Role of Advanced Steelmaking Technologies in Global Climate Change Mitigation Scenarios

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Abstract

While integrated assessment models (IAMs) are widely used for policy assessments, many IAMs represent key industrial sectors in a highly aggregated manner, which does not capture numerous technical differences between technologies. In this study, we enhance the representation of iron and steel production pathways in a multi-sector, multi-region, computable general equilibrium model that represents the world economy, namely the MIT Economic Projection and Policy Analysis (EPPA) model. This research builds upon prior techno-economic assessments of two low-emission steel production technologies: direct reduced iron-electric arc furnace with carbon capture and storage (DRI-EAF with CCS) and H_2 based direct reduced iron-electric arc furnace (H_2 DRI-EAF), which utilizes low carbon hydrogen to avoid CO_2 emissions. The low carbon hydrogen is represented by "Blue" hydrogen produced via autothermal reforming with CCS and "Green" hydrogen produced via a renewable energy powered electrolyzer. Utilizing the EPPA model, we evaluate the deployment of these technologies in global emissions mitigation scenarios. Our analysis provides insight into regional decarbonization pathways that could occur under specific technology and policy conditions. Our findings can be used to help decision-makers assess various decarbonization options and design economically efficient pathways to reduce emissions in the steel industry and other "hard to abate" sectors.

Keywords: carbon capture; hydrogen; steel production; decarbonization; integrated assessment models

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1. Introduction

Scenarios that limit global warming to 1.5 degrees Celsius relative to pre-industrial levels typically attain net-zero CO_2 emissions around 2050-2070 (IPCC, 2022). Global CO_2 emissions in 2022 were estimated to be roughly 37 billion tonnes (IEA, 2023). Reaching net-zero emissions in the second half of this century would require deep reductions in emissions across all sectors of the economy, including the industrial sector, which is responsible for approximately 25% of all global energy and process related CO_2 emissions (IEA, 2022). Heavy industry typically encompasses sectors such as cement, steel, petrochemicals, glass/ceramics, refining and other energy intensive manufacturing processes (Friedmann et al., 2019). The majority of heavy industry's CO_2 emissions come from three sectors: cement, steel, and chemicals (IEA, 2022). These sectors are classified by the IEA as "hard to abate" because their production processes depend on carbon compounds as key reagents in chemical reactions, which makes it difficult to reduce all process emissions (Mandova et al., 2020; Paltsev et al., 2021). In addition, these processes require high temperature heating, and these sectors are vulnerable to international competition because they are traded on an international market (Friedmann et al., 2019; Mandova et al., 2020). Therefore, in order to compete globally and to be economic these processes must operate with high capacity factors and use the most cost-effective processes. Also, these sectors utilize plants with long economic lifetimes, so turnover of the infrastructure occurs slowly (Mandova et al., 2020).

The iron and steel sector has the highest emissions among all heavy industry sectors (Mandova et al., 2020). Decarbonization strategies are limited because iron and steel production relies on fossil fuels not only as a source of energy but also to produce the reducing agent needed to convert iron ore to iron (IEA, 2020). Coking coal or natural gas are typically used to generate the reducing agent (IEA, 2020). Carbon is also essential for the strength of steel, with different types of steel containing 0.002%-1.2% carbon by weight (Hosford, 2012). Steel can be recycled via the electric arc furnace (EAF), which requires much lower energy and produces less emissions than primary steel production, but current scrap stock is not sufficient to meet global steel demand

(IEA, 2020).

One decarbonization strategy is to utilize hydrogen as the reducing agent to produce iron. Hydrogen is a promising alternative to fossil fuels because when combusted it emits zero greenhouse gas (GHG) emissions, and it is versatile because it can be used for energy generation, energy storage or as a feedstock. Hydrogen is able to provide high temperature heat and energy fluxes similar to fossil fuels. Hydrogen is also able to be transported and stored in a manner that electricity cannot. In iron production, hydrogen is able to act as the reducing agent and reduce iron ore without emitting any CO_2 emissions (Cavaliere, 2019). The process still requires a source of carbon input to ensure the necessary carbon content in the steel. Hybrit is currently developing this technology, and in 2020 they produced direct reduced iron (DRI) reduced by hydrogen at their pilot plant (Hybrit, 2022). Their process entails producing hydrogen via an electrolyzer powered by renewable energy, essentially eliminating CO_2 emissions from the iron production process.

Another promising decarbonizing strategy that has been implemented in commercial-scale steel plants is carbon capture where the CO_2 is captured directly from the process and then transported and stored geologically. Emirates Steel has two DRI plants located in Abu Dhabi which have been capturing CO_2 since 2016 and transporting the CO_2 to an oil field for enhanced oil recovery (IEA, 2020). The specific DRI shaft furnace process that they utilize incorporates the CO_2 separation into the process so that there are minimal additional costs to incorporate a carbon capture unit into the existing process (Duarte et al., 2010).

In this paper we focus specifically on two low carbon advanced steelmaking pathways: H_2 based DRI-EAF and natural gas (NG) based DRI-EAF with carbon capture and storage (CCS). The H_2 based DRI-EAF pathway utilizes low carbon hydrogen as the reducing agent to produce DRI which is then fed into the EAF to produce crude steel. The low carbon hydrogen is either "Blue" hydrogen produced via autothermal reforming[2] with CCS or “Green” hydrogen produced via a renewable energy powered electrolyzer. The DRI-EAF with CCS refers to a pathway in which 90% of direct CO_2 emissions are captured from the DRI shaft furnace. The DRI produced is then similarly fed into the EAF to produce crude steel. Both pathways also include a hot rolling finishing step to produce hot rolled steel which utilizes natural gas. However, this fuel could be replaced with alternative low carbon fuels or theoretically with electric heating, which could further reduce direct emissions.

We selected these technologies for our analysis because they have the potential for the greatest emissions reductions while also being more technologically ready than other decarbonization technologies for steelmaking. Other decarbonization technologies such as equipping blast furnace-basic oxygen furnace (BF-BOF) processes with CCS or injecting hydrogen into the blast furnace are capable of smaller emissions reductions (Laguna et al., 2021). Decarbonization technologies that can achieve similar if not greater reductions such as iron ore electrolysis and smelting reduction have lower technology readiness levels (IEA, 2020; Laguna et al., 2021). IEA's assessment in the “Iron and Steel Technology” report projects that EAF steelmaking will contribute the majority of global steel production by 2050 under their sustainable development scenario (IEA, 2020). The IEA also identified carbon capture, utilization and storage (CCUS) and hydrogen technologies as being important to achieving decarbonization of primary steelmaking (IEA, 2020).

Another study commissioned by the European parliament also identified hydrogen as playing a key role in the future decarbonization of steel, specifically citing several ongoing projects in Europe which are developing steel production plants that will utilize hydrogen as the reducing agent (Laguna et al., 2021). A recent report by the Pacific Northwest National Laboratory (PNNL) assessed global and regional deployment of several different low carbon steel production technologies including biomass, carbon capture & storage, and hydrogen injection.

[2] Currently, most of hydrogen is produced by steam methane reforming (SMR) of natural gas. For an option of combining natural gas-based hydrogen production with CCS, autothermal reforming (ATR) is suited better (Benavides, 2023).

Iron ore electrolysis was excluded from their analysis because of its low technology readiness factor. By year 2050 under the 1.5 °C scenario, the DRI-EAF with CCS had the highest share of steel production among the advanced steelmaking technologies and DRI-EAF with H_2 the second highest (Yu et al., 2021).

To explore how these advanced steelmaking technologies could be deployed in different regions under decarbonization scenarios, we have enhanced the global multi-region, multi-sector MIT Economic Projection and Policy Analysis (EPPA) model (MIT Joint Program, 2023) by adding representations of iron and steel production pathways based on detailed techno-economic analysis (Benavides et al., 2023). By doing so, we seek to capture inter-sectoral linkages, demand responses, competition between technologies, and substitution possibilities associated with decarbonizing iron and steel production. We assess decarbonization pathways at the global level and further examine pathways in several regions that are among the top producers and consumers of steel: China, India, USA, and Europe (IEA, 2020; worldsteel, 2022). It is important to understand the regional nuances because the optimal pathway for decarbonizing a process will be dependent on regional costs and resource availability.

Greater use of scrap-based steel offers a pathway for energy and emission reductions. In 2019, scrap steel made up about 1/3 of the total metallic input for steel production, with the remainder being produced from iron ore (in the form of pig iron or direct reduced iron) (IEA, 2020). Forecasts predict that in the future there will be more scrap stock available. These forecasts rely primarily on the assumption that China's steel stock produced in the early 2000s will soon be reaching its end of life. The World Steel Association (worldsteel) predicts ~1,000 Mt of total available scrap by the year 2030 (Ciftci, 2018, 2021). And by 2050, worldsteel forecasts the total available scrap stock to rise to 1,300 Mt (Ciftci, 2018, 2021). IEA predicts that scrap will make up 45% of metallic input by 2050 (IEA, 2020). The IEA forecast assumes scrap available for steel production will be about 1,160 and 1,400 Mt in these respective scenarios. The Mission Possible Partnership (MPP) produced a report that predicts in a Business as Usual scenario, that scrap steel usage will be approximately 1,000 Mt in 2030 and 1,100 Mt in 2050 (Delasalle et al., 2022). MPP's High Circularity Scenario assumes high levels of material efficiency resulting in lower steel demand and this scenario relies on a scrap steel usage of ~700 Mt in both 2030 and 2050 (Delasalle et al., 2022). In addition, it should be noted that scrap steel cannot achieve the highest steel quality needed for some applications due to contaminants often found in end of life scrap (IEA, 2020).

These numbers show that there might not be sufficient scrap stock to meet the overall global steel demand. The IEA's Stated Policies Scenario, predicts that in 2050 the global steel end use demand will be 2,500 Mt and in their more aggressive decarbonization policy scenario (Sustainable Development Scenario) they predict that steel demand will be only 2,100 Mt (IEA, 2020). The World Steel Association's forecast from their report "Energy Use in the Steel Industry", cites a prediction of 2,460 Mt for global steel production in 2030 (worldsteel, 2014). These values all exceed even the high-end estimate for available scrap of 1,400 Mt which indicates that primary steel production will also need to decarbonized in order to meet current and future steel demand. In our analysis, we assess the contributions from scrap and primary steel production based on the endogenous evolution of the energy inputs.

The paper is organized in the following way: In Section 2 we describe the methodology utilized to implement low carbon advanced steel production pathways in the EPPA model. Section 3 presents the results of our analysis under different technology and policy assumptions. Section 4 discusses implications of the results and provides concluding remarks.

2. Methods

2.1 Levelized Cost Assumptions for Steelmaking Pathways

To build the foundation for our analysis, in our prior work we estimated levelized costs for two low carbon steelmaking pathways: the H_2 DRI-EAF pathway and NG DRI-EAF with CCS pathway (Benavides, 2023; Benavides et al., 2022). In addition, we calculated production costs for conventional steelmaking pathways, including for natural gas based DRI-EAF, blast furnace-basic oxygen furnace (BF-BOF), and scrap-based EAF pathways (Benavides, 2023). Figure 1 summarizes the results of these levelized cost calculations. Furthermore, we estimated the levelized cost of hydrogen for two low carbon hydrogen production pathways: electrolytic hydrogen powered by renewable energy referred to as Green H_2 and natural gas-based autothermal reforming with 94.5% carbon capture, called Blue H_2 (Benavides et al., 2022). The levelized cost calculations conducted in our prior research were based on U.S. energy prices and CO_2 transportation & storage costs (Benavides, 2023; Benavides et al., 2022). This paper expands upon our prior work by determining region-specific levelized costs and conducting deeper analysis of scenarios produced by the EPPA model using these technology assumptions.

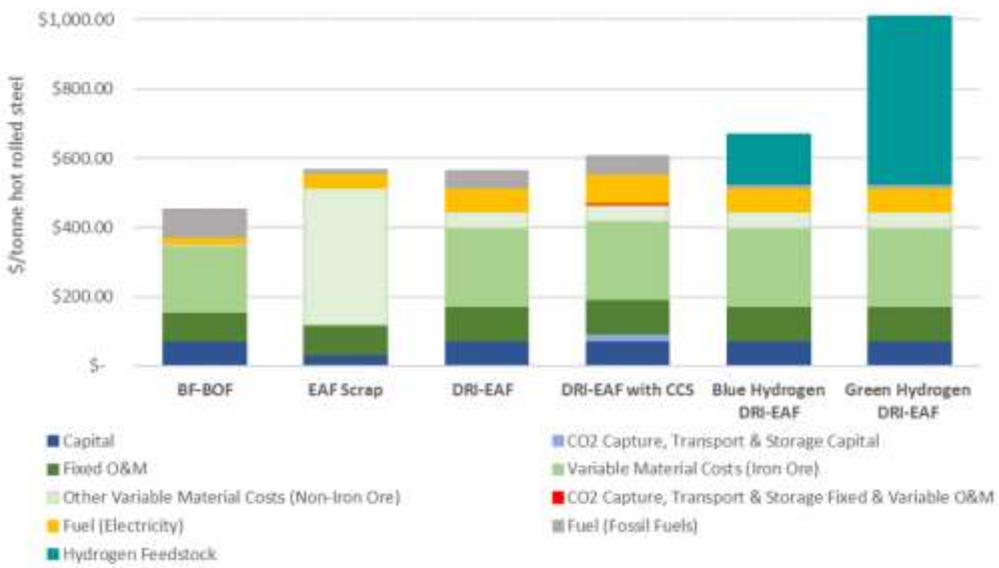

Figure 1. Steel production costs and input shares

2.2 Incorporating Advanced Steelmaking Technologies into EPPA

To reflect regional differences when incorporating steelmaking technology costs into the model, input shares and relative costs are computed for each region based on region specific costs for fuels, electricity, and CO_2 transportation and storage (T&S). Figure 2 shows the regions that are explicitly represented in the EPPA model. Regional energy prices are determined based on the

GTAP 10 power database which aligns with the EPPA model's main structure (Aguiar et al., 2019; Purdue University, 2023). Regional CO_2 T&S cost are derived from Smith et al. (2021). We assume that shares of capital and labor in steelmaking do not differ between regions. Table A1 in the Supplemental Information provides a summary of these region-specific costs. The base costs derived from these levelized cost calculations for steelmaking and hydrogen production are utilized to calculate relative costs, which are ratios of the cost of the advanced technology to the cost of the conventional technology.

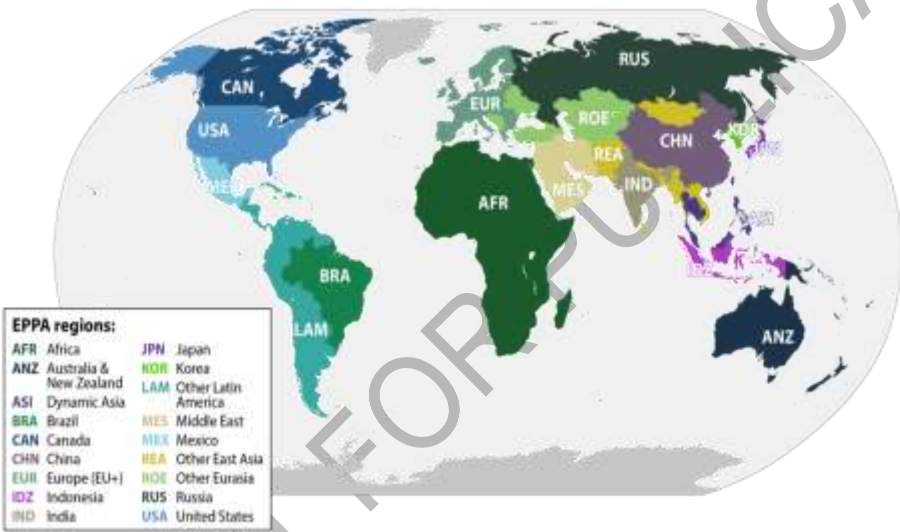

Figure 2. Regions of the EPPA model

In the EPPA model, the regional cost of the low carbon hydrogen is estimated relative to the regional cost of natural gas. The regional cost of the advanced low carbon steelmaking is estimated relative to the weighted average cost of the conventional steelmaking technologies. The conventional steel pathways include the BF-BOF, DRI-EAF and scrap-based EAF pathways. A regional cost for the conventional technology is estimated as the weighted average of the regional base costs for each process using the process share of production in that region in 2019. Table A2 in the supplemental information summarizes data from the World Steel Association (worldsteel, 2022) on regional production by process in 2019.

The region-specific relative cost for each technology in the base year for all advanced technologies is then incorporated into the EPPA model. The relative cost represents how competitive that technology will be and varies between regions, so we expect that adoption of these technologies will also vary between regions. The input shares for each technology are also incorporated into the production block in EPPA, which specifies the different inputs needed to produce one unit of product. In addition, in the EPPA model, the cost of fuels and electricity are region-dependent and time-dependent. Future technology costs decline endogenously in the EPPA model via learning and other factors such as adjustment costs (Morris et al., 2019). Traditional iron and steel production in the EPPA model is representative of all conventional iron and steel production technologies (BF-BOF, DRI-EAF and scrap-based EAF pathways). We estimate the percent share of conventional steel that is produced via the EAF pathway (DRI-EAF and scrap EAF) based on the share of energy that is electricity. In the base year the known share of EAF production and share of electricity is used to estimate the EAF share in future years based on how the share of electricity changes as an input into conventional steelmaking. This estimate allows us to show results for conventional steelmaking broken out into production from BOF and EAF pathways. The low carbon advanced steel production pathways and H_2 production pathways are represented in the model as distinct processes with fixed inputs. In the model, scrap usage is tracked based on a cost share input from the Iron and Steel sector into itself.

2.3 Scenarios

We assess steelmaking emission reduction pathways in two global scenarios: a reference scenario, which assumes the current trends in policy setting, including an assessment of commitments under the Paris Agreement for 2030; and a 1.5°C stabilization scenario, termed Accelerated Actions (AA), in which countries impose more aggressive emission targets that represent an illustrative pathway of increased mitigation. This scenario abates global CO_2 emissions by about 80% in year 2050 and about 98% in year 2070 relative to the base year of 2015. The details of these scenarios are described in the MIT Global Change Outlook (Paltsev et al., 2021).

Scenario Name	Climate Policy	Advanced Steel Production Non-Energy Input Costs	H_2 Production Costs
Reference	Current Trends	Base Costs	Base Costs
AA Base Costs	Accelerated Actions	Base Costs	Base Costs
AA Reduced Cost of Advanced Steel Production	Accelerated Actions	**Reduced Costs**	Base Costs
AA Reduced Cost of Advanced Steel and H_2 Production	Accelerated Actions	**Reduced Costs**	**Reduced Costs**

Table 1. Scenarios for 2020-2050

For the Accelerated Actions scenario, we explore the implications of several assumptions about future technology cost evolution (Table 1). Base costs represent the cost premiums determined from our levelized cost calculations, represented in Figure 1. We term this scenario as *AA Base Costs*. Reduced non-energy input costs for advanced steel production represents a scenario in which the non-energy input costs are equal to that of traditional steelmaking. This scenario is called *AA Reduced Costs of Advanced Steel Production*. Reduced cost of H_2 production assumes a cost of $1/kg H_2. This would be a significant reduction of the current cost of green hydrogen and a modest reduction of the blue hydrogen cost. This reduction in hydrogen production cost aligns with the current cost of Grey hydrogen and with the U.S. Department of Energy's "Hydrogen Shot" goal which aims to reduce the cost of clean hydrogen to $1/kg H_2 (DOE, 2021). This low hydrogen production cost reduces the input share required for hydrogen feedstock in the H_2 DRI-EAF pathway. We call this scenario as *AA Reduced Costs of Advanced Steel and H_2 Production*. In all our scenarios we assume no deployment of negative emissions technologies.

For the United States, we also explore a scenario that incorporates the Inflation Reduction Act (IRA) tax credits, applying them indefinitely to hydrogen and steel production in the United States. This scenario applies the full 45Q tax credit of \$85/t captured CO_2 to both the DRI-EAF with CCS technology and the Blue H_2 production technology. In addition, this scenario applies the full 45V tax credit of \$3/kg to the Green H_2 production cost. Applying the tax credits indefinitely effectively assumes an extension of the IRA incentives, which currently expire after 10 years.

3. Results

3.1 Global Analysis

3.1.1 Steel Production

In the Reference scenario, the shares of 2050 global steel production by process only slightly changes from the process shares in 2019. The share of EAF pathways increases from 28% to 34%. None of the low carbon advanced steel technologies are significantly deployed because they are more expensive than traditional pathways. For the policy scenarios, global steel production by process is shown in Figure 3. In the *AA Base Costs* scenario, the DRI-EAF with CCS pathway is deployed by 2030, and making about a third of global steel production by 2050. However, if the non-energy input costs of advanced steel production are reduced, then the DRI-EAF with CCS pathway becomes the dominant production pathway in EPPA (~94% of global production) and H_2 DRI-EAF is also deployed in this scenario (~1% of global production). The use of DRI-EAF with CCS in this pathway results in about 963Mt of CO_2 captured in the year 2050.

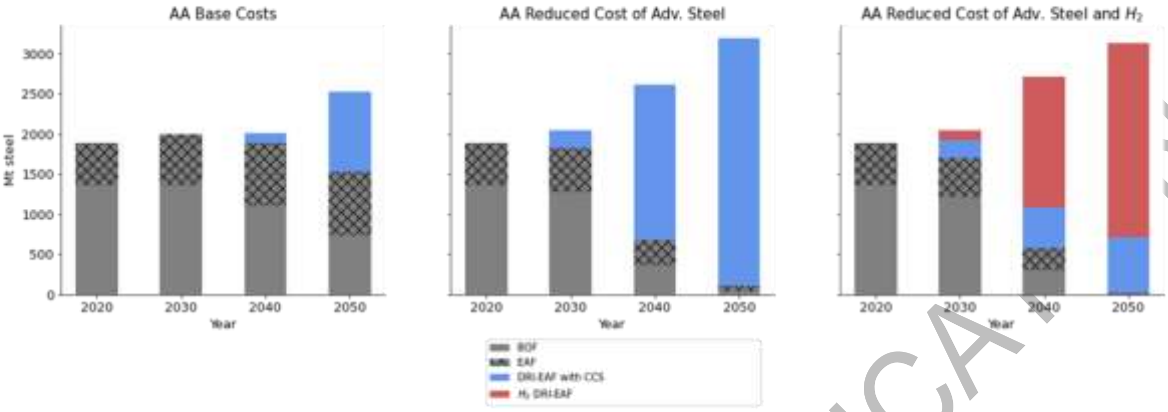

Figure 3. Global steel production by process in the AA scenarios.

In Appendix with supplementary information, we provide emission intensities of steelmaking pathways. As seen in Figure A1 in Appendix, the scrap-based EAF pathway also has a low emission intensity which makes this pathway competitive in this scenario against the advanced steelmaking technologies. In the *AA Reduced Costs of Advanced Steel Production* scenario, the DRI-EAF with CCS pathway contribute significantly to global steel production by the year 2050, with share of global steel production increasing to 96% by the year 2050.

In the scenario in which we assume that the advanced steelmaking non-energy costs are reduced and that the cost of H_2 production is reduced (*AA Reduced Costs of Advanced Steel and H_2 Production)*, most steel is produced using the H_2 DRI-EAF pathway (~77%). In this scenario, the non-energy costs of the H_2 DRI-EAF are presumed to be equal to the weighted average non-energy costs of the conventional steelmaking pathways. This, in addition to, reducing the cost of purchasing the hydrogen fuel results in the H_2 DRI-EAF pathway being very competitive with the conventional technologies. The DRI-EAF with CCS pathway accounts for 22% of global steel production.

3.1.2 Iron and Steel Sector Energy Usage

Figure 4 illustrates the changes in global energy use for iron and steel production. In the AA base cost scenario, the share of total energy from electricity that is used for traditional steelmaking increases from 4.6 to 6 EJ or from 14% to 32% of the steel sector's total energy use by 2050. This corresponds with an increase in production from the EAF pathway from 517 Mt to 1689 Mt or from 28% to 70% of total production in 2050 (as shown in Figure 3). The increase in electricity use is lower than the increase in total production from the EAF pathway due to autonomous energy efficiency improvements and an increase in the use of scrap, which requires less energy than primary steel production.

The increase in electricity that results from switching to EAF from BOF enables steel production to use less fossil fuels. Coal use in particular drops from 25.1 EJ to 9 EJ, or from 78% to 48% of total energy use, consistent with the decline in production from BOF shown in Figure 3. As a result, advanced steel technologies compete with traditional steelmaking that is increasingly efficient with declining emissions intensity. However, a 100% scrap-based EAF pathway cannot replace all primary steel production because there is insufficient scrap steel available to meet the overall steel demand. In addition, traditional steelmaking cannot fully electrify with existing commercial technology because electrification of the iron making process is not yet commercialized.

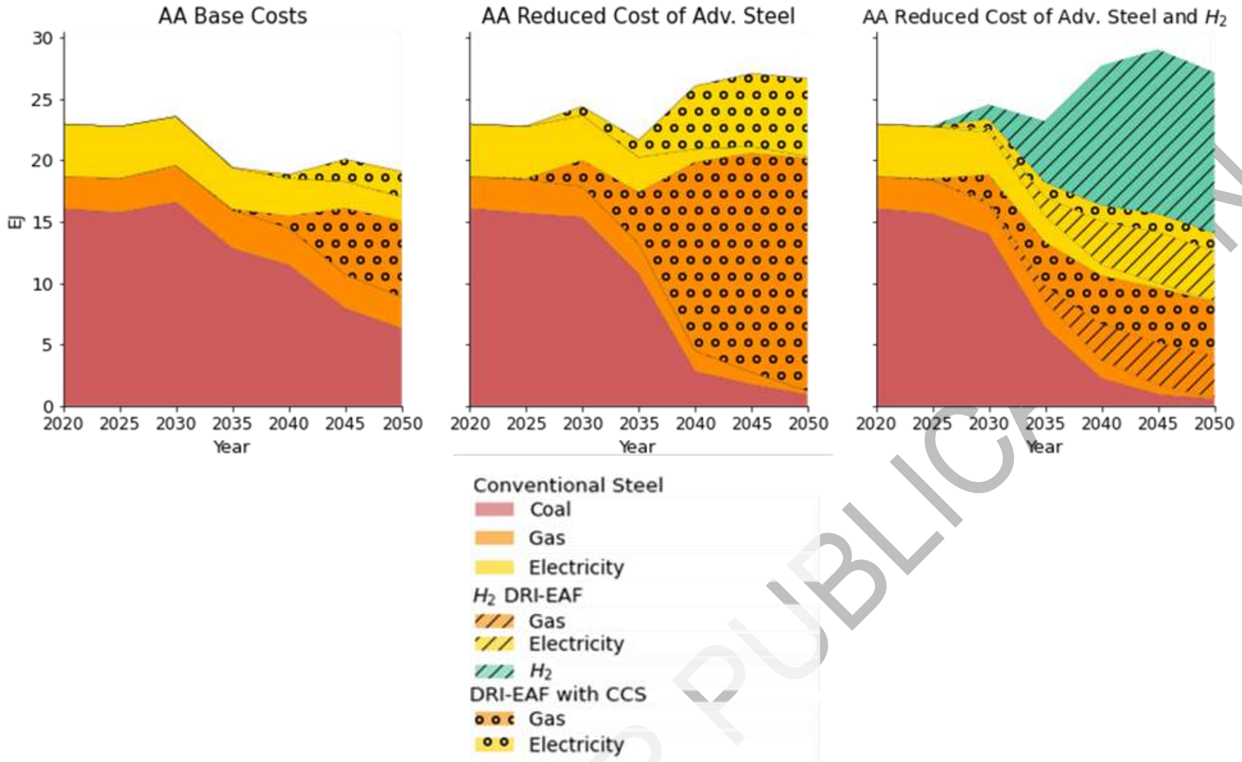

Figure 4. Energy consumed by global iron and steel production by process and type of energy input

In the AA Reduced Cost of Advanced Steel Production case, use of natural gas and electricity significantly expand as inputs to the DRI-EAF with CCS production process, which accounts for most of the steel production by 2050. Use of hydrogen also increases by 77 Mt in 2050 to provide energy for the H_2 DRI-EAF process. Current H_2 demand for all sectors globally is about 70 Mt (IEA, 2019). The model supplies the H_2 in year 2050 via the Blue H_2 production pathway which is more cost competitive than Green H_2. Approximately 754 Mt of additional CO_2 would be captured from the Blue H_2 production in 2050.

The AA Reduced Cost of H_2 Production case resembles the AA Base Cost case with the exception of minimal growth in H_2 consumption for the H_2 DRI-EAF process. This results in an annual H_2 demand of 0.005 Mt for steelmaking in 2050. All hydrogen is supplied via the Green H_2 production route because this pathway has no direct emissions, electricity generation is becoming increasingly decarbonized, and this scenario assumes the Green and Blue H_2 have equivalent production costs.

In the AA Reduced Cost of Advanced Steel Production and H_2 Production case, hydrogen consumption expands significantly given that the H_2 DRI-EAF accounts for most steel production in this case. This results in a H_2 demand of 241 Mt in 2050. As seen in the previous scenario, when the costs of the H_2 production pathways are equivalent, then by 2050 essentially all H_2 is produced using the Green H_2 production pathway. The low carbon advanced steelmaking technologies still utilize natural gas for heating in the finishing steps and for temperature control in the H_2 DRI-EAF pathway. However, this fuel could be replaced with alternative low carbon fuels or theoretically with electric heating, which could further reduce direct emissions. Furthermore, we do not directly account for regional scrap steel stock, but all pathways can also reduce their energy intensity by incorporating greater shares of their metallic input as scrap steel.

3.1.3 Energy Intensity of Steel Production

In the Reference scenario, the energy intensity is relatively unchanged with a slight increase from a global average of 17.3 to 17.6 GJ/t steel. This reflects the continued use of the same mix of conventional steelmaking technologies. In the Accelerated Actions policy scenario, when assuming base costs, the production continues to be dominated by conventional steelmaking technologies. However, the global average energy intensity declines to 7.7 GJ/t steel by 2050 (see Figure A2 in Appendix). Conventional steelmaking technologies achieve this energy intensity reduction primarily by increasing scrap steel usage. The scrap-based EAF pathway has the lowest potential energy intensity (~5 GJ/t steel) of the current commercially available steelmaking pathways The DRI-EAF and BF-BOF pathways require ∼17 GJ/t steel (Benavides, 2023; Cavaliere, 2019; worldsteel, 2014). Further detail on the energy requirements is provided in Table A3 in Appendix. The EAF process is capable of utilizing a feedstock of 100% scrap steel. The BOF pathway can also reduce energy intensity by utilizing scrap, but is limited by current process constraints to 25-30% of its feed (Cavaliere, 2019).

In the AA Reduced Cost of Advanced Steel case, global average energy intensity in year 2050 is 11.4 GJ/t steel (see details in Figure A2 in Appendix). The energy intensity decreases less than in the base cost scenario because there is less deployment of the EAF pathways, and therefore less use of scrap EAF. We assume that the advanced steel technologies do not utilize scrap steel, so their energy intensities are similar to that of the conventional natural gas-based DRI-EAF pathway. In the AA Reduced Cost of H_2 case, ironmaking and steelmaking energy intensity decreases to 7.7 GJ/t steel (see details in Figure A2 in Appendix), a result of the increased share of global steel production via the EAF pathway, and associated scrap use, as seen in Figure. In the AA Reduced Cost of Advanced Steel and H_2 case, the global average energy intensity reduces to 11.6 GJ/t Again, in this case the advanced low carbon DRI-EAF pathways make up almost all global production by 2050.

3.1.4 CO_2 Emissions from the Iron and Steel Sector

Figure 5 demonstrates that in the AA base costs scenario, even without significant adoption of the advanced low carbon steelmaking technologies, there is a substantial emission reduction potential in the iron and steel sector. Specifically, emissions decrease from 2200 Mt CO_2 in 2020 to 918 Mt CO_2 in 2050. In the EPPA model, direct CO_2 emissions from iron and steel production are significantly reduced because a significant share of the coal-based BOF process is replaced by natural gas-based DRI-EAF and to a larger extent recycled scrap EAF, which uses inputs (NG, electricity) that are less carbon-intensive and uses less energy overall as more scrap is utilized.

Figure 5 includes indirect emissions from electricity usage which are also decreasing due to the decrease in the emissions intensity of electricity generation. This demonstrates the advantages of electrifying processes in a world in which electricity generation has greatly decreased its CO_2 emission intensity. The average global emission intensity of electricity in the AA base cost scenario decreases from 424 kg CO_2/MWh to 11 kg CO_2/MWh by year 2050 (see Figure A3 in

Appendix). As a result, the iron and steel sector's indirect emissions from electricity usage declines from 539 Mt CO_2 in 2020 to 19 Mt CO_2 in 2050.

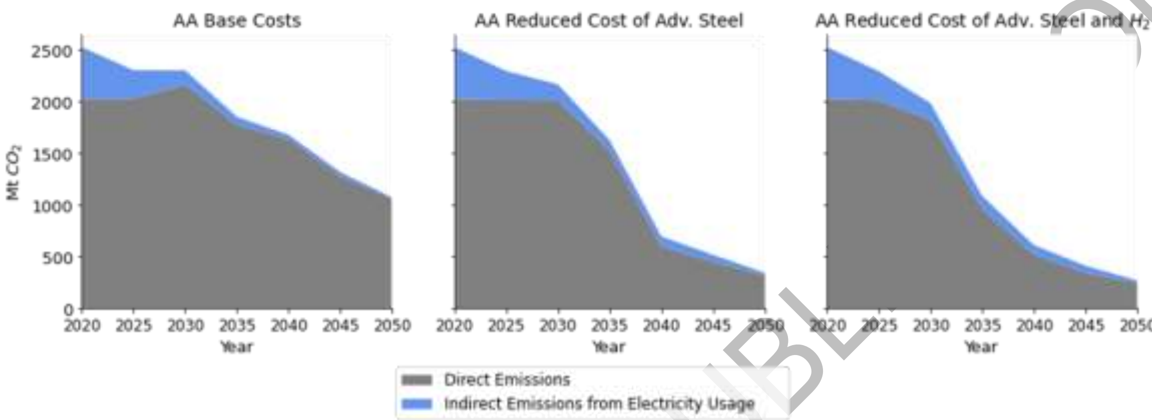

Figure 5. Direct CO_2 emissions and indirect CO_2 emissions from electricity usage associated with steel production

In the AA Reduced Cost of Advanced Steel scenario, the total direct CO_2 emissions from the steel sector decrease to 243Mt CO_2 in 2050. Coal-based BOF production drops to only 53 Mt in this case. Some emissions remain in conventional DRI-EAF steelmaking, and in DRI-EAF with CCS as well as in the H_2 DRI-EAF pathway, which uses natural gas. In the AA Reduced Cost of Hydrogen Production scenario, direct CO_2 emissions decrease to 918Mt CO_2, and in the AA Reduced Cost of Advanced Steel and Hydrogen scenario, direct emissions decrease to 223Mt CO_2. The energy use in these two cases mirrors the usage in the AA Base Cost and AA Reduced Cost of Advanced Steel Production cases, respectively (as shown in Figure 3), so the emissions are comparable to those cases.

In the Reference scenario, the direct CO_2 emission intensity is not reduced. The global average direct emission intensity of steelmaking is 1.16 tCO_2/t steel in 2020 and 1.21 t CO_2/t steel in 2050. In the Accelerated Actions scenarios, the direct emission intensities decline over time (Figure 6). In the AA Base Cost scenario, the direct emission intensity declines to 0.38 t CO_2/t steel in 2050. In the AA Reduced Cost of Advanced Steel scenario, the direct emission intensity reduces to 0.09 t CO_2/t steel by 2050. In the AA Reduced Cost of Hydrogen Production scenario, the emissions intensity decreases to 0.38 t CO_2/t steel, and in the AA Reduced Cost of Advanced Steel and Hydrogen scenario, the emission intensity is reduced to 0.07 t CO_2/t steel. The differences between these cases mirror the differences in emissions. However, the relative decreases in emissions intensities between 2020 and 2050 are slightly larger than the decreases in absolute emissions because total steel production is increasing in all cases.

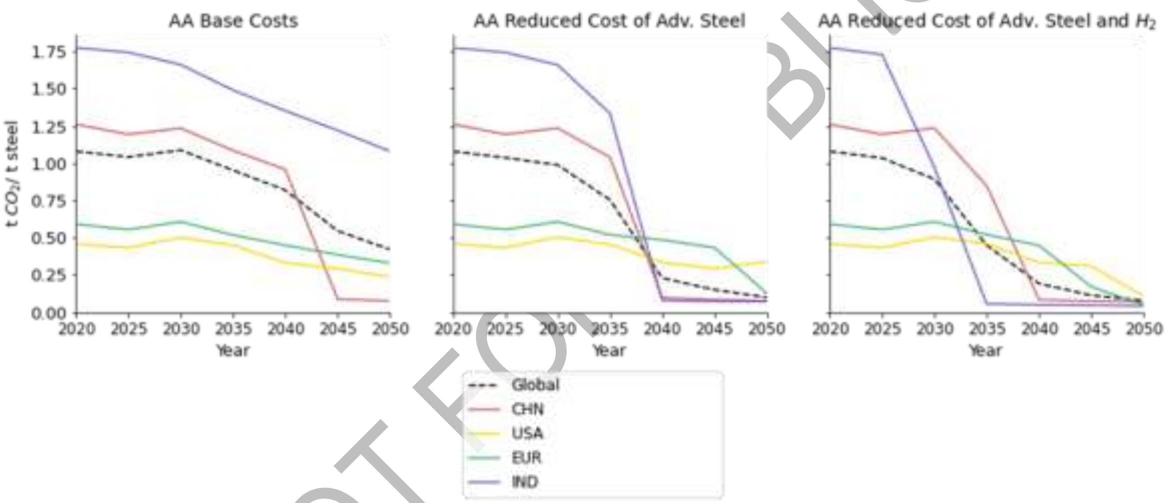

Figure 6. Direct CO_2 emission intensity of iron and steel production

3.1.6 Marginal Abatement Costs for Global Steel Production

We compare the CO_2 abatement potential of the iron and steel sector for a range of carbon prices under the different cost reduction scenarios, as illustrated in Figure 7. The fraction of abated CO_2 (x-axis) is calculated as the direct CO_2 emissions that have been abated relative to the direct emissions in the Reference scenario. The curves are developed for each case by plotting the fraction abated versus the carbon price in each model year, thereby approximating a marginal abatement cost curve (MACC). The actual MACC (in the EPPA model) would depend on numerous input and output variables in a particular year, but our simplified illustrative approach, presented in Figure 7, allows us to relate the fraction of sectoral abatement to the carbon price, which is sufficiently informative to provide general insights, particularly about how the scenarios differ from one another.

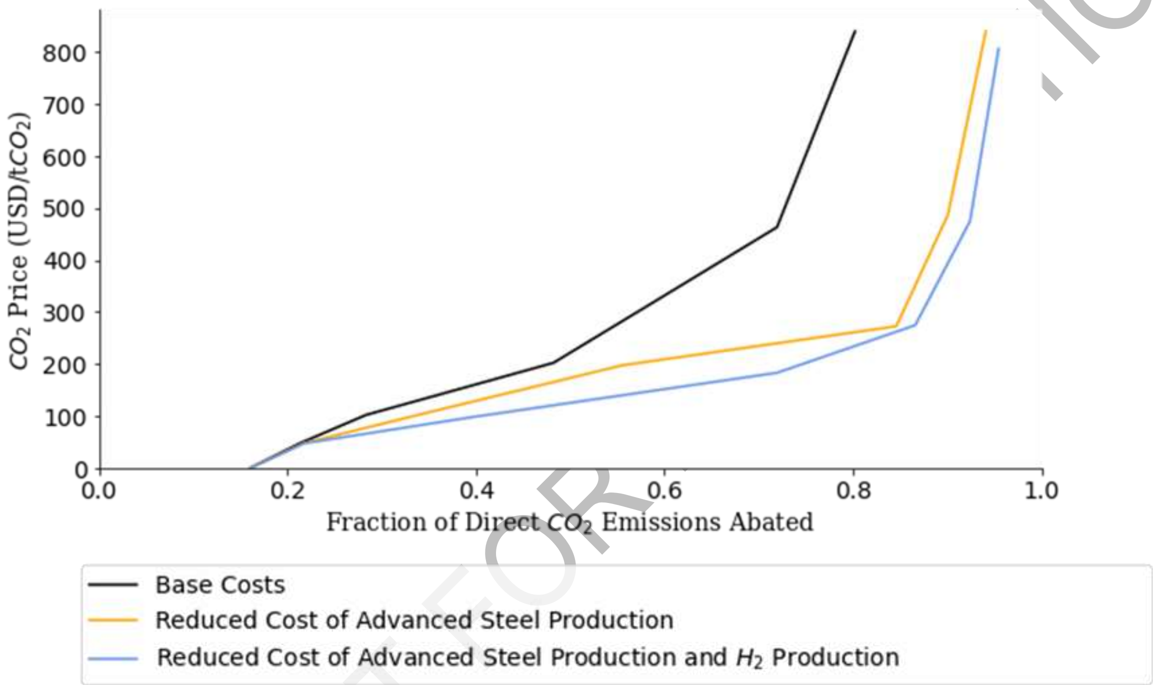

Figure 7. Abatement of direct CO_2 emissions from iron and steel production relative to the Reference case

In the scenarios that rely primarily on switching to EAF pathways (AA Base Costs and AA Reduced Cost of H_2 production), ~37% of emissions are abated below \$100/tonne, and ~65% of emissions are abated below \$300/ton. These relatively low-cost reductions can be achieved by displacing coal use in steelmaking and increasing process efficiency, primarily through the use of scrap. However, this technology shift is limited by scrap use, and even scrap DRI-EAF relies on natural gas. As a result, the MACC becomes increasingly steep at higher abatement fractions, with about 83% of emissions abated at ~$800/tonne in 2050.

In the scenarios that primarily deploy advanced steel technologies (both AA cases that include reduced cost of advanced steel production), abatement can be attained at lower cost up until very high levels of abatement are attained. About 63% of emissions can be abated under $100/tonne, and about 94% of emissions can be abated below $200/tonne. However, after about 95% abatement, emissions are not reduced further even as the carbon price increases to ~$800/tonne. Even advanced technologies, particularly those relying on CCS, have some remaining emissions.

3.2 Regional Analysis

A closer look at the regional results for China, India, U.S.A, and Europe shows distinct differences between the regions in terms of steel production pathways and decarbonization strategies. In the base year (2020), these four regions have different dominant production pathways which results in different direct CO_2 emission intensity of steel production (as seen in Figure 6). In addition, there are subsequent difference in energy intensity (see Figure A2 in Appendix). Indirect emissions from electricity usage also differ due to differences in the regional CO_2 emission intensity of electricity generation (as shown in Figure A3 in Appendix). These differences as well as differences in energy costs all contribute to the development of different regional decarbonization pathways in the policy scenarios.

3.2.1 China

In 2019 China produced 53% of global steel production (worldsteel, 2022). China is currently a net exporter, although the majority of its steel production is used domestically (worldsteel, 2022). While China's steel sector experienced rapid growth in the early 2000s, their rate of growth is anticipated to slow (IEA, 2020). Currently, China produces 90% of its steel using the BF-BOF pathway and relies heavily on coal (worldsteel, 2022). Their reliance on coal-based primary steel production pathways makes their steel production sector very energy and emissions intensive (as demonstrated in Figure 6 and Figure A2). In the base year (2020), the energy intensity of China's steel sector was approximately 20 GJ/t steel, and the direct emission intensity was 1.38 tCO_2/t steel. Figure 8 shows that in the Accelerated Action (AA) Scenario with base costs, the conventional EAF pathway grows its share of production from 10% to 18% by year 2050. Over this same period, China's total steel production also begins to decline which also reduces emissions from the steel sector. In the AA scenario assuming reduced cost of advanced steel production, the DRI-EAF with CCS scenario makes up nearly all the production. In the AA scenario assuming reduced cost of H_2 production, the model produces the similar results as in the base cost scenario with the share of conventional EAF pathways increasing to 18% by year 2050. In the scenario with reduced cost of both advanced steel production and H_2 production, the H_2 DRI-EAF pathway makes up nearly all of production by year 2050.

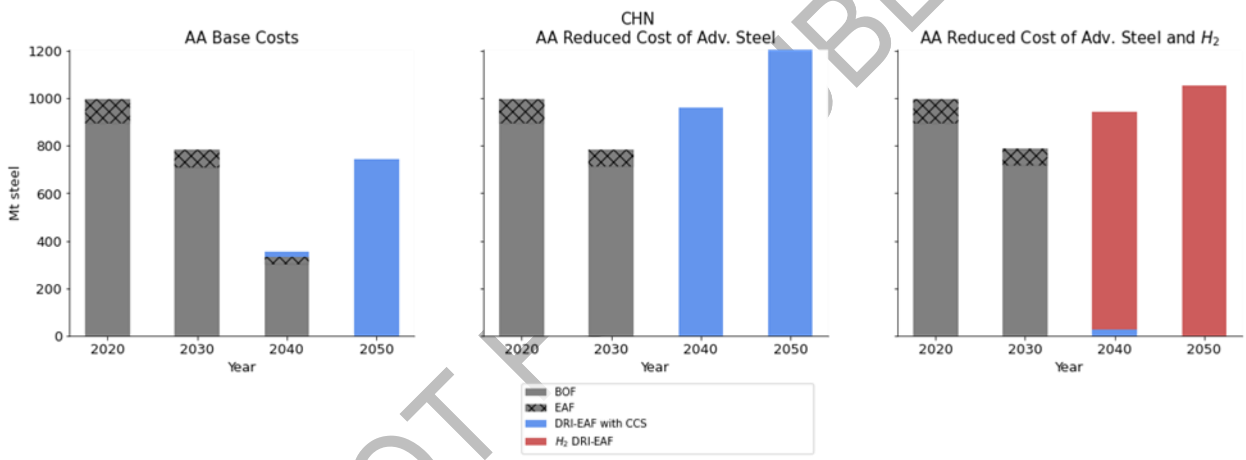

Figure 8. China's steel production by process in different cost scenarios

3.2.2 India

India's economy is rapidly expanding and its steel production is projected to increase by a factor of 3-4 by 2050 (IEA, 2020; Paltsev et al., 2022). In 2019, India produced 100 Mt of steel, making up about 6% of global production (worldsteel, 2022). India's current production is about 44% via BOF, 28% via coal-based DRI-EAF and 28% scrap-based EAF (worldsteel, 2022). India's DRI shaft furnaces primarily use coal as the reducing agent and for energy supply, which differs from other regions which primarily use natural gas in the DRI process (Paltsev et al., 2022). In the base year, India's steel production has an energy intensity of 18.9 GJ/t and a direct

CO_2 emission intensity of 1.59 tCO_2/t steel. In the Accelerated Actions scenario assuming base costs, India's steel production increases and they increasingly switch away from coal energy. Figure 9 shows that in the base cost scenario, the share of conventional EAF produced steel increases from ~56% to ~100% by year 2050. When assuming reduced cost of advanced steel production, by 2050, ~96% of production is via the DRI-EAF with CCS pathway and the remaining share of 4% is produced via the H_2 pathway. Assuming reduced cost of hydrogen production results in the EAF pathway producing ~99.9% of production. Of the four regions that we examined, in our model India's natural gas price is the highest and their electricity price the second most expensive. This makes the hydrogen more competitive when assuming a low cost of $1/kg and reduced non-energy cost of steel production. In the scenario assuming reduced cost of advanced steel and hydrogen production, 100% of production is via the H_2 DRI-EAF pathway.

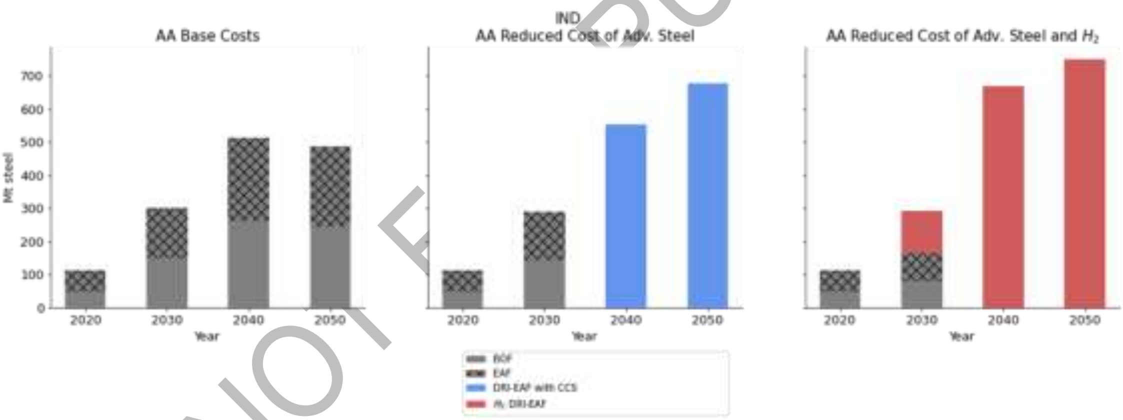

Figure 9. India's steel production by process in different cost scenarios.

3.2.3 USA

The U.S.A. is currently produces about 4.7% of global steel production. In 2019, 67% was produced via the scrap-based EAF pathway, 30% via the BOF pathway and 3% via the DRI-EAF pathway (worldsteel, 2022). In the base year of 2020, the energy intensity of U.S. steel production was 9 GJ/t steel and the direct CO_2 emission intensity was 0.57 t CO_2/t steel.

Figure 10 shows that in the Accelerated Actions base costs scenario in year 2050, the U.S.

produces 100% of its steel via conventional EAF pathways. When assuming reduced cost of advanced steel production then 91% is produced from the H_2 DRI-EAF pathway and 9% via conventional BOF pathways. Assuming reduced cost of H_2 production, by year 2050, 100% of production is via conventional EAF pathways. When assuming reduced cost of both advanced steel production and H_2 production then 100% is produced from H_2 DRI-EAF pathways.

We also explore the impact of the Inflation Reduction Act (IRA) tax credits (Woollacott et al., 2023) on the cost of CCS steel and H_2 production. This scenario is based on the Accelerated Action policy scenario but also incorporates the IRA 45Q tax credits of $85/t captured CO_2 to both the DRI-EAF with CCS technology and the Blue H_2 production technology. In addition, this scenario applies the full 45V tax credit of $3/kg to the Green H_2 production cost. The tax credits are implemented indefinitely with no end date. The tax credits reduce the H_2 production costs by 42% for the Blue and 52% for the Green H_2.

These tax credits resulted in a 7% reduction in the cost the DRI-EAF with CCS pathway, a 9% reduction in the cost of Blue H_2 DRI-EAF and a 23% reduction in the cost of the Green H_2 steelmaking pathway. However, the DRI-EAF with CCS is still the cheapest option with a total steel production cost that is 7% cheaper than the Blue H_2 DRI-EAF. When these tax credits are implemented in the EPPA model's Accelerated Action scenario, it results in large scale deployment of DRI-EAF with CCS, and by 2050, this pathway makes up 100% of U.S. steel production. In this scenario, in 2050 the United States produces ~128 Mt/yr of steel resulting in the capture of ~69 Mt/yr of CO_2.

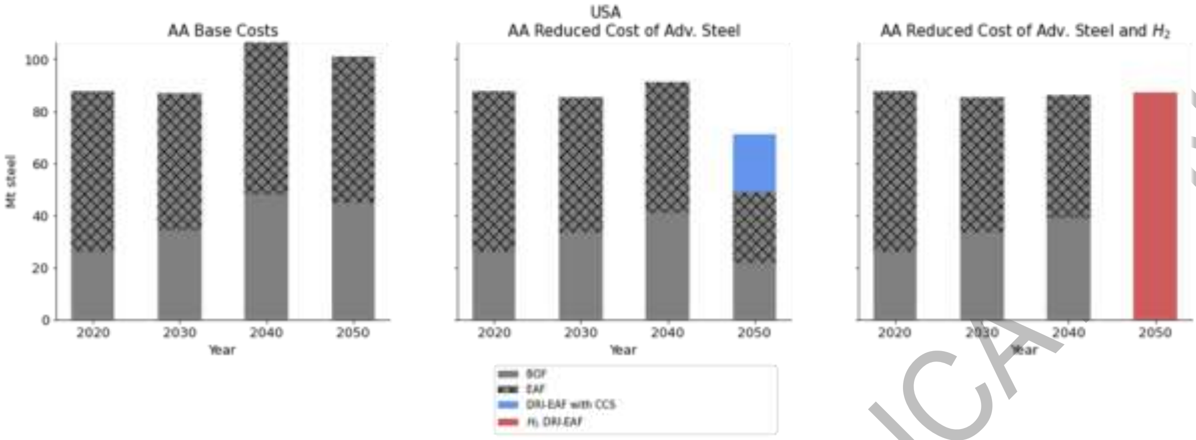

Figure 10. USA's steel production by process under different cost scenarios

3.2.4 *Europe*

Europe is currently produces about 8.5% of global steel production (worldsteel, 2022). In the base year the European region produced 40% of their steel via the EAF pathway and 60% via the BOF pathway (worldsteel, 2022). In the base year, the energy intensity was ~11.5 GJ/t steel and the direct CO_2 emission intensity was 0.76 t CO_2/t Steel. Figure 11 demonstrates that in the Accelerated Actions scenario when assuming base costs, 100% of the European region's steel is produced via the conventional EAF pathways. When assuming reduced non-energy costs of advanced steel technologies, then 100% of production is via the H_2 DRI-EAF pathway. The DRI-EAF with CCS pathway is assumed to utilize natural gas and in Europe the natural gas price is the second highest of the four regions that we analyzed. This contributed to the H_2 DRI-EAF pathway being more competitive. Assuming reduced cost of H_2 production, then Europe uses conventional EAF pathways for 100% of total production. Lastly, when assuming reduced cost of advanced steel production and reduced cost of H_2 production then 100% of production is via the H_2 DRI-EAF pathway, which utilizes ~15 Mt of H_2 in the year 2050.

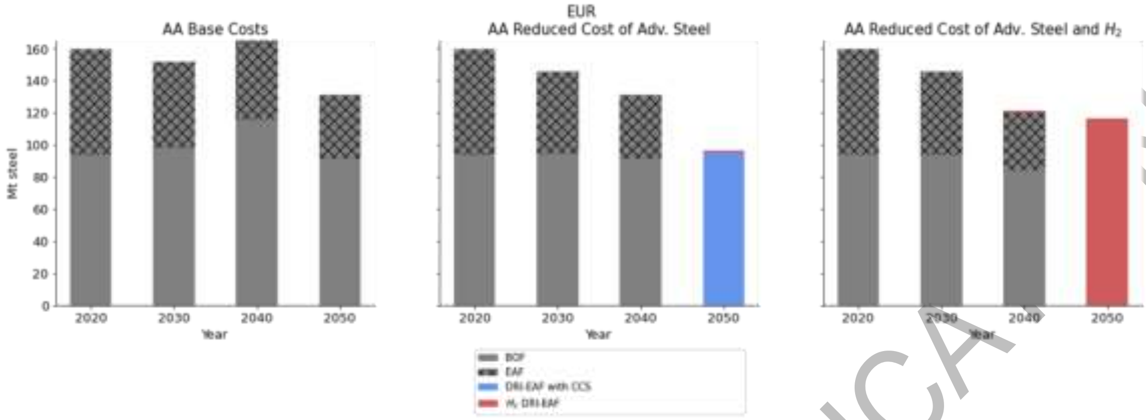

Figure 11. Europe's steel production by process in different cost scenarios

4. Concluding Remarks

Deployment of advanced steelmaking technologies in different regions are affected by cost and policy developments. In a base costs decarbonization scenario, the DRI-EAF with CCS pathway is currently more cost-competitive than the H_2 DRI-EAF pathway. If the cost of H_2 production is reduced then the H_2 DRI-EAF pathway is deployed in several regions. However, even in this scenario the cost of \$1/kg (or \$7/GJ) still exceeds the price of natural gas in low-cost regions such as the United States. We show that H_2 cost reductions (as an input to steelmaking) need to be combined with cost reductions in the steelmaking process itself.

Both Blue and Green hydrogen production pathways are currently more expensive than conventional fossil fuels. Low carbon H_2 production costs may decrease in the future due to technological advances or become more competitive if carbon prices are implemented. Targeted policies such as the U.S.'s Inflation Reduction Act (IRA) can lower H_2 production costs significantly, however they will be in competition with the other IRA tax credits such as the 45 Q tax credit for carbon capture. While these IRA tax credits resulted in a 7% reduction in the cost the DRI-EAF with CCS pathway, a 9% reduction in the cost of Blue H_2 DRI-EAF and a 23% reduction in the cost of the Green H_2 steelmaking pathway, in this scenario the DRI-EAF with CCS is still the cheapest steelmaking option in USA.

An important finding is that the steel sector can substantially reduce its CO_2 emission intensity using currently available conventional steelmaking pathways. BF-BOF, DRI-EAF and scrap-based EAF pathways can achieve greater energy efficiencies and thus use less fossil fuels. The use of scrap steel can also further reduce energy usage. The scrap-based EAF pathway is more energy efficient than the BOF pathway and switching to this pathway further reduces energy consumption. Furthermore, under a decarbonization policy scenario the electricity generation sector is also decarbonizing which makes electrification of steelmaking increasingly advantageous. However, scrap steel stock is limited and will not be sufficient to meet steel demand. Our analysis shows that scrap use will be increasing and about 1,300 Mt of scrap will be used by the year 2050. Hence, advanced pathways for primary steel production should also be explored further.

In this paper we focused on the advanced steelmaking using the EAF pathways. While CCS is also possible for the BF-BOF route, the major steel producing countries where currently the share of BF-BOF is large (China, India and Japan) aim to shift to EAF steelmaking to fulfill their declared net-zero emission targets. Future research is needed to explore the full set of advanced steelmaking options. Our analysis shows that the optimal decarbonization pathways for steelmaking are region specific. Technology deployment is influenced by the region's current steel production processes and by their regional costs. For example, India's current reliance on coal for the DRI- EAF pathway can be altered by gradual switching to natural gas and biofuels. Regional differences in the types of processes deployed also influence that region's competitiveness with other regions.

Under deep decarbonization policy scenarios, pathways with lower emission intensities are more advantageous to deploy and regions will select the technology most favorable to their region. Reducing the cost of advanced steelmaking leads to substantial increases of CCS deployment in China and India, while in Europe steelmaking switches to hydrogen. Steelmaking in the United

States initially deploys CCS, while hydrogen is playing a large role by mid-century. While we find that in general the DRI-EAF with CCS pathway is currently more cost-competitive that the H_2 DRI-EAF pathway, actions in the form of research and development (R&D), technology demonstration, technology transfers, infrastructure development and policy incentives could accelerate the transition to a low-emitting steelmaking industry and further impact the competition among advanced technology options.

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Appendix. Supplemental Information

Table A1. Regional Costs

Region	**Coal ($/MMBTU)**	**Natural Gas ($/MMBTU)**	**Electricity ($/kWh)**	**CO_2 T&S ($/t$CO_2$)**	**Blue Hydrogen ($/GJ)**	**Green Hydrogen ($/GJ)**
Reference	(Aguiar et al., 2019)	(Aguiar et al., 2019)	(Aguiar et al., 2019)	(Smith et al., 2021)	(Benavides et al., 2022)	(Benavides et al., 2022)
CHN	$ 3.32	$ 4.33	$ 0.08	$ 14.96	$ 13.44	$ 46.54
IND	$ 4.09	$ 13.04	$ 0.15	$ 24.31	$ 27.58	$ 52.89
USA	$ 3.72	$ 4.77	$ 0.10	$ 10.55	$ 13.87	$ 40.92
EUR	$ 4.71	$ 12.72	$ 0.17	$ 33.65	$ 26.58	$ 37.74
JPN	$ 6.06	$ 14.80	$ 0.22	$ 33.65	$ 30.01	$ 31.85
KOR	$ 6.11	$ 14.86	$ 0.11	$ 33.65	$ 28.63	$ 47.31
CAN	$ 3.36	$ 9.48	$ 0.09	$ 10.55	$ 19.30	$ 42.02
MEX	$ 4.62	$ 11.86	$ 0.11	$ 10.55	$ 25.66	$ 68.17
BRA	$ 4.67	$ 11.11	$ 0.15	$ 14.96	$ 25.02	$ 57.01
RUS	$ 3.46	$ 9.15	$ 0.07	$ 10.55	$ 18.54	$ 43.50
LAM	$ 4.02	$ 8.49	$ 0.11	$ 14.96	$ 20.59	$ 57.01
ROE	$ 4.65	$ 8.53	$ 0.10	$ 14.96	$ 19.05	$ 43.50
ASI	$ 4.84	$ 11.62	$ 0.14	$ 14.96	$ 24.20	$ 47.31
REA	$ 3.58	$ 4.04	$ 0.11	$ 14.96	$ 14.06	$ 47.31
ANZ	$ 4.13	$ 7.69	$ 0.16	$ 14.96	$ 19.71	$ 44.63
MES	$ 4.81	$ 6.07	$ 0.13	$ 10.55	$ 16.76	$ 47.31
AFR	$ 3.08	$ 6.18	$ 0.10	$ 24.31	$ 19.17	$ 68.17
IDZ	$ 3.13	$ 8.12	$ 0.07	$ 14.96	$ 18.03	$ 47.31

Table A2. Regional steel production by process type in 2019. Data derived from the World Steel Association *(worldsteel, 2022)*

Region	**BOF [Mt]**	**DRI-EAF [Mt]**	**EAF [Mt]**
China	896	0	100
European Union	94	1	65
India	49	31	32
Japan	75	0	24
USA	26	3	59
Russia	47	7	18
S. Korea	49	0	23
Other Eurasia	37	0	28
Middle East	3	36	6
Dynamic Asia	14	1	21
Brazil	25	0	7
Other East Asia	13	0	14
Africa	4	6	9
Mexico	4	5	9
Canada	8	1	4
Other Latin America	7	1	2
Indonesia	4	0	5
Australia and New Zealand	5	0	1

Table A3. Energy Intensities of Steel Production Pathways

Energy Usage [GJ/tonne hot rolled steel]	BF-BOF	DRI-EAF	Scrap-based EAF	DRI-EAF with CCS	Hydrogen-based DRI-EAF
Coal	15.3	0	0.6	0	0
Natural Gas	1.1	12.9	1.7	12.9	3
Electricity	1.0	3.6	2.3	4.4	3.6
Hydrogen	0	0	0	0	11.5

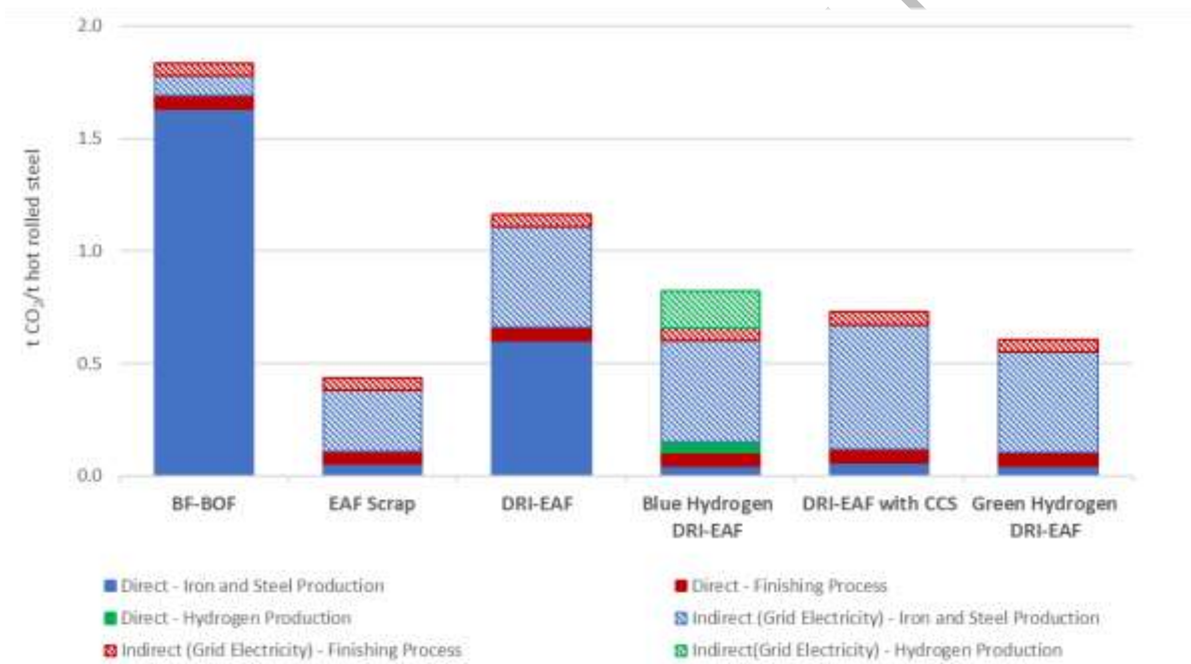

Figure A1. Emission Intensity of Steelmaking Pathways

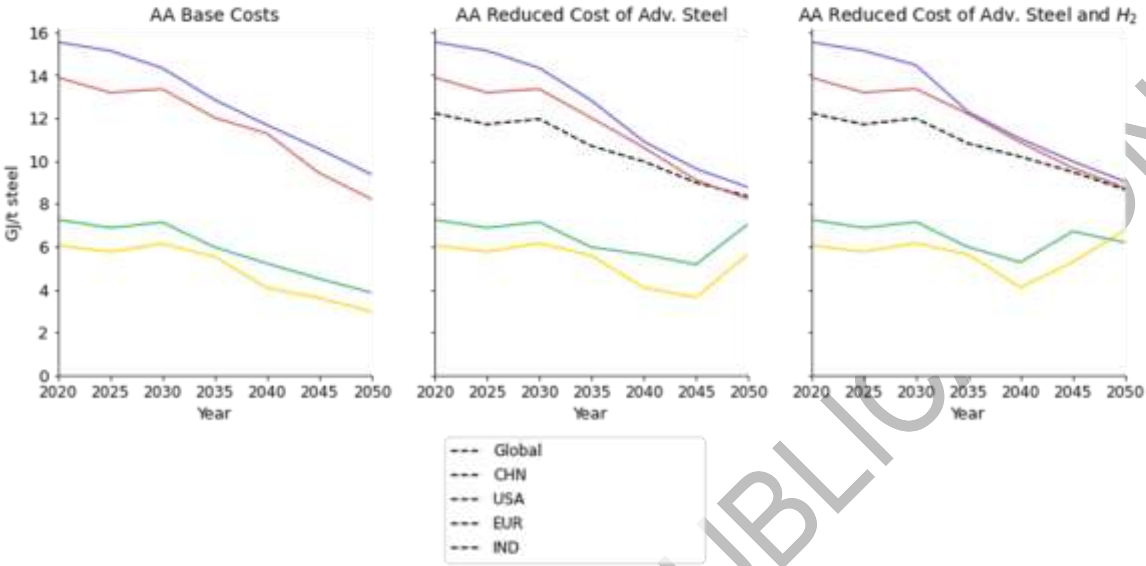

Figure A2. Energy intensity of iron and steel production (CHN=China, USA=USA, EUR=Europe, IND=India).

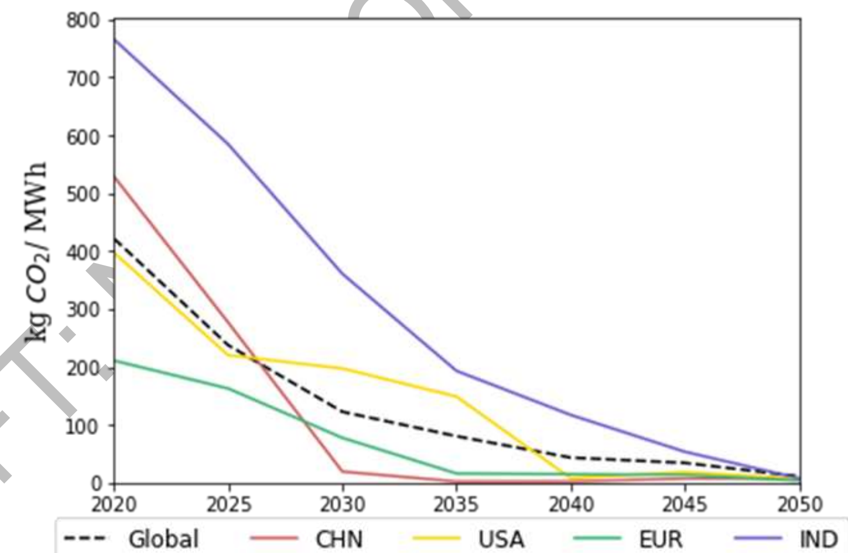

Figure A3. Direct CO_2 Emission Intensity of Electricity Generation for the Accelerated Action policy case with base cost assumptions without deployment of negative emission technologies (CHN=China, USA=USA, EUR=Europe, IND=India).