC budget (further ambition) (assuming 2050 grid decarbonisation). A greater proportion of the scenarios achieve the constant sector share budget at the further ambition level, which suggests that this budget level may be more realistic in light of the technical potential without assuming CCS capacity in the sector.

Fig. 7 indicates that at a central level of ambition in the technology scenarios and assuming the ETC (2018) material efficiency estimate, most scenarios are in line with the core CCC budget, but further mitigation would be required to reach levels aligned with the 'further ambition' budget.

4.2.1. Sensitivity 2: demand reduction profiles

The sensitivity analysis on the rate at which material efficiency would be implemented, thus affecting final demand for crude steel, suggests - as might be expected - that earlier action reduces the cumulative emissions of the scenarios (Table 7). However, as compared to the cumulative emissions in a linear reduction scenario, only the 2030 logistic scenario achieved reductions whilst later logistic trends increased the cumulative emissions against the linear scenario. This suggests that

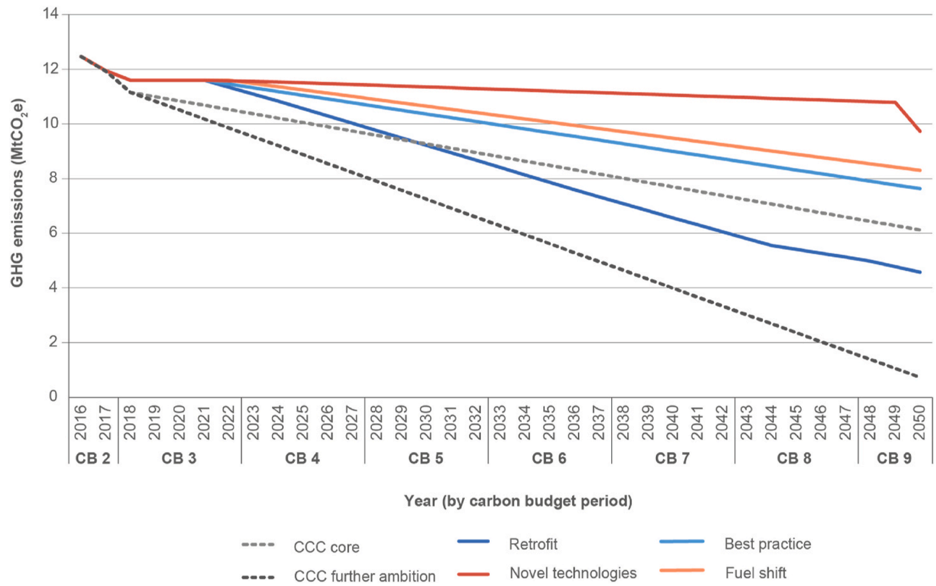

Fig. 5. Summary of technology scenario results at central ambition levels.

Table 5
Summary of changes to cumulative emissions by technology scenario and year in which net zero electricity is achieved.

Scenario	Ambition level	Percentage change in cumulative emissions against constant grid carbon intensity to 2050 (%)		
		2040	2050	2060
Retro	Low	−5%	−4%	−4%
	Central	−5%	−4%	−4%
	High	−5%	−4%	−4%
Best	Low	−4%	−4%	−3%
	Central	−4%	−4%	−3%
	High	−4%	−4%	−3%
Shift	Low	−5%	−4%	−4%
	Central	−7%	−6%	−5%
	High	−9%	−8%	−7%
Novel	Low	−5%	−5%	−4%
	Central	−5%	−4%	−4%
	High	−7%	−6%	−5%

earlier action on material efficiency can be more effective, but that this is contingent on immediate action (i.e. front-weighted before 2030).

4.3. Strategies and policies for sustainable steel

Current policy for the iron and steel sector centres on industrial strategy, compensating for carbon reduction policy costs, and protecting the UK steel industry from international imports (Rhodes, 2018). Government policy currently consists of public procurement, anti-dumping levies, and EU ETS compensation (p. 13, ibid). A 2015 meeting of the EU Competitiveness Council on the Steel Industry agreed on several actions, including adopting European Commission ‘circular economy’ strategy, state aid rules for energy-intensive industry, and committing to a review of the EU ETS and its impact on the sector (pp. 14–15, ibid). It can be seen that post-recession, policy has been directed towards the economic stability and sustainability of the sector through industrial strategy, rather than environmental improvement.

UK policy emerging to address the recession resulting from Covid-19 has been framed around ‘green recovery’, for instance the 10 Point Plan and a £350m raft of investment announced in August 2020 (BEIS, 2020;

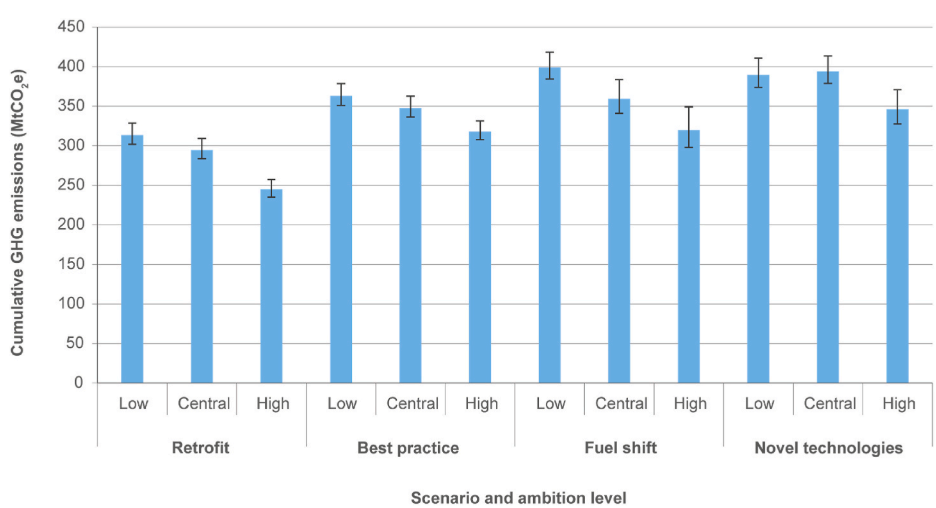

Fig. 6. Cumulative emissions of the technology scenarios in the electricity sensitivity analysis. Error bars indicate the range in results in assuming 2040 year decarbonisation (lower bound), and 2060 decarbonisation (upper).

Table 6
Summary of cumulative emissions in each technology and combined technology and material efficiency scenario, according to the three estimates of material efficiency potential.

Budget assumption	Total (2016-2050)
Less than	< 222
CCC Industry Budget (FA)	222
Maintained sector share (FA)	230
CCC Industry Budget (Core)	322
Maintained sector share (Core)	334
Over 10% more than highest budget	≥ 367

Scenario	Ambition level	Cumulative GHG emissions (2016-2050; $MtCO_2e$)				
		Technology scenarios		Technology and material efficiency scenarios (linear, 2050 decarbonisation)		
		Constant	2050 electricity decarbonisation	ETC (2018)	IEA (2015)	Dunant et al. (2019)
Retro	Low	313	300	261	273	288
	Central	295	282	247	258	271
	High	245	234	207	216	226
Best	Low	363	349	297	314	333
	Central	348	335	286	302	319
	High	318	306	263	277	293
Shift	Low	399	382	322	341	363
	Central	359	338	290	305	323
	High	320	295	257	269	283
Novel	Low	390	371	314	332	353
	Central	394	377	318	337	358
	High	346	325	280	294	311

HM Government, 2020). More detail is required on the design of industrial policies to determine whether recent commitments mark a substantively new approach. Strategic support will need to address decarbonisation alongside financial stability (Chiappinelli et al., 2021).

There are several policy tools which could be pursued to strategically decarbonise the steel sector, falling under the following strands: 1) driving deployment of available and novel technologies; 2) promoting material efficiency across the value chain; 3) addressing embodied emissions through standards; 4) developing effective business models; 5) defining a regional approach to the sector; and 6) considering the value of sectoral carbon budgets.

4.3.1. Driving deployment of available and novel technologies

The deployment of mitigation technologies with large upfront capital costs could be encouraged by policy tools which de-risk investment in the context of policy uncertainty, such as soft loans and partial risk guarantees. New policy mechanisms such as Carbon Contracts for Difference could also have potential applications in the steel sector by providing a stable price for low-carbon materials (Sartor and Bataille, 2019).

Moya and Pardo (2013, p. 81) suggest that 'demand-pull instruments', for instance, 'emission taxes, adoption subsidies or direct public-sector investments', which create incentives and lower the costs of adopting new, cleaner technologies. Tax mechanisms (for instance capital allowances or corporation tax reliefs) could be applied at the technology or firm level, or could take the form of outcome-based rebates. Accelerated depreciation is another taxation approach incentivising investment in low-carbon technologies by writing off tax at the early stages of the asset lifetime (Larkin, 2014). Vogl et al. (2021a) provide a comprehensive evaluation of the role of demand creation and direct subsidy approaches to develop the green steelmaking industry.

Since the analysis suggests earlier action may be disproportionately effective and that existing technologies may be best positioned in the near-term to deliver the cumulative emissions reductions required, policy action in this area is critical.

4.3.2. Promoting material efficiency across the value chain

As a relatively low-cost option, demand reduction can be incentivised through policy, as indicated by the recent EU Circular Economy Action Plan (EC, 2020). Milford et al. (p. 3461, 2013) also identify several policy options in this area, including: creating business opportunities for deconstruction, re-use, maintenance of steel products and scrap processing, as well as influencing consumers through extending product lifetimes and encouraging shared ownership.

Developing improved logistics for more efficient scrap utilisation could enable greater EAF production capacity and enhance material efficiency opportunities, with more domestic use of UK scrap. This is particularly important given an estimated 80% of scrap is currently exported (Harvey, 2019). Better scrap processing capacity could provide streams of diverse scrap qualities. Material pricing mechanisms such as virgin material taxes and material price stabilisation mechanisms have been also proposed as means of respectively creating value in secondary materials and guaranteeing the stability of that price (Green Alliance, 2018).

There are also a number of consumption-based material efficiency strategies. For instance, there is evidence for the high public acceptability of shared ownership and lifetime extension initiatives (Cherry et al., 2018). Creutzig et al. (2016) also draw attention to the behavioural practices which could contribute to demand reduction without requiring new technologies. Such strategies could be supported through policy such as Right to Repair and Extended Producer Responsibility regulations, improving reparability by design and reducing final demand for new products, whilst also delivering cost savings to consumers.

4.3.3. Addressing embodied emissions through standards

Two forms of standards could be relevant policy tools to decarbonise

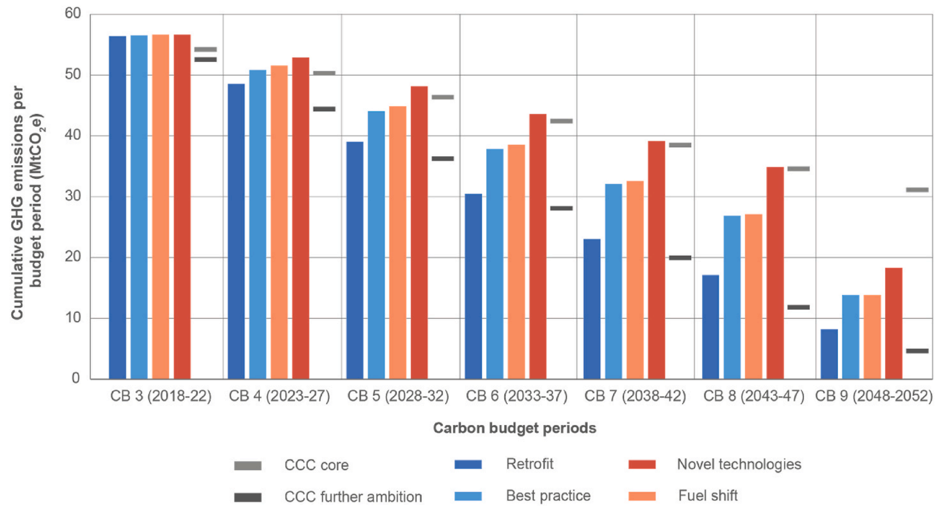

Fig. 7. Comparison of coupled technology and material efficiency scenario budgets with CCC net zero budgets, across the carbon budget periods. Technologies are modelled at central ambition, and the ETC (2018) material efficiency estimate is assumed.

Table 7
Summary of the percentage change in cumulative emissions according to the rate of final demand reduction through material efficiency. All scenarios assume 2050 grid decarbonisation.

Scenario	Cumulative GHG emissions in the linear reduction scenario ($MtCO_2e$)	Percentage change to cumulative GHG emissions in varied logistic implementation scenarios, against the linear baseline (%)			
		2030	2035	2040	2045
Retro	247	−6%	6%	5%	4%
Best	286	−6%	6%	6%	5%
Shift	290	−6%	6%	6%	5%
Novel	318	−7%	6%	6%	6%

the steel sector, if appropriately designed. Product standards specify a 'carbon cap' on embodied emissions for certain materials and products, and could function to phase-out emissions-intensive goods from the market. Such standards would require a robust methodology for carrying out Whole Life Carbon Assessments (WLCA), and the potential risk of carbon leakage from the standard would need to be evaluated. Border Carbon Adjustment (BCA) mechanisms price or regulate carbon embodied in imported goods at the border, and have been proposed as methods to address carbon leakage. However, their political and technical complexity could limit their effectiveness (Sakai and Barrett, 2016).

Public procurement guidelines or purchasing standards could be appropriate levers to signal demand for low-carbon steel (ETC, 2018), but this would be dependent on how strong an effect the new source of demand has on the sector and whether this provides sufficient incentive to invest in decarbonisation. The Buy Clean California Act sets a carbon cap on the public procurement of construction materials within the state (including steel); materials eligible for procurement must fall under an embodied emissions benchmark (State of California, 2020). The relative ability of standards to drive the market transformation of steel purchasing in the UK needs further assessment.

4.3.4. *Developing effective business models*

The technology and material efficiency scenarios assessed could be encouraged through new business models (Allwood, 2013). Axelson et al. (2021) provide a systematic evaluation of the business models that could be used to implement industrial decarbonisation strategies in the steel industry.

HYBRIT is a Swedish public-private partnership, demonstrating the use of hydrogen as a reducing agent (Hydrogen Direct Reduction or H-DR) (Åhman et al., 2019; ETC, 2018). The involvement of Vattenfall, the state electricity company, indicates how new national energy infrastructures could be integrated to the manufacturing sector. This provides a model for deployment and demonstration of high-cost technologies for the sector, and for the role of government intervention in supporting steel decarbonisation (Karakaya et al., 2018; Kushnir et al., 2020).

Steel demand is driven disproportionately by the construction industry, with half of global steel production used for the development of infrastructure and buildings (Moynihan and Allwood, 2012). Therefore sector-level partnerships could be appropriate as a way of capturing opportunities for material efficiency across the steel value chain. For instance through the recovery of end-of-life products used in the construction industry.

4.4. *Directions for future research*

Given the supply-chain complexity of the UK steel sector, particularly reliance on production of intermediate goods, it would be valuable to assess the impact of the scenarios on consumption-based emissions. An extension to the analysis could involve applying the material efficiency scenarios to imported steel products, to assess the extent to which overseas action on material efficiency could contribute towards domestic mitigation. However, this would necessarily require further assumptions about the future trade of UK steel.

There is scope for considering the implications of the technologies for changes in non-energy inputs/outputs, which may represent limitations on the feasibility of the scenarios (i.e. scrap availability). More granular economic analysis would also be valuable, particularly in considering the trade-offs between scenarios, for instance in investing in integrated route retrofit, when there is a broader shift to replacement with EAF capacity.

5. Conclusion

Material efficiency was demonstrated to be a critical strategy towards achieving net zero steel emissions in the UK, in combination with rapid deployment of existing technologies. Nonetheless, the share of residuals in most scenarios indicated the need for some allocation of CCS removal capacity in the industry. In-line with much of the literature, the analysis has suggested the continuing importance of retrofit to near-term emissions reductions, given the low expected commercialisation of most breakthrough technologies by 2050 (Griffin and Hammond, 2019a). However, demand reduction is also considered important in order to meet emissions targets on a cumulative basis, and it is seen that 'faster' demand reduction would be more effective in reducing pressure on the need for technological decarbonisation. The results also demonstrate the importance of the rate of grid electricity decarbonisation in the UK for the viability of different steel production routes.

The analysis has provided a novel series of steel decarbonisation scenarios for the UK industry, contributing to the broader debate in the literature by situating the results in the context of national and global climate policy in the form of carbon budgets.

There a few key dependencies of the scenarios which underscore the illustrative nature of the analysis; namely, the assumption of constant demand for steel when set in a global context of potentially growing demand (Allwood et al., 2010). Many other studies adopt projections of declining demand to 2050, but this means that the scale of change indicated as necessary in this analysis represents the upper end of action that would be required.

Our finding that only a high ambition retrofit case, coupled with material efficiency and grid decarbonisation achieves the least CCS-reliant CCC sectoral budget, makes a clear case for early action. It suggests that it may be more effective to implement available technologies alongside material efficiency strategies, rather than 'wait' for commercialisation processes which may be delivered too late to address cumulative emissions from the sector. It underlines the need to act quickly in this hard-to-abate sector if future emissions are to be effectively managed.

It has been shown that there are many complex challenges facing the UK iron and steel sector, in maintaining production levels in a competitive international market, whilst also decarbonising to reduce regulatory costs. But it is also possible that action to reduce emissions would contribute to both ends, by creating greater compliance with carbon policies and filling what could become a high demand market niche for low-carbon steel given recent policy developments in the EU. Difficulties exist in reducing emissions when the precedent for reductions in the sector has been driven by recession and plant closure. Well-designed policy could lead to reductions in both emissions and regulatory costs, rather than adding to the regulatory burden which has contributed to economic instability in the sector to date. There is also scope to explore the role of sectoral carbon budgets in planning decarbonisation across industry in line with net zero. Policy must capitalise on the opportunity for early action in shaping a sustainable UK steel sector.

CRediT authorship contribution statement

Alice Garvey: Methodology, Formal analysis, Investigation, Writing – original draft. **Jonathan B. Norman:** Methodology, Writing – review & editing, Supervision. **John Barrett:** Conceptualization, Writing – review & editing, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2021.130216.

References

Åhman, M., Olsson, O., Vogl, V., Nyqvist, B., Maltais, A., Nilsson, L.J., Hallding, K., Skånberg, K., Nilsson, M., 2019. Hydrogen Steelmaking for a Low-Carbon Economy: A Joint LU-SEI Working Paper for the HYBRIT Project. Stockholm.
Allwood, J.M., 2013. Transitions to material efficiency in the UK steel economy. Phil. Trans. R. Soc. A. 371, 20110577. https://doi.org/10.1098/rsta.2011.0577.
Allwood, J.M., Cullen, J.M., Milford, R.L., 2010. Options for achieving a 50% cut in industrial carbon emissions by 2050. Environ. Sci. Technol. 44, 1888–1894. https://doi.org/10.1021/es902909k.
Allwood, J.M., Dunant, C.F., Lupton, R.C., Serrenho, A.C.H., 2019. Steel Arising: Opportunities for the UK in a Transforming Global Steel Industry. https://www.uselessgroup.org/outreach/publications/reports/steel-arising.
Arens, M., Worrell, E., Eichhammer, W., Hasanbeigi, A., Zhang, Q., 2017. Pathways to a low-carbon iron and steel industry in the medium-term – the case of Germany. J. Clean. Prod. 163, 84–98. https://doi.org/10.1016/j.jclepro.2015.12.097.
Axelson, M., Oberthür, S., Nilsson, L.J., 2021. Emission reduction strategies in the EU steel industry: implications for business model innovation. J. Ind. Ecol. 25 (2), 390–402. https://doi.org/10.1111/jiec.13124.
BBC News, 2018. Scunthorpe-based British Steel Announce £50m Mill Investment.
BBC News, 2019. £50m Fresh Start for Port Talbot Tata Steelworks.
Burke, J., Sato, M., Taylor, C., Li, F., 2021. What Does an EU Carbon Border Adjustment Mechanism Mean for the UK? Grantham Research Institute on Climate Change and the Environment and Centre for Climate Change Economics and Policy, London School of Economics and Political Science, London. https://www.lse.ac.uk/granthaminstitute/publication/what-does-an-eu-carbon-border-adjustment-mechanism-mean-for-the-uk/.
CDP, UN Global Compact, WRI, WWF, 2019. Science based targets. https://sciencebasedtargets.org/.
Cherry, C., Scott, K., Barrett, J., Pidgeon, N., 2018. Public acceptance of resource-efficiency strategies to mitigate climate change. Nat. Clim. Change 8, 1007–1012. https://doi.org/10.1038/s41558-018-0298-3.
Chiappinelli, O., Gerres, T., Neuhoff, K., Lettow, F., de Coninck, H., Felsmann, B., Joltreau, E., Khandekar, G., Linares, P., Richstein, J., Śniegocki, A., Stede, J., Wyns, T., Zandt, C., Zetterberg, L., 2021. A green COVID-19 recovery of the EU basic materials sector: identifying potentials, barriers and policy solutions. Clim. Pol. https://doi.org/10.1080/14693062.2021.1922340.
Chisalita, D., Petrescu, L., Cobden, P., van Dijk, H.A.J., Cormos, A., Cormos, C., 2019. Assessing the environmental impact of an integrated steel mill with post-combustion CO2 capture and storage using the LCA methodology. J. Clean. Prod. 211, 1015–1025. https://doi.org/10.1016/j.jclepro.2018.11.256.
Climate Change Committee (CCC), 2018. Hydrogen in a Low-Carbon Economy. London.
Climate Change Committee (CCC), 2019a. Net Zero Technical Report. London.
Climate Change Committee (CCC), 2019b. Net Zero: the UK's Contribution to Stopping Global Warming. London.
Climate Change Committee (CCC), 2020a. Reducing UK Emissions: 2020 Progress Report to Parliament. London.
Climate Change Committee (CCC), 2020b. The Sixth Carbon Budget: the UK's Path to Net Zero. London.
Creutzig, F., Fernandez, B., Haberl, H., Khosla, R., Mulugetta, Y., Seto, K.C., 2016. Beyond Technology: demand-side solutions for climate change mitigation. Annu. Rev. Environ. Resour. 41, 173–198. https://doi.org/10.1146/annurev-environ-110615-085428.
Department for Business Energy and Industrial Strategy (BEIS), 2017. Future Capacities and Capabilities of the UK Steel Industry. Technical Appendices, London.
Department for Business Energy and Industrial Strategy (BEIS), 2018a. Industrial Strategy: Building a Britain Fit for the Future. London.
Department for Business Energy and Industrial Strategy (BEIS), 2018b. Updated Energy and Emissions Projections: 2017. London.
Department for Business Energy and Industrial Strategy (BEIS), 2018c. 2018 Government GHG Conversion Factors for Company Reporting: Methodology Paper for Emission Factors.
Department for Business Energy and Industrial Strategy (BEIS), 2019. Creating a clean steel Fund: call for evidence. URL. https://www.gov.uk/government/consultations/creating-a-clean-steel-fund-call-for-evidence. (Accessed 30 August 2020).
Department for Business Energy and Industrial Strategy (BEIS), 2020. The Ten Point Plan for a Green Industrial Revolution. https://www.gov.uk/government/publications/the-ten-point-plan-for-a-green-industrial-revolution.
Department for Business Energy and Industrial Strategy (BEIS), 2020a. Energy White Paper: Powering Our Net Zero Future. https://www.gov.uk/government/publications/energy-white-paper-powering-our-net-zero-future.
Department of Energy and Climate Change, the Department for Business Innovation and Skills, 2015. Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050: Iron and Steel.
Dunant, C.F., Skelton, A.C.H., Drewniok, M.P., Cullen, J.M., Allwood, J.M., 2019. A marginal abatement cost curve for material efficiency accounting for uncertainty. Resour. Conserv. Recycl. 144, 39–47. https://doi.org/10.1016/j.resconrec.2019.01.020.
D'Amore, F., Carmelo Romano, M., Bezzo, F., 2021. Carbon capture and storage from energy and industrial emission sources: a Europe-wide supply chain optimisation. J. Clean. Prod. 290, 125202. https://doi.org/10.1016/j.jclepro.2020.125202.
Energy and Climate Intelligence Unit, 2021. Stuck on the Starting Line: How the UK Is Falling behind Europe in the Race to Clean Steel. https://eciu.net/news-and-events/press-releases/2021/report-uk-is-falling-behind-europe-in-clean-steel-race.
Energy Transitions Commission, 2018. Mission Possible: Reaching Net-Zero Carbon Emissions from Harder-To-Abate Sectors by Mid-century.

European Commission, 2020. EU Circular Economy Action Plan. https://ec.europa.eu/environment/circular-economy/.

Fischedick, M., Marzinkowski, J., Winzer, P., Weigel, M., 2014a. Techno-economic evaluation of innovative steel production technologies. J. Clean. Prod. 84, 563–580. https://doi.org/10.1016/j.jclepro.2014.05.063.

Fischedick, M., Roy, J., Abdel-Aziz, A., Acquaye, A., Allwood, J.M., Ceron, J.-P., Geng, Y., Kheshgi, H., Lanza, A., Perczyk, D., Price, L., Santalla, E., Sheinbaum, C., Tanaka, K., 2014b. Industry. In: Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B., Savolainen, J., Schlömer, S., von Stechow, C., Zwickel, T., Minx, J.C. (Eds.), Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Garcia, M., Berghout, N., 2019. Toward a common method of cost-review for carbon capture technologies in the industrial sector: cement and iron and steel plants. Int. J. Greenh. Gas Control 87, 142–158. https://doi.org/10.1016/j.ijggc.2019.05.005.

Gonzalez Hernandez, A., Paoli, L., Cullen, J.M., 2018. How resource-efficient is the global steel industry? Resour. Conserv. Recycl. 133, 132–145. https://doi.org/10.1016/j.resconrec.2018.02.008.

Green, Alliance, 2018. Less in, More Out: Using Resource Efficiency to Cut Carbon and Benefit the Economy. London.

Griffin, P.W., Hammond, G.P., 2019a. Analysis of the potential for energy demand and carbon emissions reduction in the iron and steel sector. Energy Proc. 158, 3915–3922. https://doi.org/10.1016/j.egypro.2019.01.852.

Griffin, P.W., Hammond, G.P., 2019b. Industrial energy use and carbon emissions reduction in the iron and steel sector: a UK perspective. Appl. Energy 249, 109–125. https://doi.org/10.1016/j.apenergy.2019.04.148.

Griffin, P.W., Hammond, G., Norman, J.B., 2013. Industrial Energy Use from a Bottom-Up Perspective: Developing the Useable Energy Database (Beta Version).

Grübler, A., Wilson, C., Bento, N., Boza-Kiss, B., Krey, V., McCollum, D.L., Rao, N.D., Riahi, K., Rogelj, J., De Stercke, S., Huppmann, D., Kiesewetter, G., Rafaj, P., Schoepp, W., Valin, H., 2018. A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. Nat. Energy 3, 515–527. https://doi.org/10.1038/s41560-018-0172-6.

Hardt, L., Owen, A., Brockway, P.E., Heun, M.K., Barrett, J., Taylor, P.G., Foxon, T.J., 2018. Untangling the drivers of energy reduction in the UK productive sectors: efficiency or offshoring? Appl. Energy 223, 124–133. https://doi.org/10.1016/j.apenergy.2018.03.127.

Harvey, F., 2019. Recycling Steel Could Give Lifeline to the Industry, Report Says. The Guardian.

Hertwich, E., Lifset, R., Pauliuk, S., Heeren, N., 2020. Resource efficiency and climate change: material efficiency strategies for a low-carbon future. In: A Report of the International Resource Panel. United Nations Environment Programme, Nairobi, Kenya.

Hidalgo, I., Szabo, L., Carlos Ciscar, J., Soria, A., 2005. Technological prospects and CO2 emission trading analyses in the iron and steel industry: a global model. Energy 30, 583–610. https://doi.org/10.1016/j.energy.2004.05.022.

HM Government, 2020. PM Commits £350 Million to Fuel Green Recovery. https://www.gov.uk/government/news/pm-commits-350-million-to-fuel-green-recovery.

IIASA Energy, Transitioning to New Technologies Program, 2018. Low Energy Demand (LED) Database. https://db1.ene.iiasa.ac.at/LEDDB.

International Energy Agency (IEA), 2015. World Energy Outlook 2015.

International Energy Agency (IEA), 2017. Energy Technology Perspectives 2017. Catalysing Energy Technology Transformations, Paris.

Karakaya, E., Nuur, C., Assbring, L., 2018. Potential transitions in the iron and steel industry in Sweden: towards a hydrogen-based future? J. Clean. Prod. 195, 651–663. https://doi.org/10.1016/j.jclepro.2018.05.142.

Kushnir, D., Hansen, T., Vogl, V., Åhman, M., 2020. Adopting hydrogen direct reduction for the Swedish steel industry: a technological innovation system (TIS) study. J. Clean. Prod. 242, 118185. https://doi.org/10.1016/j.jclepro.2019.118185.

Larkin, 2014. A Simple Accounting Change Can Make Green Infrastructure More Attractive. The Guardian, London. https://www.theguardian.com/sustainable-business/simple-change-green-infrastructure-profitable.

Lechtenböhmer, S., Schneider, C., Yetano Roche, M., Höller, S., 2015. Re-industrialisation and low-carbon economy—can they go together? Results from stakeholder-based scenarios for energy-intensive industries in the German state of north rhine westphalia. Energies 8, 11404–11429. https://doi.org/10.3390/en81011404.

Liu, Y., Huajiao, L., Huang, S., An, H., Santagata, R., Ulgiati, S., 2020. Environmental and economic-related impact assessment of iron and steel production. A call for shared responsibility in global trade. J. Clean. Prod. 269, 122239. https://doi.org/10.1016/j.jclepro.2020.122239.

Mandova, H., Patrizio, P., Leduc, S., Kjärstad, J., Wang, C., Wetterlund, E., Kraxner, F., Gale, W., 2019. Achieving carbon-neutral iron and steelmaking in Europe through the deployment of bioenergy with carbon capture and storage. J. Clean. Prod. 218, 118–129. https://doi.org/10.1016/j.jclepro.2019.01.247.

Milford, R.L., Pauliuk, S., Allwood, J.M., Müller, D.B., 2013. The roles of energy and material efficiency in meeting steel industry CO2 targets. Environ. Sci. Technol. 47, 3455–3462. https://doi.org/10.1021/es3031424.

Morfeldt, J., Wouter, N., Semida, S., 2015. The impact of climate targets on future steel production – an analysis based on a global energy system model. J. Clean. Prod. 103, 469–482. https://doi.org/10.1016/j.jclepro.2014.04.045.

Moya, J.A., Pardo, N., 2013. The potential for improvements in energy efficiency and CO2 emissions in the EU27 iron and steel industry under different payback periods. J. Clean. Prod. 52, 71–83. https://doi.org/10.1016/j.jclepro.2013.02.028.

Moynihan, M.C., Allwood, J.M., 2012. The flow of steel into the construction sector. Resour. Conserv. Recycl. 68, 88–95. https://doi.org/10.1016/j.resconrec.2012.08.009.

Oda, J., Akimoto, K., Sano, F., Tomoda, T., 2007. Diffusion of energy efficient technologies and CO2 emission reductions in iron and steel sector. Energy Econ. 29, 868–888. https://doi.org/10.1016/j.eneco.2007.01.003.

Oda, J., Akimoto, K., Sano, F., Homma, T., 2009. Diffusion of CCS and energy efficient technologies in power and iron and steel sectors. Energy Proc. 1, 155–161. https://doi.org/10.1016/j.egypro.2009.01.023.

Pardo, N., Moya, J.A., 2013. Prospective scenarios on energy efficiency and CO2 emissions in the European Iron & Steel industry. Energy 54, 113–128. https://doi.org/10.1016/j.energy.2013.03.015.

Pauliuk, S., Heeren, N., 2020. Material efficiency and its contribution to climate change mitigation in Germany: a deep decarbonization scenario analysis until 2060. J. Ind. Ecol. 25 (2), 479–493. https://doi.org/10.1111/jiec.13091.

Pauliuk, S., Milford, R.L., Müller, D.B., Allwood, J.M., 2013. The steel scrap age. Environ. Sci. Technol. 47, 3448–3454. https://doi.org/10.1021/es303149z.

Pimm, A.J., Cockerill, T.T., Gale, W.F., 2021. Energy system requirements of fossil-free steelmaking using hydrogen direct reduction. J. Clean. Prod. 312, 127665. https://doi.org/10.1016/j.jclepro.2021.127665.

Pimm, A., Garvey, A., Norman, J., Gale, W., Richardson-Barlow, C., 2021a. Cumbria mine: is there a technical need for new coal mines in the UK? Centre for Research into Energy Demand Solutions. https://www.creds.ac.uk/cumbria-mine-is-there-a-technical-need-for-new-coal-mines-in-the-uk/.

Priestley, S., 2019. Briefing Paper: Legislating for Net Zero. London.

Rhodes, C., 2018. UK Steel Industry: Statistics and Policy. London.

Rhodes, C., 2020. UK Steel Industry: Statistics and Policy. London.

Rogelj, J., Shindell, D., Jiang, K., Fifita, S., Forster, P., Ginzburg, V., Handa, C., Kheshgi, H., Kobayashi, S., Kriegler, E., Mundaca, L., Séférian, R., Vilariño, M.V., 2019. Mitigation pathways compatible with 1.5°C in the context of sustainable development. In: Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J.B.R., Chen, Y., Zhou, X., Gomis, M.I., Lonnoy, E., Maycock, T., Tignor, M., Waterfield, T. (Eds.), Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty, pp. 93–174.

Sakai, M., Barrett, J., 2016. Border carbon adjustments: addressing emissions embodied in trade. Energy Pol. 92, 102–110. https://doi.org/10.1016/j.enpol.2016.01.038.

Sartor, O., Bataille, C., 2019. IDDRI Policy Brief: Decarbonising Basic Materials in Europe: How Carbon Contracts-For-Difference Could Help Bring Breakthrough Technologies to Market. Institute for Sustainable Development and International Relations (IDDRI), Paris. https://www.iddri.org/en/publications-and-events/study/decarbonising-basic-materials-europe.

Science Based Targets Initiative, 2015. Sectoral Decarbonization Approach (SDA): A Method for Setting Corporate Emission Reduction Targets in Line with Climate Science.

Scott, K., Giesekam, J., Barrett, J., Owen, A., 2018a. Bridging the climate mitigation gap with economy-wide material productivity. J. Ind. Ecol. 1–14. https://doi.org/10.1111/jiec.12831.

Scott, K., Roelich, K., Owen, A., Barrett, J., 2018b. Extending European energy efficiency standards to include material use: an analysis. Clim. Pol. 18, 627–641. https://doi.org/10.1080/14693062.2017.1333949.

Serrenho, A.C., Mourão, Z.S., Norman, J.B., Cullen, J.M., Allwood, J.M., 2016. The influence of UK emissions reduction targets on the emissions of the global steel industry. Resour. Conserv. Recycl. 107, 174–184. https://doi.org/10.1016/j.resconrec.2016.01.001.

State of California, 2020. Buy Clean California Act. In: https://www.dgs.ca.gov/PD/Resources/Page-Content/Procurement-Division-Resources-List-Folder/Buy-Clean-California-Act.

van Ruijven, B.J., van Vuuren, D.P., Boskaljon, W., Neelis, M.L., Saygin, D., Patel, M.K., 2016. Long-term model-based projections of energy use and CO2 emissions from the global steel and cement industries. Resour. Conserv. Recycl. 112, 15–36. https://doi.org/10.1016/j.resconrec.2016.04.016.

van Soest, H.L., den Elzen, M.G.J., van Vuuren, D.P., 2021. Net-zero emission targets for major emitting countries consistent with the Paris Agreement. Nat. Commun. 12, 2140. https://doi.org/10.1038/s41467-021-22294-x.

Vögele, S., Rübbelke, D., Govorukha, K., Grajewski, M., 2020. Socio-technical scenarios for energy-intensive industries: the future of steel production in Germany. Climatic Change 162, 1763–1778. https://doi.org/10.1007/s10584-019-02366-0.

Vogl, V., Åhman, M., Nilsson, L.J., 2018. Assessment of hydrogen direct reduction for fossil-free steelmaking. J. Clean. Prod. 203, 736–745. https://doi.org/10.1016/j.jclepro.2018.08.279.

Vogl, V., Sanchez, F., Gerres, T., Lettow, F., Bhaskar, A., Swalec, C., Mete, G., Åhman, M., Lehne, J., Schenk, S., Witecka, W., Olsson, O., Rootzén, J., 2021. Green Steel Tracker, Version 04/2021. Stockholm, Dataset. www.industrytransition.org/green-steel-tracker.

Vogl, V., Åhman, M., Nilsson, L.J., 2021a. The making of green steel in the EU: a policy evaluation for the early commercialization phase. Clim. Pol. 21 (1), 78–92. https://doi.org/10.1080/14693062.2020.1803040.

Wiley, D.E., Ho, M.T., Bustamante, A., 2011. Assessment of opportunities for CO2 capture at iron and steel mills: an Australian perspective. Energy Proc. 4, 2654–2661. https://doi.org/10.1016/j.egypro.2011.02.165.

Winter, O., 2020. Green hydrogen for steel production: RWE and thyssenkrupp plan partnership. https://www.group.rwe/en/press/rwe-generation/2020-06-10-green-hydrogen-for-steel-production.
World Steel Association (WSA), 2018. World steel in Figures 2018. https://www.worldsteel.org/steel-by-topic/statistics/World-Steel-in-Figures.html.
World Steel Association (WSA), 2020a. Worldsteel short range outlook June 2020. https://www.worldsteel.org/media-centre/press-releases/2020/worldsteel-short-range-outlook-june-2020.html.
World Steel Association (WSA), 2020b. World steel in Figures. https://www.worldsteel.org/steel-by-topic/statistics/World-Steel-in-Figures.html.
Worrell, E., Biermans, G., 2005. Move over! Stock turnover, retrofit and industrial energy efficiency. Energy Pol. 33, 949–962. https://doi.org/10.1016/j.enpol.2003.10.017.
Worrell, E., Price, L.K., Neelis, M., Galitsky, C., Zhou, N., 2008. World Best Practice Energy Intensity Values for Selected Industrial Sectors. Berkeley, CA.