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Policy and pricing barriers to steel industry decarbonisation: A UK case study

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ABSTRACT

Global climate targets have highlighted the need for a whole-systems approach to decarbonisation, one that includes targeted national policy and industry specific change. Situated within this context, this research examines policy and pricing barriers to decarbonisation of the UK steel industry. Here the techno-economic modelling of UK green steelmaking provides a technical contribution to analysis of pricing barriers and policy solutions to these barriers in the UK specifically, but also to the broader industrial decarbonisation literature. Estimated costs and associated emissions projections reveal relevant opportunities for UK steel in contributing to national climate and emissions targets. Modelling demonstrates that green steelmaking options have been put at price disadvantages compared to emissions-intensive incumbents and that fossil-free hydrogen-based steelmaking has lower emissions and lower levelised costs than carbon capture and storage options, including top gas recycling blast furnace (TGR-BF) with CCS, and HIsarna smelter with CCS. Two primary policy recommendations are made: the removal of carbon pricing discrepancies and reductions in industrial electricity prices that would level the playing field for green steel producers in the UK. The research also provides relevant policy considerations for the international community in other industrial decarbonisation efforts and the policies that must accompany these decarbonisation choices.

1. Introduction

Decarbonising industry is a key focus of the UK's approach to achieving net zero (Busch et al., 2018). A number of national policy measures are contributing to this goal: The UK government's "Ten Point Plan for a Green Industrial Revolution," for example, sets out the government approach to 'building back better' while moving the country closer towards industrial decarbonisation via a focus on green energy development amid domestic covid recovery measures (HM Government, 2020). The UK's green industrial revolution is further supported by £100 billion in infrastructure spending via the National Infrastructure Strategy (HM Treasury, 2020). Both the Ten Point Plan and infrastructure strategy preceded UK Steel's roadmap to net zero steel production (British Construction Steelwork Association, 2021) and the UK Net Zero Strategy (Department for Business, Energy & Industrial Strategy, 2021a). In UK heavy industries, industry-policy engagement on national decarbonisation efforts is taking place, evidenced by industrial decarbonisation and energy efficiency roadmaps (Department of Energy & Climate Change; Department for Business, Innovation & Skills, 2015) and action plans (Department for Business, Energy & Industrial Strategy, 2017) in eight of the UK's most heat-intensive sectors. Recommendations on the level of the UK's sixth carbon budget by the Climate Change Committee (the UK's independent advisor on tackling climate change) and adopted by the Government in April 2021, sets out key milestones that will need to be met in order to achieve the UK's Net Zero by 2050 target (Committee on Climate Change, 2020). Key among these milestones is a 78% reduction in greenhouse gas emissions on 1990 levels by 2035; in 2020, UK emissions were 49.7% below 1990 levels, largely attributed to long-term increases in renewable electricity generation, plus some short-term impacts as a result of covid restrictions, especially on transport (Department for Business, Energy & Industrial Strategy, 2021). Combined, these various strategies and plans form what is a comprehensive approach to national decarbonisation, although a process that will take decades and requires continued financial, political and social will to achieve (Garvey and Taylor, 2020).

Internationally, policy options for industrial decarbonisation are largely centred around national targets that will help achieve global emissions reductions targets as outlined in the Paris Agreement. In

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addition to the Paris Agreement and associated COP meetings, national roadmaps that target specific sectors, and overarching industry approaches (such as the UK's Industrial Decarbonisation Strategy (Department for Business, Energy & Industrial Strategy, 2021b)) set forward policy options for industries that will play a vital role in emissions reductions, such as the carbon-intensive sectors of steel and cement, or construction. On an international scale, the collective Climate Aligned Finance Agreement (Rocky Mountain Institute (RMI), 2021) intends to set common standards of practice for decarbonisation of the steel industry, aiming to support the carbon intensive industry in reaching decarbonisation targets and monitoring progress. The COP26 Glasgow Breakthrough Agenda similarly sets goals targeting clean technology solutions in four different emitting sectors, including steel (COP26, 2021). In this regard the Breakthrough Agenda strives to foster a net zero-aligned steel industry that utilises existing targets and initiatives but places the steel industry within the larger global fight against climate change and emissions-heavy industrial practices. Building on the momentum of the 26th UN Climate Change Conference of the Parties (COP26), hosted in 2021 in the UK, there is ample opportunity for industry to capitalise on post-covid support, regional 'levelling up' (Nurse and Sykes, 2020) and global movements towards more sustainable business practices (Painter et al., 2019).

Previous research into the decarbonisation of steel production has typically focused on specific technology options (Vogl et al., 2018; Leeson et al., 2017; Mandova et al., 2019) or the development of country-specific roadmaps (Dixon et al., 2022; Garvey et al., 2022; Griffin and Hammond, 2021), for example based on improvement potentials and marginal abatement cost curves. To date, little attention has been given to the barriers that prevent steel producers from deploying green steelmaking technologies whilst remaining competitive with emissions-intensive incumbents, or to the policy changes that would be necessary to remove these barriers. We aim to fill this gap with a detailed assessment of a small number of key barriers and policy options. The analysis focuses on the UK, but the barriers, policy options, and results are widely applicable. While a variety of technologies are under development for industrial decarbonisation in the iron and steel industry, in this research we focus primarily on top gas recycling blast furnace (TGR-BF) with carbon capture and storage (CCS), HIsarna smelter with CCS, and electric arc furnaces (EAFs) with a 100% scrap charge. These options, and their alternatives, are described in more detail in the following section.

Specifically, this research seeks to answer the following questions: what are the most cost-effective methods for decarbonising the UK steel industry; what are the barriers to implementing these production methods, and how can these barriers be addressed via policy? The rest of this paper proceeds as follows: section 2, Methodology, explains the mathematical model used to compare the costs and emissions from different steelmaking processes and the qualitative approach to identifying policy options, then section 3, Results, presents techno-economic analyses of the processes and the impacts of the selected policies, section 4, Discussion, explores the implications of the results in both a UK and international context, and finally Section 5 concludes and outlines policy implications of our findings.

2. Methodology

To investigate the policy options available to drive deep decarbonisation of the iron and steel industry, we use a mixed methods approach that combines quantitative and qualitative data collection and analysis.

The quantitative analysis builds on a previous investigation by the research team into the economics of hydrogen-based steelmaking (hydrogen direct reduction of iron (H_2-DRI) with electric arc furnaces (EAFs), known as "fossil-free steelmaking" when operated with green hydrogen) (Pimm et al., 2021), and is broadened to cover two of the most promising carbon capture and storage (CCS) options: top gas recycling blast furnace (TGR-BF) with CCS, and HIsarna smelter with CCS. We also consider EAFs with a 100% scrap charge.

Several technologies are in development to decarbonise the iron and steel industry. Two of the most promising options for deep decarbonisation are: 1) modifying existing blast furnace – basic oxygen furnace (BF-BOF) plants to use pulverised coal and iron ore (known as the HIsarna technology (Tata Steel, 2020)), while fitting carbon capture technology and storing the captured CO_2 in aquifers or disused oil and gas reservoirs, and 2) hydrogen direct reduction of iron (H_2-DRI) using green hydrogen produced with water electrolysis, along with electric arc furnaces (EAFs). HIsarna smelter with CCS is one of several options for integrating CCS with plant which continue to use coal as the primary reductant, and Tata Steel is planning a full-scale HIsarna + CCS plant at IJmuiden in the Netherlands (Athos, 2020). Using H_2-DRI and EAFs with zero-carbon electricity is known as fossil-free steelmaking (Vogl et al., 2018; Tata Steel, 2020; Müller et al., 2021), and this approach has seen growing interest in recent years, with several of the world's major steelmakers announcing plans for full-scale plants (ArcelorMittal, 2021; Liberty Steel, 2021; H2 Green Steel, 2021). Other proposed approaches to decarbonising steel production include adding top gas recycling (TGR) and CCS to existing blast furnaces (TNO, 2020; Cavaliere, 2019), whereby CO_2 is removed from the blast furnace top gas and the remaining stream is heated and reinjected into the blast furnace, and steel scrap recycling using EAFs (Cavaliere, 2019), however the variety of steel products that can be manufactured using this approach is limited by scrap quality.

In the hydrogen-based steelmaking analysis employed in this research, we assume that all hydrogen is produced using water electrolysis. We do this because when the electricity comes from renewables ("green hydrogen"), this production method has negligible CO_2 emissions during operation (Friends of the Earth, 2020). In contrast, hydrogen produced using natural gas with CCS (known as "blue hydrogen"), for example using a steam methane reformer fitted with carbon capture technology, has typical estimated emissions intensities in the range 45–120 gCO_2/kWh of hydrogen (Committee on Climate Change, 2018). Also, recent research by Howarth and Jacobson (2021) for the US found that, in some circumstances, blue hydrogen can produce higher levels of greenhouse gas emissions than just using the natural gas directly, as a consequence of upstream emissions, imperfect CO_2 capture rates, and the need to generate electricity to power the CO_2 capture facility. Similar levels of upstream methane emissions were found in a 2018 study of high pressure gas transmission pipelines in the UK (Boothroyd et al., 2018). We do this because recent research by Howarth and Jacobson (2021) found that production of hydrogen using natural gas with CCS (known as "blue hydrogen"), for example using a steam methane reformer fitted with carbon capture technology, can produce higher levels of greenhouse gas emissions than just using the natural gas directly, as a consequence of upstream emissions, imperfect CO_2 capture rates, and the need to generate electricity to power the CO_2 capture facility. While the Howarth and Jacobson study was focused on the USA, similar levels of upstream methane emissions were found in a 2018 study of high pressure gas transmission pipelines in the UK (Boothroyd et al., 2018). However, while we do not consider blue hydrogen here, we recognise that DRI operated with natural gas or with hydrogen produced using gas reforming could provide useful intermediate steps towards fossil-free steelmaking.

The qualitative analysis utilises a combination of interpretive and reflexive documentary analysis, identifying common themes in the political economy of green steelmaking. This process was iterative, building upon identified themes across both the qualitative and quantitative research. Modelling results of the green steelmaking options are analysed against the policy options utilised to reduce industrial electricity pricing in the EU. This international example provides context for the further analysis of UK policy options and the challenge of these choices in the UK. Here we find that national efforts to reduce emissions highlight the role of industry as the next phase of decarbonisation policy-making. However, these net-zero motivated choices must be met by equally strong economic policy making, which our modelling shows is limited by current pricing of industrial electricity in the UK.

2.1. Techno-economic modelling of green steelmaking

To determine the costs and greenhouse gas emissions of green steelmaking, a spreadsheet-based tool has been developed to perform discounted cash flow analysis. This accounts for a wide range of parameters, including CAPEX, fixed OPEX, lifetimes, and emissions intensities. Variable costs comprise coking coal, natural gas, grid electricity, iron ore, scrap, lime, alloying additions, graphite (for electric arc furnace (EAF) electrodes), oxygen, and labour, along with costs of carbon emissions. They are determined on an annual basis from 2021 to 2050 using consumption figures for the two CCS-based (Fan and Friedmann, 2021) approaches taken from the Useable Energy Database (Griffin et al., 2013), and for the hydrogen-based approach taken from Vogl et al. (Vogl et al., 2018; Fan and Friedmann, 2021). The hydrogen DRI analysis includes separate CAPEX and lifetimes for direct reduction furnace and EAF (CAPEX/lifetime 1 in Table 1), and electrolyser (CAPEX/lifetime 2). In all cases, annual fixed operating expenses have been assumed to equal 3% of CAPEX, following the approach used in ref. (Vogl et al., 2018). In the hydrogen-based approach, CAPEX for shaft furnace and electrolyser are assumed to scale with DRI production capacity.

The electricity demands of hydrogen-based steelmaking are calculated using the techno-economic model developed by Vogl et al. (2018), as recently adapted for an assessment of the energy system costs of fossil-free steelmaking in the UK (Pimm et al., 2021). This calculates energy demands and resource flows through mass and energy balances, using the open-source thermophysical property library CoolProp (Bell et al., 2014) to calculate thermodynamic properties of water and hydrogen. In the hydrogen-based approach, it is assumed that 60% of the oxygen by-product from water electrolysis can be sold at the market rate. This follows the assumptions of Pardo (Pardo and Moya, 2013) and Vogl (Vogl et al., 2018) that there would be a large-scale consumer of oxygen nearby, and that part of the oxygen can be used in downstream processing operations, such as in oxyfuel burners. We recognise that DRI steelmaking has particular ore quality requirements (Linklater, 2021) and that ramping up of this approach would increase global demand for high grade pellets, however we do not investigate the relationship between DRI deployment and pellet prices here.

Parameters specific to each technology are shown in Table 1, and prices used to calculate variable costs are shown in Table 2. These include recent projections of natural gas prices (Department for Business, Energy & Industrial Strategy, 2020) and traded carbon prices (HM Treasury, 2021) made by the UK government, and projections of power grid carbon intensity made by Great Britain's electricity system operator, specifically the 'System Transformation' scenario in which the 2050 net zero target is met with measures that are relatively less disruptive for consumers (National Grid ESO, 2021a). This was chosen because it is one of the system operator's central scenarios in terms of ambition. The full gas price, carbon price, and grid carbon intensity data are provided in the Supplementary Material. Table 3 gives parameters specific to the investment appraisal. It is assumed that an investment is made in 2025, with production commencing the following year. A 25-year appraisal period and 5% discount rate are used.

The cost of emissions allowances are fully accounted for. Each year, participants in the UK Emissions Trading Scheme (ETS) must submit UK ETS allowances for each product that they manufacture that is covered by the scheme. For any given product covered by the scheme, E allowances must be submitted, effectively given by

$$E = P - B \times \text{CLEF} \quad (1)$$

Table 2
Other parameters used to calculate variable costs and indirect CO_2 emissions.

Parameter	Units	Value	Ref.
Iron ore	£/t	85	Vogl et al. (2018)
Coking coal	£/t	91	U.S. Energy Information Administration (2021)
Natural gas	p/therm	49–64	Department for Business, Energy and Industrial Strategy (2020)
Fluxes	£/t	100	Pimm (2021)
Scrap	£/t	154	Vogl et al. (2018)
Alloys	£/t	1519	Vogl et al. (2018)
Graphite	£/t	3419	Vogl et al. (2018)
Oxygen	£/t	52	Vogl et al. (2018)
Labour	£/tCS	45	Vogl et al. (2018)
Traded CO_2 emissions	£/tCO_2e	22–253	HM Treasury (2021)
Power grid CO_2 intensity	gCO_2/kWh	−57.2–111.9	National Grid ESO (2021a)
CO_2 transport & storage	£/tCO_2	19	Ray and Ferguson (2018)

Table 3
Investment appraisal parameters.

Parameter	Value
Investment year 0	2025
Investment appraisal period	25 yrs
Discount rate	5%

Table 1
Technology costs[11] and parameters for the steelmaking technologies of interest.

Parameter	Units	TGR-BF + CCS		HIsarna + CCS		H_2-DRI + EAF (0% scrap charge)	
CAPEX 1	£/tCS/yr	666.55	TNO (2020)	444.44	TNO (2020a)	353.85	(Vogl et al., 2018; TNO, 2020b)
CAPEX 2	£/tCS/yr	–		–		136.75	(Vogl et al., 2018; TNO, 2020b)
Fixed OPEX (exc. fuel costs)	£/tCS/yr	20		13.33		14.72	(Vogl et al., 2018; TNO, 2020b)
Variable costs	£/tCS	See Table 2					
Lifetime 1	yrs	25	TNO (2020)	20	TNO (2020a)	20	Vogl et al. (2018)
Lifetime 2	yrs	–		–		10	Vogl et al. (2018)
Captured CO_2	tCO_2/tCS	0.8363	Griffin et al. (2013)	1.3586	Griffin et al. (2013)	0	
Direct CO_2 emissions	tCO_2/tCS	1.053	Griffin et al. (2013)	0.34	Griffin et al. (2013)	0.053	Vogl et al. (2018)
Specific (grid) electricity consumption	kWh/tCS	345	Griffin et al. (2013)	345	Griffin et al. (2013)	3016	(Vogl et al., 2018; Pimm et al., 2021)
Natural gas consumption	kWh/tCS	1231	Griffin et al. (2013)	772	Griffin et al. (2013)	0	
Coking coal consumption	kWh/tCS	4731	Griffin et al. (2013)	4011	Griffin et al. (2013)	0	
Iron ore consumption	t/tCS	1.1881	Griffin et al. (2013)	1.4074	Griffin et al. (2013)	1.5038	(Vogl et al., 2018; Pimm et al., 2021)
Scrap consumption	t/tCS	0.1166	Griffin et al. (2013)	0.1166	Griffin et al. (2013)	0	(Vogl et al., 2018; Pimm et al., 2021)
Lime consumption	t/tCS	0.0355	Griffin et al. (2013)	0.0355	Griffin et al. (2013)	0.050	Vogl et al. (2018)
Alloy consumption	t/tCS	0.011		0.011		0.011	Vogl et al. (2018)
Graphite consumption	t/tCS	0		0		0.002	Vogl et al. (2018)
Oxygen consumption	Nm^3/tCS	298.3	Griffin et al. (2013)	412.61	Griffin et al. (2013)	−185.45	(Vogl et al., 2018; Pimm et al., 2021)
Effective emissions benchmark	tCO_2/tCS	1.484		1.219		0.487	

where P is the emissions intensity achieved by the manufacturer in manufacturing the product, B is a greenhouse gas emissions benchmark for the product, set by the UK government and periodically updated, and CLEF is the carbon leakage exposure factor (European Commission, 2019), which is a sector-specific value between 0 and 1 and effectively reduces the number of allowances that must be provided in sectors under risk of carbon leakage. If E is positive, emissions allowances must be bought from the market; if E is negative, excess emissions allowances can be sold on the market. Compensation is provided for the costs of indirect emissions (i.e., those arising from generation of electricity supplied to the site, which are paid by electricity suppliers and passed through to consumers) at the maximum permissible aid intensity of 75% (Department for Business, Energy & Industrial Strategy, 2021).

The current emissions benchmarks in the UK ETS for coke, sinter, lime, hot metal, and EAF carbon steel (currently identical to those used in the EU ETS (European Commission, 2021a)) are combined with specific consumption data from the Useable Energy Database (Griffin et al., 2013) to determine an equivalent emissions benchmark for each green steelmaking technology. These are fixed over the appraisal period, in lieu of further information on the likely reduction over time. While this approach may give lower calculated production costs than might occur in reality as emissions benchmarks reduce, the relative differences between the production costs from the three steelmaking technologies are unaffected.

We assume that the carbon leakage exposure factor (European Commission, 2019) for steel production in the UK ETS remains at 1 until 2030, as was originally planned in phase 4 of the EU ETS (European Commission, 2021b; European Union, 2019), then reduces linearly to 0 over the ten-year period to 2040, after which it remains at 0. It is now expected that free allowances in the EU ETS will be phased out by 10 percentage points each year from 2026, reaching zero in 2035 (European Roundtable on Climate Change and Sustainable Transition (ERCST), 2021), as the EU carbon border adjustment mechanism (CBAM) (European Commission, 2021c) is phased in. On the basis that the UK ETS arrangements are so far very similar to those of the EU ETS, and that a UK CBAM may be introduced on the same timescale as the EU CBAM (though the UK's approach to preventing carbon leakage remains unclear), we also examine the possible effect on levelised costs of this earlier phasing out of free allowances (i.e., we also consider the effect of reducing the carbon leakage exposure factor from 1 to 0 over the ten-year period of 2026–2035). It is assumed that the costs of indirect emissions are passed through to steel producers in electricity prices, and that the compensation rate for the cost of indirect emissions remains at 75% (Department for Business, Energy & Industrial Strategy, 2021) until 2030, then also reduces linearly to 0% over the ten-year period to 2040, after which it remains at 0%. Full details of the ETS parameters are provided in the Supplementary Material.

It is possible that these compensation measures for the costs of direct and indirect emissions may be phased out earlier than modelled here. If this is the case then it can be expected that the price of ETS allowances will increase (Shearman and Sterling, 2021), magnifying the economic benefits of ultra-low carbon technologies. The UK's additional cost for indirect emissions from fossil fuel electricity generation, known as the Carbon Price Support (CPS) (Hirst, 2018), is not included in the analysis, on the basis that it could be phased out once coal power has been phased out in 2024. In any case, inclusion of the CPS over the full appraisal period has very little effect on the levelised costs of steel production, actually reducing levelised costs slightly (by less than 50p per tonne of steel) as a result of negative emissions electricity production expected from around 2035.

The levelised cost of crude steel production (LCOS) is calculated using an approach similar to the widely used method of calculating levelised cost of electricity (Krey et al., 2014). We discount both the total production cost (including greenhouse gas emissions costs) and the quantity of steel produced in each year of the appraisal period, and thus LCOS is given by

$$LCOS = \frac{\sum_{t=0}^{n} \frac{I_t + M_t + V_t}{(1+r)^t} - \frac{R_n}{(1+r)^n}}{\sum_{t=0}^{n} \frac{S_t}{(1+r)^t}} \tag{2}$$

where I_t is the total capital expenditure in year t of the n-year long appraisal period, M_t is the fixed operating expenditure, V_t is the variable expenditure (including fuel, energy, emissions permits, and steelmaking inputs), S_t is the steel production, r is the discount rate, and R_n is the total residual value at the end of the appraisal period (assumed to reduce linearly to zero over the life of an asset).

3. Results

The carbon intensity of the three steel production technologies, as well as that of EAF scrap recycling, is shown against power grid carbon intensity in Fig. 1, with full data provided in the Supplementary Material. The potential for hydrogen-based steelmaking to provide negative emissions by using negative emissions electricity is clear, as is the considerably greater environmental impact of top gas recycling blast furnace as compared with HIsarna smelter and hydrogen DRI shaft furnace. For the two scrap charges shown, hydrogen-based steelmaking with grid electricity has lower CO_2 emissions than HIsarna with CCS at grid carbon intensities below 105 gCO_2/kWh (0% scrap charge, i.e., primary steelmaking) and 212 gCO_2/kWh (50% scrap charge).

While electricity grid CO_2 intensity remains above zero, the CO_2 intensity of EAF steelmaking using 100% scrap is less than that of both CCS options and green hydrogen DRI, and considerably less than that of BF-BOF steelmaking. This is a clear option for immediate gains and is particularly relevant in the UK, which was the largest steel scrap exporter in Europe in 2020 (Bureau of International Recycling, 2021). With the UK's 2020 grid carbon intensity of 181 gCO_2/kWh (National Grid ESO, 2021b), the carbon intensity of EAF steel production is estimated to have been approximately 130 $kgCO_2/tCS$ in the UK in 2020, 93% lower than the carbon intensity of BF-BOF steel production (Vogl et al., 2018).

The approaches that have been outlined in this section are used in the rest of this paper to determine the costs and carbon emissions of the most promising options for green steelmaking, informing our analysis of existing policies and potential future policies. We focus on the UK here as a case study, but the modelling approaches and policy discussions have much wider relevance.

Two primary pricing policies have been identified as providing options for green steelmaking to thrive in the UK. The removal of carbon pricing discrepancies and reductions in industrial electricity prices would make the financial realities of green steelmaking more palatable but are also within the economic and political realm of possibility. These options are largely tied together by the need to level the playing field for green steel producers in the UK, which are currently at a disadvantage to both incumbent steel producers in the UK and international competition in terms of energy and carbon costs. There exists a range of other possible policy options (Rissman et al., 2020; Nilsson et al., 2021) to drive green steelmaking, including the implementation and utilisation of carbon border adjustments or product standards (European Roundtable on Climate Change and Sustainable Transition (ERCST), 2021), and the introduction of an international carbon price floor (Hirst, 2018), but these options require multilateral and international cooperation (Gerres et al., 2021) that falls outside of unilateral UK action. What follows is an analysis of these pricing options and the industrial impacts they will have: first, the following subsection will outline the technologies to address the emissions from the iron and steel industry, then the primary policy options are discussed in more detail.

[1] Where necessary, costs are converted to GBP at the mid-2021 exchange rates of 1.17 EUR = 1 GBP and 1.39 USD = 1 GBP.

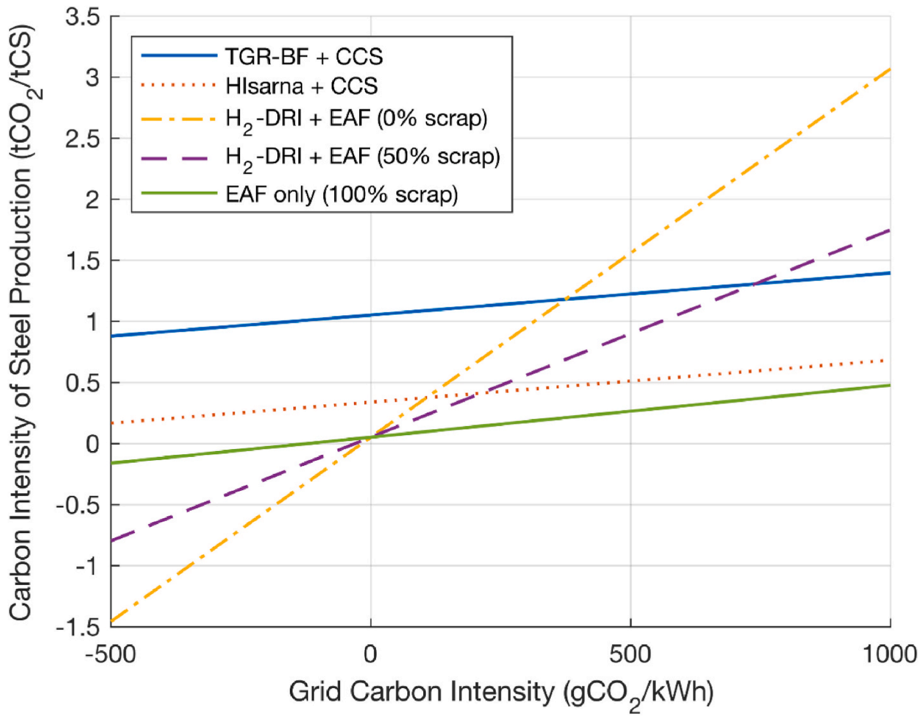

Fig. 1. Greenhouse gas emissions from the most promising options for green steel production against power grid carbon intensity. Full data provided in the Supplementary Material. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.1. Emissions from the iron and steel industry

The iron and steel industry is heavily dependent on coke, derived from coal, both to provide heat and act as a reducing agent, and accounts for around 7% of CO_2 emissions from the energy system, ranking first among heavy industries (International Energy Agency, 2020). In the UK, the Climate Change Committee recently recommended that the government should target near-zero emissions from ore-based steelmaking by 2035 (Climate Change Committee, 2020).

Using the approaches laid out in Section 2, and assuming that electricity is drawn from the GB power grid with grid carbon intensities projected by the GB electricity system operator, National Grid ESO (National Grid ESO, 2021a), the carbon intensity of steel produced using these technology options has been projected out to 2050, as shown in Fig. 2. It should be noted that grid carbon intensities are projected to rise slightly in some years, explaining the jagged nature of the curves

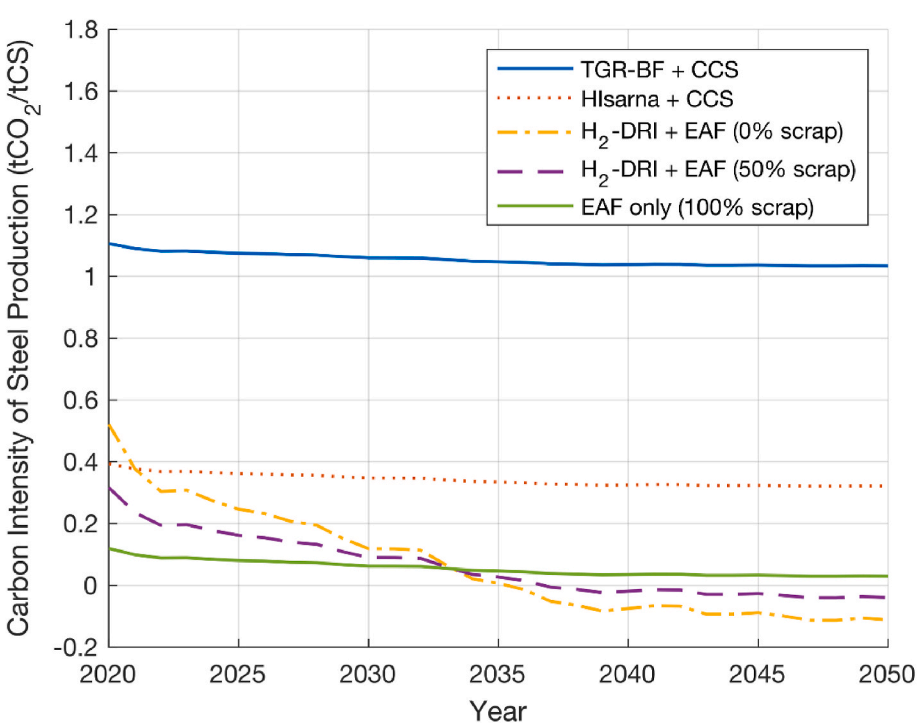

Fig. 2. Projected carbon intensity of steel produced using two CCS approaches (top gas recycling blast furnace + CCS and HIsarna smelter + CCS), hydrogen-based steelmaking with water electrolysis (H_2-DRI + EAF for two different mixes of DRI and scrap), and steel scrap recycling (EAF operating on 100% scrap), with the power sector carbon intensity in the GB electricity system operator's 'System Transformation' future energy scenario. Full data provided in the Supplementary Material.

(particularly noticeable in the 2040s), and are projected to go negative in some scenarios, due to the deployment of biomass with CCS. The GB electricity system operator's 'System Transformation' scenario (National Grid ESO, 2021a) is used for the figure, which is compatible with the government's recent commitment to zero-emissions grid electricity by 2035. Results for all four future energy scenarios are provided in the Supplementary Material and are generally similar to the 'System Transformation' scenario results shown here.

In all four future energy scenarios, the emissions from H_2-DRI + EAF are below 200 $kgCO_2$/tCS by 2030, and emissions are net zero by 2036 in the three scenarios which meet the UK government's net zero by 2050 target (Consumer Transformation, System Transformation, and Leading the Way), after which point H_2-DRI + EAF steel production provides negative emissions as a consequence of using negative emission power generated using biomass + CCS. Negative emissions settle to around −100 $kgCO_2$/tCS in the early 2040s. When the carbon intensity of grid electricity becomes negative in the early 2030s, the relationship between EAF scrap charge and carbon intensity of steel production inverts, because use of scrap tends to reduce electricity consumption and hence reduce the rate of CO_2 removal from the atmosphere.

Emissions from HIsarna + CCS are less affected by power generation carbon intensity because uncaptured CO_2 from furnace operation is a significant source of emissions in this approach, and emissions remain above 320 $kgCO_2$/tCS in 2050 in all four scenarios. For context, emissions from unabated BF-BOF steelmaking are currently around 1.9 tCO_2/tCS (Vogl et al., 2018; Lytton and MacDonald, 2021). Of course, steel producers could accelerate decarbonisation of existing technologies (such as BF-BOF steelmaking) and the new technologies being considered here by procuring low-carbon electricity from specific generators through power purchase agreements. However, the effect of this for BF-BOF plants in particular would be relatively small; with a specific grid electricity consumption of 211 kWh/tCS for BF-BOF steelmaking (Griffin et al., 2013), the relationship between grid carbon intensity and carbon intensity of steel production is even weaker than that for the two CCS-based technologies considered here.

3.2. *Analysis of policies to support green steelmaking*

3.2.1. *Removal of carbon pricing discrepancies*

The carbon price paid by the steel industry depends upon production route, and there exist significant discrepancies between the carbon price paid by BF-BOF and EAF plants, putting EAF plants at a competitive disadvantage (Skelton and Allwood, 2017).

The UK steel industry pays for its greenhouse gas emissions through several different mechanisms, largely comprising the following:

- **UK Emissions Trading Scheme (UK ETS)** (Department for Business, Energy & Industrial Strategy, 2021c). All large energy consumers in the UK are obliged to participate in the UK ETS, but a free allocation of allowances is provided to certain industries (including iron and steel) to maintain international competitiveness. The UK ETS replaced the EU ETS in the UK post-Brexit, and the first UK ETS auction took place in May 2021 (Financial Times, 2021a).
- **Carbon Price Support (CPS)** (Hirst, 2018). The CPS was introduced in 2013 to underpin the price of carbon at a level that drove low-carbon investment, which the EU ETS was not achieving at the time due to very low ETS prices. The CPS is paid by electricity generators and the costs are passed through to end-users. The CPS is added to the costs of ETS allowances, ensuring that the cost of carbon emissions from electricity generation is above the Carbon Price Floor (CPF), set by the government. The CPF is considered to have been highly effective in driving down the use of coal-fired electricity generation in the UK (Hirst, 2018; Helm, 2017). However, the CPS has not been adjusted in recent years even though ETS prices have risen considerably above the intended carbon price floor, so the CPF effectively no longer exists while the CPS continues to exist as an additional carbon tax for electricity generators.
- **Climate Change Levy (CCL)** (HM Government, 2021). The CCL is a tax on energy delivered to non-domestic users. It is paid by the steel industry at a reduced rate as a result of it having an umbrella Climate Change Agreement in place with the UK government, by which it commits to sector-wide energy efficiency or carbon efficiency improvements over time.

The UK ETS clearing price in the first auction in May 2021 was around £44/tCO_2 (Financial Times, 2021a) and has since risen to over £80/tCO_2. The carbon price in the EU ETS has increased considerably in recent years and at the time of writing is €96/tCO_2 (equivalent to £81/tCO_2). Many observers have noted that formal or informal alignment of the UK ETS with the EU ETS would increase the market size and drive efficiencies, attracting abatement from across the EU (Hatherick, 2021). The CPS has been fixed at £18/tCO_2 since 2016 (Hirst, 2018).

By charging for greenhouse gas emissions through several different mechanisms, each with different applicability and exemptions, there exist inherent discrepancies between the price paid by different actors in the steel supply chain. Before the EU ETS price rose considerably in the last three years, the EU ETS price was around £5/tCO_2. This was less than a quarter of the £23/tCO_2 paid for fossil-fuel electricity through the combination of the EU ETS and the CPS at the same time. Accounting for a 95% free allocation of allowances in the EU ETS and 85% compensation towards the costs of indirect emissions, research published in 2017 showed that BF-BOF plants paid an effective carbon tax of £0.3/tCO_2 whereas EAF plants paid £2.3/tCO_2 (Skelton and Allwood, 2017).

As shown in Table 4, these figures have been revised based on the first UK ETS auction clearing price of £44/tCO_2 (Financial Times, 2021a) and a reduction in compensation for costs of indirect emissions to 75% (Department for Business, Energy & Industrial Strategy, 2021), while also considering that power generation is subject to both the UK ETS and CPS. The emissions intensity data have also been brought up-to-date based on emissions and production data for UK steelworks in 2018 (Lytton and MacDonald, 2021), the direct emissions intensity of EAF steelmaking of 53 $kgCO_2$/tCS from Vogl et al. (2018), the specific electricity consumption of EAF steelmaking with oxyfuel burners of 425 kWh/tCS estimated by the Heat Consortium (2020) (aligning with data from a recent study of EAF steelmaking in Poland (Gajdzik et al., 2021), that does not indicate age of EAFs), and the UK's 2020 grid carbon intensity of 181 gCO_2/kWh (National Grid ESO, 2021b). This analysis reveals that carbon costs have increased to £2.2/tCO_2 for BF-BOF plants and £10.1/tCO_2 for EAF plants. By paying an effective carbon tax over 4.5 times that paid by BF-BOF plants, UK electric arc furnace steelmakers are being put at a competitive disadvantage as a consequence of differing carbon prices and levels of compensation for direct and indirect

Table 4
Effective carbon costs to primary (BF-BOF) and secondary (EAF) steel producers in the UK in 2021. Adapted from ref. (Skelton and Allwood, 2017).

Measure	Units	BF-BOF	EAF
Emissions intensity	tCO_2/t steel	1.92	0.13
of which direct	tCO_2/t steel	1.92	0.05
of which indirect	tCO_2/t steel	0.00	0.08
Carbon prices			
UK ETS price: direct and indirect emissions	£/tCO_2	44	44
UK CPS price: indirect emissions	£/tCO_2	18	18
Carbon costs (exc. compensation)	£/t steel	84.5	7.1
of which UK ETS (direct)	£/t steel	84.5	2.3
of which UK ETS (indirect)	£/t steel	0.0	3.4
of which CPS	£/t steel	0.0	1.4
Carbon costs compensation	£/t steel	−80.3	−5.8
of which free allowances UK ETS	£/t steel	−80.3	−2.2
of which indirect carbon cost compensation UK	£/t steel	0.0	−3.6
Carbon costs (net compensation)	£/t steel	4.2	1.3
Effective carbon tax paid	£/tCO_2	2.2	10.1

emissions.

If the effective carbon tax paid by BF-BOF producers was raised to the level paid by EAF producers, the carbon costs (net compensation) for BF-BOF production would increase to almost £20/t steel, £18/t steel higher than that paid by EAF producers. Considering that the cost of steel is typically around £500/t steel, and that the steel industry operates with very narrow profit margins, this discrepancy is likely to have a material impact. Putting low-carbon steelmaking approaches at a disadvantage to emissions-intensive incumbents provides the wrong signals if industrial decarbonisation is to be realised in the medium-term.

The inconsistency of carbon prices across the economy, and the resulting inefficiencies and substitution effects, have been highlighted previously, with Helm stating that applying the same price of carbon in every sector, and globally, is the most efficient policy instrument to internalise the carbon externality (Helm, 2017). However, we recognise that there are problems with global uniform carbon pricing in that it does not address diversity and heterogeneity (Verbruggen and Brauers, 2020), though the means to address these are not obvious at present. In any case, higher carbon prices to EAF steel producers would seem perverse considering the lower carbon intensity of steel produced using this route.

In order to harmonise carbon prices between BF-BOF steelmakers and EAF steelmakers, two features of the current arrangements must be addressed: 1) differences between the carbon price for direct emissions (UK ETS only) and indirect emissions from power generation (pass-through of UK ETS and CPS costs paid by power generators), and 2) differences between levels of compensation for the costs of direct emissions (free allocation of UK ETS allowances to sectors exposed to carbon leakage, which include the steel industry but not power generation) and indirect emissions (reimbursement of 75% of costs).

One option to address the difference in carbon price would be to phase out the CPS. This would be reasonable since the CPS was introduced in 2013 to raise the carbon price in the UK at a time when EU ETS prices were so low as to be almost ineffective (e.g., £5/tCO_2); in recent years, prices in the EU ETS have risen considerably, and UK ETS prices have reached similarly high levels since the UK scheme launched in May 2021 (Financial Times, 2021a), as noted above. An effective carbon price floor could be maintained through the auction reserve price in the UK ETS. Phasing out the CPS would have the added benefit of removing an unfavourable aspect of the UK's current carbon pricing system, which is that all proceeds from the CPS are currently treated as general tax revenue. This differs from the approach used in other countries, where carbon tax revenue is provided as a rebate to firms or households, or used for green infrastructure spending (Burke and Byrnes, 2019).

To address the differences in levels of compensation for the costs of direct and indirect emissions once the CPS has been phased out, compensation could be provided for the costs of indirect emissions at the same rate as compensation is provided towards direct emissions through free allocation of emissions allowances. Alternatively, the UK ETS legislation could potentially be amended so that indirect emissions from electricity consumption are included. In this way, the emissions cap and associated free allocation of allowances would apply to an organisation's combined direct (scope 1) and indirect (scope 2) emissions.

These changes would ensure that: 1) the carbon price is made uniform across the steel industry, 2) a market-based approach to setting the carbon price remains present in the form of the UK ETS, and 3) a price floor remains present in the form of the UK ETS auction reserve price, providing confidence in carbon prices.

3.2.2. Reduced industrial electricity prices

Scrap steel recycling is highly electro-intensive. It is estimated that electricity comprises 75% of energy costs for an EAF but only 35% for integrated BF-BOF sites (Aaskov, 2021). As a result, increasing the share of iron from scrap would lead to a considerable increase in electricity's share of total energy costs. This is particularly important in the UK, where heavy industry faces high electricity prices relative to those in many other countries. Accounting for the various compensations given to the sector, the UK steel industry pays £47/MWh for electricity in 2020/21, compared with £25/MWh in Germany and £29/MWh in France (Aaskov, 2021). This differential is largely a result of higher policy and network costs in the UK, with wholesale costs being similar across the three countries (Aaskov, 2021).

There are several reasons why industrial electricity prices are higher in the UK than in other European countries, including relatively poor interconnection with other countries and less support for long-term supply contracts (Grubb and Drummond, 2018). One of the key reasons is that policy and network costs are recovered equally across all electricity consumers in the UK, whereas in many other countries these costs are recovered proportionately less from large energy users in recognition of their importance to international competitiveness and their role in balancing the electricity system (Aaskov, 2021; Grubb and Drummond, 2018). The policy and network costs seen by the UK steel sector have risen steadily over the last four years, even though wholesale costs have fallen by over 50% since 2018 (Aaskov, 2021). In the last year, steadily increasing energy costs coupled with rising material costs across steel (66% price increases over 12 months, for example) and other industries have put similar potentially long-term pressures on construction and heavy industry (Plimmer and Pfeifer, 2022). Combined, policy and network costs now account for more than half of the electricity price seen by UK steel producers but comprise a much smaller fraction of costs in countries such as France and Germany (Aaskov, 2021). This disparity is expected to increase in 2022 as the UK energy regulator implements a major new network reform, the Targeted Charging Review (UK Steel, 2019).

It is estimated that the electricity price disparities with Germany translate to a total additional cost to UK steelmakers of £54 m/yr (Aaskov, 2021). If this difference could be socialised through addition to income tax (viewed as more progressive than addition to energy bills (Edmondson, 2020), then the UK's total income tax bill (HM Revenue & Customs, 2021) would increase by 0.029%, raising the median income tax bill by £0.68/yr. This increase would rise to around £5.47/yr if the UK switched to green hydrogen-based fossil-free steelmaking (assuming an 800% increase in electricity demand (Pimm et al., 2021; Aaskov, 2021)). Further work could examine the likely effects on these costs of decarbonising other industrial sectors.

The high price of electricity to UK industry is often quoted as one of the reasons why the UK steel industry struggles to compete internationally. This was rejected by Evans in 2015 (Evans, 2015), who argued that electricity makes up a small share of steel production costs, at around 6%. However, this was based on costs at integrated BF-BOF steelworks which cannot use high levels of scrap metal. Scrap utilisation is much higher at EAF sites, where the situation is quite different. Electricity is the primary energy source for an EAF steelworks as it is used to generate the electric arc for melting of the charge (scrap and any additional source of iron such as DRI). It has been estimated that electricity costs make up around 7–10% of EAF steelmaking costs in the UK, with scrap metal accounting for the bulk of the remaining costs (Steelonthenet.com, 2021). In an industry known for its very slim operating margins, the cost of electricity is therefore an important factor in international competitiveness and will be increasingly important if scrap provides a larger share of iron in steelmaking.

To understand the effect of electricity costs on the competitiveness of the most promising CCS- and hydrogen-based options for decarbonising steel production, the techno-economic modelling tool presented in Section 2 has been applied with recent estimates of technology and resource costs, and projections of power grid emissions factors and natural gas prices out to 2050. Fig. 3 shows how total steel production cost per tonne of crude steel (tCS) varies with electricity price for top gas recycling blast furnace (TGR-BF) with CCS, HIsarna with CCS, hydrogen DRI with EAF, and EAF being fed entirely with scrap. The full results are also provided in the Supplementary Material. The 100% scrap recycling approach generally has considerably lower levelised cost than the other

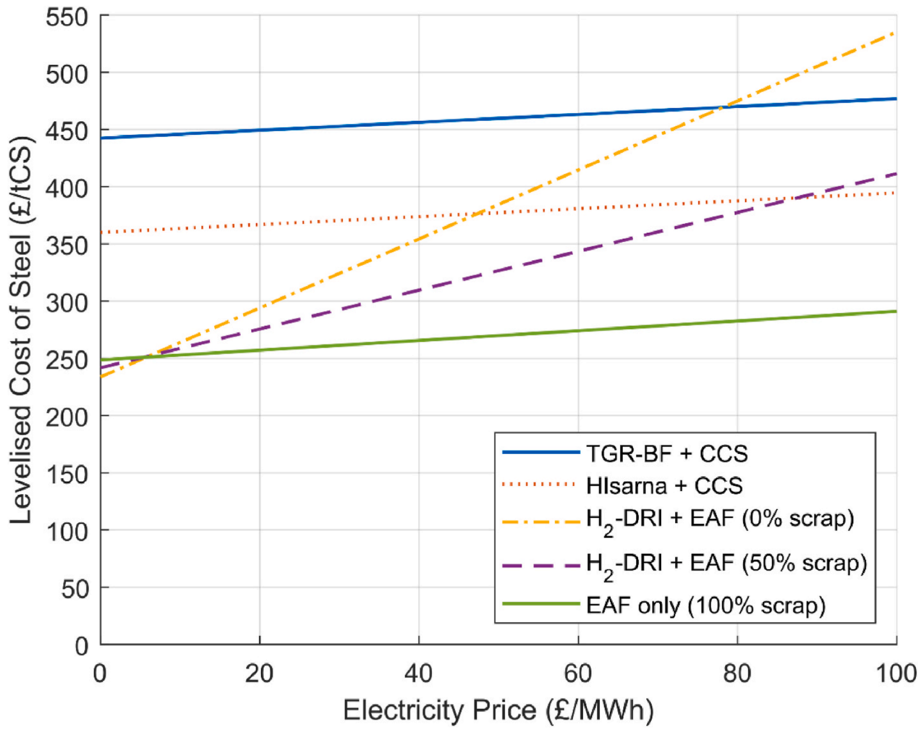

Fig. 3. Projected levelised cost of crude steel production in the UK against electricity price in three promising options for decarbonisation of primary steelmaking: top gas recycling blast furnace (TGR-BF) with CCS, HIsarna smelter with CCS, and hydrogen DRI with EAF. Results also shown for hydrogen DRI + EAF with 50% scrap/50% DRI, and 100% scrap recycling using EAF. Full data provided in the Supplementary Material.

approaches, particularly when electricity prices are high. Coupled with the very low carbon emissions of this approach, as shown in Fig. 1, the importance of increasing steel scrap recycling is abundantly clear, though we recognise that steel produced from scrap is unsuitable for some applications and hence there remains a need for primary steel production.

The hydrogen-based primary steelmaking approach has lower levelised production cost than both CCS-based approaches at electricity prices below about £45/MWh. At the electricity price currently paid by the UK steel industry of around £47/MWh (Aaskov, 2021), the levelised cost of primary steel production from hydrogen DRI with EAF is estimated to be £374/tCS, almost exactly equal to that of HIsarna with CCS (£376/tCS) and 18% lower than TGR-BF with CCS (£459/tCS). If the cost of electricity could be reduced to the level in Germany (£25/MWh), then these costs would reduce to £309/tCS for hydrogen DRI with EAF, £369/tCS for HIsarna with CCS, and £451/tCS for TGR-BF with CCS. Such a saving of 17% in the case of hydrogen-based steelmaking could be critical to maintaining competitiveness while decarbonising primary steel production.

As explained in Section 2, until recently the EU was committed to providing the steel industry with 100% of its EU ETS allowances for free until 2030 (European Commission, 2021b). However, it is now expected that free allocation of allowances will be phased out over the ten-year period from 2026 to 2035 (European Roundtable on Climate Change and Sustainable Transition (ERCST), 2021) as the CBAM is phased in. The costs shown in this section have been calculated assuming that free allocation of UK ETS allowances is gradually phased out over the ten-year period from 2030 to 2040, as the UK is yet to make any commitment to introducing a CBAM. It is found that with no changes to emissions benchmarks or carbon prices, the earlier removal of free allowances from 2026 has the effect of raising the levelised cost of steel production by between £6/tCS (for EAF scrap recycling) and £38/tCS (for TGR-BF with CCS). However, it can be expected that the earlier removal of free ETS allowances will drive up prices of ETS allowances and fuel investment in green steelmaking technologies, reducing the benchmark CO_2 intensity of steel products. Both of these effects will serve to magnify the benefits of ultra-low carbon technologies, and further research in this area would be worthwhile.

To understand the sensitivity of these results to carbon price, levelised costs have been determined over a range of *effective* carbon prices, as shown for three different electricity prices in Fig. 4. To avoid complicating the results with the uncertainty surrounding levels of compensation provided to the steel industry going forward, the emissions benchmark and compensation rate for indirect emissions have been set to zero in all years of the analysis to generate this figure. At present, the effective carbon price is much lower than the actual carbon price, though it will rise to meet the actual carbon price as compensation for emissions costs is phased out. It should be noted that effective carbon price varies between steelmaking technologies and is negative when the carbon intensity of steel production is below the emissions benchmark.

The impact of carbon prices on the levelised costs of the coal-based technologies is evident from this figure, as is the impact of electricity price on the competitiveness of hydrogen DRI, due to the high electricity demands of hydrogen electrolysis. In particular, high electricity prices magnify the importance of scrap utilisation in fossil-free steelmaking, making a considerable difference to its competitiveness with the CCS-based technologies.

Total costs for a 1 MtCS/yr plant over the 25-year appraisal period are shown in Table 5, highlighting the significant expenditure involved in decarbonising the steel industry. With the electricity price currently paid by the UK steel industry, electricity could account for almost 40% of steel production costs if hydrogen-based primary steelmaking is deployed.

Our findings highlight the importance of electricity prices to the cost of green steel, particularly for the cleanest technologies that make use of green hydrogen, as well as the considerable investment that will be required to decarbonise the UK steel industry.

The UK government could implement several different changes to reduce the network and policy costs to heavy industry, such as increasing exemptions for payment of renewable levies, or transferring

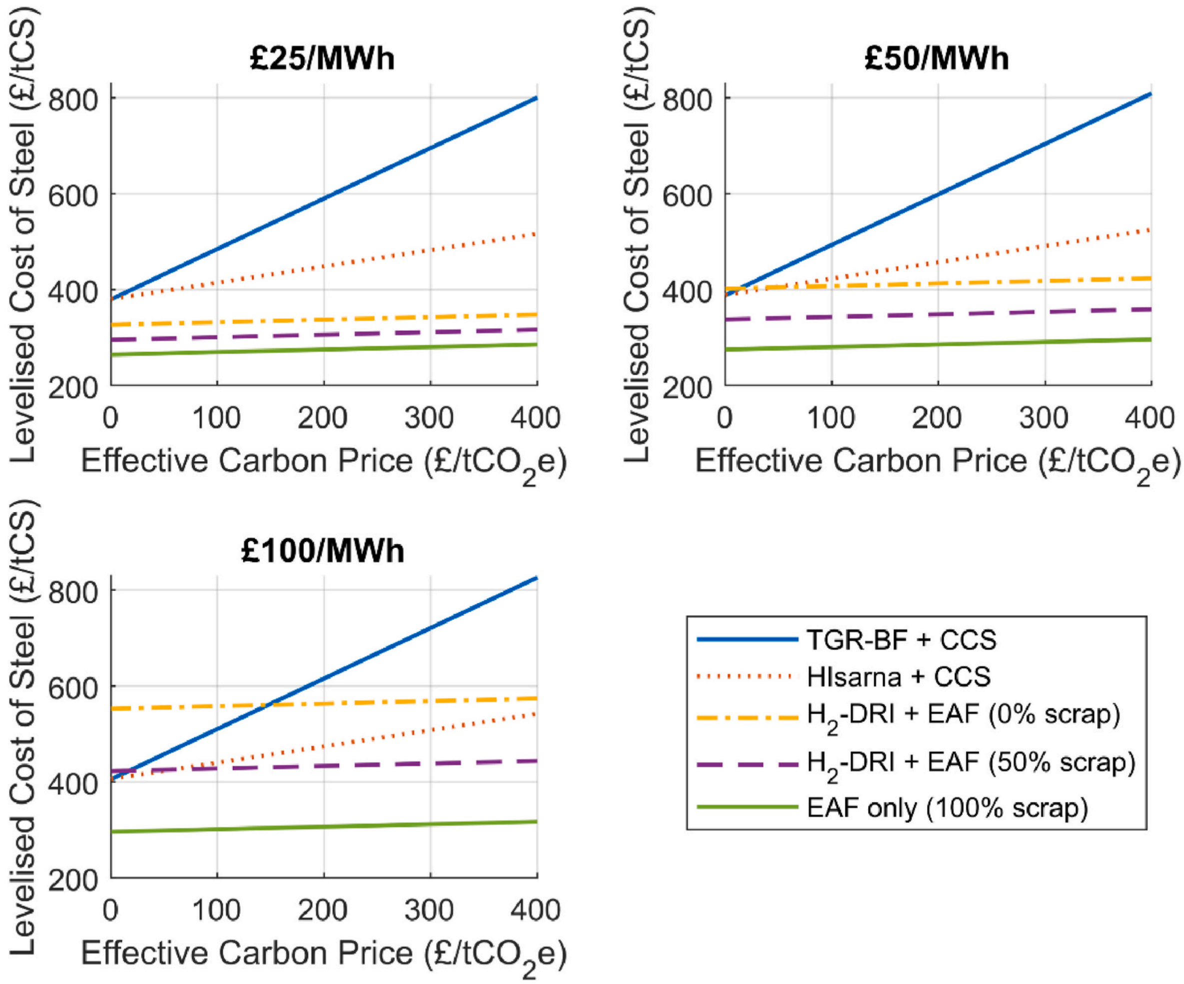

Fig. 4. Projected levelised costs of steel production in the UK against effective carbon price for three different electricity prices. Effective carbon price is the carbon price after emissions benchmarks and other compensations have been removed.

Table 5
Cost breakdown for the steelmaking technologies of interest deployed in a 1 MtCS/yr plant over the 25-year appraisal period, at an electricity price of £46.60/MWh.

	Units	TGR-BF + CCS	HIsarna + CCS	H_2-DRI + EAF (0% scrap)	EAF Only (100% scrap)
Net CAPEX[a]	£m	667	556	784	197
Fixed OPEX	£m	500	333	368	118
Net Variable OPEX[b]	£m	10,728	8669	7996	6369
Total Net Expenditure	£m	11,894	9558	9148	6683
Discounted Total Net Expenditure	£m	6463	5302	5275	3784
Levelised Net CAPEX	£/tCS	47	36	47	13
Levelised Fixed OPEX	£/tCS	20	13	15	5
Levelised Net Variable OPEX	£/tCS	391	326	313	251
Levelised Cost of Steel	£/tCS	459	376	374	268

[a] CAPEX net of salvage value.
[b] Variable OPEX net of income from emissions trading and sale of excess oxygen.

renewable levies from electricity (where energy intensity is already being steadily reduced) to gas (taxing a carbon intensive fuel), as is being implemented in the domestic energy sector (Financial Times, 2021b). Making reforms to how network costs and the costs of renewable energy policies are recovered is an important policy lever available to the UK government and could be investigated through consultations and further research.

Research into the historical relationship between input prices, steel production, and specific energy consumption across five of the largest steel producing countries in Western Europe showed that higher energy prices tend to raise energy efficiency (or tend to reduce specific energy consumption) in the steel sector (Flues et al., 2013). However, a structural shift to greater electrification of the industry must be supported financially and reducing industrial electricity prices is one of the clearest means of improving the profitability of electrified steelmaking.

4. Discussion

While the UK steel industry is experiencing economic pressure and continuous declines in a competitive global market, low-cost and low-carbon options for steel production are a clear solution to long-term industry sustainability (Griffin and Hammond, 2021). Record levels of UK government and corporate debt have risen over the past 2 years as the government has provided significant funding to address impacts of the coronavirus pandemic and keep finance markets liquid while maintaining businesses' access to finance and support (Moore and Collins, 2021). The UK steel industry has been one such recipient of government investment, with a variety of support measures implemented over recent years, including emergency loans to Celsa, the ongoing potential for nationalisation and restructuring of Liberty Steel, and the Ministry of Defence (MoD) acquisition of Sheffield Forgemasters (Hutton, 2021). The MoD acquisition in August 2021 (Financial Times, 2021a) for a cost of £2.56 million plus debt was a record deal that sees one of the UK's oldest steel companies nationalised following years of reliance on loan guarantees from defence contracts (Jolly, 2021). When considering low-cost and low-carbon options for the UK steel industry, this modelling has revealed that green hydrogen-based steelmaking has not just lower levelised costs than CCS options, but also lower emissions, providing a two-fold benefit for UK steel.

Based upon modelling and analysis, potential for industry change that would have a positive impact on decarbonisation within the steel industry is largely focused around three primary areas for incentives—industry, national and international levels of policy choices.

First, industry levers to influence decarbonisation include the type of steelmaking used, for example hydrogen-based or CCS options, as well as scrap usage. Higher shares of scrap increase circularity, reduce waste, and have potential positive price impacts. Our analysis has demonstrated the price and emissions impacts type of steelmaking can have, but additional impacts could also be felt when choosing between steelmaking types, as well. Further, industry must organise internationally (and, in fact, many of these companies are multinational) in order to maintain progress in decarbonisation—low carbon standards need to be agreed internationally in order to level the playing field for low carbon products. This would not only assuage competitiveness concerns, but also maintain green steel progress domestically. In the UK, where industry-policy coordination is progressing (Department for Business, Energy & Industrial Strategy, 2021a), there is a continued need for investment and scaling of green steel options in order to maintain pace with European steel industries (McDonald et al., 2021). Any policy coordination between international industries will aid in this area, as well as assist in market creation for green steel via domestic and international coordination.

Second, policy levers available in the United Kingdom are primarily clustered around cost reductions and pricing, as well. Reductions in network and policy costs to heavy industry could be achieved by increasing exemptions for payment of renewable levies or transferring renewable levies from electricity to gas. Reforms to network costs and the recovery of renewable energy costs could also serve the UK steel industry via national policy making choices. These options need to be further researched to explore the wider implications (both positive and negative), but offer promising options based on the above analysis. Further, changes in electricity cost coupled with hydrogen-based steelmaking could result in savings of over 10% and are critical to maintaining competitiveness while decarbonising steel production. The cost of electricity is further important to international competitiveness and higher scrap usage will make these changes increasingly important and offer cross-over with industry levers. To realise energy efficiency that results from higher energy prices, a structural shift to greater electrification of the industry will need to be supported financially. Reducing industrial electricity prices is one of the clearest means of improving the profitability of electrified steelmaking.

Finally, international policy levers are similarly economically focused. CBAM and export tariffs on scrap offer pricing incentives, but both could have negative impacts on the UK's steel industry if requirements are not carefully met by industry. Both CBAM and export tariffs also require careful WTO compliance and harmonisation of rules and/or implementation in order for negative international impacts to be mitigated. Inclusion of emerging markets in these plans also has long term impacts on global net zero targets and could therefore have industry implications outside of the UK as well.

5. Conclusion and policy implications

Techno-economic analyses of a range of the most promising green steelmaking processes in the UK finds that steel scrap recycling currently has the lowest costs and emissions of all options and this is likely to remain the case until the early 2030s. Amongst primary production processes fossil-free hydrogen-based steelmaking has lower emissions and lower levelised costs than carbon capture and storage options, presenting a two-fold benefit for UK steel in a global environment where decarbonisation and emissions reductions are of international priority. Modelling of costs demonstrates the importance of electricity prices and shows that low-carbon steelmaking approaches in the UK have been put at a disadvantage compared to emissions-intensive incumbents due to unequal carbon costs and higher electricity prices than many other countries. This disadvantage to low-carbon steelmaking options sends mixed signals regarding the government's commitment to Net Zero and places pressure on an industry already suffering increased competition in global markets. Addressing these cost challenges should therefore be a policy priority but may not be sufficient to deliver a competitive and decarbonised UK steel industry. Co-ordinated international action on issues such as market creation for green steel via CBAMs and export tariffs on scrap will also likely be needed given the global nature of the steel industry.

CRediT authorship contribution statement

Clare Richardson-Barlow: Conceptualization, Formal analysis, Writing – review & editing. **Andrew J. Pimm:** Conceptualization, Data curation, Formal analysis, Writing – review & editing. **Peter G. Taylor:** Conceptualization, Writing – review & editing. **William F. Gale:** Supervision, Writing – review & editing.

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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All data used in this research are included in the paper or the Supplementary Material.

Appendix A. Supplementary data

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