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Decarbonization scenarios for the iron and steel industry in context of a sectoral carbon budget: Germany as a case study

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ABSTRACT

CO_2 emissions from global steel production may jeopardize climate goals of 1.5 °C unless current steel production practices will be rapidly decarbonized. At present, primary iron and steel production is still heavily dependent on fossil fuels, primarily coke. This study aims to determine which decarbonization pathways can achieve the strongest emission reductions of the iron and steel industry in Germany by 2050. Moreover, we estimate whether the German iron and steel industry will be able to stay within its sectoral carbon budgets for a 1.5 °C or 1.75 °C target. We developed three decarbonization scenarios for German steel production: an electrification, coal-exit, and a carbon capture and storage (CCS) scenario. They describe a phase-out of coal-fired production plants and an introduction of electricity-based, low-carbon iron production technologies, i.e. hydrogen-based direct reduction and electrowinning of iron ore. The scenarios consider the age and lifetimes of existing coal-based furnaces, the maturity of emerging technologies, and increasing recycling shares. Based on specific energy requirements and reaction-related emissions per technology, we calculated future CO_2 emissions of future steel production in Germany. We found that under the decarbonization scenarios, annual CO_2 emissions decrease by up to 83% in 2050 relative to 2020. The reductions of cumulative emissions by 2050 range from 24% (360 Mt CO_2) under the electrification scenario up to the maximum of 46% (677 Mt CO_2) under the CCS scenario compared to a reference scenario. This clearly demonstrates that the technology pathway matters. Nevertheless, the German steel sector will exceed its sectoral CO_2 budget for a 1.5 °C warming scenario between 2023 and 2037. Thus, drastic measures are required very soon to sufficiently limit future CO_2 emissions from German steel production, such as, a rapid decarbonization of the electricity mix, the construction of a hydrogen and CCS infrastructure, or early shutdowns of current coal-based furnaces.

1. Introduction

Studies have shown that CO_2 emissions due to global steel production will jeopardize the 1.5 °C climate target unless steel production is rapidly decarbonized through low-emission production technologies (Tong et al., 2019; Wang et al., 2021).

Of all metals, steel production is responsible for the highest greenhouse gas emissions (GHG), i.e. 9% of global emissions (Nuss and Eckelman, 2014; Wang et al., 2021). As steel is required for buildings, infrastructure, and technologies, it is a key metal for modern societies. Consequently, its demand is expected to increase due to the future industrialization of developing countries (van Ruijven et al., 2016; Elshkaki et al., 2018). Therefore, studies stress the need to develop and implement low-emission technology alternatives for the currently coal-fired primary production (Arens et al., 2017; Tong et al., 2019; Ryan et al., 2020).

The largest steel producer in Europe is Germany, ranking seventh worldwide (WSA, 2020). In Germany as well as globally, the majority of steel is produced via primary production, around 70%, while secondary production accounts for about 30% (WSA, 2019b, 2020). Primary steel is commonly produced via the blast furnace and basic oxygen furnace route (BF-BOF), which mainly uses coke as energy carrier and therefore has a very high emission intensity of 1.6–2.2 t CO_2/t steel (Hasanbeigi et al., 2014; Toktarova et al., 2020).

Previous research has shown that the commonly used BF-BOF route can barely be decarbonized (Madeddu et al., 2020) as it requires very

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high temperatures of up to 2000 °C (de Beer et al., 2000; Hasanbeigi et al., 2014). The only other mature process currently being applied is natural gas-based direct reduction (NG-DRI). NG-DRI has a lower emission-intensity than the BF, but it is not widely deployed as natural gas is in most countries not cost-competitive with coke (Moya and Pardo, 2013). Retrofitting BF-BOFs with post-combustion carbon capture and storage (BF-BOF-CCS) can reduce emissions by up to 60% (IEAGHG, 2013), yet this is insufficient for the long term targets.

Thus, in the case of primary steel production a significant CO_2 reduction can only be achieved through a switch to different technologies. For a deep emission reduction, the key strategy is electrification (Philibert, 2017; de Coninck et al., 2018; Lord, 2018; Madeddu et al., 2020). The technologies considered most promising are hydrogen-based direct reduction (H2-DRI) and electrolysis of iron ore (Fischedick et al., 2014; Lechtenböhmer et al., 2016; Weigel et al., 2016; Philibert, 2017). H2-DRI enables an indirect electrification through hydrogen from water electrolysis, and iron electrolysis allows for a direct electrification of primary steel production.

Hydrogen-based direct reduction (H2-DRI) can be almost CO_2 emission-free if operated with hydrogen from renewable electricity (Fischedick et al., 2014). H2-DRI is often considered the most suitable technology for the near future, as it can be adapted from the already existing technology of natural gas-based DRI (NG-DRI). Direct reduction furnaces can be operated with a mix of natural gas and hydrogen (de Beer et al., 2000). Thus, DRI enables a transition from natural gas to hydrogen in the same furnaces, once enough hydrogen is available (Bhaskar et al., 2020). In Germany, various steel producers plan to implement H2-DRI facilities, e.g. Salzgitter, ArcelorMittal or Thyssenkrupp (Ruhwedel, 2020; Agora Energiewende and AFRY Management Consulting, 2021).

A less mature alternative, yet directly electrified technology, is electrolysis of iron ore. It applies electricity to reduce iron ore and thus avoids the conversion losses during hydrogen production, that occur in the case of H2-DRI. Two types of electrolysis are at pilot stage: first, electrowinning (EW) in a low-temperature (110 °C) alkaline solution (Yuan et al., 2009) with a pilot plant in France under the SIDERWIN project (Lavelaine, 2019; IEA, 2020a); secondly, using high-temperature molten oxide with a temperature of 1600 °C (Ryan et al., 2020). This type using high temperatures is considered less mature than the electrowinning at lower temperatures (Hasanbeigi et al., 2014).

For more information on current and future steel production technologies, the reader is referred to the existing literature, such as Zhang et al. (2021), Wang et al. (2021), or IEA (2020a).

The German Federal Ministry for Economic Affairs and Climate Action (BMWK, former BMWi) considers NG-DRI for the very near future with a transition to H2-DRI for the long-term as key technologies for a decarbonization of primary steel production according to its Steel Action Concept (BMWi, 2020), yet it does not propose concrete transition pathways. Germany's Climate Protection plan suggests implementing CCS to address unavoidable emissions in industry and to reach GHG reductions of 95% by 2050 (BMU, 2016).

Many previous studies investigated emission-reduction potentials of different technologies individually (Hasanbeigi et al., 2014; Otto et al., 2017; Tian et al., 2018; Vogl et al., 2018; Bhaskar et al., 2020; Zhang et al., 2021). Amongst these only a few consider the novel technology of electrolysis of iron (Fischedick et al., 2014; Lechtenböhmer et al., 2016; Weigel et al., 2016).

Some studies model regional transformation pathways, e.g. for Sweden (Toktarova et al., 2020) or the US (Ryan et al., 2020), and investigate their emission reduction potential by a certain target year. Arens et al. (2017) calculated potential future CO_2 emissions from German steel production by 2035 considering amongst others the technologies of NG-DRI or smelting reduction, which replaces coke with pulverized coal (Zhang et al., 2021). They found that the emission-intensities of these technologies are still too high to reach climate goals. Therefore, they recommend the inclusion of more technology alternatives, such as H2-DRI or electrolysis of iron ore.

Other studies developed transformation pathways for the steel industry and compared their future *cumulative* emissions to a global carbon budget. Tong et al. (2019) show that emissions of currently existing industrial plants alone will exhaust the entire global carbon budget for a 1.5 °C scenario, if operated until their average end-of-life. Wang et al. (2021) estimated future cumulative emissions by 2050 from the global steel industry under scenarios for efficiency improvements. Even their strictest efficiency scenarios would exceed a sectoral 1.5 °C budget for the steel sector by more than 100%, if the global budget was distributed to sectors based on current emission shares. Similarly, Ryan et al. (2020) stress that immediate action is required for the steel industry in the US to achieve a linear reduction of emissions by 70% by 2050.

Research to date has not yet determined decarbonization pathways for the iron and steel industry in Germany to stay within the sector's carbon budget, considering the deployment of both indirectly and directly electrified primary production technologies, such as electrowinning of iron ore. This study aims to answer the following two research questions:

1. Which technology pathways can achieve the strongest decarbonization of the iron and steel industry in Germany by 2050 and what are their implications in terms of future final energy demand?
2. To which extent may the German iron and steel industry be able to stay within its sectoral carbon budget for a 1.5 °C target?

In this study, we developed three decarbonization scenarios for steel production with the goal to phase out fossil fuels-based furnaces and to achieve a primarily electricity-based steel production by 2050. The scenarios model the replacement of currently existing BFs in Germany with directly and indirectly electrified production technologies, such as electrowinning and H2-DRI. To calculate future CO_2 emissions, we developed process models for energy consumption and reaction-related emissions of six steel production routes. We compared the resulting emissions with carbon budgets, which we allocated to the sector from carbon budgets for Germany (see section 2.4).

The results can inform decision-makers which technology pathway may be most efficient to minimize future CO_2 emissions from the iron and steel industry in Germany. Moreover, they reveal implications for the energy system and infrastructure requirements, for example, in terms of future demand for hydrogen, electricity or carbon storage facilities.

2. Material and methods

2.1. Process models for current and future steel production routes

We developed a process model to calculate current and future CO_2 emissions from steel production in Germany considering six different steel production routes (see Fig. 1). Three of them are current practice, these are the blast furnace and basic oxygen furnace (BF-BOF), natural gas-based direct reduction (NG-DRI), and the scrap-based electric arc furnace (scrap-EAF) routes. Two technology routes represent low-carbon, electrified technologies for iron production: the hydrogen-based direct reduction (H2-DRI) for indirect electrification and electrowinning (EW) for direct electrification. They are followed by the electric arc furnace (EAF) to refine iron to steel. The BF-BOF-CCS route applies post-combustion carbon capture and storage (CCS) to the BF-BOF route.

Using data from literature, we modelled process-specific energy requirements and derived CO_2 emissions for each route, i.e. energy- and reaction-related CO_2 emissions (see section 2.3). The specific energy demand of existing technologies was calibrated using energy statistics for the steel sector for the year 2018 (Rohde, 2019).

The model describes the steel production chain from raw material preparation, e.g. sinter or pellet production from iron ore, up to the steel

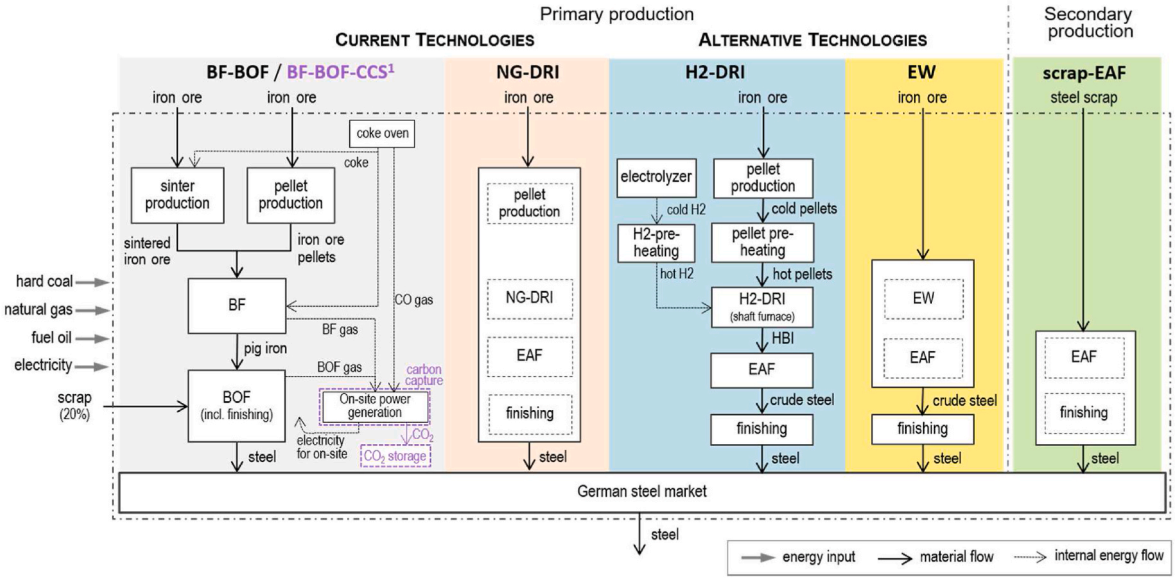

Fig. 1. Process model of the six steel production routes considered. For the BF-BOF route, on-site power generation from process gases is included in the system. For the BF-BOF-CCS route, post-combustion carbon capture is applied to the on-site power plant. BF-BOF = blast-furnace and basic-oxygen furnace; BF gas = blast-furnace gas; BOF gas = basic-oxygen furnace gas; CCS = carbon capture and storage; CO gas = coke oven gas; EW = electrowinning; H2-DRI = hydrogen-based direct reduction; NG-DRI = natural gas-based direct reduction; scrap-EAF = scrap-based electric arc furnace. 1: BF-BOF-CCS is illustrated here within the current technology of BF-BOF due to space restrictions, but it is technically also an alternative technology.

market. Mining of iron ore is excluded. The main characteristics and assumptions for each production route are given in Table 1. The complete dataset is provided in a repository (Harpprecht et al., 2022).

The BF-BOF route is a highly integrated system, which reuses flue gases from different ovens (BF, BOF, and CO gas) (Remus et al., 2013). Our model takes this into account including on-site power generation from these gases.

For the BF-BOF-CCS, we assumed that post-combustion carbon capture facilities are deployed at the on-site power plant to clean the flue gases (Chisalita et al., 2019). Additional electricity and steam required for the carbon capture facility are produced on-site in the gas-fired power plant and increase its natural gas consumption. Carbon transport and storage, i.e. CO_2 compression and injection require additional electricity from the grid (15.65 kWh/t steel). We assume transport in pipelines over 800 km and storage in the North Sea based on Chisalita et al. (2019). Losses of CO_2 from CCS are neglected, as they amount to less than 0.2% of CO_2 captured according to Chisalita et al. (2019). In this study, we consider CCS for BF-BOFs only as an interim and not a long-term solution. It should only be applied on already existing fossil fuel-based furnaces to reduce their emissions until they can be replaced by electrified technologies in the future.

The developed process model is implemented in the Activity Browser, an open-source software, which was used to calculate the final energy demand and emissions (Steubing et al., 2020). The python code for this can be found in our repository (Harpprecht et al., 2022).

2.2. Scenario definition: development of technology pathways

We developed a reference scenario, in which current production practices are continued, and three decarbonization scenarios for the German iron and steel industry: an electrification, a coal-exit, and a carbon capture and storage (CCS) scenario. The decarbonization scenarios were derived as explorative pathways which have as an objective to phase out coal- and natural-gas based furnaces and to achieve a primarily electricity-based steel production by 2050. The reference scenario shows a future where electrification cannot be achieved.

The backbone of all scenarios is the future development, specifically the phase-out, of blast furnace capacities in Germany. We assume that only if a BF is shut down, a new technology can enter the market and take over the then available capacity. The phase-out of BFs is modelled using data on capacity and age of each individual BF currently existing in Germany from Arens et al. (2017). The lifetime of the BFs is varied according to the narrative of each scenario, see Table 2. Based on the future capacity of BFs (see section B.2.1 for details), we then modelled the future market shares of the other five production routes in five-year intervals until 2050 with the following constraints and assumptions.

2.2.1. Constraints for all scenarios

- Total steel production stays constant at 42.4 Mt steel/year as in 2018 (WSA, 2019a). In the past, steel production in Germany has stayed relatively constant (WSA, 2019a). We assume a constant production also for the future since high-income countries require steel mostly for maintaining already existing infrastructure (Brown et al., 2012; Brunke and Blesl, 2014; Mayer et al., 2019). This is different from developing countries, which are expected to have an increasing steel demand in the future to build up completely new infrastructure (Brown et al., 2012).
- Depending on the scenario narrative, BF capacity is replaced with other technologies (see Table 2) but not before the technology-specific year of market entry from Table 1.
- Scrap availability increases by 0.9% per year (Arens et al., 2017) with scrap being input to the BF-BOF, scrap-EAF and, if necessary, to EW. This scrap availability cannot be exceeded by the scrap consumption (see section B.2.3).
- For the decarbonization scenarios: Diffusion of NG-DRI and H2-DRI, i.e. building new furnaces for direct reduction, takes place from 2025 to 2040. After 2040, DRI capacity does not increase anymore, as new capacities are assumed to be realized through EW, which then enters the market. NG-DRI serves as a bridging technology for H2-DRI, until sufficient hydrogen is available in 2040. The diffusion of hydrogen for direct reduction follows a typical s-shape (Hall and Khan, 2002) (see Figure B-2).

Table 1

Description and used data sources for the modeled steelmaking technologies. The complete dataset is provided in the repository (Harpprecht et al., 2022).

Technology	BF-BOF	BF-BOF-CCS	NG-DRI	H2-DRI	EW	Scrap-EAF
Name	Blast furnace and basic oxygen furnace	BF-BOF with post-combustion carbon capture and storage (CCS)	Natural gas-based direct reduction	Hydrogen-based direct reduction	Electrowinning	Steel scrap recycling in electric arc furnace
Main energy carrier	coal	coal	natural gas	electricity for H2 from water electrolysis	electricity	electricity
Market shares in DE in 2018[1]	70%	0%	1.2%	0%	0%	28.8%
Technology readiness level (TRL)[2]	9	>5[7]	9	5–7[3]	4–6	9
Assumed year of market entry	–	2025[6]	–	2025[4]	2040[5]	–
Data source for energy demand	Remus et al. (2013)	IEAGHG (2013), Chisalita et al. (2019)	Arens et al. (2017)	Bhaskar et al. (2020), Worrell et al. (2007)	Fischedick et al. (2014), Worrell et al. (2007)	Arens et al. (2017)
Details and assumptions	Integrated system with on-site power generation from flue gases. No export of flue gases or other energy carriers. Scrap is added to BOF (20% of input into BOF, see section B.2.3).	Carbon capture (CC) technology is chemical absorption with mono-ethanol amine. Additional electricity and steam for CC are produced on-site from additional natural gas, i.e. 3.36 GJ NG/t steel. CCS reduces emissions of current BF-BOF by 50%.	Bridging technology for H2-DRI, as planned by Salzgitter and Arcelor Mittal. Mixtures of natural gas and hydrogen can be applied. Pure hydrogen can be used later without retrofitting (Agora Energiewende and Wuppertal Institut, 2019).	Shaft furnace, e.g. by Midrex (same as existing DRI plant in Hamburg), which can be fed with pellets or lump ore. Varying mixtures of natural gas and hydrogen can be applied.	Electrolysis of iron ore, using a low-temperature (110 °C) alkaline solution (Zhang et al., 2021). A TRL of 4 has been achieved by previous projects. The Siderwin project led by ArcelorMittal aims to achieve TRL 6 by 2022 (Lavelaine, 2019).	Some fossil fuels (hard coal and natural gas) are required for the EAF for heat provision. 1.1 t scrap are required to produce 1 t of steel (Remus et al., 2013).

1: (WV-Stahl, 2019; WSA, 2019a); 2: ranges from 1 (initial idea) to 9 (maturity). From (Agora Energiewende and Wuppertal Institut, 2019; IEA, 2020a; Toktarova et al., 2020; Wang et al., 2021); 3: if pure hydrogen is used, the TRL is 5. For a mixture with natural gas, the TRL is 7; 4: (Agora Energiewende and Wuppertal Institut, 2019; Ruhwedel, 2020; Toktarova et al., 2020); 5: (Fischedick et al., 2014); 6: (Agora Energiewende and Wuppertal Institut, 2019; IEA, 2020a); 7: For iron and steel, the TRL for amine-based CO_2 capture is 5 (IEA, 2020a). At power plants, the TRL is already 7–8 (Hills et al., 2016).

Table 2
Description of the four scenarios modelled for the German iron and steel industry. The average (av.) lifetime of blast furnaces (BFs) is assumed to be 50 years, which can be prolonged by 20 years through relining of the furnaces to reach 70 years (Arens et al., 2017, Agora Energiewende and Wuppertal Institut, 2019).

Scenario	Description	Assumptions for BF lifetimes	Technologies replacing BF-BOFs			
			NG-DRI	H2-DRI	EW	BF-BOF-CCS
Reference	• Continuation of current production practices with the goal of minimizing investment costs. • Low-carbon technologies are not deployed, instead av. lifetimes of BFs are prolonged.	70 years Prolongation of av. lifetime of BFs by 20 years through relining	x			
Electrification	• Efforts are taken to achieve a decarbonization through the deployment of low-emission technologies as soon as they are available.	50 years Av. lifetime with earlier shutdowns of the last BF in 2050 and 2025 as announced by Salzgitter (Ruhwedel, 2020).	x	x	x	
Coal-exit	• Variant of electrification scenario but with an earlier shutdown of all BFs in 2038. • Aligned to the goal in Germany to achieve an early coal-exit of coal-fired power plants in 2038.	50 years as electrification scenario, but not beyond 2038	x	x	x	
Carbon capture and storage (CCS)	• Variant of electrification scenario adding CCS. • CCS is deployed in 2025 for BFs which will still have a lifetime of at least 10 years.	50 years (as electrification scenario)	x	x	x	x

Table 3
Emission factors of energy carriers to calculate direct energy-related CO_2 emissions from fuel usage (source: Arens et al. (2017); Umweltbundesamt (2020)).

Energy carrier	Emission factor in kg CO_2/GJ
hard coal	93.1
fuel oil	79.9
natural gas	55.7
CO gas, BF gas, BOF gas[a]	0

[a] For coke oven gas (CO gas), blast furnace (BF) gas and basic oxygen furnace (BOF) gas, emission factors are assumed to be 0, as they contain CO_2 from the fuels used or from chemical reactions, which are already accounted for by the fuel usage or by the reaction-related emissions (Climate Climate Leaders, 2003).

Table 4
Assumed direct CO_2 emissions for the German electricity mix in kg CO_2/GJ (calculated from Naegler et al. (2021)). Minimum and maximum values are taken from ten different electricity scenarios for Germany with emission reduction goals of 80% or more by 2050. They are applied to all steel scenarios.

	2018	2020	2025	2030	2035	2040	2045	2050
Min	124.9[a]	112.3	103.5	68.7	39.4	17.4	9.7	1.1
Max		114.0	109.7	85.8	63.1	45.4	30.2	20.4

[a] Average value.

2.2.2. *Additional assumptions for the three decarbonization scenarios*

- For DRI, varying mixes of natural gas and hydrogen can be applied.
- Hydrogen is produced via electrolysis of water with an efficiency of 74% (Bhaskar et al., 2020).

The narratives and resulting assumptions of the four scenarios are described in Table 2. The electrification scenario forms the baseline of the three decarbonization scenarios, with the coal-exit and CCS scenario being variants of the electrification scenario.

It is important to note that the above-mentioned constraints and assumptions in combination with the objective of reaching a primarily electricity-based steel production by 2050 are sufficient to determine scenarios for future production amounts of each production route in five-year intervals. Based on expert judgment and an explorative modelling approach, we developed plausible pathways, or so-called what-if scenarios, consistent with the constraints and assumptions.

Table 5
Suggested carbon budgets for Germany from different sources for different distribution approaches. The budgets are for January 2020 onwards.

Climate target	Distribution approach	Source	Percentile	Amount	Unit
1.5 °C	equal per capita	SRU (2020)	50th	4.2	Gt CO_2
		Wuppertal Institut (2020)	67th	2.5	Gt CO_2
	grandfathering	Mengis et al. (2021)[a]	50th	7.9	Gt CO_2
		Mengis et al. (2021)[a]	67th	4.2	Gt CO_2
	contraction & convergence	Mengis et al. (2021)[a]	-[b]	7.6	Gt CO_2
1.75 °C	equal per capita	Wuppertal Institut (2020)	50th	9.3	Gt CO_2
		SRU (2020)	67th	6.7	Gt CO_2

[a] Adapted by subtracting emissions of Germany in 2018 and 2019 from UNFCCC (2021).

[b] For the contraction & convergence approach, it is not possible to specify uncertainties as it is derived from an emission trajectory based on current emissions, the convergence year and the global equal per capita emissions.

Table 6
Ranges of sectoral carbon budgets for the iron and steel industry in Germany from January 2020 onwards, derived with an average share of 7.6% and an increased share of 10% of the national carbon budgets from Table 5.

Climate target	Average share (proportional)		Increased share	Unit
	Min	Max	Max	
1.5°C	0.19	0.60	0.79	Gt CO_2
1.75°C	0.51	0.71	0.93	Gt CO_2

2.3. *Calculation of CO_2 emissions*

We calculate CO_2 emissions based on the energy requirements defined in the process model (see section 2.1) and the future production amounts per production route (see derivation in section 2.2). We determine both energy-related and reaction-related CO_2 emissions during steel production. Our analysis focusses on CO_2 as it is the most relevant GHG (Ryan et al., 2020): for energy-related emissions it

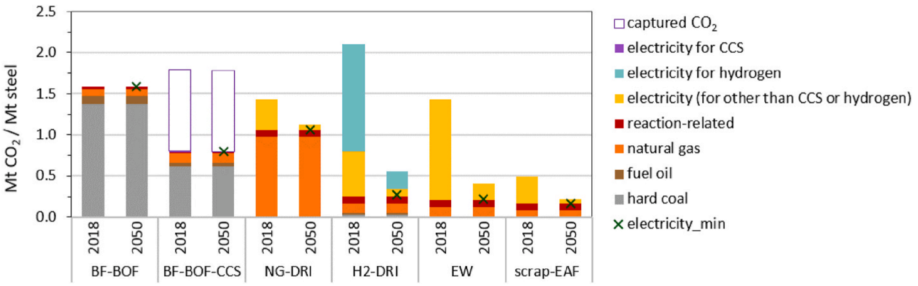

Fig. 2. CO_2 emissions per production route considering energy- and reaction-related emissions. For 2018, the average emission factor for electricity is assumed. For 2050, the green cross (electricity_min) shows total emissions if the minimum instead of the maximum emission factor for electricity is assumed (see Tables 3 and 4 for the assumed emission factors). Emissions caused by the electricity for carbon storage in the BF-BOF-CCS route are so low that they are barely visible in the chart. Energy requirements per route are provided in Figure C-1.

accounts for 98.8% and for reaction-related for 100% of GHG emissions from steel production (Otto et al., 2017).

2.3.1. Energy-related emissions

We define energy-related CO_2 emissions as emissions caused by the application of energy carriers for energy provision or as reducing agents. Thus, they are related to fuel and electricity usage. For fuels, we consider direct emissions using constant emission factors (see Table 3).

For electricity, we apply time-dependent emission factors of the average German electricity mix (see Table 4) considering minimum and maximum values. Those are derived from an energy scenario comparison from Naegler et al. (2021), who assessed ten energy transformation pathways for Germany, ranging from 80% to 95% emission reduction goals by 2050 (see Figure B-4). This range of electricity emission factors is applied to all scenarios to explore respective ranges of future emissions from steel industry.

2.3.2. Reaction-related emissions

Reaction-related CO_2 emissions were modelled based on data from literature (see section B.3.2 for details). They occur in the EAF, e.g. due to the electrode burn-off, and in the BF and the BOF, due to the reaction of calcining limestone, which is added to remove impurities.

2.4. Definition of a sectoral carbon budget for the iron and steel industry in Germany

2.4.1. Carbon budgets for Germany

The IPCC determined global carbon budgets from the year 2020 onwards for different temperature increases, e.g. 400–500 Gt CO_2 for a climate goal of 1.5 °C (67th and 50th percentile) (IPCC, 2021). Different approaches exist to distribute the global carbon budget among nations, each having some shortcomings regarding international and intergenerational justice (Neumayer, 2000; Stott, 2012; Raupach et al., 2014; Gignac and Matthews, 2015; Robiou du Pont and Meinshausen, 2018). The grandfathering approach uses current shares of global emissions, while the equal per capita approach applies the respective national share of the global population (Neumayer, 2000). A compromise between these two is the contraction & convergence approach, where national emissions converge to a global equal per capita value in a convergence year, e.g. in 2035, and then follow the same equal per capita trajectory (Meyer, 2000). To date, shares by country and sector have not officially been decided (Matthews et al., 2020).

For a national carbon budget for Germany, we collected different suggestions from literature (see Table 5). This leads to a range of 2.5–7.9 Gt CO_2 for the 1.5 °C target and 6.7–9.3 Gt CO_2 for the 1.75 °C target.

2.4.2. Allocating a sectoral carbon budget to the iron and steel industry

The share of emissions by the steel industry of Germany's total emission has been growing slightly since 1990 from 6% to 8.1% in 2019 (UNFCCC, 2021). To allocate a sectoral carbon budget to the steel industry, we first assume the average share of the last 5 years, i.e. 7.6%, resulting in proportional carbon budgets. Secondly, as it is a hard-to-abate sector (Davis et al., 2018), which might receive a higher share of a carbon budget (SRU, 2020), we also consider an increased share of 10%. This leads to ranges for carbon budgets as shown in Table 6.

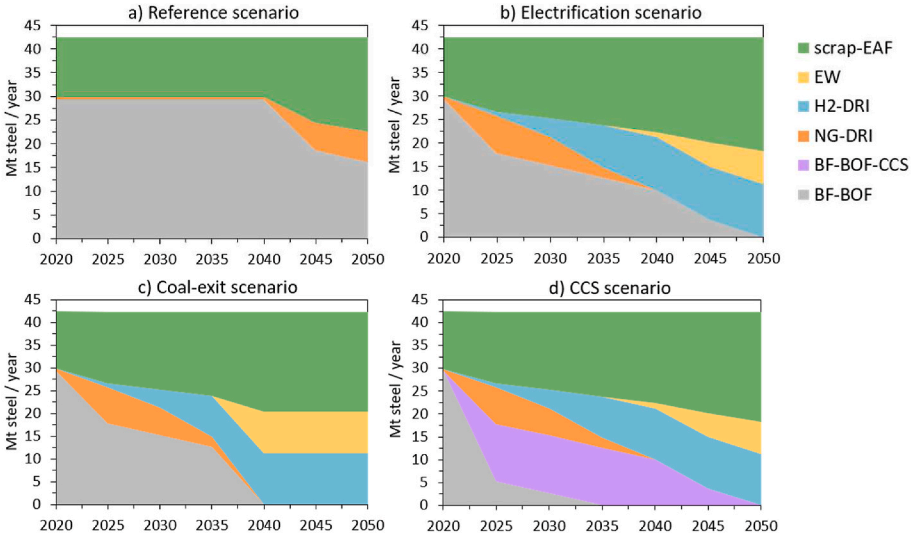

Fig. 3. Development of the technology pathways, i.e. the market shares of different steel production technologies, for each scenario. For details on the scenario definition see Table 2, and for the BF-BOF capacities see Figure B-1. Underlying data is supplied in our repository (Harpprecht et al., 2022).

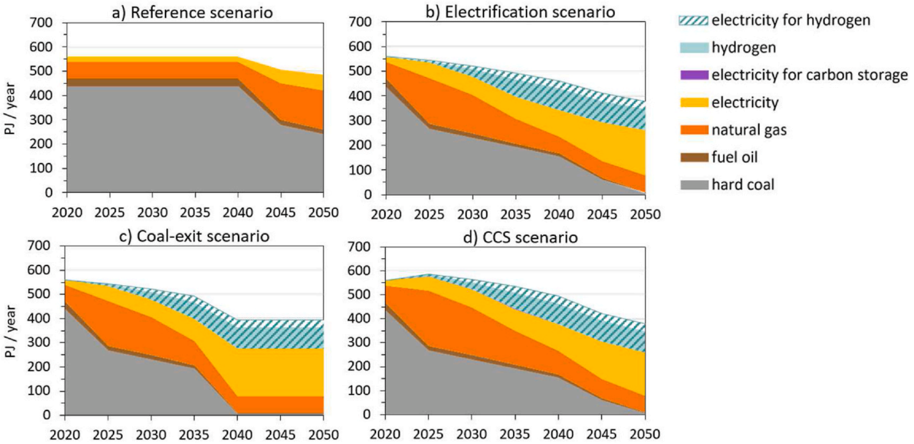

Fig. 4. Annual energy demand for iron and steel production per energy carrier for each scenario. The hatched area illustrates the electricity demand to electrolyze hydrogen. The hydrogen demand is shown in blue. Electricity for carbon storage in the CCS scenario is so low that it is not visible in the chart.

3. Results

3.1. *Emission-intensity of production routes*

Fig. 2 compares the specific CO_2 emission-intensities of the different production routes. It shows that process alternatives are highly sensitive to power production. If power is decarbonized, the lowest emission-intensities can be achieved by H2-DRI, EW, and scrap-EAF, which are 83%, 86% and 90% lower than for the BF-BOF route. Then, they clearly outperform CCS, i.e. the BF-BOF-CCS route, which achieves an emission reduction by only 50%. In the BF-BOF-CCS route, the emissions due to the increased requirements of electricity for the CCS processes are negligible compared to the overall energy demand and CO_2 emissions of that route (see Figure C-1).

It stands out that DRI purely run on hydrogen, i.e. H2-DRI, currently has a higher emission-intensity than BF-BOF. It might become lower than BF-BOF between 2027 and 2029 (for electricity_min and electricity_max respectively), lower than NG-DRI between 2028 and 2032, and lower than BF-BOF-CCS between 2036 and 2043 when power in Germany will become increasingly renewable (90; 79; and 37 kg CO_2/GJ electricity respectively). Emission-intensities of NG-DRI are now already lower than of BF-BOF (−10%) which makes natural gas beneficial to mix with hydrogen in the early years of H2-DRI.

3.2. *Technology pathways of the decarbonization scenarios*

Fig. 3 illustrates the technology pathways of each decarbonization scenario to reach electrification by 2050 compared to the reference

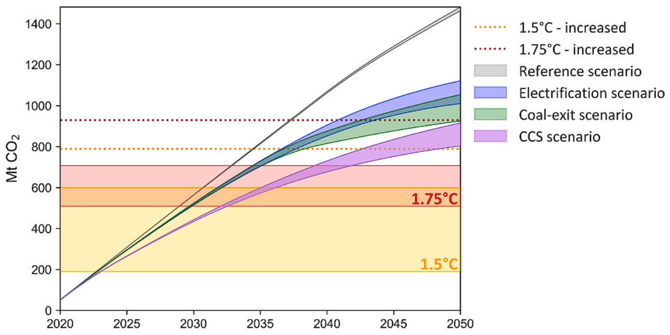

Fig. 6. Cumulative CO_2 emissions for 2020–2050 per scenario compared to proportional carbon budgets of the iron and steel industry in Germany for a 1.5 °C (yellow area, average share) and a 1.75 °C (red area, average share) climate target (for budget definition see Table 6). The dashed horizontal lines represent the carbon budgets if the allocation share for the steel industry is increased from its average of 7.6% to 10%. For each scenario, the emission factor of electricity is varied between minimum and maximum values (see Table 4).

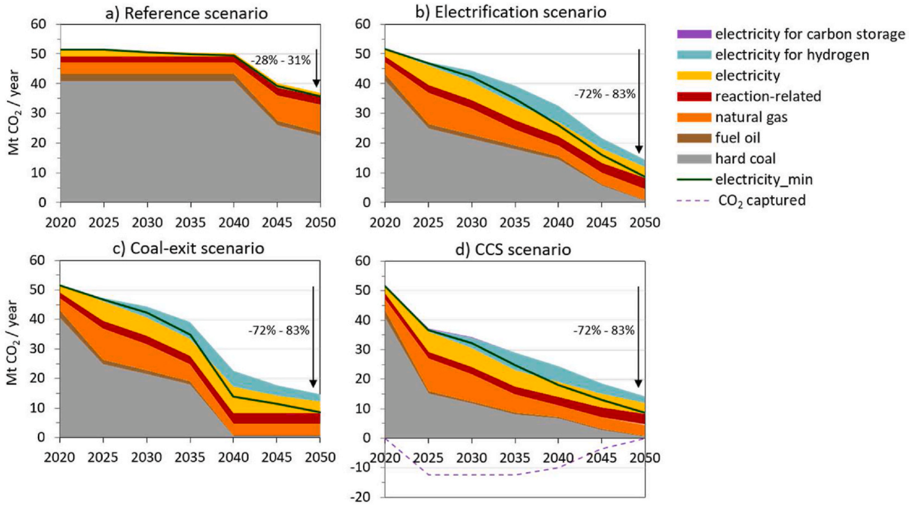

Fig. 5. Annual CO_2 emissions into the atmosphere per energy carrier for each scenario. The green line (electricity_min) shows the emissions in 2050 if the minimum instead of the maximum emission factor is assumed for electricity (see Tables 3 and 4 for the assumed emission factors). The values given in percentage stand for the emission reduction in 2050 compared to 2020 if the maximum and minimum emission factors for electricity are assumed. The captured emissions shown as negative in d) are only provided for reference, this means they are already subtracted respectively from the sum of emissions.

scenario. In the three decarbonization scenarios (Fig. 3b) – d)), the coal-based BF-BOF is replaced by low-carbon technologies, firstly by NG-DRI, then H2-DRI and from 2040 onwards by EW-EAF. The BF-BOF route is completely phased out by 2050 for the electrification and CCS scenario and by 2038 in case of the coal-exit scenario. For all decarbonization scenarios, the main energy carrier will be electricity by 2050. The new DRI capacity, which is built from 2020 to 2040, serves as a bridging technology from NG-DRI to H2-DRI. The DRIs are firstly run with natural gas but can later switch to hydrogen, when enough green hydrogen is available. In the CCS scenario, CCS is installed in 2025 on still existing BF-BOFs. The share of scrap-EAF increases from 30% in 2020 to up to 57% by 2050.

An analysis describing when investments into new furnace capacities are required in each scenario is provided in section C.5 and Figure C-2 in the supplementary information.

3.3. Future energy requirements

Fig. 4 illustrates the implications of the decarbonization scenarios in terms of future energy demand. While the decarbonization scenarios lead to similar energy requirements in 2050, they require different developments of energy supply and cumulative future energy demand from 2020 until 2050. Under the decarbonization scenarios, the final energy demand for iron and steel production in Germany decreases by 30%–33% by 2050 compared to 2020, which is more than double than in the reference scenario (see Fig. 4a) – d)). The reason is that the technologies prevailing in 2050 (EW-EAF and scrap-EAF) are more energy-efficient than the conventional BF-BOF route (see Figure C-1).

In all three decarbonization scenarios, the current primary energy carriers of coke and hard coal are continuously phased out in the future due to the declining share of BF-BOF (see Fig. 4a) – d)). We can see a shift firstly to natural gas and later to electricity and hydrogen. The demand of natural gas peaks in 2025 due to the increasing market share of NG-DRI in all three decarbonization scenarios. The peak for natural gas is the highest in the CCS scenario due to additional natural gas requirements for the carbon capture facilities. After 2025, the demand for natural gas shifts to electricity for hydrogen given the transition from NG-DRI to H2-DRI.

In 2050, all decarbonization scenarios realized a transition to electrification, such that 79–80% of the energy demand in 2050 could be covered through electricity. As a result, annual electricity demand increases by a factor of 14–15, i.e. from 5.9 TWh/year in 2020 to 83–87 TWh/year by 2050. From this, a share of 37%–39% (32.7 TWh) is required for hydrogen electrolysis to satisfy the demand of 87 PJ of hydrogen (24.2 TWh) in 2050. In 2050, small amounts of natural gas (ca. 70 PJ), fuel oil, and hard coal are still assumed for the pellet production (Remus et al., 2013), finishing of crude steel (Worrell et al., 2007; Arens et al., 2017) and as heat provision for the EAF (Kirschen et al., 2011; Otto et al., 2017) (see Figure C-1).

3.4. Future CO_2 emissions

Fig. 5 demonstrates how the resulting CO_2 emissions drastically decrease by 2050 under the decarbonization scenarios, i.e. by up to 83% compared to 2020, while the reference scenario achieves only a 31% emission reduction. The reason is mainly that coke and coal can be replaced by electricity, whose emission factor is assumed to decrease over time and become almost 0 in 2050. Moreover, we can see the large impact of the power sector on an electrified industry: only a very ambitious power sector transformation decreases emissions by up to 83%. With less ambition (maximum electricity emission factor assumed) only about 72% of today's emission can be avoided. In the CCS scenario, 255 Mt CO_2 are assumed to be captured and stored by 2050. Furthermore, it becomes visible that reaction-related emissions from the EAF will gain in relevance in the future. They increase from 2.0 Mt CO_2 (4%) in 2020 to 3.6 Mt CO_2 (24–42%) in 2050.

Fig. 6 compares the cumulative emissions of the four scenarios with the predefined carbon budgets for the iron and steel industry in Germany. Compared to the reference scenario, all three decarbonization scenarios reduce cumulative emissions considerably by 2050, i.e. by 24% (360 Mt CO_2) in case of the electrification_max scenario to a maximum of 46% (677 Mt CO_2) under the CCS_min scenario. Nevertheless, all decarbonization scenarios exceed the sectoral carbon budgets for both climate targets by up to 490% (electrification_max scenario and min. 1.5 °C budget). For the 1.5 °C target, the budget may be exceeded between 2023 and 2033 under the electrification and coal-exit scenario, and in 2037 under the CCS scenario. Only the increased budget for the 1.75 °C target may be met by some scenarios: the coal-exit_min, CCS_max and the CCS_min scenario. The implementation of CCS considerably reduces emissions, i.e. by up to 206 Mt CO_2 by 2050 compared to the electrification scenario. Within each decarbonization scenario, a more renewable electricity supply reduces cumulative emissions by 10%–12% (111–128 Mt CO_2), which is the difference between the minimum and the maximum emission trajectories.

3.5. Implications for the future energy supply

Fig. 7 compares the future cumulative energy demand for each scenario with their respective cumulative CO_2 emissions from 2020 to 2050. Under the decarbonization scenarios, the cumulative demand for coal decreases by 52–60%, while the demand for natural gas increases by 17–47% and for electricity by a factor of 5.6–6.3 compared to the reference scenario.

Among the decarbonization scenarios, the coal-exit scenario

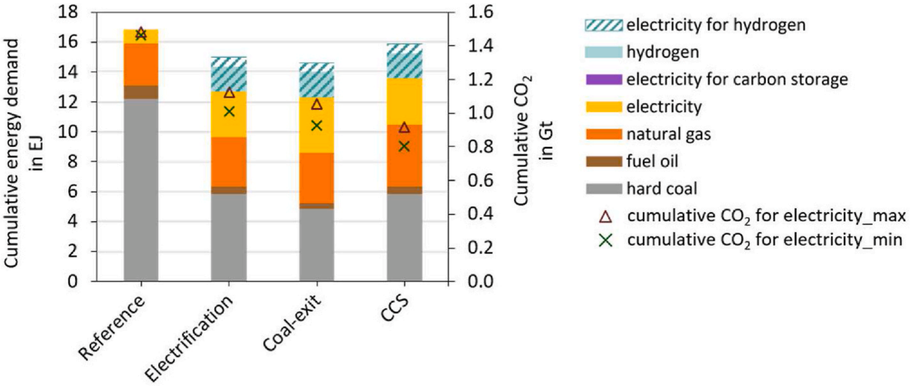

Fig. 7. Cumulative energy demand per energy carrier (stacked columns, left axis) compared to cumulative CO_2 emissions (right axis) from 2020 until 2050 for each scenario. The red triangle (electricity_max) and the green cross (electricity_min) show the cumulative CO_2 emissions in 2050 if the maximum or minimum emission factors are assumed for electricity (see Tables 3 and 4 for the emission factors).

achieves the highest reduction of the cumulative energy demand in total, i.e. by 13%, as well as for fossil fuels, i.e. by 46%, compared to the reference scenario (see Fig. 7). The reason is its early phase out of the BF-BOF route. The electrification scenario ranks second with a reduction of 11% in total, while the CCS scenario leads to lowest reduction of 6% of the cumulative energy demand compared to the reference scenario. The reason is that carbon capture increases the cumulative natural gas demand by 26% (0.86 EJ) compared to the electrification scenario (3.32 EJ). Despite its higher energy demand, CCS enables a considerable reduction of cumulative CO_2 emissions, i.e. by 206 Mt CO_2 or 18–20% compared to the electrification scenario.

4. Discussion

4.1. Key findings

This study aimed at comparing the decarbonization potential of different technology pathways of the iron and steel industry in Germany modelled with the help of three decarbonization scenarios: an electrification scenario deploying hydrogen-based DRI (H2-DRI) and electrowinning (EW), as well as two variants thereof, an early coal-exit scenario and a carbon capture and storage (CCS) scenario. We found that the reduction of annual CO_2 emissions by 2050 are very similar across scenarios (72–83%), while their cumulative emissions from 2020 to 2050 differ considerably, as the timing of the strongest emission reductions differs among scenarios. The reductions of cumulative emissions by 2050 range from 24% (360 Mt CO_2) under the electrification scenario up to the maximum of 46% (677 Mt CO_2) under the CCS scenario relative to the reference scenario. This clearly demonstrates that the technology pathway, i.e. the implementation speed and choice of alternative technologies, matters. Moreover, the results showed that the electricity emission factor plays an important role: within each decarbonization scenario, our optimistic trajectory for future emission factors of the power mix reduces cumulative emissions by up to 12% (128 Mt CO_2) (see electricity_min vs. electricity_max in Fig. 7, Table 4).

Nevertheless, all three decarbonization scenarios considerably exceed the sectoral carbon budgets, adopted for this study for the German iron and steel industry, not only for the 1.5 °C but also for the 1.75 °C target up to a factor of almost five.

Additionally, we investigated some implications of the decarbonization scenarios. Maximum emission reduction under the CCS scenario would require storing 255 Mt CO_2 and increase the cumulative natural gas demand by 26% compared to the electrification scenario to run CCS facilities. In all decarbonization scenarios, hard coal is almost completely phased out by 2050, and a shift to primarily electricity-based production is achieved with electricity accounting for about 80% (up to 87 TWh) of the energy demand (see Fig. 4). As a result, annual electricity demand rapidly rises by a factor of ca. 15 from 2020 to 2050. From this, up to 39% are required to produce 87 PJ of hydrogen in 2050. Nevertheless, final energy demand decreases in 2050 by up to 33% compared to 2020, as the prevailing technologies of EW and scrap-EAF are more energy-efficient than BF-BOF.

4.2. Comparison with previous studies

A comparison of the technology pathways of our study (see Fig. 3) with three recent studies on decarbonization scenarios for the German steel industry by 2050 (Purr et al., 2019; Prognos et al., 2020; Robinius et al., 2020) confirms our result that scrap-EAF can supply 52–57% of steel in 2050 (see Table D-1). However, our study is the only one which considers the introduction of electrowinning (EW) from 2040 onwards as well as the interim technology of carbon capture and storage for existing BF-BOFs (BF-BOF-CCS) between 2020 and 2050.

Although a direct comparison of results between studies is not possible due to different system boundaries and process assumptions, a rough comparison illustrates that our emission intensities of production routes (see Fig. 2) are within the range of emission intensities reported by previous research (IEAGHG, 2013; Fischedick et al., 2014; Arens et al., 2017; Otto et al., 2017; Chisalita et al., 2019; Agora Energiewende and Wuppertal Institut, 2019; Bhaskar et al., 2020; Lösch et al., 2020) (see Figure D-1). For BF-BOF, our emission intensity lies in the lower end of the found emission intensities. The reason is that we slightly reduced the consumption of hard coal and coke in our BF-BOF model which is based on European averages (Remus et al., 2013) during the calibration of our model to the German energy statistics (Rohde, 2019). For the novel technology of H2-DRI, different process configurations exist leading to a large range of emission intensities. For EW, studies for a detailed comparison are currently lacking.

Our conclusion that it will be very challenging for the German iron and steel industry to stay within its proportional carbon budget for a 1.5 °C climate target is in line with results by studies for the global iron and steel industry (Tong et al., 2019; IEA, 2020b; Wang et al., 2021). Even the strictest scenarios by Wang et al. (2021) exceed the proportional 1.5 °C budget by more than 100%.

4.3. Implications and recommendations

This study determines different transformation pathways for the German steel industry in line with the Steel Action Concept of the German Federal Ministry for Economic Affairs and Climate Action (BMWK) (BMWi, 2020). As suggested by the BMWK, our decarbonization scenarios assume the use of natural gas in direct reduction furnaces (NG-DRI) as an intermediate energy carrier to transition to a 100%-fired hydrogen-based direct reduction (H2-DRI).

Based on this study, we can identify the following challenges and recommendations for the iron and steel industry to meet its sectoral budget.

First, our findings provide further evidence that the emission intensity of the German electricity mix needs to be reduced as fast as possible, such that the minimum emission intensity of indirectly (H2-DRI) or directly (EW, EAF) electrified technologies can be achieved. This is quite challenging for the energy sector especially in the next decade (Simon et al., 2022), due to an expected increase of power demand also in other sectors in the future. According to our findings, for the iron and steel industry alone, additional 81 TWh/year of electricity would be required by 2050. This additional power demand translates into an additional PV capacity of ca. 80 GW, which is ca. 150% of currently installed PV capacity in Germany (53.7 GW (AGEE-Stat, 2021)), or into additional 32 GW of onshore wind turbines (54.4 GW in Germany in 2020 (AGEE-Stat, 2021)). For hydrogen electrolyzers, a capacity of 7.2 GW_{el} would be needed in 2050 (assuming 4545 full-load hours/year (Simon et al., 2022)), which represents an increase by a factor of 360 compared to today (0.02 GW_{el} in 2020 (THEnergy, 2021)) (see section D.6.3).

Secondly, we recommend investments to advance the technology of EW, such that it reaches market maturity earlier than expected, i.e. before 2040. Our findings suggest that EW offers the lowest emission intensity among the technologies considered in this study. Therefore, efforts are needed, such as funding and research capacities, to advance its currently too low TRL. EW seems especially attractive as its specific electricity consumption is roughly one third less than that of H2-DRI (see Figure C-1). Moreover, it does not require a new infrastructure for hydrogen or CCS, but “only” the expansion of capacities for renewable electricity supply.

In contrast, the current lack of a hydrogen infrastructure forms a severe obstacle for a large-scale implementation of H2-DRI. Here, a market revolution would be necessary, similar to what PV experienced during the last decade.

Another obstacle for a large-scale switch to H2-DRI before 2030 is a potentially still large capacity of BF-BOFs ranging from 50% to 100% of current capacities depending on whether relining takes place to extend BF lifetimes (see Fig. 3). By 2030, electricity emission factors will ideally have decreased sufficiently to make H2-DRI favorable over BF-BOF. To minimize emissions from these still functional BF-BOFs, one solution could be their early shutdown while simultaneously rapidly switching to H2-DRI. Another solution is the addition of CCS to BF-BOFs.

Our findings suggest that emissions could be minimized the fastest through the implementation of CCS to BF-BOFs as early as possible, e.g. before 2025. First, BF-BOF-CCS may have a lower emission intensity than H2-DRI until 2036–2043 unless electricity is decarbonized sooner than in our optimal assumption (electricity_min). Second, the CCS scenario achieved the lowest cumulative emissions.

This study highlights the need to open the discussion on CCS in Germany, where CCS is currently strongly limited to research purposes and a maximum of 4 Mt CO_2 stored/year within Germany (Federal Ministry of Justice, 2012). The results of this study revealed some points in favor of implementing CCS for BF-BOFs soon: i) the market entry and diffusion rates of H2-DRI and EW alongside the carbon budgets are uncertain and modelled with rather optimistic assumptions in our scenarios; ii) life time extensions of BF-BOFs could limit market entry and thus emission reductions through H2-DRI and EW (see reference scenario); iii) CCS or alternatively negative emission technologies could tackle reaction-related emissions from EAFs to achieve net-zero emissions by 2050 (see Fig. 5), which may be about 3.6 Mt CO_2 in 2050, i.e. up to 42% of emissions in 2050. Furthermore, recent research shows that CCS is likely to be required for reaching net-zero emissions in Germany by 2050, e.g. for unavoidable reaction-related emissions from cement production, given the limited capacities of natural sinks (Mengis et al., 2022). Moreover, Germany's Climate Protection Plan mentions CCS as an option to reduce unavoidable emissions in industry (BMU, 2016). Yet, this study can merely show emission reduction potentials of CCS for the steel industry, which is only one of many diverse aspects concerning CCS. Thus, more detailed analyses are required to gain more insights into technical, social, and legal feasibility of CCS, as well as into risk assessments and comparisons to CCU.

Furthermore, future emission reductions in the decarbonization scenarios rely substantially on the increasing market share of scrap-EAF, which almost doubles from 30% in 2020 to up to 57% by 2050 (see Fig. 3). Thus, next to decarbonizing primary production, it is crucial to continuously extend capacities of scrap-EAFs in the future (see section C.5 for details), such that the scrap which will be becoming increasingly available can actually be processed and replace primary production.

Lastly, this study emphasizes the necessity to internationally agree on national and ideally also sectoral carbon budgets to accelerate the definition of concrete decarbonization strategies. Despite the uncertainty about the carbon budget for Germany (see Table 5), our results can clearly demonstrate that the German steel sector is likely to exceed its proportional carbon budget by 2037 or even much earlier, unless very drastic measures are taken. As it is a race against time and early measures are needed, we would like to stress again that the cumulative emissions are strongly influenced by the technology pathway (see Fig. 6), even though different pathways may lead to very similar emission reductions by 2050, i.e. up to 83% in this study (see Fig. 5). Thus, to bring about early as well as effective action, a national strategy is required which outlines a concrete technology pathway for iron and steel producers in Germany. This should be developed considering infrastructure requirements, e.g. for hydrogen, CCU or CCS, and in dialogue with not only research, but also industry and other stakeholders.

4.4. Limitations and future research

There are some limitations associated with this study, which could be improved by future research. First, technologies are modelled based on data available from literature due to our primary focus on pathways of future technology mixes instead of an in-depth analysis of each steel production route. Thus, details of individual technologies could be improved in our model, e.g. with primary data from industry. For H2-DRI, future research could try to reduce the uncertainty about its future process configurations and thus its emission-intensity (see Figure D-1). Moreover, the role of hydrogen electrolyzers within future energy systems could be explored. For EW, we could not include the production and consumption of the required alkaline solution due to a lack of reliable data given the novelty of EW. As this process can be energy-intensive (Siderwin, 2021), further research about its effect on the technology's performance is required to avoid problem-shifting.

Secondly, while our study investigated three different scenarios, other future developments are possible. Further research could explore more scenarios and include additional technologies, e.g. high-temperature electrowinning, or scale-up effects of novel technologies (Santos et al., 2016). Moreover, we assumed that the overall demand for steel will stay roughly unchanged, which is in line with other studies (Brunke and Blesl, 2014; Lechtenböhmer et al., 2016, Prognos et al., 2020). Thereby, we addressed the supply side to reduce emissions. To get a full picture, additional research for other potential developments, such as a reduced demand or the influence of a circular economy, is required.

Thirdly, we focused on the switch to primarily electricity-based technologies for primary steel production, since this is key to minimize emissions (Arens et al., 2017; de Coninck et al., 2018). Thus, we did not investigate the application of biomass or syngas to replace residual coal and natural gas requirements in conventional processes, such as the EAF or pellet production, to reach net-zero emissions. Both options might help to further reduce CO_2 emission (Otto et al., 2017), but are alone insufficient for deep emission reductions. Further work could investigate the suitability and implications of such alternative energy carriers alongside the avoidance of reaction-related emissions to achieve net-zero emissions.

This study presents what-if scenarios in which we assume deployment of low-carbon technologies at the scale required for German steel production and calculate the CO_2 emissions on that basis. Analyzing if such scaling up is feasible, and if yes under which economic, political or social conditions, is out of the scope of this paper. Costs play a decisive role in the steel industry, which is internationally highly price-competitive. It has been roughly estimated that a transformation to a low-carbon primary steel production in Germany would require investments of around €30 billion (i.e. €1000/t primary steel production capacity) (BMWi, 2020). Thus, requests for regulations have been voiced to create a level global playing field. Policies under discussion by other studies (Bataille et al., 2018; Wyns et al., 2019; Agora Energiewende and Wuppertal Institut, 2019; BMWi, 2020; IEA, 2020a; Koasidis et al., 2020; Muslemani et al., 2021) are for example: carbon contracts for difference, carbon border adjustments, a labelling scheme for low-carbon steel products, financing of CCS infrastructure, or green public procurement. Moreover, Germany commissioned a study (IEA, 2022) to determine effective policies and economic measures to facilitate the creation of international markets for green steel. Further research is necessary to develop comprehensive national and international policy frameworks taking a systems perspective (Bataille, 2020; Bataille et al., 2021; Nilsson et al., 2021), to investigate societal acceptance, the behavior of individual actors (e.g. using agent-based modelling), or to optimize the operation of the steel industry within the context of larger economic systems.

Lastly, this study assessed *direct* CO_2 emissions of major steel production processes (see Fig. 1) and of electricity supply. Emissions occurring across the entire supply chains required to produce steel could be evaluated via the methodology of life cycle assessment (LCA). LCA also allows to evaluate impacts other than greenhouse gases, such as human toxicity or metal depletion. It can thereby reveal whether decarbonization measures may cause negative side-effects in other impact categories, as it has been found for BF-BOF-CCS technologies by Chisalita et al. (2019). Moreover, LCA can help to identify effects of changes in one sector on the environmental performance of other downstream sectors, such as electric vehicles (Koroma et al., 2020;

Harpprecht et al., 2021) or the building sector (Zhong et al., 2021).

It is important to note that this study does not aim at offering predictions for the future but analyzes explorative, so-called what-if scenarios. This means that the scenarios are subject to unforeseeable events, such as the Ukraine war and its consequences for the natural gas supply in Germany. On the one hand, the recent steep increase of prices for natural gas in Germany may hamper investments into DRI capacities, which are planned to be firstly run on natural gas, and may thereby delay the transition to H2-DRI (Hermwille et al., 2022). On the other hand, they may incentivize a faster build-up of green hydrogen generation capacities and distribution networks (Hermwille et al., 2022). Future work is required to determine decarbonization scenarios for heavy industry under such very recent, highly uncertain and rapidly changing geopolitical conditions.

As this study openly publishes data and code in a repository (Harpprecht et al., 2022), it provides a basis for future research, e.g. to investigate additional technologies or scenarios. The model and analysis could also be applied to other countries. For this, the following country-specific data inputs would need to be adapted: a) current and future production amounts per technology; b) emission factors of energy carriers, especially of electricity; c) the sectoral carbon budget; and d) the assumptions of the production model may need to be slightly adjusted, as it uses technology data from German and European data sources.

5. Conclusions

This study successfully assessed the compatibility of various decarbonization pathways for the German iron and steel industry with a carbon budget. We quantitatively demonstrated that it will be a race against time, since each of our decarbonization scenarios, which we considered already rather optimistic, would exceed the sectoral 1.5 °C carbon budgets already in the 2030s.

While we cannot offer a silver bullet to solve the problem, we can conclude that a whole portfolio of measures and technologies will be required to sufficiently limit future CO_2 emissions from iron and steel production in Germany. These comprise a rapid decarbonization of the electricity mix, the construction of a hydrogen infrastructure, the implementation of CCS with a respective infrastructure, early shutdowns of BF-BOFs, and investments to accelerate both maturing processes and final deployment of low-carbon technologies, such as H2-DRI and EW.

Ultimately, the question of the ideal technology mix for steel production is not only about CO_2 emissions, but concerns also aspects such as infrastructure requirements for electricity and hydrogen supply, environmental impacts, stakeholders, societal acceptance, regulatory conditions and costs. Future research could investigate these additional aspects, e.g. using life cycle assessment, agent-based modelling or cost optimization.

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CRediT authorship contribution statement

Carina Harpprecht: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Tobias Naegler:** Conceptualization, Methodology, Supervision, Validation, Writing – review & editing. **Bernhard Steubing:** Supervision, Writing – review & editing. **Arnold Tukker:** Supervision, Writing – review & editing. **Sonja Simon:** Conceptualization, Funding acquisition, Investigation, Methodology, Supervision, Validation, Writing – review & editing.

Declaration of competing interest

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

Data availability

The data and python code to produce the results of this study are available in a zenodo repository (Harpprecht et al., 2022): https://doi.org/10.5281/zenodo.7305509.

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List of abbreviations

av	average
BF	blast furnace
BF-BOF	blast furnace and basic oxygen furnace
BF-BOF-CCS	blast furnace and basic oxygen furnace equipped with carbon capture and storage
BMU	Federal Ministry for the Environment, Nature Conservation, and Nuclear Safety (Bundesministerium für Umwelt, Naturschutz, und nukleare Sicherheit)
BMWi	Federal Ministry for Economic Affairs and Energy in Germany (Bundesministerium für Wirtschaft und Energie)
BMWK	Federal Ministry for Economic Affairs and Climate Action (Bundesministerium für Wirtschaft und Klimaschutz) (former BMWi)
BOF	basic oxygen furnace
CCS	carbon capture and storage
CCU	carbon capture and utilization
CO gas	coke oven gas
DRI	direct reduced iron
EAF	electric arc furnace
EW	electrowinning
GHG	greenhouse gas emissions
H2-DRI	hydrogen-based direct reduced iron
LCA	life cycle assessment
NG-DRI	natural gas-based direct reduced iron
scrap-EAF	scrap-based electric arc furnace
SRU	German advisory council on the environment (Sachverständigenrat für Umweltfragen)
TRL	techonology readiness level
WSA	world steel association

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2022.134846.

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