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Regional uptake of direct reduction iron production using hydrogen under climate policy

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ABSTRACT

The need to reduce CO_2 emissions to zero by 2050 has meant an increasing focus on high emitting industrial sectors such as steel. However, significant uncertainties remain as to the rate of technology diffusion across steel production pathways in different regions, and how this might impact on climate ambition. Informed by empirical analysis of historical transitions, this paper presents modelling on the regional deployment of Direction Reduction Iron using hydrogen (DRI-H2). We find that DRI-H2 can play a leading role in the decarbonisation of the sector, leading to near-zero emissions by 2070. Regional spillovers from early to late adopting regions can speed up the rate of deployment of DRI-H2, leading to lower cumulative emissions and system costs. Without such effects, cumulative emissions are 13% higher than if spillovers are assumed and approximately 15% and 20% higher in China and India respectively. Given the estimates of DRI-H2 cost-effectiveness relative to other primary production technologies, we also find that costs increase in the absence of regional spillovers. However, other factors can also have impacts on deployment, emission reductions, and costs, including the composition of the early adopter group, material efficiency improvements and scrap recycling rates. For the sector to achieve decarbonisation, key regions will need to continue to invest in low carbon steel projects, recognising their broader global benefit, and look to develop and strengthen policy coordination on technologies such as DRI-H2.

Acronyms

AE	aqueous electrolysis
BF-BOF	Blast furnace-basic oxygen furnace
CC	continuous casting
CCS	carbon capture and storage
DRI	Direct Reduction Iron
DRI-H2	Direct Reduction Iron using hydrogen
EA	early adopters
EAF	electric arc furnaces
EOL	end of life
ETC	Energy Transition Commission
HR	higher recycled
IAMs	integrated assessment models
IDDI	Industrial Deep Decarbonization Initiative
IEA	International Energy Agency
IETS	International Energy Related Technology Systems
LA	late adopters
LD	lower demand
MOE	molten oxide electrolysis
ODA	other developing Asia
UNFCCC	United Nations Framework Convention on Climate Change

Introduction

Steel is a fundamental component of building structures (40% of 2019 global demand), industrial equipment (20%), consumer products (18%), infrastructure (13%), and vehicles (10%) [2]. However, the current production process for primary steel is energy-intensive, relying predominantly on coal, and is therefore also carbon-intensive. The sector currently uses about 8% of global final energy demand (20% of industrial energy use) and is responsible for 7% of energy sector CO_2

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emissions, including process emissions (or 25% of industrial sector emissions) [14]. Existing primary production is dominated by the Blast Furnace - Basic oxygen furnace (BF-BOF) pathway, in which coal is the main source of energy, accounting for 74% of energy input.

Tackling emissions from the steel sector is therefore a priority if global climate targets are to be met. There are a range of actions that could be taken; (i) no new investment in existing BF-BOF technologies; (ii) high levels of investment in low carbon primary production capacity; (iii) increased secondary steel production using recycled steel; (iv) a focus on reducing demand for steel; and (v) the policies to scale R&D and investment rapidly (see Appendix 1 for further information).

One of the key approaches to assessing pathways for sector decarbonisation is through the use of global energy system and integrated assessment modelling, allowing for many of the above measures to be assessed together. van Sluisveld et al. [39] explored decarbonisation of energy-intensive industry sectors, including iron and steel using the IMAGE model. Full decarbonisation of the sector was shown to occur in those scenarios that have high electrification of the steel making process, and increased levels of secondary steel production via EAF. Using the GCAM model, Yu et al. [50] showed the importance of material efficiency, increased steel recycling, limiting investment in existing BF-BOF technologies, and the increased uptake of low carbon production methods to meet 1.5 °C. Bataille et al. [3], using a bottom-up, facility level model of the global steel sector, explored pathways to decarbonisation across different regions. Insights included the importance of doubling the use of recycled steel, and limiting reinvestment in existing high emitting plants and key long lived subcomponents.

In this paper, we undertake an integrated assessment analysis of the role for steel sector decarbonisation options, with a focus on the deployment of hydrogen-based Direct Reduction Iron with electric arc furnace (DRI-H2). This primary production pathway has emerged as a front-runner in the production of green steel [45], and is being fully demonstrated as part of the HYBRIT project in Sweden [27]. The novelty of this research is the focus on the diffusion dynamics of steel production technologies and the implications for regional deployment of those technologies in modelling analyses. The representation of technology diffusion, and the processes that determine the speed and shape of these transitions responds to the criticism of lack of such representation in IAMs [20].

Here we implement and explore empirically-observed diffusion dynamics in a scenario modelling framework. The specific dynamic that we consider relates to the idea that technology diffusion accelerates in later-adopting regions [47]. The intuition behind this is clear; later-adopting (or periphery) regions can benefit via spillovers from the learning that took place in the early-adopting (or core) region. They do not need to undergo a lengthy 'formative phase', as observed in early adopting regions, during which the technology matures through a process of experimentation and development of core technological options, typically culminating in a dominant design or dominant product or system architecture. They thus offer greater relative advantage in later-adopting regions (because of better performance and lower costs), and there are also likely to be spillovers related to more mature complementary goods and services.

To summarise, the novelty of this research is the integration of empirical insights into a global energy system model to explore patterns of diffusion and associated spillovers related to DRI-H2. Much of the empirical work has tended to sit outside of the global modelling analysis, while here we aim to integrate such empirically grounded dynamics. We focus on differences in regional deployment of DRI-H2 and the implications of this on the pace and level of sector decarbonisation. These differences are based on empirical observation that technology diffusion will be impacted by which regions move first in deployment, and the spillover effects from these regions into late-adopting regions. We also consider these regional patterns of deployment in view of other decarbonisation measures, specifically material efficiency gains that reduce overall demand, and increased secondary production from recycled steel.

The paper is structured as follows; Section 2 focuses on the methods of our analysis, including analysis of historical patterns of diffusion of selected steel technologies, which informs the scenario design, and the approach to scenario modelling in TIAM-UCL. Section 3 presents the results, followed by discussion of those results (Section 4) and conclusions (Section 5).

Material and methods

The approach to the analysis is split into two parts. The first is to consider the empirical data on the deployment of steel technologies to determine early-late adopter dynamics. This provides a basis for parameterising the diffusion curves in the model. The second part is the integration of these data into TIAM-UCL, a global energy system model, and the design and set-up of the scenario modelling.

First, we consider approaches to improving dynamics in models to inform our approach. For those models that have an optimisation focus, representation of technology diffusion can be highly simplified, often driven only by physical constraints and relative costs, often in a perfect-foresight framework. Real-world barriers to diffusion are typically not considered. This includes imperfect information, the existence of routines and heuristics in decision-making that might overlook novelties, risk aversion, time required for the acquisition of associated skills, co-ordination failures where complementary goods and infrastructure are required, time necessary to build a supply chain for new technologies and their maintenance, and the misalignment of the new technology with existing institutions and rules.

There are two broad choices to improving representation. Firstly, models can be adapted or redeveloped, through introducing the micro-economic foundations of diffusion models. Whilst adopted in some global models [21], this has proven challenging to do in optimisation-type models. To the best of our knowledge, Leibowicz et al. [22] presents the only attempt to incorporate inter-regional knowledge spillovers in an optimisation-type model. Secondly, models can be constrained to avoid scenarios that are implausible when judged against evidence on the dynamics of diffusion (although such judgements are often made subjectively by modellers rather than against clear empirically-derived criteria). The modelling literature has a number of examples where plausibility of scenarios and model outcomes have been assessed ex post, comparing the rates of diffusion of specific technologies with historical evidence [5,19,38,40].

In this paper, we focus on the latter approach, improving the empirical basis for diffusion constraints on DRI-H2. We specifically consider representing early-late adopter acceleration, which Wilson and Grubler [47] observed for a wide range of technologies in the energy sector, based on fitting logistic curves to the data, and comparing the time taken to go from 10% to 90% of the ultimate saturation level (a metric they call delta-t). They found that delta-t is shorter for the late-coming regions, and longer for the regions in which the technology was first developed and diffused.

This has also been studied previously in the case of steel, with Ray [32] amongst the first to identify the pattern. Poznanski [30] also explored the idea, finding that continuous casting[1] did display core-periphery acceleration, while the basic oxygen furnace did not. However, Poznanski's analysis took place nearly 40 years ago at a time when many countries had not yet fully adopted either technology. The analysis thus excluded many subsequent adopters of both BOF and continuous casting. Perkins and Neumayer [29] also identified late-comer advantages for continuous casting, with potential benefits highlighted for developing countries who have smaller installed capacity and deploy the technology later.

[1] Continuous casting represents part of the finishing process, where molten steel is cast into different steel products for further use in manufacturing.

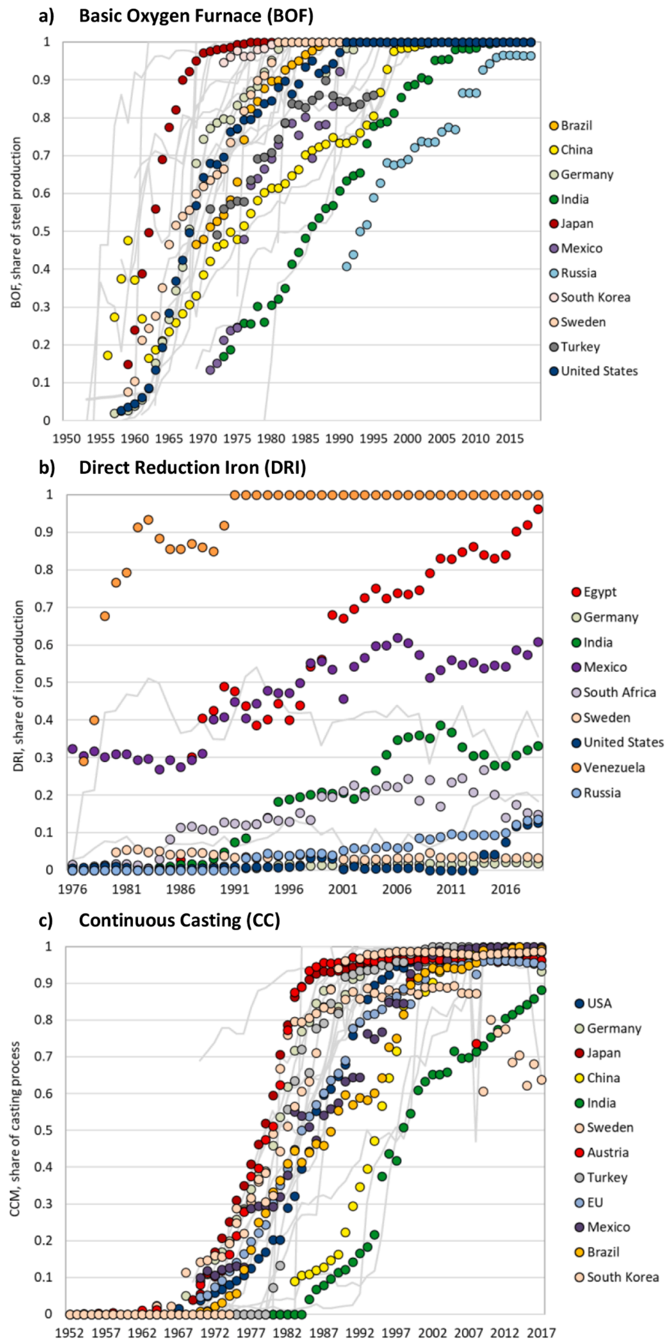

Fig. 1. Diffusion of different iron and steel production technologies. Selected countries are plotted based on the legend colours shown, while all other countries in the dataset have grey coloured trends.

Empirical patterns of technology deployment in the steel sector

To inform our diffusion constraints, we reviewed the historical deployment data of three iron and steel technologies - continuous casting of steel, the production of steel through basic oxygen furnaces (BOF), and iron production through DRI. It is worth noting that all three technologies are diverse and are at different stages in the steel production process. Continuous casting (CC) represents part of the finishing process, where molten steel is cast into different steel products for further use in manufacturing. The BOF process is used in an earlier stage of steel making, and coverts pig iron produced in the blast furnace to steel and stainless steel through tailoring of the carbon content, removal of impurities and alloying with other metals. DRI is an alternative iron making process, as described previously. While diverse technologies, they do represent useful examples for assessing whether the aforementioned dynamic can be seen in the historical data. Historical patterns of diffusions can be seen in Fig. 1 below. Table A1 (Appendix 2) describes how these datasets were compiled. The DRI dataset (Fig. 1b) is not considered further in this paper due to specific factors that make it unsuitable for this analysis, as described in Appendix 2.

Taking the above data for BOF and CC, there are two ways we can assess the presence of early-late adopter acceleration. The first is to estimate the number of years taken to reach a particular milestone (such as 10% or 75% market share) following the years of introduction. For BOF and CC, we can see that later adopting regions take fewer years to hit those market share levels. This is evident from the negative sloping best-fit trend lines which show that countries with later years of introduction have a shorter period to reach different levels of deployment (Fig. 2). In the BOF data, there are a number of data gaps in the time series, which means that the earliest available data start at high shares of deployment, sometimes well above 10%. This means that the analysis of the time it takes to go from 0 to X% diffusion levels has some limitations. Data from complementary sources to address this problem was only available in a few cases. Figures including only those countries whose data series started below 10% diffusion are provided in Appendix 2 (Fig. A2).

The second approach is that taken by Wilson and Grubler [47], who estimate delta-t, i.e. the period duration from one deployment milestone (10%) to another (90%), which is essentially the period of growth, post formative phase, to near saturation. Here we use actual diffusion data as opposed to the approach by Wilson and Grubler [47] where s-curves were fitted to the diffusion data. This is then plotted against year of introduction. For BOF and CC, the estimates are not very conclusive (Fig. 3). The trend line for BOF shows only a weak negative slope, while the CC case actually has a slightly positive slope. We also plot beta, a parameter measuring the steepness of fitted logistic curves. For BOF, the trend line has a slightly negative slope, from which no clear trend can be determined. For CC, the plot of year of adoption against beta also shows no clear trend of increasing diffusion rates over time.

The lack of a clear negative correlation may be counter-intuitive given the earlier results (in Fig. 2), which imply faster growth for late adopters. However, the reason for this is that later adopting regions see similar overall rates of growth but lack the long, slow initial formative phase shown by the first adopting regions. In summary, the historical diffusion of steel technologies does show that later adopting regions tended to see faster diffusion paths. For BOF and CC this appears to have been largely to do with shorter formative phases in later adopting countries, as these benefited from spillovers.

Approach to scenario modelling

Our review of the wider literature and empirical data on steel technology deployment suggests that there appears to be an early-late adopter acceleration effect for different technologies. We now describe the inclusion of these dynamics in a global energy model, TIAM-UCL.

For our scenario design, we first focus on parameterising regional diffusion of DRI-H2, informed by the empirical analysis in section 2.1. The dataset we have used are provided in Table 1. Model regions are firstly designated as early adopters versus late adopters, with different diffusion curves assigned to those regions based on their designation. The shape of the diffusion curves is influenced by a number of factors including the saturation level (set to 90% of regional primary production), when growth starts to ramp up, and the rate of growth. These factors determine the duration from current levels of deployment to saturation, with future saturation level based on exogenously derived demand for primary steel production. For example, in the case of D1, we observed from the empirical data that the formative phase (to 10% deployment) is around 14 years for early adopters (EA), but much lower for late adopters (LA) at 8 years. We also observed the time taken to saturation (90%) to be around 23 years for EA, compared to 17 years for

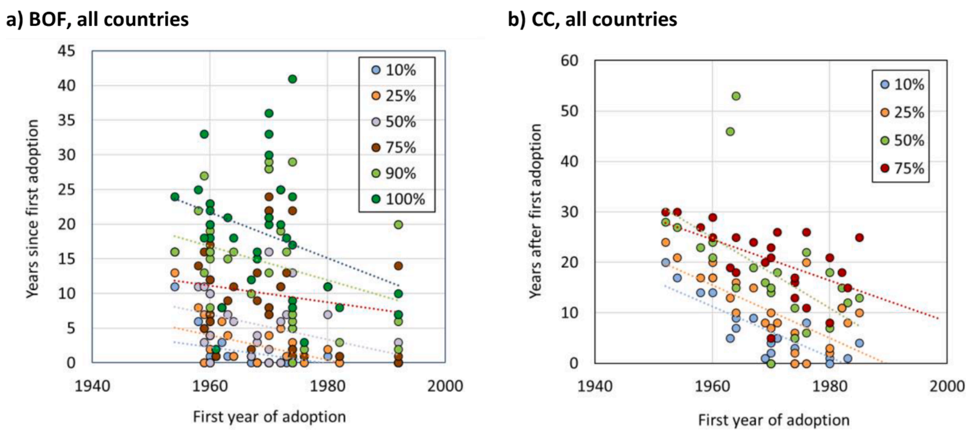

Fig. 2. Years to meet deployment milestones versus the first year of adoption. Deployment milestones are distinguished by colour, with each representing different market shares. a&b) includes all data points, while Fig. A2 (Appendix 2) excludes data points where a country's first data point shows deployment above 10%. Note that in some data series, the first year of adoption might simply be the first available data point given the sources available.

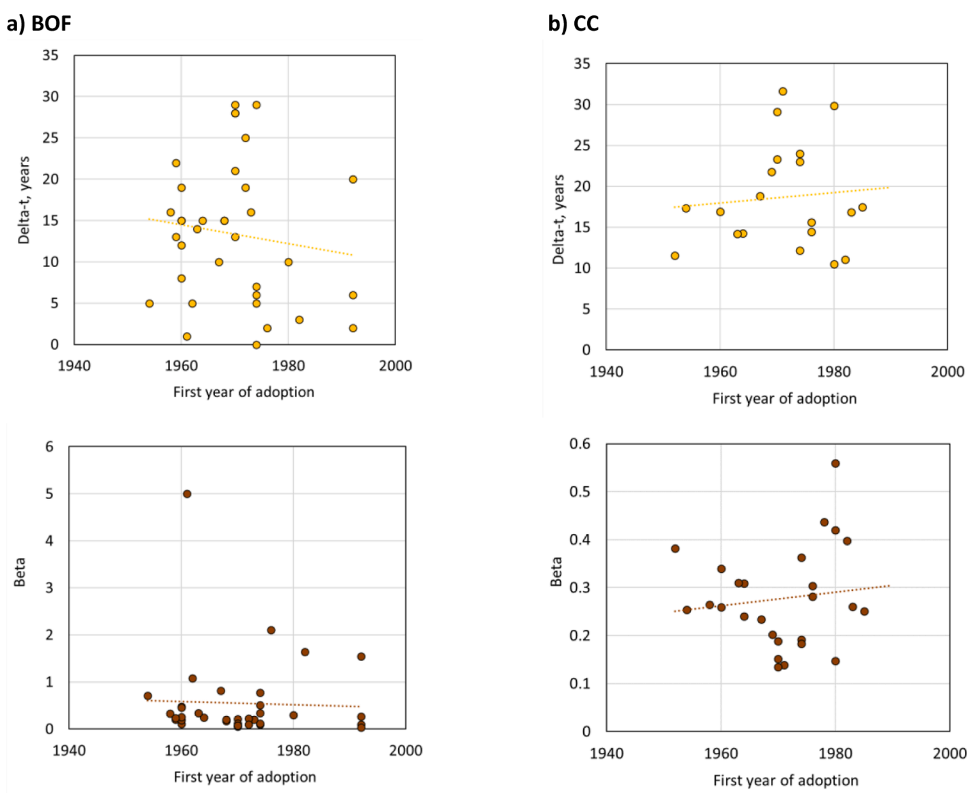

Fig. 3. Plots of a&b) delta-t and c&d) beta against year of introduction. Each marker in the plots represents a specific country, all of which have been included from the dataset. Plots in which countries are removed where the first data point is at more than 10% level of diffusion are provided in Figure A3 (Appendix 2). These do not change the results significantly. However, the insights they provide are limited because of the low number of data points and the presence of outliers.

LA. While these lengths are typical of historical patterns for steel sector technologies, there is of course some variation between technologies. Here we have focused on ensuring the relative differences between EA and LA are robust, based on empirical insights derived from the CC and BOF cases (see Section 2.1) as well as checked against data from energy technologies presented in Wilson and Grubler [47]. In addition, while the steel production technologies considered are not equivalent to DRI-H2, the similar patterns from these and a wider range of energy sector technologies provide confidence that similar effects would be observed for DRI-H2.

Four cases are considered (labelled D1 to D4), with diffusion curve parameters provided in Table 1, and the resulting curves shown in Fig. 4. D1 and D3 both include spillover effects, with late adopters seeing shorter periods to saturation, and faster deployment rates (see bottom two rows of Table 1). They differ in terms of the composition of the early adopter group. D1 includes Europe, Japan and South Korea, countries that are currently most active in developing green steel projects [45], while D3 includes those same countries but with the addition of China and India. D3 therefore results in larger spillover effects to late adopting regions – and means that these large producing regions move to deploy earlier (as early adopters). For these cases, we assume a shorter formative phase and faster rate of deployment for LA countries, meaning that saturation is reached slightly before the EA countries. This 'result' is sensitive to when the LA formative phase begins; this is a necessary

Table 1
Diffusion curve specification for DRI-H2 technologies. D1&2 include Europe, Japan and South Korea as early adopters (EA). D3&4 add China and India as early adopters, in addition to the early adopting regions / countries specified in D1&2. All other regions are designated as late adopters (LA) where not specified. On parameters, k controls the steepness of the s-curve gradient (growth rate). Higher values increase the steepness of the curve. a controls how quickly the s-curve moves into its growth phase. Higher values extend the time before growth phase.

	D1 (spillover / EA no China & India)		**D2** (no spillover / EA no China & India)		**D3** (spillover / EA w/ China & India)		**D4** (no spillover / EA w/ China & India)	
Diffusion curve parameter	EA	LA	EA	LA	EA	LA	EA	LA
Period start	2021	2031	2021	2031	2021	2031	2021	2031
Period end	2055	2065	2055	2065	2055	2065	2055	2065
Period mid-point	2038	2048	2038	2048	2038	2048	2038	2048
k*	0.3	0.57	0.3	0.3	0.4	1.6	0.4	0.4
a**	2	0.5	2	2	1.2	0.14	1.2	1.2
10% level reached	2035	2039	2035	2045	2033	2037	2033	2043
90% level reached	2058	2056	2058	2068	2052	2050	2052	2062
Formative pH. Duration, yrs	14	8	14	14	12	6	12	12
10% to 90% duration, yrs	23	17	23	23	19	13	19	19
Ann. growth rate (10–90%)	11%	15%	11%	11%	14%	20%	14%	14%

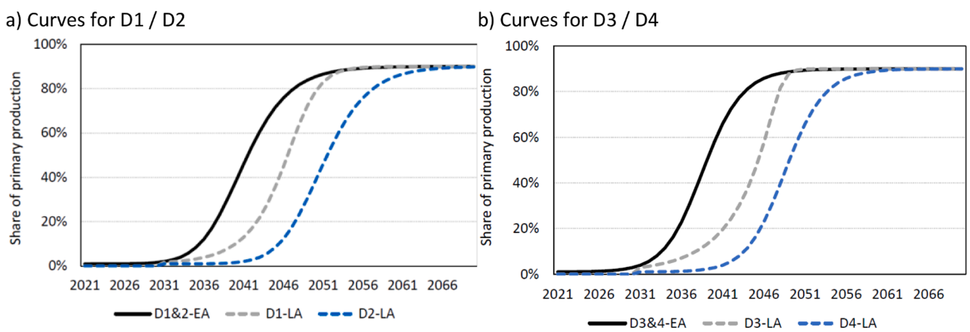

Fig. 4. Diffusion curves for a) cases D1 & D2 and b) cases D3 & D4. These illustrate the parameter values in Table 1. EA = early adopter, and LA = late adopter.

Table 2
Scenarios used in study. Note that HR = higher recycling, LD = lower demand. For all cases, climate ambition is based on a 800 $GtCO_2$ budget, from 2020 for all cases. For 'Diffusion case', refer to Table 1 & Fig. 4 for details.

Scenario abbreviation	Diffusion case	Diffusion case description	Demand level	Recycling rate
D0	None	Standard growth rate implementation (no s-curve)	Higher	Lower
D1	D1	Diffusion curve with spillover, EA group = Europe, Japan, South Korea	Higher	Lower
D2	D2	Diffusion curve with no spillover, EA group as per D1	Higher	Lower
D3	D3	Diffusion curve with spillover, EA group = Europe, Japan, South Korea, China, India	Higher	Lower
D4	D4	Diffusion curve with no spillover, EA group as per D3	Higher	Lower
D1_LD	D1	As above for D1	Low	Lower
D3_LD	D3	As above for D3	Low	Lower
D1_HR	D1	As above for D1	Higher	Higher
D3_HR	D3	As above for D3	Higher	Higher

scenario setting which needs to be made (but could be set differently) in the absence of knowledge as to when regions will start to adopt DRI-H2.

D2 and D4 have the same regional groupings as D1 and D3 respectively, and the same diffusion curves for early adopters. However, in these cases, there are no spillover effects assumed, providing a counterfactual to assess such effects. For D1-D4, DRI-H2 is the most cost-effective primary production route for steel so typically follows the s-curve diffusion set. D0 is an additional scenario that does not include s-curve diffusion, but standard linear growth constraints (% growth on capacity in the previous period) that are typical of the previous TIAM-UCL implementation.

As noted earlier, we model scenarios using the global energy system model, the TIMES Integrated Assessment Model at UCL, or TIAM-UCL [10,31,46]. More information on this model can be found in Appendix 3, including how the steel sector has been enhanced to improve its representation. Cost and performance assumptions for steel production technologies are also provided in Appendix 3. With the focus on diffusion in a decarbonising world, all scenarios have been run using an 800 $GtCO_2$ carbon budget from 2020, equivalent to limiting the global average temperature increase to 1.75 °C (for a 66% probability).

As highlighted in section 1.1, there are a range of other approaches to decarbonisation that will impact on the level of primary production, and therefore the role of DRI-H2. To explore how changes to demand for primary steel impact on the regional diffusion of DRI-H2, we consider two additional sensitivity cases; i) lower demand (LD) case, accounting for strong action of material efficiency, and ii) higher recycled (HR) scrap availability, increasing the role for secondary steel production. These sensitivity cases are run with D1 and D3. For LD, we use a crude steel demand of 1980 Mt in 2050, versus 2450 Mt across all other scenarios [14,16]. This reflects material efficiency gains leading to approximately a 20% reduction in overall demand. For HR, we use a higher level of recycled steel in 2050 of around 1150 Mt versus 800 Mt across all other scenarios. Further information on how estimates were derived for these sensitivities can be found in Appendix 3.

The full list of modelled scenarios is shown below in Table 2.

Results

TIAM-UCL was run for the scenarios listed in Table 2, with insights for how regional specific diffusion curves impact DRI-H2 deployment, and the broader mix of production technologies (3.1), the wider system implications, notably on emissions and costs (3.2), and regional

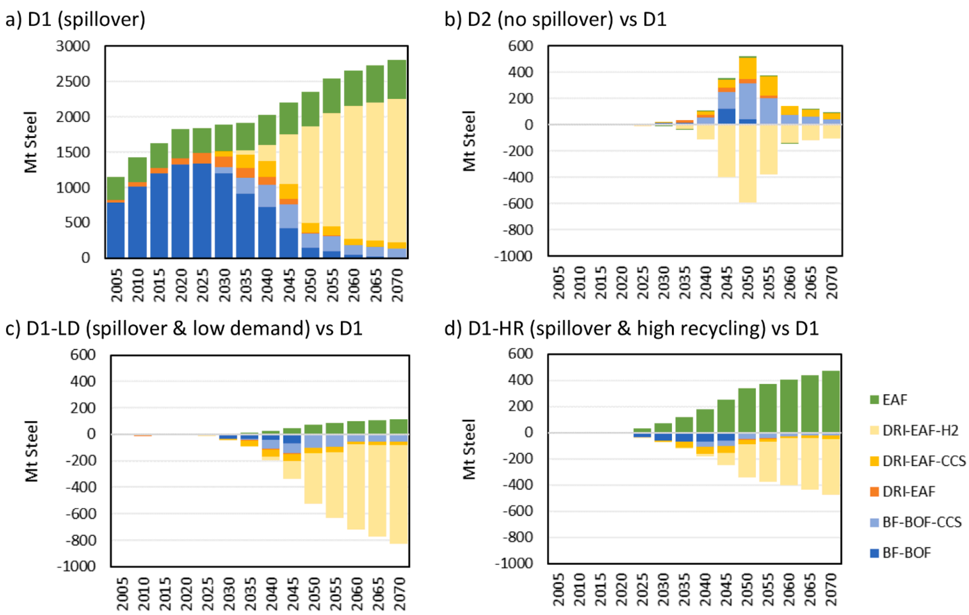

Fig. 5. Global steel production by technology pathway for selected scenarios, 2005–2070. a) Annual production under D1. The other panel plots (b-d) show the difference in production relative to D1, with negative values denoting less production by a given technology compared to D1.

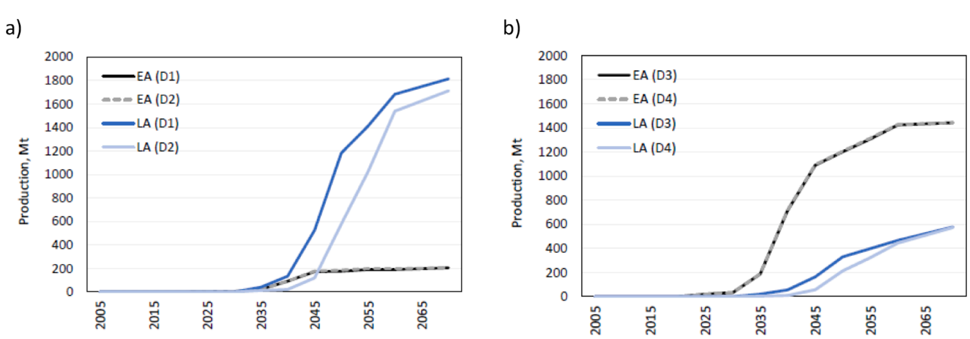

Fig. 6. DRI-H2 steel production for early adopters (EA) versus late adopters (LA), 2005–2070. (a) DRI-H2 production (in Mt) in scenarios D1 and D2; and (b) DRI-H2 production (in Mt) in scenarios D3 and D4.

deployment (3.3).

Global steel production pathways

Prior to implementation of diffusion constraints, scenario D0 suggests that, under climate targets and standard growth rates (as previously implemented in TIAM-UCL), DRI-H2 is deployed as the dominant production pathway, and therefore considered most cost-effective.

Selected scenarios implemented with diffusion constraints are shown in Fig. 5, illustrating the technology mix for global steel production. For D1 (Fig. 5a), early adopters (EA) of DRI-H2 include Europe, Japan and South Korea, with positive spillover effects for late adopters (LA), that is all other regions. In D2 (Fig. 5b), the EA-LA configuration is the same but these spillover benefits are not included; as a result, as shown in this difference plot, the potential increased level of deployment resulting from spillover is not realised and other primary production technologies are deployed instead. While all pathways show the strong emergence of DRI-H2 in future years, the levels are somewhat moderated by a lower demand outlook (Fig. 5c) and an increased role for secondary production (Fig. 5d).

For other low carbon pathways for primary production, such as CCS either with BF-BOF or fossil-based DRI, these play a more marginal role in these scenarios, which is further reduced under lower steel demand and high recycling scenarios. All pathways also see near complete phase-out of BF-BOF (without CCS) by 2050.

Fig. 6 focuses on production from DRI-H2 only, based on the s-curve deployment for EA versus LA in D1/D3 (spillover) and D2/D4 (no spillover) shown in Fig. 4. In Fig. 6a, the difference between D1 and D2 illustrates the implications for LAs, with delayed and slower deployment in the D2 case, particularly during the 2040s and 2050s. In this case, it is notable the much larger size of the LA group which includes large Asian economies, incl. China and India). It shows the relatively large impact of spillover effects (difference between blue trend lines) from the efforts of much smaller producing EA regions. The equivalent plots for D3 and D4 are shown in Fig. 6b. In these scenarios, India and China are now part of the EA group, increasing the relative size of this group of countries. Their inclusion in EA results in more rapid deployment of DRI-H2, creating stronger spillover effects albeit for a smaller LA group in production terms. In aggregate, this leads to a higher and more rapid deployment of DRI-H2 globally, as discussed below.

The deployment of DRI-H2 at the aggregate global level is shown in Fig. 7. Fig. 7a shows the much faster initial and then linear deployment of DRI-H2, where no s-curve dynamic is assumed (D0, red dashed line). The difference between D1 and D2 highlights the difference in resulting level of global production capacity if no spillover effects are assumed. Figure 7bshows the case where India and China are part of the early adopter (EA) group, leading to earlier and more rapid deployment. The limited gap between D3 and D4 reflects limited spillover benefit due to

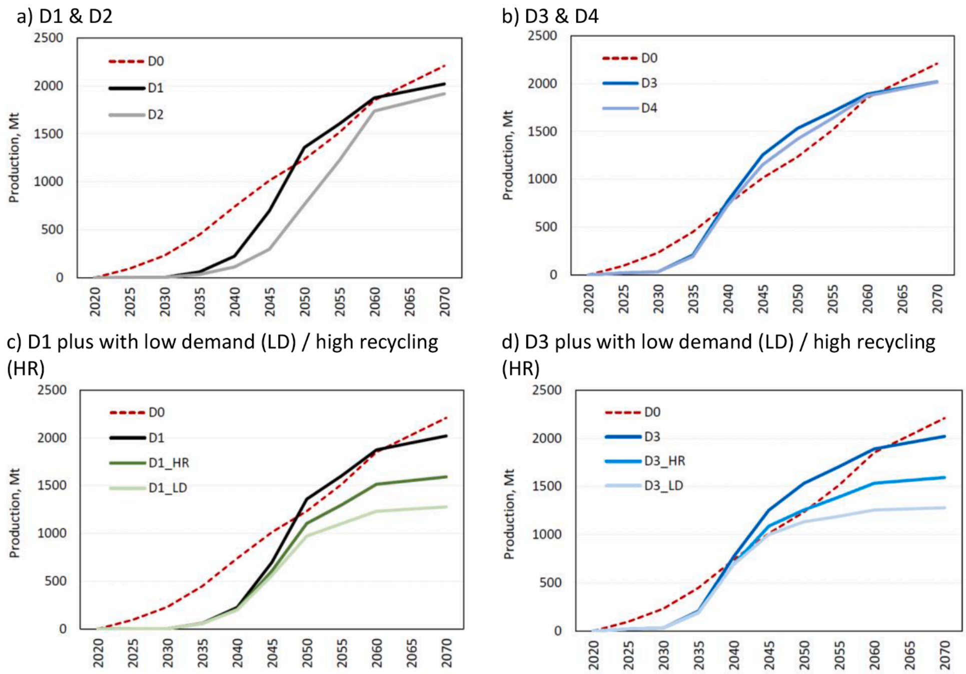

Fig. 7. DRI-H2 global steel production, 2020–2070. a) D1 & D2 scenarios (EA – Europe, South Korea and Japan); b) D3 & D4 scenarios (EA – Europe, South Korea, Japan, India and China); c) D1 plus low demand (LD) and high recycling (HR) variants; d) D3 plus low demand (LD) and high recycling (HR) variants.

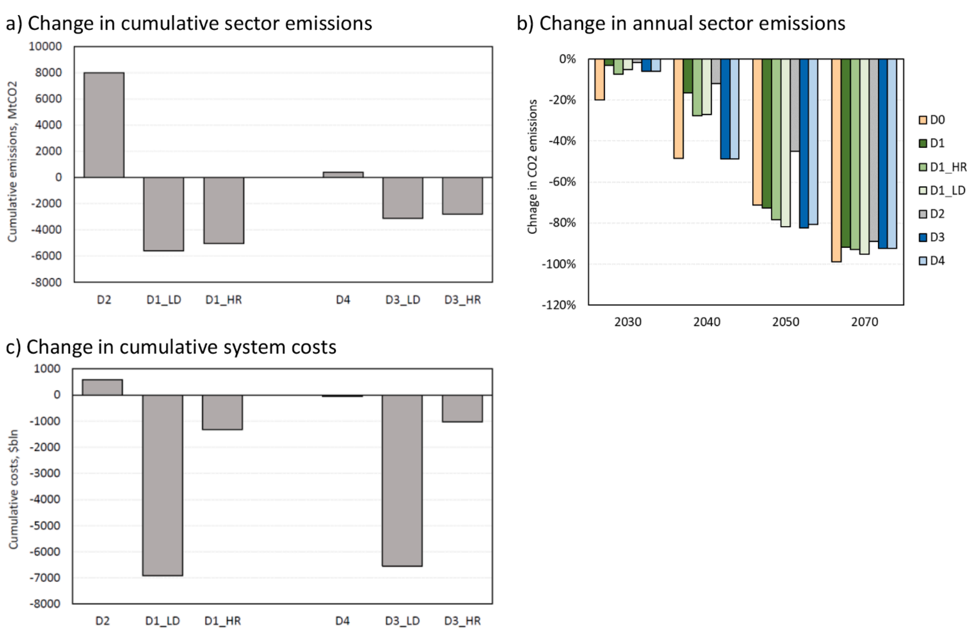

Fig. 8. Emission and cost metrics. Change in (a) cumulative sectoral CO2 emissions relative to D1 and D3, 2020–70; (b) percentage change in annual global sectoral CO2 emissions relative to 2020, 2030–70; and c) cumulative system costs relative to D1 and D3, 2020–2070.

most production being in the EA group. This highlights how the assumptions about early and late adopter designation has a significant bearing on the scenario results. In the longer term, assumptions about recycling rates and demand level have even larger impacts on total production, as show in Fig. 7c and d.

Emissions, costs and system wide implications

Given the pattern of deployment shown above, we now consider the impacts on costs and emissions. Firstly, in respect of CO_2 emissions, we have compared the no spillover cases (D2/D4) and high recycling (HR) / low demand (LD) variants against D1 and D3 (Fig. 8a). On the left hand side, the plot shows higher emissions under D2 (due to no spillover) of around 8GtCO_2 (or 13% of cumulative sector emissions), but lower emissions for LD and HR variants, due to lower demand and reduced primary production respectively. On the right hand side, due to most production being in the EA group in D3, the lack of spillover (in D4) has a limited impact on overall emissions.

The rate of emissions reduction over time is shown in Fig. 8b. It highlights the lower level of emission reductions from D2, which sees lower take-up of DRI-H2 due to the absence of spillovers, particularly in 2050. Conversely the impact of putting China and India in the early

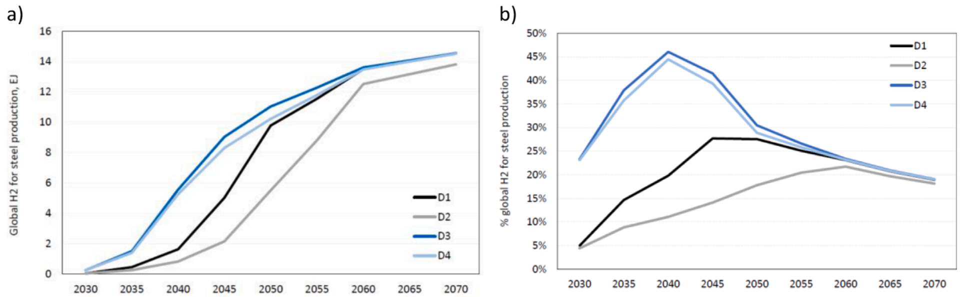

Fig. 9. Steel sector H2 consumption in (a) absolute terms and (b) as a share of global consumption.

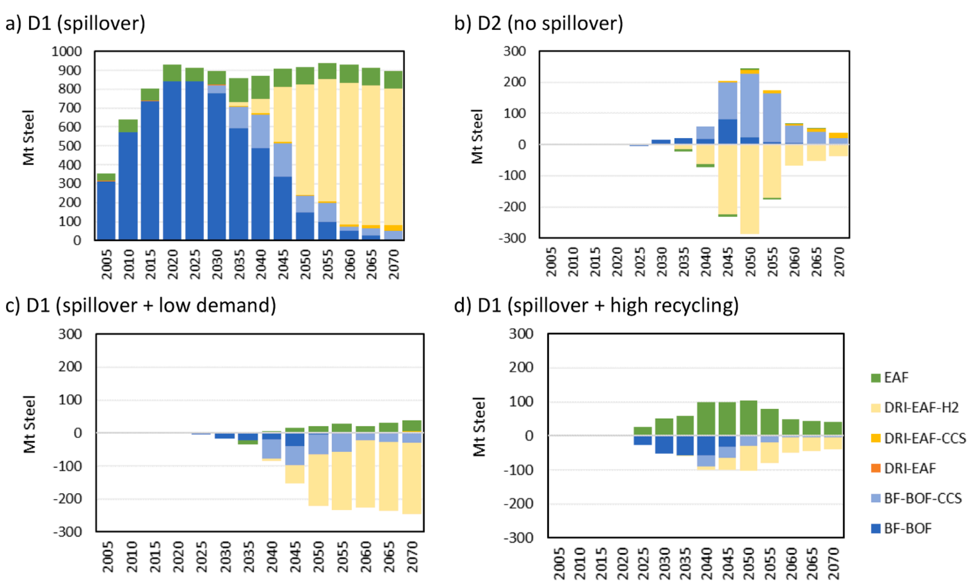

Fig. 10. China steel production by technology pathway for selected scenarios, 2005–2070. (a) Annual production under D1. The other panel plots (b-d) show the difference in production relative to D1, with negative values denoting less production by a given technology compared to D1.

adopter group (D3/D4) see a much faster rate of reduction, similar to the rate observed with diffusion constraints (D0).

We have also assessed the impact on costs, using a cumulative system cost metric (Fig. 8c). As might be expected, the negative / positive direction of differences relative to D1/D3 is similar as for the emissions metric. Costs are slightly higher under D2, reflecting slower deployment of DRI-H2 in this case. Costs are considerably lower in the LD cases, showing the significant impact of lower demand on the wider system. The costs for HR are also lower (although not to the same extent as LD) highlighting the cost-effectiveness of the secondary EAF route relative to other production pathways.

For DRI-H2 to deploy at the rates shown in these scenarios, H2 production, which is primarily sourced from renewable electricity in these scenarios, needs to also scale very quickly (Fig. 9a). In the decades prior to 2050, the steel sector is an important driver of growth in hydrogen production, accounting for over 45% of global demand in 2040 under D3/D4, and almost 30% in D1 in 2050 (Fig. 9b). The demand for hydrogen is markedly lower in D2, where spillover effects are not included. The sector's demand share then begins to fall, as hydrogen continues to scale and provides low carbon energy to other economic sectors.

Regional patterns of deployment

It is also informative to consider the deployment of steel production pathways in the largest producing regions, either today (China) or as a result of future growth (India, Other Developing Asia). China, as shown in Fig. 10, is critical to overall sector decarbonisation due to the size of its current steel production capacity. BF-BOF (without CCS) needs to decline to near zero capacity by 2065. Overall production is not set to expand, with levels maintained out to 2070, although there is a decline in the lower demand case (Fig. 10c). Therefore, China continues to be an important producer of primary steel, with secondary steel production not increasing substantially, except in the high recycling case (Fig. 10d). This is because China continues to maintain primary production levels, with regions such as other emerging and developing countries in Asia taking a higher proportion of the global scrap market (Appendix 4, Fig. A7).

Fig. 10b illustrates the difference due to assuming spillover benefits. D1 includes spillover effects, leading to faster expansion of DRI-H2 than observed in D2. As a result, in D2, BF-BOF with CCS plays a more prominent role in the 2040s and 50 s. D3, which is not plotted above, includes China in the early adopter group, resulting in an even faster deployment of DRI-H2, with limited roles for other primary production technologies. While China reflects the global outlook to some extent, due to its sheer size, contrasting regional patterns are shown for India (Fig. A6) and other developing Asian economies (Fig. A7) in Appendix 4. For both of these regions, there is much more of a push towards EAF for secondary production, moderating the role of DRI-H2.

The implications on regional emission reductions are shown in Fig. A8 (Appendix 4), illustrating the difference in cumulative emissions. China reflects the global trend in Fig. 8a, highlighting its importance in driving the global model results. Emerging economies such as those in Other Developing Asia (ODA) and India benefit particularly from increases in recycling rates, as their stocks grow and trade in scrap grows. Similarly, a reduction in demand suppresses some of the growth that is projected under D1/D3, resulting in CO_2 emission gains. For more developed economies, the picture differs, with more limited gains from recycling and reduced demand. On the spillover effects, the USA is also impacted when these are absent (D2/D4) due it not being in the EA group, while Europe is not as an EA group member.

Fig. A9 shows the emissions trends over time. In China, D3 sees faster and deeper reductions based on the country moving more rapidly in deploying DRI-H2. It is also interesting to note the difference between D1 (with spillovers) and D2 (no spillovers), to highlight again the role that incorporating such effects has. For India, emissions increase relative to 2020 in D1 and D2, although decrease more rapidly under D1 (where spillover effects are included). Emissions growth is moderated by the LD / HR variants, while under D3, where India is part of the EA group, emissions drop much more rapidly. For ODA, emissions increase more rapidly due to production growth but then starting to fall in the latter part of the 2030s. At this point, stronger reductions are observed under D3 (compared to D1), due to the larger impact of spillover effects from China and India in the early adopters group.

Discussion

Research insights

The rate of steel sector decarbonisation is highly uncertain, and will depend on a range of factors including the commercial emergence of low carbon primary production technologies, the role of secondary production, and material efficiency gains. However, as with other IAM analyses, this research shows a pathway to near full sector decarbonisation by 2070, based on a pattern of typical diffusion for equivalent technologies.

Inevitably some regions will move faster than others in developing and deploying new primary production technologies. As discussed in this paper, Europe is emerging as a key region for commercialisation of Direct Reduction Iron production with hydrogen (DRI-H2). If this technology can scale in the European context, we have shown, based on historical precedents both in the steel and wider energy sector, that other regions could benefit from spillovers that lead to more rapid deployment. This is particularly important for large producers, such as China, who might be able to transition their sector more rapidly as a result of deployment elsewhere.

We find that the absence of spillover effects results in cumulative emissions that are 13% higher than if spillovers are assumed and approximately 15% and 20% higher in China and India respectively. Given the estimates of DRI-H2 cost-effectiveness relative to other primary production technologies, we also find that the costs increase in the absence of spillovers, due to the deployment of alternative primary production technologies.

Such spillover effects are therefore important, given the urgency arising from the climate crisis, where rapid change is required to ensure cumulative CO_2 emissions are kept to a minimum. The regional focus of Europe and other regions on DRI-H2 therefore matters, not only for European decarbonisation, but global efforts to meet the ambition set out in the Paris Agreement. If other significant regions also moved as early adopters of DRI-H2, such as China, the transition would be even quicker due to the size of their primary production sector and reduced lock-in from avoiding re-investment into existing blast furnace capacity and promoting investment in DRI-H2.

The deployment of DRI-H2 is contingent on the growth of the hydrogen production sector. This important dependency sees the steel sector as a primary driver of demand, particularly in the case where India and China are also early adopters. Most of the production in this modelling is green hydrogen from electrolysis, which in turn will require further increases in electricity generation capacity (alongside a large expansion of the sector due to demand growth across all sectors). One of the benefits of this DRI-H2 expansion will be to help drive the hydrogen production sector, building capacity for demand across other sectors.

While the deployment of DRI-H2 will be crucial for maintaining and expanding primary production capacity, this analysis has also highlighted that there are key measures to moderate the increased investment in such capacity, bringing significant emission and cost benefits. Material efficiency gains as demonstrated by lower demand, and higher steel recycling reducing the requirement for primary production, lead to similar albeit slightly lower emission benefits compared to the spillover benefits (8–9%), but much more significant cost benefits. This highlights the importance of demand side measures in helping the steel sector decarbonise, notably by reducing the investment requirement in DRI-H2 capacity and other low carbon technologies.

Policy implications

The steel industry is in the early emergence phase of the low carbon transition, with some way to go before strong technology diffusion and sector reconfiguration [41]. Policies will need to be developed that can help rapidly scale investment in low carbon technologies [42], particularly given the current cost barriers to investment in green steel production, and the lack of markets for a higher price commodity [2]. Policy also needs to contend with the fact that this is a global sector that is both fragmented, making coordination difficult, and highly competitive, giving rise to cost concerns and worries about carbon leakage [41]. Currently, only Sweden and to an extent the EU have the necessary policies in place to specifically drive the required R&D and investment in low carbon production, as evidenced by the Green Steel Tracker [42].

A number of strong policy implications arise from this analysis, if a decarbonisation pathway commensurate with 1.5 °C is to be realised. Firstly, steel producers and large steel consumers would need to increase investment levels in the development and deployment of low carbon steel technologies. This is critical for ensuring deployment can happen during the 2030s to ensure sector decarbonisation soon after 2050. Key constraints around levels of R&D, support for pre-commercial deployment, mobilising investment, and developing markets will all need to be addressed so that historical precedents around slower transitions are not repeated [26].

Secondly, the spillover effects that can arise from country and regional action should be recognised and seen as a further benefit for rapid action, particularly in the context of different capabilities and differing responsibilities of individual countries in addressing climate change. Thirdly, international coordination should be enhanced to ensure wider early adoption of DRI-H2, to speed up formative phase and to increase spillover benefits for other regions. How this coordination is to be achieved is very much under debate, with several different proposals and institutional initiatives representing different perspectives.

Initiatives on production technology include Mission Innovation,[2] which aims to scale up the deployment of clean energy technologies, and the IEA's International Energy Related Technology Systems (IETS) which focuses focusses on shared R&D.[3] The UNIDO/Clean Ministerial Industrial Deep Decarbonization Initiative (IDDI) ,[4] has focussed on creating green public and private procurement lead markets to reduce investment risk. On trade, the EU-US Trade and Technology Council initiative is focused on reducing steel tariffs and ensuring resilient supply chains, with a subsidiary focus on GHG intensity. They have also committed to a Global Sustainable Steel and Aluminium agreement by 2024. Several groups are focused on establishing roadmaps to industrial decarbonization and key enabling factors, including the Leadership

[2] Mission Innovation, http://mission-innovation.net/

[3] Industrial Energy-Related Technologies and Systems, IEA Technology Cooperation Programme. https://iea-industry.org/

[4] Industrial Deep Decarbonisation Initiative, UNIDO. https://www.unido.org/IDDI

Group for Industrial Transition (Lead It), the Energy Transition Commission (ETC), and Mission Possible. On governance, initiatives include the Glasgow Breakthroughs (at COP26), with 41% countries representing all major emitters and 71% of global GDP, with steel as the flagship sector for cooperation [37]. This was the most significant effort to date to provide a coordinating platform for many of the already listed initiatives. Following this, there have been several advancements including Germany seeking to form a “climate club” for countries with more industrial decarbonization ambition (Agora [1,12]).

How all these elements are brought together is still a matter of debate, but all will be required. Significantly however, other than India’s co-leadership of IDDI, most current initiatives lack significant developing country participation, where most new industrial demand will occur. Also, the first generations of green steel are likely to be more expensive than current practices, requiring policy to drive their market uptake once the technologies are full commercialized using lead markets. Only the European, Scandinavian and UK carbon pricing systems are remotely stringent enough to achieve market uptake post lead market commercialization without further policies.

Methodological issues

This research also highlights some important implications for global integrated assessment modelling and the improved representation of diffusion dynamics. It is evident that the inclusion of empirically derived diffusion dynamics is important, as their inclusion can have a significant impact on the rate of deployment of a given technology, and sector decarbonisation. Without the inclusions of these effects, two issues arise; firstly, as shown in the case of D0, an assumption of linear growth could lead to unrealistic growth in near term deployment, resulting in more rapid emission reductions than if an s-curve pattern of diffusion is used. Secondly, without assumptions of spillover effects, we may be underestimating the rate of deployment in late-adopting regions.

Modelling needs to better consider these effects, to provide for a more ‘realistic’ outlook for technology diffusion. This does not just apply to DRI-H2 but other technologies in the energy sector. This is recognised within the IAM community as an important area for improvement ([20]; Trutnevyte et al. 2019). A number of modelling teams are making advances in this area to better integrate diffusion dynamics into IAMs endogenously, including to represent spillovers [22,24].

One of the big challenges with the use of diffusion curves is anchoring them to a saturation level. In the case of DRI-H2, we know the ultimate level of primary steel produced, and therefore on what to base the saturation level. However, this is not the case with many of the other technologies whose ultimate level is endogenously determined by the model. In addition, the paradigm of many models is such that the dynamics of deployment, in terms of technological learning, rate of deployment and spillovers is not easily represented. More consideration is need as to whether underlying model formulation can effectively support these transition dynamics.

Future research avenues

Finally, there are a number of important avenues for further research that emerge from this particular analysis. While the DRI-H2 production pathway has been determined to be the most cost-effective zero-carbon primary production route, further work is needed to explore sensitivities, notably in terms of costs for different parts of the production pathway. Higher costs for DRI-H2 could results in a stronger role for BF-BOF with CCS, for example. Conversely, the reality on the ground suggests that DRI-H2 is emerging as the most promising route to decarbonisation, making the focus of the paper all the more pertinent. It would also be of interest to explore further how more or less stringent decarbonisation rates impact on the deployment of DRI-H2 and other production technologies.

In addition to cost and policy sensitivities, there are a number of other areas for additional research. Firstly, this early-late adopter phenomena is not restricted to the steel sector; it could be extended in the modelling to be applied to other industrial sectors, or to power generation. Secondly, the approach taken in this study was to implement diffusion curves using an exogenous scenario-based approach. Additional consideration of how to endogenise these dynamics into IAMs, building on work by Leibowicz et al. [22], would help develop this type of analysis further.

The empirical work undertaken to develop the diffusion curves could also be further developed by sourcing additional deployment data, and further assessing the reasons for faster deployment in late adopting regions. There would be particular value in additional research re-examining the original Wilson and Grubler [47] data, to assess whether the observed changes are more related to changes in maximum slope of the diffusion curve, or longer formative phases. This is likely to have been obscured in their reported results, given that all the results are based on curves fitted to data, rather than the data themselves.

Conclusion

The decarbonisation of the steel sector will be critical to meeting global climate ambition. This paper has highlighted the key role that DRI-H2 can play in driving emission reductions from primary production, across most regions. An important contribution of the research is to highlight, through a scenario-based approach, how formative phases of technology deployment in early adopting regions can lead to spillovers in later adopting regions, speeding up deployment. The novelty of this approach is to translate empirically-grounded diffusion curves into a global energy system model to explore the impact of spillovers, particularly in a demand sector such as steel production. We find that incorporating regional spillovers reduces both the cost of decarbonisation and the level of emission reductions from the steel sector.

While the level of spillover is subject to some uncertainty, the empirical evidence highlights that these effects do shorten time to saturation for late adopters. In our analysis, this is shown particularly for China and India. However, it may also be the case that China and / or India become early adopters of such technology, providing spillover benefits for other regions. This highlights that strong regional and sector coordination on specific technologies such as DRI-H2 can lead to wider global benefits in terms of decarbonisation and its costs.

While DRI-H2 has been shown as a cost-effective route to decarbonisation relative to other options, other supply side technologies may have a role to play, notably CCS-focused options and more novel and emerging steel production technologies. Such options should continue to be explored, particularly where DRI-H2 may have deployment constraints. Furthermore, strong gains in terms of emissions and cost reductions can be realised from a focus on increasing the use of recycled steel, and driving material efficiency. These measures are shown to outweigh the benefits from spillover effects in isolation. It is clear that both demand and supply side actions can result in higher levels of emission reduction than any action in isolation.

To realise the sector decarbonisation pathways shown in this paper, this will of course require significant near-term investment in development, and then deployment, in key regions to provide momentum and more rapid deployment across later-adopting regions. If such momentum can be achieved, sector decarbonisation could be realised soon after 2050. Critical to this will be a range of other factors, such as the scaling of hydrogen production, ensuring re-investment does not lock-in the high emission BF-BOF pathway, and stronger coordination across the industry in development of this infrastructure.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Steve Pye reports financial support was provided by EU Horizon 2020.

Data availability

Data will be made available on request.

Acknowledgments

S.P. and W.M. developed the research idea. S.P. undertook the scenario modelling and wrote the first draft of the paper. D.W. led on the update of the representation of the steel sector in the model TIAM-UCL, with input from S.P. O.D. supported S.P. in the scenario modelling. W.M. and T.R. led the empirical work on historical steel technology deployment, and writing of that section of the paper. A.C. and M.W. provided input on the steel demand projections and secondary steel production potentials. C.B. advised on the steel production technologies and their model implementation. All authors contributed to the writing and review of this paper.

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Appendix 1. Options for steel decarbonisation

There a number of options and pathways to steel decarbonisation. These are briefly summarised here but described in detail across a range of publications [7,8,11,16]. They can be differentiated between options that decarbonise steel production (as shown in Fig. A1), or lower demand for crude steel.

BF-BOF pathway

This is the main production pathway for steel in the global economy, accounting for 70% of total global production, and 90% of primary production [16]. A blast furnace (BF) is fed with iron ore (sinter or pellets), coke and limestone. Hot air is blast into the furnace, combusting the coke to produce heat and carbon monoxide. The heat melts the charge, while the CO removes oxygen from the iron ore. The process involves large amounts of coal to generate the very high temperatures needed in the furnace (>1550 °C). The basic oxygen furnace (BOF) process takes the melted pig iron produced and blows oxygen through it, removing most carbon (which must be driven down to 0.1–2% depending on the final use) and other impurities, to produce steel. Alloying with other metals (nickel, chromium, molybdenum, zinc, etc.) to make stainless steel may be done at this step or later.

To ensure the decarbonisation of the sector, it will be critical that existing BF-BOF plant are not reinvested in, notably the relining of blast furnaces as part of the investment cycle [14]. This would help ensure that emissions of 21 $GtCO_2$ associated with this reinvestment are avoided [44]. Other pathways will be needed to replace existing capacity, such as increasing the use of low carbon fuels such as bioenergy and hydrogen as primary input fuels and integrating CCS systems into the process. Bioenergy is likely to be limited by supply constraints [7], while high levels of hydrogen may be limited as a replacement reduction agent due to competition with other uses. For sequestration of CO_2, this pathway would typically require post-combustion CCS, although this will be limited by geographical proximity to storage or use sites [3]. Retrofit of existing BF-BOF facilities is possible but would likely result in relatively low capture rates (<=50%) [7], so they are not considered in this study.

DRI-EAF pathway

The direct reduction process involves the removal, or reduction, of oxygen from typically pelletized iron ore in its solid state, therefore without melting. Natural gas is the main fossil fuel used to produce the reducing syngas gas, composed of hydrogen and carbon monoxide, although coal can also be used, albeit with much higher emissions. DRI produces sponge or briquetted iron, which is then fed into an electric arc furnace to produce steel. The most common type of DRI technology is MIDREX, first used in 1969, which uses a shaft furnace design. The majority of these plants are producing steel in countries with large availability of fossil fuels, such as gas in the Middle East. These plants do not need to be part of integrated steel plant, providing flexibility and lower capital costs, with the sponge iron being used in electric arc furnaces (EAFs) to produce crude steel.

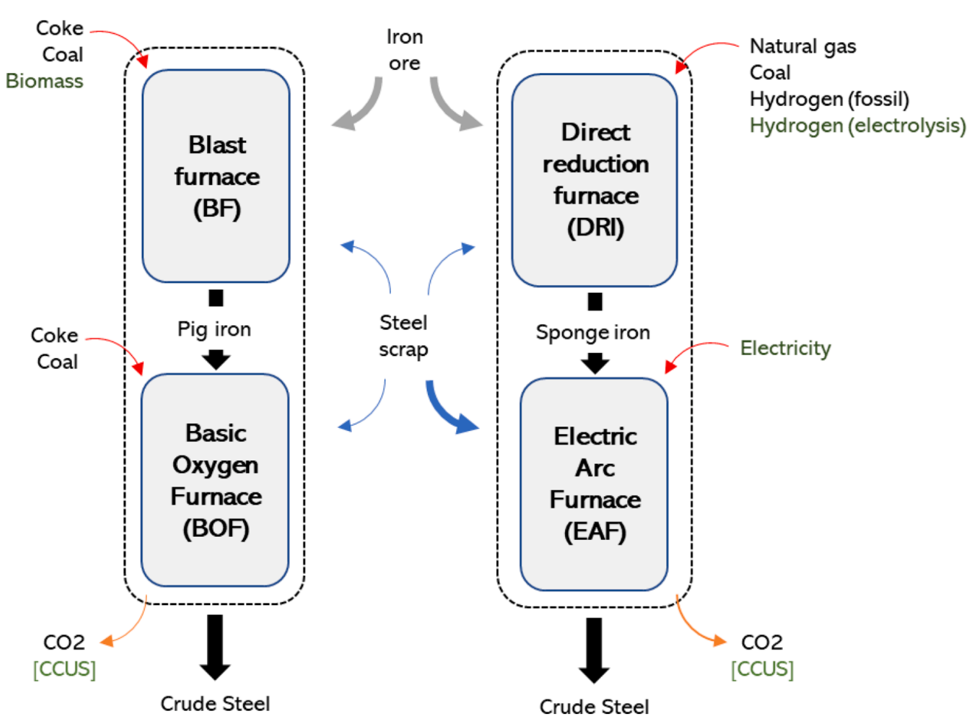

Fig. A.1. Schematic of key steel production pathways. Note that EAF can operate independently, primarily using steel scrap (i.e. it does not need to be fed by sponge iron). Green labels indicate decarbonisation options.

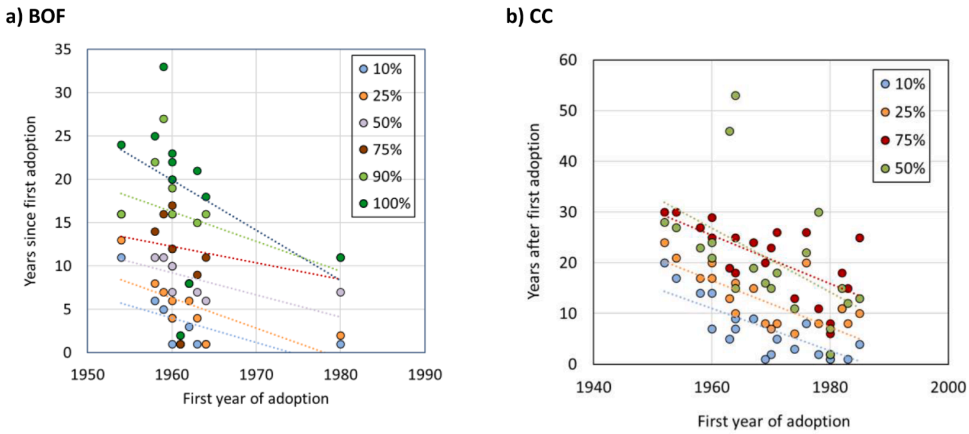

Fig. A.2. Years to meet deployment milestones versus the first year of adoption. Deployment milestones are distinguished by colour, with each representing different market shares. a&b) exclude data points where a country's first data point shows deployment above 10%. Note that in some data series, the first year of adoption might simply be the first available data point given the sources available.

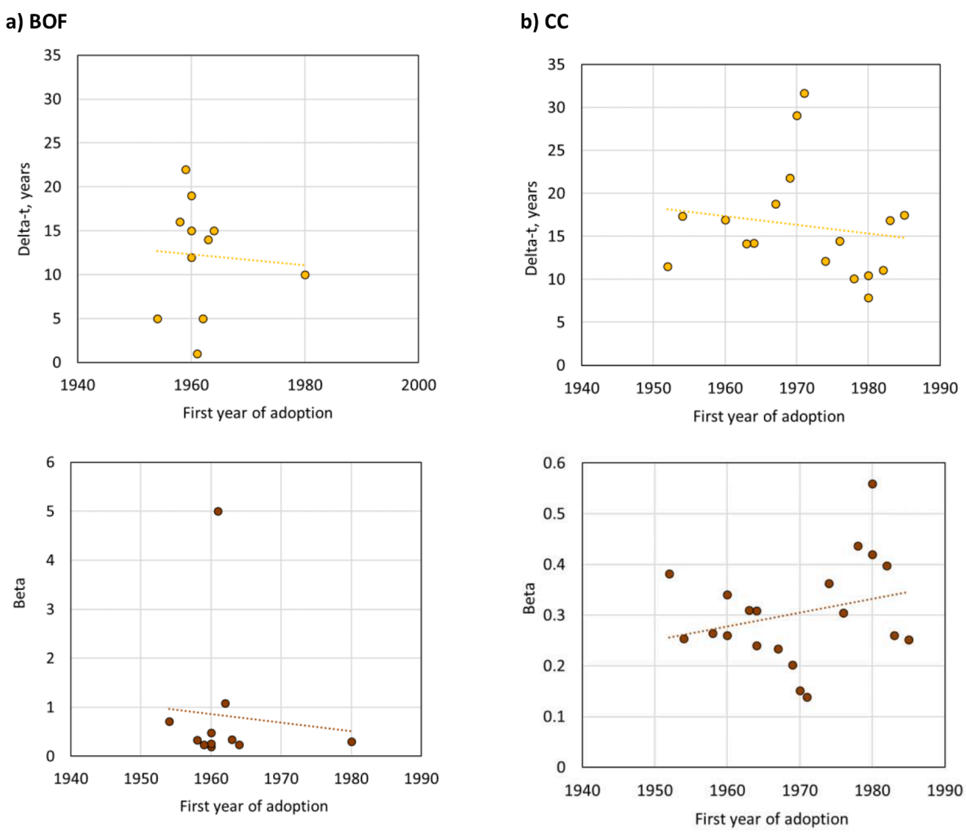

Fig. A.3. Delta-t and Beta metrics for (a) BOF and (b) CC technologies, to include only those cases where initial diffusion is less than 10%.

The current leading approach to decarbonising steel is to use hydrogen in the DRI process rather than fossil fuels, and to produce that hydrogen through electrolysis using carbon-free electricity [43]. This pathway is emerging as a front-runner in the production of green steel [45], and is being fully demonstrated as part of the HYBRIT project in Sweden [27]. This process involves the removal, or reduction, of oxygen from typically pelletized iron ore in its solid state, therefore without melting. To produce carbon-free green steel, the reducing syngas in this process would be hydrogen, produced through electrolysis using low carbon electricity. This DRI process produces sponge or briquetted iron, which is then fed into an electric arc furnace to produce steel [43]. A key challenge for green steel production via DRI-H2 will be the availability of low carbon electricity supply for the production of green hydrogen via electrolysis.

The other approach is to integrate CCS into the fossil fuel-based DRI process (post-combustion) or into blue hydrogen production (pre-combustion), which is then used in the DRI process. A full scale DRI with CCS facility has been operating since 2016 in Abu Dhabi, with the CO_2 going to enhanced oil recovery [17]. A key challenge for green steel production via DRI-H2 is the available supply of low carbon electricity that can be used to produce hydrogen.

EAF

Electric arc furnaces are normally used for secondary, recycled steel making, and are used to melt steel scrap and can be fed with sponge or briquetted iron, as described above. Electricity is used to generate heat to melt the scrap, based on an electric arc between the charge (input scrap) and a set of electrodes. This production approach is widely used across the world, given its smaller, more modular size and investment requirements, and in countries that often have a good supply of scrap (although scrap is also a traded commodity).

A key approach to decarbonising overall steel production is to increase secondary production through increasing the level of recycled scrap, and using low carbon electricity to power the EAF [3,16,50]. Whilst subject to considerable uncertainties, estimates put the potential share of steel produced through secondary production in 2050 at 45–50% [3], with wide regional variation based on development level i.e. the stock of steel products in use. These stock levels constrain the level of potential of secondary production [7]. Scrap can, however, be supplemented with new briquetted DRI iron in electric arc furnaces [36].

There are a number of other options to decarbonise production that are not described above, which are listed in detail in [16], Table 2.1. A number of options have not been considered in detail in this paper due to their low technology readiness, for example smelting reduction technologies e.g. Hisarna, COREX and FINEX,[5] and direct iron ore electrolysis, such as high-temperature molten oxide electrolysis (MOE) or lower temperature aqueous electrolysis (AE), which can directly electrify primary steel production.[6]

Recycled steel and material efficiency

Whilst investment in primary production of green steel is key, increasing secondary steel production using scrap metal in Electric Arc Furnaces (EAF) is also an important option to decarbonise the steel sector, particularly as the carbon intensity of the electricity system reduces and steel stocks increase. This production route currently accounts for 25% of total steel produced, with end-of-life recycling rates of 85% [14]. There are also opportunities to reduce demand for steel, and therefore the level of overall production and associated emissions [50].

Through material efficiency measures, less steel can be used to meet the same production end-use service e.g. in construction or manufacturing. For example, the IEA see a 24% reduction in steel demand in their clean technology scenario compared to the reference. This is achieved through various measures such as 'designing for long life, lightweighting, reducing material losses during manufacturing and construction, lifetime extension, more intensive use, reuse and recycling' [18]. While there is potential for large gains here, estimated at 25–40% by the IEA [18], the relatively low cost of steel and the practice of overbuilding mean that in practice such gains may be difficult to realise [2].

Appendix 2. Additional information on empirical analysis

Compilation process of empirical data

Empirical patterns of diffusion

Unlike for BOF and CC, for DRI on years to specific levels of deployment, no such patterns can be observed in the data (and therefore results are not plotted), in part due to large gaps in the data or given the nature of the technology that results in a specific geographical focus. This technology has largely been deployed in regions that have significant amount of fossil fuels, including the Middle East with its large gas supply (40% of global production) and India (30%) using coal-based production to feed into large EAF sector. It is also prevalent in countries where the smaller scale of DRI facilities better suit local investment conditions compared to the highly capital-intensive BF-BOF route. Few countries reach DRI production shares of more than 25%, which makes it challenging to compare diffusion milestones by first year of adoption (as shown in Fig. 1b). In addition, the data series is often limited for specific countries, and diffusion in some countries jumps from 0 to 100% diffusion, because of generally small iron production levels (although none of these countries are plotted). This means that we cannot calculate any of our diffusion metrics.

The following figures provide the same graphs for BOF and CC as in the main paper (Figs. 2 and 3) but in these the data points for countries are excluded where the time series starts at a value greater than 10% i.e. the formative phase data points appear missing.

Table A.1
. Process of data collation for each of the iron and steel technologies.

Dataset	Description
BOF	Steel production data from the CHAT dataset for the period from 1950 to 2001 [6]. Years 2002–2019 are taken from World Steel Association [48, 49]. Many gaps in early years in CHAT database, so we combined it with sources including [23,30,32–35]. Dataset compiled by converting all values to annual production in million tonnes steel. BOF share of primary steel production considered Bessemer and Open Hearth furnace pathways. Countries were excluded from dataset that have not produced via BOF pathway, where there is a very short time series, or where countries not longer exist (e.g. USSR). For production shares, we also excluded countries that were at 100% BOF diffusion at all times, as we were unable to calculate meaningful diffusion metrics in these cases.
DRI	Production data taken from World Steel Association [48,49]. All values converted to annual production in million tonnes iron. DRI shares were based on DRI sponge iron production levels relative to total iron production. Countries were excluded from the dataset that have not produced any DRI, where there is limited time series data, where there are big gaps in the time series, or where countries no longer exist. As with BOF, countries are also excluded where they are at 100% DRI diffusion at all times, or where there is a jump from 0 to 100% within a year.
CC	Data on continuous casting from 1970 to 2018 was taken from the annual statistical yearbooks of the World Steel Association. Data for before 1970 was taken from other publications [30,32].

Appendix 3. Model description and assumptions

TIAM-UCL description

TIAM-UCL provides a representation of the global energy system, capturing primary energy sources (oil, fossil methane gas, coal, nuclear, biomass, and renewables) from production through to their conversion (electricity production, hydrogen and biofuel production, oil refining), their transport and distribution, and their eventual use to meet energy service demands across a range of economic sectors. Using a scenario-based approach, the evolution of the system over time to meet future energy service demands can be simulated, driven by a least-cost objective.

The model represents the countries of the world as 16 regions, allowing for more detailed characterisation of regional energy sectors, and the trade flows of energy commodities between regions. Regional coal, oil and fossil methane gas prices are generated within the model, based primarily on differing resource supply curves [46]. Exogenous future demands for energy services (e.g. mobility, lighting, heating) drive the evolution of the system so that energy supply meets the energy service demands across the whole time horizon (i.e. 2005–2100), which have increased through the population and economic growth. For this paper, we use energy service demands derived from Shared Socio-economic Pathway 2 (SSP2) which can be generally characterized as a set of socio-economic assumptions that 'cover the middle ground in terms of mitigation and adaptation challenges' relative to other SSPs [9]. Further information of development of steel production outputs are provided below, as are specific assumptions on steel production technologies.

The model is run with an elastic demand function, with energy service demands e.g. steel produced, mobility in pkm/tkm etc., reducing as the marginal price of satisfying the energy service increases. A social

[5] Smelting reduction combines the gasification of coal with the melt reduction of iron ore, reducing energy intensity compared to a blast furnace, as coke production is not needed and the need for ore preparation is reduced.

[6] The MOE/AE approach is to directly melt the iron ore using electricity using an inert metallic anode, or reduce it like in an electrolytic liquid, similar to the process for transforming bauxite into aluminium.

discount rate of 3.5% is used for deriving a NPV in 2005. In conjunction with a cumulative CO_2 budget, an upper limit is placed on annual CH_4 and N_2O emissions based on pathways from the IPCC's Special Report on 1.5 °C scenario database [13]. The model version used is documented in more detail in Welsby et al. [46].

The version of the model used for this study includes a steel sector providing a much more granular representation of the key production pathways. Previously the representation was very generic, consisting of energy services needed for the steel sector e.g. high temperature process heat, machine drive etc. but with no specific detail on individual technologies. The new structure now uses explicit steel production pathways, as illustrated in Fig. A1.

The model has been calibrated between 2005 and 2020 primarily using two key sets of data – production statistics from the World Steel Association (2020, [49]), and extended energy balances from the International Energy Agency [15]. The existing plant stock in the sector is fixed in 2005, with new investments made from 2005 but calibrated for the period 2005–2020, to ensure correct representation of increasing steel production capacity and energy use.

Post-2020, in addition to the standard production routes (BF-BOF, DRI-EAF, and EAF), low carbon options added include –

- A new BF-BOF pathway with a higher biomass input, based on prospects for using bioenergy as a low carbon feedstock into the process. (Use of up to 40% co-firing with hydrogen was not considered)
- A new DRI-EAF pathway which uses hydrogen, rather than natural gas, as the main source of input to generate heat in the DRI process.
- Three technology options that allow for carbon capture and storage, including a standard BF-BOF CCS option, a DRI-EAF (fossil) CCS option, and a BF-BOF CCS option with higher bioenergy inputs. For the first two CCS options, carbon is sequestered at an assumed capture rate of 90%. For the higher biomass availability case, some of the capture carbon is assumed to be negative emissions (i.e. removed from the total pool of CO_2 emissions).

Energy balance alignment in 2005, 2010, 2015 and 2020 has been achieved by regionalising energy input requirements for each region and each production process within the sector. The challenge of determining the electricity input for each pathway was achieved by using regional-

Table A.2
. Steel production technology costs assumptions. Point estimates for CAPEX used in the model, based on range median.

Technology name	Technology abbr.	CAPEX[1], \$2005/t (Range)	CAPEX[1], \$2005/t (Point estimate)	OPEX,% of CAPEX
Electric Arc Furnace	EAF	187–292	240	7.5%
Direct Reduction Iron and EAF	DRI-EAF	459–471	465	7.5%
Direct Reduction Iron with hydrogen and EAF	DRI-H2-EAF	459–471 (excl. H2 production)	465	7.5%
Direct Reduction Iron with CCS and EAF	DRI-CCS-EAF		580	10%
Blast furnace and BOF	BF-BOF	490–597	550	7.5%
Blast furnace and BOF with CCS	BF-BOF-CCS	628–743	680	10%

1 Upfront investment, not annualised.

Table A.3
. Steel production technology non-cost assumptions.

Technology name	Technology abbr.	Energy input (GJ/t)[2]	Capture rate[1]	Scrap input (t)[3]
Electric Arc Furnace	EAF	2		1.1
Direct Reduction Iron and EAF	DRI-EAF	17		0.15
Direct Reduction Iron with hydrogen and EAF	DRI-H2-EAF	9		0.15
Direct Reduction Iron with CCS and EAF	DRI-CCS-EAF	17	90%	0.15
Blast furnace and BOF	BF-BOF	19		0.15
Blast furnace and BOF with CCS	BF-BOF-CCS	19	90%	0.15

1 90% capture rate assumed [3,16].
2 For DRI-H2-EAF, based on [43]; 59 kg H2 per tonne steel, based on 15% scrap charge.
3 For primary production, these can vary significantly but are based on typical levels from the World Steel Association.

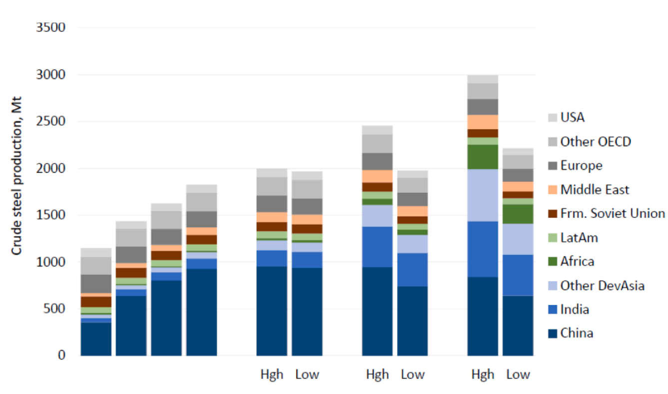

Fig. A.4. Production of crude steel in high & low demand variants, by region and for selected time periods.

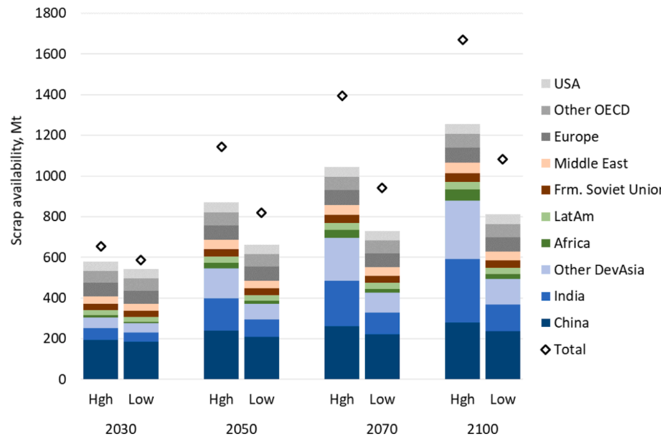

Fig. A.5. Global scrap steel availability, and minimum regional take, 2025–2100. Black markers denote total available scrap. For the high case, this is based on global growth rates of 2.8% (2020–50), 1% (2050–80) and 0.4% (2080–2100), while for the low case 1.7%, 0.7% and 0.4%. The bars denote regional lower levels of region scrap (which cannot be traded). These are based on differentiated multipliers on the global growth rates including 170% for developing regions (IND, ODA, AFR), 40% for emerging economies (CHI, CSA, FSU, MEA, MEX) and 10% for all other regions (OECD). The difference between the bar total and black marker is available for trade.

ised benchmarks of electricity requirements by pathway, although this aspect could be further refined.

Production costs and other assumptions

The cost estimates used in this paper are sourced from a range of literature where we can determine individual cost components [8,16,39,43]. These are summarised in Table A2. Note that costs do not change over time but are rather estimates of fully commercialised production pathways.

Further pinformation on technical parameters for the above technologies are shown in Table A3.

Estimates of steel demand and recycling for sensitivity cases

Crude steel demand

Demand for crude steel is subject to numerous uncertainties. We use recent IEA scenario estimates to derive our global demand range, with a higher case similar to the STEPS scenario, hitting 2450 Mt of crude steel in 2050, and a lower demand case similar to IEA net-zero scenario, at 1980 Mt in 2050 [14,16]. The lower case reflects material efficiency gains leading to approximately a 20% reduction in overall demand relative to the higher case.

In TIAM-UCL, because steel is not traded, we determine how global demand projections translate into regional steel production. Future production uses different growth rates projected from the year 2020, with aggregate regional production capped at assumed global demand. Out to 2050, only India, other developing Asia and Africa sees strong growth over the next decade. Most other regions see no growth or decline, with the share of China's production reducing from 51% to 38% by 2050 (a similar trend to that assumed by the IEA [16]). Post 2050, the rate of growth slow, starting to plateau in 2080. The annual growth rate is 0.4% for the period 2050–2100, compared to 1% for the period 2020–2050. For the lower demand case, global production is 20% lower in 2050 compared to the higher demand case, based on a growth rate of 0.3% per year. Post-2050 see annual growth at 0.2%, resulting in a level 26% below the higher case in 2100 (Fig. A4).

Recycled steel

A key uncertainty in relation to primary steel production is the level of recycled steel that can be realised in future years, with scrap primarily used for secondary production via the EAF route. This depends on the levels of waste from steel production itself (home scrap), that is generated and recycled at the point of manufacture by industries using steel (prompt scrap), and scrap recycled from products / infrastructure using steel (end-of-life (EOL), or obsolete scrap). Obsolete scrap levels are a function of the accumulated steel stocks (steel in use) in different regions, with 85% of end of life steel recycled [3].

In the future, it is likely that the potential for scrap (post-consumer, or obsolete) will increase in emerging and developing economies as stocks build up, and steel using products come to end-of-life. For developed economies, there are likely to be saturation effects, where stocks do not grow on per capita basis, limiting further growth in recycled steel [4,28]. For a country such as China, this means that as stocks grow, the use of recycled steel for secondary production will increase, with EAF currently only accounting for 10% of steel production [25].

Estimates of recycled steel availability in 2050 has been reviewed by Bataille et al. [3], putting estimates of scrap (prompt and EOL) in the range of 1000–1500 Mt/yr, with a usable estimate of 1200 Mt/yr, of which 83% was fully usable. This corresponds to the estimates produced in based on detailed analysis of stock levels across different regions of the world. For implementation in the model, we use the range of recycled steel supply estimates highlighted above for 2050. Post 2050, we assume lower growth rates, as shown in Fig. A5. We use minimum scrap level availabilities on a regional basis (shown by the bars) but also set a global availability of scrap (shown by the markers). The difference between the top of the bar and the markers is the available scrap that can be 'traded', providing flexibility for specific regions to increase their scrap take. The representation of trade is highly stylised, with no costs of trade assumed (in addition to the $200/tonne cost of scrap assumed in this modelling).

Appendix 4. Additional scenario modelling results for selected regions

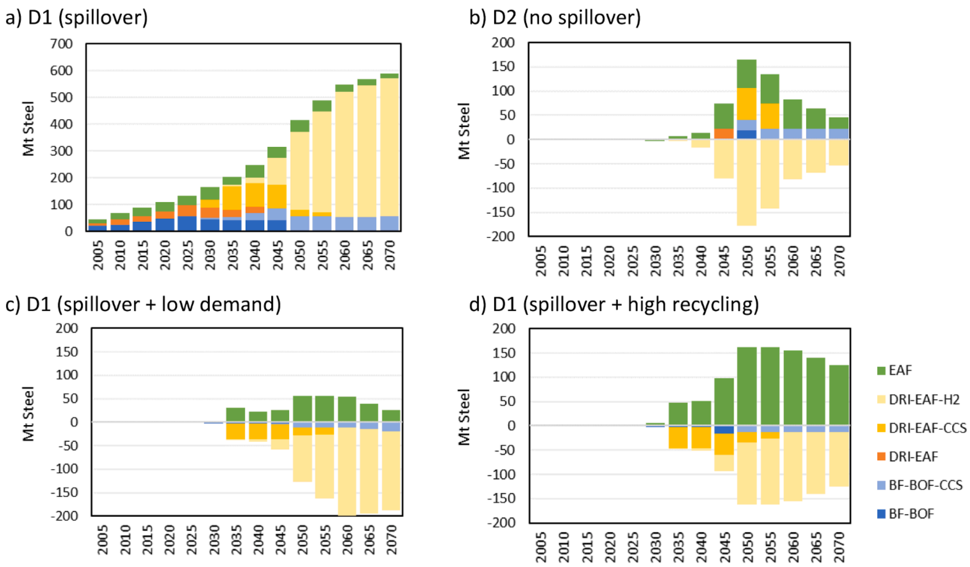

Fig. A.6. India steel production by technology pathway for selected scenarios, 2005–2070. (a) Annual production under D1. The other panel plots (b-d) show the difference in production relative to D1, with negative values denoting less production by a given technology compared to D1.

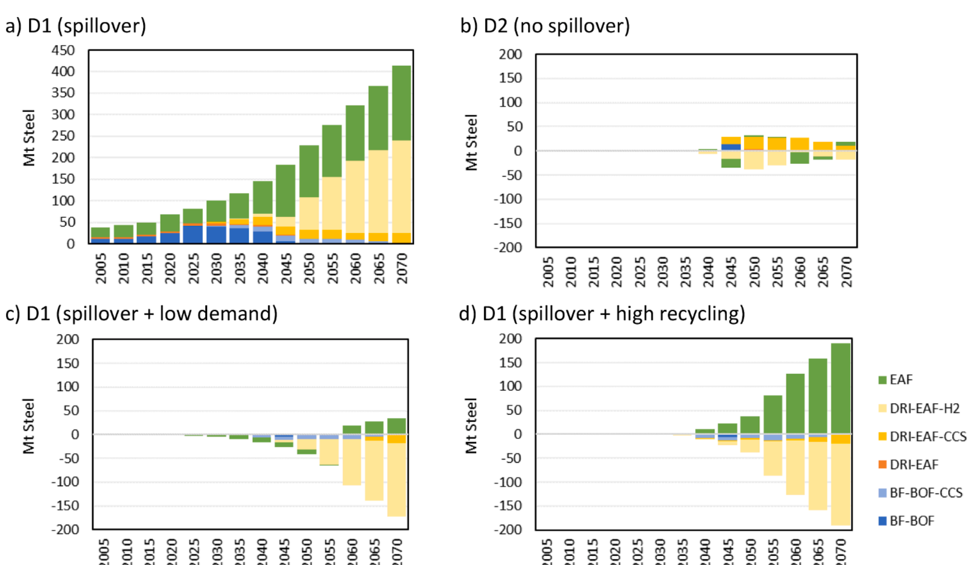

Fig. A.7. Other Developing Asia steel production by technology pathway for selected scenarios, 2005–2070. (a) Annual production under D1. The other panel plots (b-d) show the difference in production relative to D1, with negative values denoting less production by a given technology compared to D1.

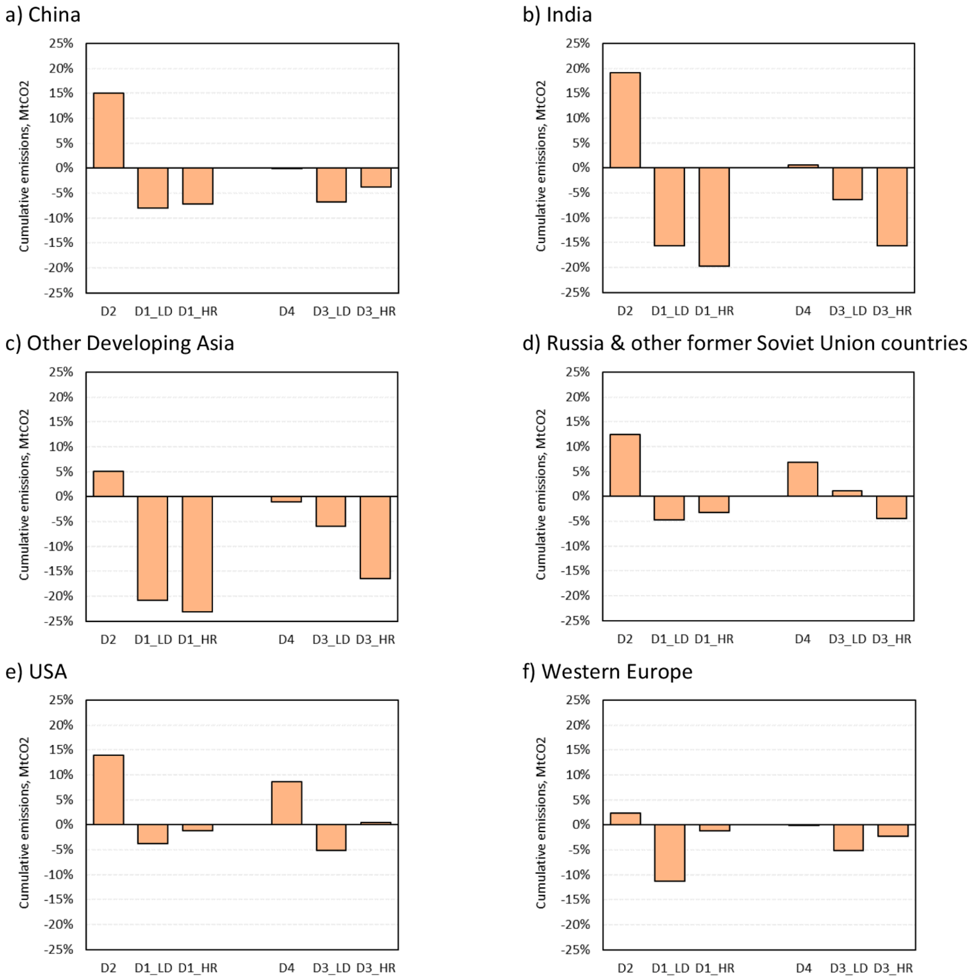

Fig. A.8. Change in cumulative sectoral CO2 emissions for selected regions, 2020–70. Change in emissions for D2, D1_LD, and D1_HR are relative to D1, and change for D4, D3_LD, and D3_HR are relative to D3.

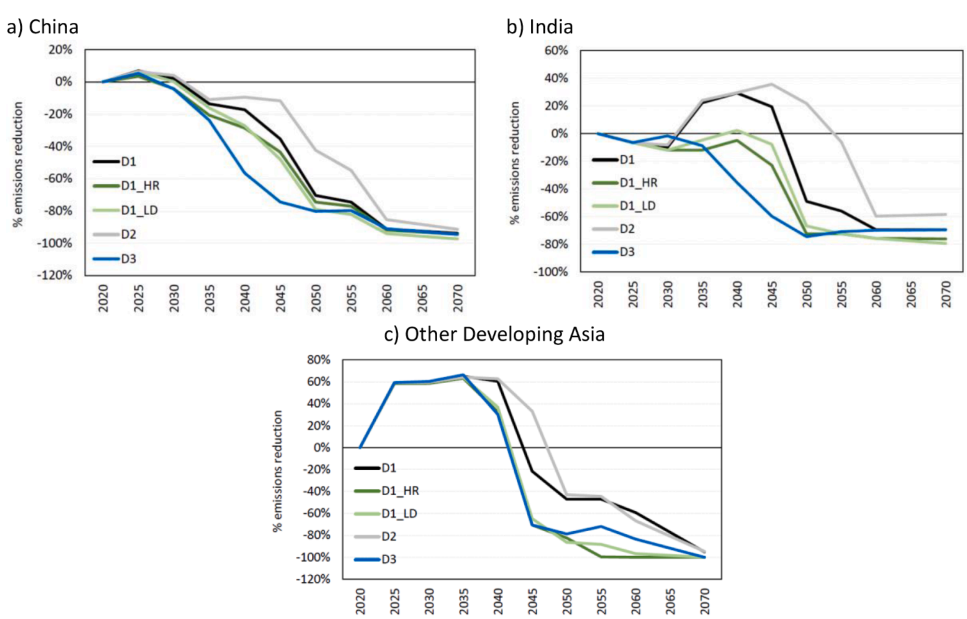

Fig. A.9. Emission reductions from the steel sector in selected regions, relative to 2020, 2020–2070. a) China; b) India; and c) Other Developing Asia.

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