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Future environmental impacts of global iron and steel production†

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The iron and steel industry is not only responsible for up to 9% of global greenhouse (GHG) emissions, but also associated with other environmental impacts. Anticipated growth in steel demand thus poses significant challenges to climate and environmental objectives. This study evaluates the future life cycle environmental impacts of global steel production, accounting for the adoption of emerging production technologies, including carbon capture and storage (CCS), hydrogen-based or electrified processes. We couple state-of-the-art life cycle assessment (LCA) models of current and future steel production routes with multi-sectoral, internally consistent scenarios for future energy and steel supply from the integrated assessment model (IAM) of IMAGE. This approach provides a comprehensive assessment of regional and temporal environmental impacts for three climate mitigation pathways: a 3.5 °C baseline, a <2 °C- and a 1.5 °C-target. Results demonstrate that electrified steel production technologies, both directly and indirectly powered, offer the highest GHG reduction potential achieving up to −95% by 2060 compared to current coke-based processes, provided that decarbonized electricity is used. They thereby clearly outperform CCS technologies for coke-based processes. Nevertheless, it is unlikely that global steel production will reach net-zero GHG emissions by 2060, with its emission intensity decreasing by −33% (3.5 °C-baseline), −56% (<2 °C-target), and −79% (1.5 °C-target) compared to 2020. Considering future steel demand growth, global annual GHG emissions may only be reduced by up to −67% by 2060, from 3.7 in 2020 to 1.2 Gt CO_2-eq. per year. Cumulative emissions from steel production could thus consume 18–30% of the global end-of-the-century 1.5 °C carbon budget and 9–14% of the 2 °C budget by 2060. Our analysis reveals that the decarbonization scenarios could shift burdens from climate change to other impact categories, such as ionising radiation, land use, or material resources. The drivers of rising impacts are diverse and caused by different processes, *e.g.*, electricity generation, furnace slag treatment, metal mining, or chemical production. Achieving sustainable steel production requires not only rapid decarbonization and demand reduction but also targeted process-specific interventions throughout the entire life cycle to mitigate future environmental impacts.

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Broader context

Steel production is a major contributor to greenhouse gas (GHG) emissions globally. Given the need to mitigate climate change, it is crucial to reduce the emissions of the iron and steel industry in the future. As a key building material for infrastructure and technologies, steel demand is expected to rise further, which poses significant challenges to climate and environmental goals. This study quantifies GHG emissions and other life-cycle environmental impacts of future global steel production until 2060 under three climate mitigation scenarios: a 3.5 °C baseline, a <2 °C- and a 1.5 °C-target. Our assessment considers general societal developments, like the energy transition, as well as changes in future steel production, such as using novel technologies, including carbon capture and storage (CCS), hydrogen-based or electrified processes. Based on our scenarios, we find: (1) global steel production is unlikely to reach net-zero GHG emissions by 2060; (2) even in the most ambitious scenario, steel production would consume a substantial share of the carbon budget; (3) decarbonizing steel production can have both positive and negative side-effects, as it can reduce other non-GHG emissions, *e.g.*, crucial for air quality, but may increase other impacts, *e.g.*, due to a higher electricity demand.

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1 Introduction

The iron and steel industry is responsible for about 9% of global GHG emissions due to its high energy intensity and current dependence on fossil fuels.[1] Being a key building material for infrastructure and technologies, steel ranks third in most produced materials globally, following cement and timber.[2] Steel demand is expected to increase further,[1,3] potentially up to 86% by 2050.[4] This poses significant challenges to climate and environmental goals,[1,5,6] since steel production causes environmental pressures not only for GHG emissions but also for various indicators, such as human toxicity (*e.g.*, due to chromium emissions in landfilled slags)[7] or particulate matter emissions (*e.g.*, from blast furnaces, coke ovens or sinter plants).[8–10]

Addressing demand growth solely through energy efficiency improvements is insufficient to curb the steel sector's global emissions.[1,11] Hence, substantial emission cuts may only be achieved by reducing demand or adopting novel technologies, such as electrified production technologies,[1,3,11] while simultaneously decarbonizing upstream processes for material and energy supply, such as electricity and hydrogen supply.

Technologies considered promising are direct reduction of iron (DRI), which can be operated either with natural gas (NG), or hydrogen (H2).[12] Although NG-DRI is already a mature technology with a lower emission intensity than the conventional coke-based blast furnace (BF), it is currently not widely adopted because natural gas is in most regions not economically competitive with coke.[13] As an alternative to natural gas, direct reduction can also be operated with hydrogen (H2-DRI),[14] which can offer even greater CO_2 emission reduction depending on the emission intensity of hydrogen generation.[15,16] Another emerging but less mature technology is the electrolysis of iron ore, which uses electricity to reduce iron, thus enabling direct electrification. Specifically, electrowinning (EW) allows iron production at low temperatures (110 °C).[17–19] To reduce direct emissions of iron production, carbon capture and storage (CCS) technologies can be deployed and potentially retrofitted to existing furnaces, *e.g.*, BFs.

Current assessments often prioritise direct GHG emissions of the steel industry at national‡ or global scales,[6,26–30] yet frequently neglect indirect emissions or broader environmental impacts.

Some studies adopt a life cycle approach to assess emissions from emerging low-carbon technologies like hydrogen-based direct reduction of iron (H2-DRI),[31,32] carbon capture and storage (CCS),[33] or electricity-based electrowinning (EW).[34] These analyses reveal potential burden shifting to upstream supply chains or non-climate change impact categories, emphasising the need for comprehensive life cycle assessments (LCAs) to guide investment decisions to a low-impact steel supply chain.

LCA offers a systematic method for evaluating environmental impacts across the entire life cycle of a product enabling stakeholders to identify strategies to minimize emissions based on a systems perspective.[35] Prospective LCAs extend this capability by integrating future scenarios to provide insights into the environmental implications of future developments, *e.g.*, emerging technologies or policies.[36,37] Achieving coherent results requires consistency in scenario assumptions across regions and sectors.[38] Such a holistic approach equips decision-makers with the necessary information to align steel industry pathways with global climate and environmental goals.

Previous studies evaluated future life cycle impacts of iron and steel supply in conjunction with global demand scenarios, but used scenario data from disparate sources. Moreover, they primarily assessed climate change impacts.[1,3] Only one study investigates additional impact categories.[11]

Research has yet to fully explore the environmental implications of global steel supply using multi-sectoral, internally consistent decarbonization scenarios while accounting for a broad range of emerging technologies and non-climate impacts.

Integrated assessment models (IAMs) are promising sources for internally coherent scenario data across multiple sectors.[38] IAMs are global energy-economic-environmental models aiming at capturing the interactions between human systems and the implications for the environment.[39–41] They are applied, for example, to develop cost-optimal decarbonization pathways for various sectors under varying socioeconomic narratives (*e.g.*, Shared Socioeconomic Pathways (SSPs)) and emission constraints (*e.g.*, Representative Concentration Pathways (RCPs)).[42]

While prior work has coupled IAM scenarios and LCA, studies mostly focused on the electricity,[43–45] and recently, the cement sector.[46] Specific climate change impacts of the global steel market have been assessed using scenarios from IAMs,[45] *e.g.*, IMAGE,[40] but the assessment did not include novel technologies, such as H2-DRI or EW. Another analysis investigated future climate change impacts of a single German steel mill[47] using background energy scenarios from the IAM REMIND.[48]

In this study, we couple state-of-the-art LCA models of current and future steel production routes with multi-sectoral, internally consistent scenarios for future energy and steel supply, as the scenarios have been modelled by one IAM, *i.e.*, IMAGE. We obtain a comprehensive and supply chain-based overview of the environmental impacts of steel production across different world regions over time. This approach allows us to investigate the following research questions:

1. What are the future environmental impacts of global steel production under consistent energy and steel supply scenarios?

2. Could a decarbonization of steel production cause adverse side effects in impact categories other than climate change?

3. Can global climate change and other environmental impacts of steel production be reduced despite growing demand, such that a decoupling may be achieved?

2 Methods

2.1 Goal and scope

This study aims to assess the environmental impacts of future global steel production using coherent multi-sectoral scenarios, *i.e.*, for both steel and energy supply. We conduct a prospective

‡ For example for US,[20,21] DE,[22,23] SW[24] or CHN.[25]

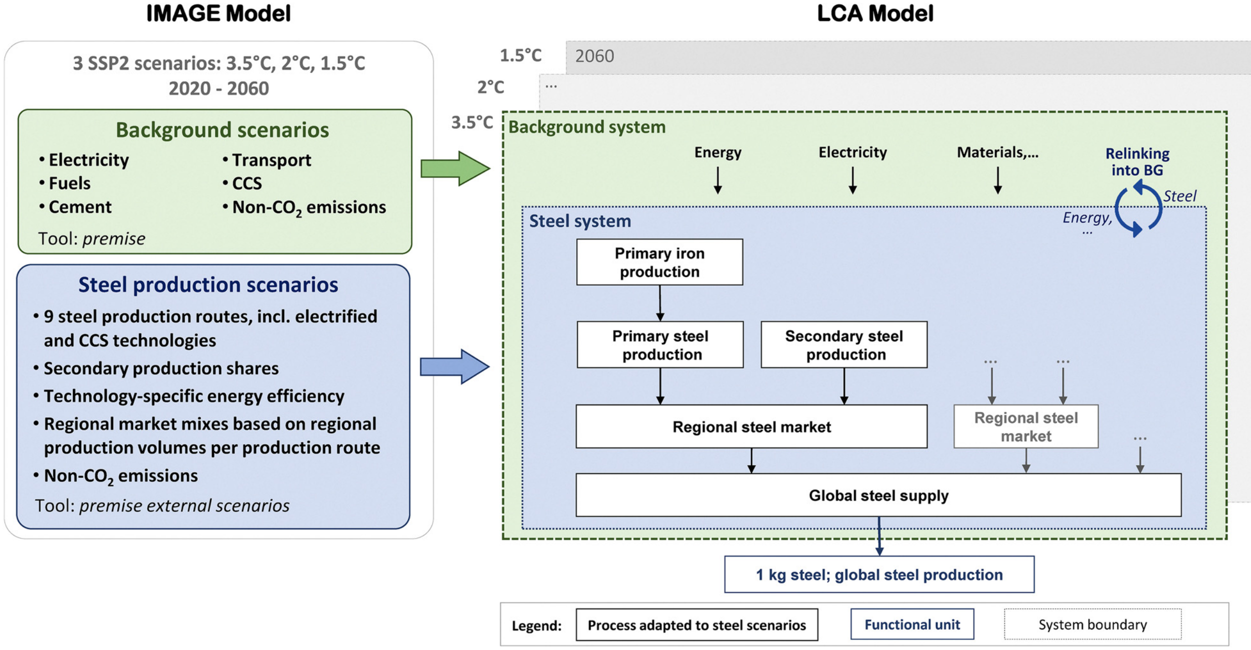

Fig. 1 Model coupling and scenario integration of the IMAGE scenarios into the LCA model using *premise*. More detailed flowcharts for the different steel production routes are provided in Fig. 2, Section 2.2.3 explains the IMAGE scenarios. BG: background; CCS: carbon capture and storage; SSP: Shared Socioeconomic Pathways.

attributional life cycle assessment (LCA) from 2020 to 2060 with a cradle-to-gate scope. The functional units are 1 kg of steel supplied by the average global steel market, and the total supply required to meet future global steel demand (quantities are scenario-specific).

The scenarios are based on the IAM IMAGE§ (ref. 40) (Fig. 1, Section 2.2.3). The IMAGE steel production model includes eight primary and one secondary production route (Fig. 2), representing the most common and promising technologies. They are regionalised into 26 world regions (ESI,† Section S1.1.3).

We integrate the energy and steel supply scenarios from IMAGE into the life cycle inventory (LCI) database of ecoinvent (v3.9.1 cut-off[50]) using the open-source Python library *premise*¶ (ref. 45) (Fig. 1). For each sectoral scenario, *premise* imports new LCIs, creates supply chains for 26 world regions, generates new regional supply markets based on production volumes by supply chain (*e.g.*, for future electricity mixes), and finally relinks these new supply chains and markets to downstream consumers within the database. We thereby create futurized versions of the database representing the future system described in the scenarios—an approach referred to as 'background scenario' integration.

All scenario data is sourced from IMAGE for the SSP2 pathway and three climate change mitigation pathways: 3.5 °C, <2 °C, and 1.5 °C (Section 2.2.3), representing the global mean surface temperature increase by 2100, relative to pre-industrial levels. The background scenarios futurize major energy-consuming sectors (electricity, fuels, cement, and transport) in the LCI database and are generated using *premise*.

The steel production scenarios of IMAGE cover:

• Eight primary steel production routes and secondary production (Fig. 2): blast-furnace and basic-oxygen furnace (BF-BOF); BF-BOF with top gas recycling (TGR-BF-BOF); natural gas-based direct reduction (NG-DRI); hydrogen-based direct reduction (H2-DRI); electrowinning (EW); application of carbon capture and storage (CCS) to three routes (BF-BOF-CCS, TGR-BF-BOF-CCS, NG-DRI-CCS); and scrap-based electric arc furnaces (scrap-EAF);

• Technology-specific energy efficiency improvements;

• Regional production volumes for 26 regions per production route (primary and secondary) are used to create regional steel markets (Fig. 4).

2.2 Inventory analysis

2.2.1 Life cycle inventories of steel production routes. We developed detailed bottom-up LCIs of each steel production route to translate the IMAGE scenarios into a comprehensive LCA model. Our steel model considers nine steel production routes which supply steel in varying shares to regional steel markets (Fig. 2). It includes the main stages of raw material preparation production (*e.g.*, sinter or pellet production), iron production (*e.g.*, *via* BF, DRI, or EW), and steel production (*e.g.*, *via* BOF or EAF).

Current steel production (BF-BOF, scrap-EAF): The conventional steel production routes are the coke-based blast-furnace

§ IMAGE = Integrated Model to Assess the Global Environment, scenarios are used from version 3.3.[49]

¶ Version: 2.1.1.dev4, *premise* = PRospective EnvironMental Impact asSEssment, see ESI,† Section S1.4.1

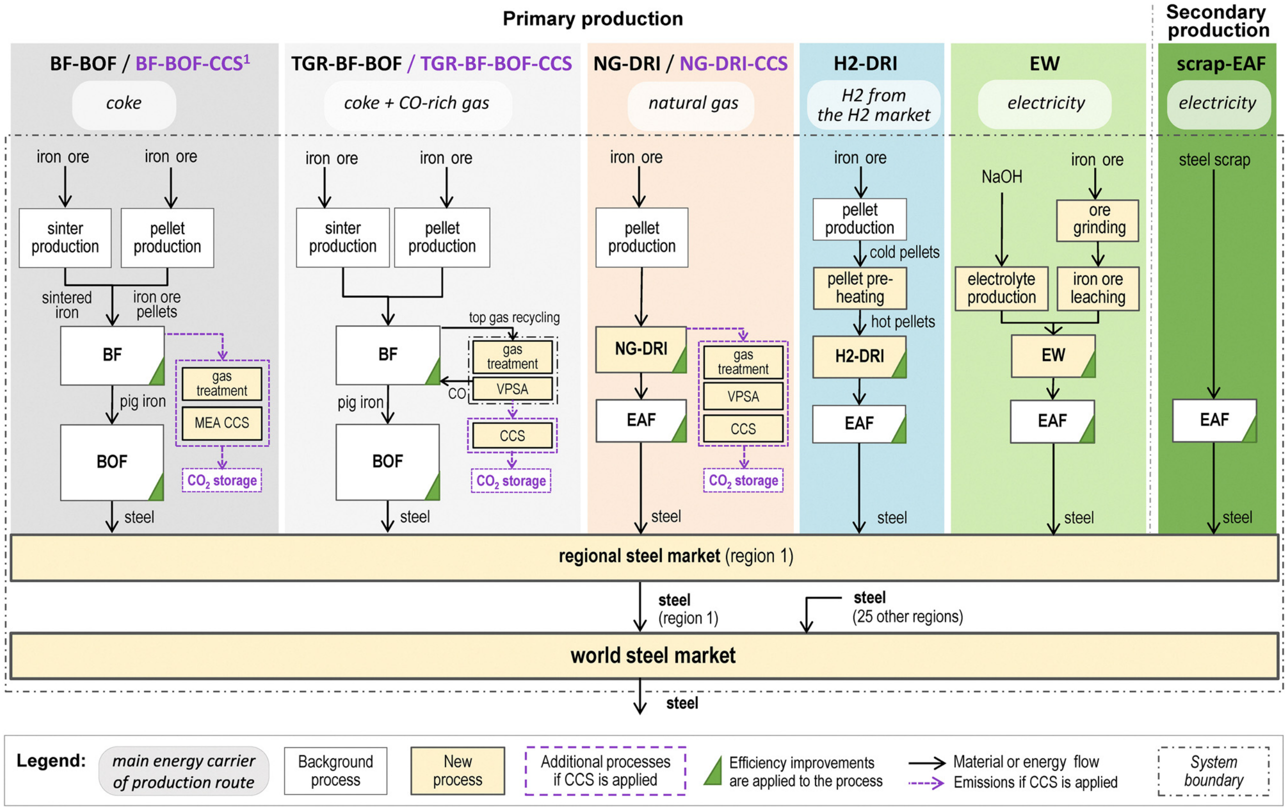

Fig. 2 Simplified flowcharts of the steel production model and the creation of regional steel markets. For all processes, incl. the CCS processes, emissions occur but are not depicted due to space restrictions. This example shows a regional market for unalloyed steel. For the other steel markets, see ESI,† Sections S1.4.2–S1.4.3. More details about each production route are provided in Section S1.3. [1]: CCS is illustrated here within the respective base technologies (BF-BOF, TGR-BF-BOF, NG-DRI) due to space restrictions, but it represents a respective individual production route. BF-BOF: blast-furnace and basic-oxygen furnace; CCS: carbon capture and storage; CO: carbon monoxide; EW: electrowinning; H2-DRI: hydrogen-based direct reduction; MEA: mono-ethanolamine; NaOH: sodium hydroxide; NG-DRI: natural gas-based direct reduction; scrap-EAF: scrap-based electric arc furnace; TGR-BF-BOF: top gas recycling blast-furnace and basic-oxygen furnace; VPSA: vacuum pressure swing adsorption.

and basic-oxygen furnace (BF-BOF) for primary production and the electric arc furnace (EAF) for secondary production, which is predominantly electricity-operated. Their processes, and all other white boxes in the figure, are primarily based on ecoinvent processes, although they might be slightly modified, *e.g.*, to align models (see Section 2.2.2).

TGR-BF-BOF: A top gas recycling (TGR) unit can be retrofitted to BFs. TGR separates CO_2 from the BF top gas using vacuum pressure swing adsorption (VPSA) to produce a CO-rich gas for reinjection into the BF as a reducing agent. Thereby, coke and hard coal consumption of the BF can be decreased by 24.5%, reducing direct CO_2 and CO emissions of the BF by 24% and 90%, respectively.[51] For the VPSA, we assume an adsorbent based on zeolite (0.75 kg per ton pig iron[52]) and an electricity consumption of 83 kWh per ton pig iron.[53]

NG-DRI: For natural gas-based direct reduction (NG-DRI), we assume that iron is produced in a shaft furnace using the Midrex process.[54] The iron is refined to steel *via* an electric arc furnace (EAF), which is also applied to iron from H2-DRI and EW.

H2-DRI: We assume that hydrogen is sourced from the respective regional markets of hydrogen from IMAGE, which includes efficiency scenarios and scenarios for the generation mix. Thus, hydrogen may not be generated purely from renewables, but, for example, from natural gas too (ESI,† Section S1.2.5). The LCI for DRI is based on a recent study[32] and is complemented by the electrical preheating of iron ore pellets and hydrogen.[16,55] In a sensitivity analysis, we assess green hydrogen for iron production, labelled green H2-DRI. The green hydrogen is sourced from PEM (proton exchange membrane) electrolysers operated with renewable electricity only, *i.e.*, from onshore wind turbines (ESI,† Section S1.3.3), as hydrogen from electrolysis causes lower GHG emissions than from fossil fuels.[56]

EW: Iron production can be directly electrified *via* the novel process of electrolysis of iron ore. This eliminates conversion losses associated with hydrogen generation. Specifically, electrowinning (EW) allows iron production at low temperatures (110 °C) using an alkaline electrolyte, *e.g.*, sodium hydroxide.[17] We use data from a pilot plant of the SIDERWIN project[18,19,57] in France. We assume that electricity is sourced from the respective regional markets for electricity.

CCS technologies for BF-BOF-CCS, TGR-BF-BOF-CCS, and NG-DRI-CCS: To reduce direct emissions of the iron production processes of the BF, TGR-BF, and NG-DRI, carbon capture and storage (CCS) facilities can be retrofitted, leading to three additional production routes. BF-BOF-CCS uses monoethanolamine (MEA) as CO_2 absorbent.[58] The TGR-BF-BOF-CCS and NG-DRI-CCS options apply the zeolite-based VPSA followed by a cryogenic flash and compression process, which increases the purity of the CO_2 gas and makes it suitable for transport.[51,59] The CCS processes require additional energy but also reduce NO_x, SO_2 and dust emissions during gas pretreatment (ESI,† Section S1.3).[52,60,61] CO_2 transport and storage are taken from *premise* based on Volkart *et al.* (2013)[62] assuming the most conservative transport distance (400 km) and storage depth (3 km).

Further details for the LCIs are provided in the ESI,† Section S1.3.

2.2.2 Global steel production model. We model global steel supply as the sum of regional steel markets based on their respective production volumes in the respective scenario. Each regional market is created for six different steel types.

Steel types: We consider six different steel types using their current global production shares from ecoinvent: unalloyed (82.9%), low-alloyed (3.7%), chromium (1.8%), reinforcing steel (4.5%), hot-rolled low-alloyed (5.3%) and hot-rolled chromium (1.8%) steel (ESI,† Section S1.4.2). A global market group summarises global steel production from all six steel types (ESI,† Section S1.4.3). The future regionalised and technology-specific steel production mix is implemented for all steel types apart from chromium steel, which is produced using the EAF.

Alloying elements: Alloying elements are added depending on the steel type based on data from existing ecoinvent processes (ESI,† Section S1.4.4).

Additional assumptions: Given the different model structures of IMAGE and LCA models, specifically ecoinvent and our steel LCIs, we adapted the LCA models to ensure consistency of assumptions. Primary production routes are purely primary, only using iron-bearing materials from primary sources, excluding scrap, while secondary production is purely secondary, using only scrap as input (Sections S1.4.5 and S3.2, ESI†).

2.2.3 Steel scenarios from IMAGE. Three scenarios from the IAM IMAGE are considered: a Base (3.5 °C) scenario, a <2 °C, and a 1.5 °C scenario. They all use the Shared Socioeconomic Pathway SSP2, also called middle-of-the-road, as economic, demographic and political trends continue without major changes[63] (Fig. 3). The Base scenario assumes no specific

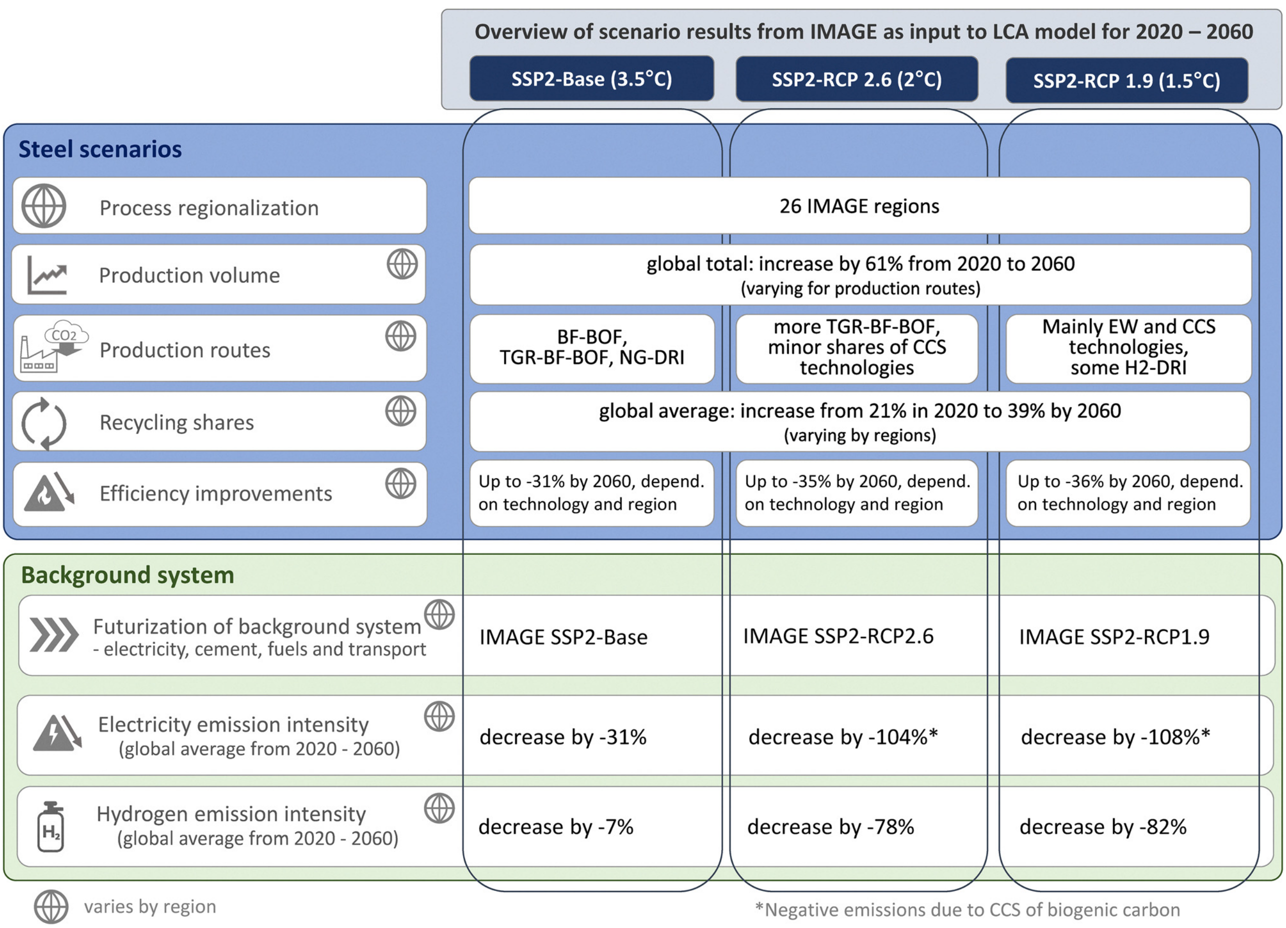

Fig. 3 Overview of multi-sectoral scenarios from the integrated assessment model IMAGE for steel and background scenarios. BF-BOF: blast-furnace and basic-oxygen furnace; CCS: carbon capture and storage; EW: electrowinning; H2-DRI: hydrogen-based direct reduction; NG-DRI: natural gas-based direct reduction; RCP: Representative Concentration Pathways; SSP: Shared Socioeconomic Pathways; TGR-BF-BOF: top gas recycling blast-furnace and basic-oxygen furnace.

climate mitigation targets, leading to about 3.5 °C warming by 2100. For the <2 °C- and 1.5 °C scenarios, the SSP is combined with two Representative Concentration Pathways (RCPs), which represent the climate targets and limit the atmospheric radiative forcing by 2100 to 2.6 and 1.9 W m^{-2}, respectively.

IMAGE is a process-based IAM which models physical flows with high sectoral and regional resolution. Its strength lies in a detailed representation of the industrial sector, especially for the steel and cement sectors.[29,30,40,46] While other IAMs model the industrial sectors based on exogenous assumptions without technology-specific process data, IMAGE distinguishes different production technologies and their respective parameters.[64]

We updated the steel technology parameters for IMAGE v.3.3 to more recent data regarding specific energy consumption (SEC), floor values, and carbon capture rates (ESI,† Section S1.1.2).

Steel production capacities are modelled considering current stocks (assuming a lifetime of 30 years) and optimising the costs of new capacities, considering capital and operational expenditures (*e.g.*, for fuel demand and considering efficiency improvements) and context-related costs, such as carbon taxes (ESI,† Section S1.1.2). Steel demand is based on a stock model for four product categories of variable lifetimes (buildings, machinery, cars and packaging),[30] which also determines scrap availability and future secondary steel production shares. More details about IMAGE and the steel sub-module are provided in the ESI† (Sections S1.1 and S1.2) or related literature.[29,30,40]

Future global steel production: For all scenarios, global steel production grows by 61% from 2020 to 2060 (from 1640 to 2634 Mt steel per year) with primary production increasing by 25% (see Fig. 4a, ESI,† Section S1.2.3). In IMAGE, material production is GDP-driven, which is the same across all scenarios for SSP2.

Regionalization of steel production: Steel production is regionalized distinguishing 26 world regions (ESI,† Section S1.1.3). While China is the largest producer in 2020, accounting for 55% of the market share, production partly relocates by 2060, *e.g.*, to India (14%) and Eastern Africa (13%) (see Fig. 4a, ESI,† Section S1.2.2).

Market shares of steel production routes: Secondary production shares (scrap-EAF) increase from 21% to 39% by 2060 (see Fig. 4b, ESI,† Section S1.2.3). Primary production, however, exhibits a shift towards novel primary production, which intensifies with

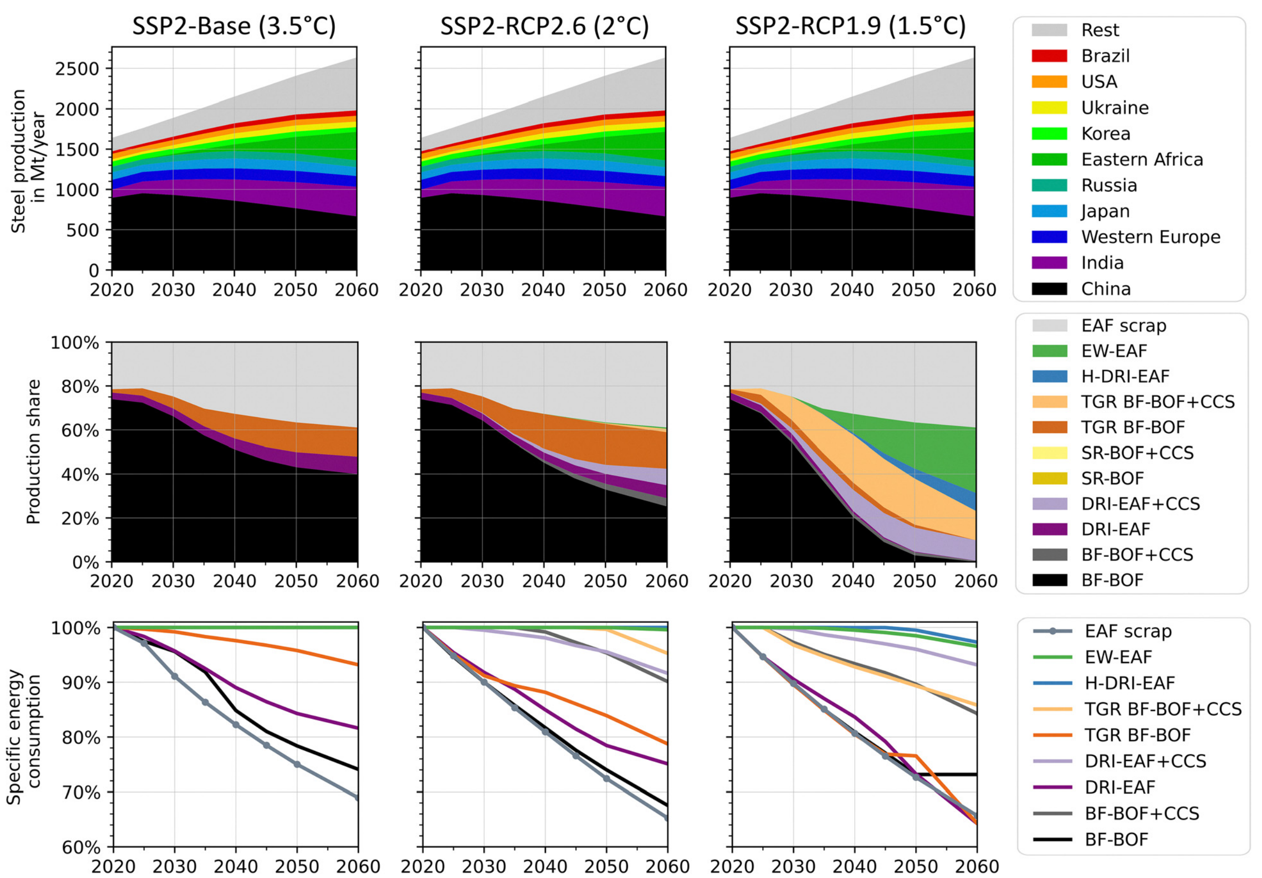

Fig. 4 Global steel production scenarios according to the scenarios from IMAGE. Steel production by (a) region showing the top ten steel producing regions; and (b) by production route. (c) Development of specific energy consumption (SEC) for each steel production route relative to the energy consumption in 2020. More detailed figures are provided in the ESI:† regional production shares (Section S1.2.2, ESI†); market mixes of different regions (Section S1.2.3, ESI†); and SEC for each technology depending on the region (Section S1.2.4, ESI†). BF-BOF: blast-furnace and basic-oxygen furnace; CCS: carbon capture and storage; EW: electrowinning; H2-DRI: hydrogen-based direct reduction; NG-DRI: natural gas-based direct reduction; RCP: Representative Concentration Pathways; scrap-EAF: scrap-based electric arc furnace; SR-BOF: smelting reduction and basic-oxygen furnace; SSP: Shared Socioeconomic Pathways; TGR-BF-BOF: top gas recycling blast-furnace and basic-oxygen furnace.

stronger climate goals. While the coke-based BF-BOF production decreases from 74% in 2020 to 40% and 25% in the 3.5 °C and 2 °C scenarios by 2060, it gets entirely phased out in the 1.5 °C scenario. In the Base scenario, alternatives for primary production are limited to TGR-BF-BOF (13.5%) and DRI-EAF (6.8% in 2060).

In the 2 °C scenario, CCS is deployed as a minor technology for BF-BOF-CCS (3.7%), NG-DRI-CCS (7.5%), and TGR-BF-BOF-CCS (1.5%), but it gains relevance in the 1.5 °C scenario, with TGR-BF-BOF-CCS supplying 13.3% and NG-DRI-CCS 9.3% by 2060.

The electrified EW becomes a key technology in the 1.5 °C scenario representing the majority (29.8%) of primary production. In contrast, H2-DRI plays only a minor role (8.2%) given a too high emission intensity of hydrogen generation.

Smelting reduction furnaces, *i.e.*, SR-BOF and SR-BOF-CCS, are not deployed, given their comparatively high energy requirements and low CCS capture rate (ESI,† Section S1.1.2). Therefore, they are not further considered in this study.

Efficiency improvements of steel production: We apply technology- and region-specific efficiency improvements to the processes of iron and steel production (see Fig. 2, ESI,† Section S1.2.4). Efficiency improvements are derived from the IMAGE scenarios (see Fig. 4c) but slightly corrected as documented in ESI,† Section S1.2.4. For instance, they are limited to a maximum of 1.1% year^{-1}, *i.e.*, the maximum rate from literature,[29] leading to a maximum decrease of specific energy consumption (SEC) of −36% from 2020 to 2060. Efficiency improvements are not applied to iron-bearing materials or alloying elements to ensure the correctness of mass balances (Section S1.2.4, ESI†).

2.3 Life cycle impact assessment

We use the IPCC 2021 GWP 100a method[65] to assess climate change impacts. We complement the GWP100a indicator with characterisation factors for hydrogen emissions to air (+11 kg CO_2-eq. per kg H_2[66]) and non-fossil CO_2 emissions and uptake (±1 kg CO_2-eq. per kg CO_2) (ESI,† Section S1.5), to correctly account for emissions of hydrogen supply and biomass-fuelled CCS technologies.[45] Midpoint indicators from the Environmental Footprint 3.0 method[67] are used for other impact categories.

The LCA results are calculated using the Activity Browser[68] and the superstructure approach.[69]

3. Results

3.1 Future climate change impacts of steel production routes

Fig. 5 illustrates climate change impacts per kg of steel for the nine production routes in 2060 under the three scenarios compared to 2020.

The net emission intensity (black crosses) of all production routes decreases with more ambitious climate goals, ranging from −46 to −95% by 2060 compared to the BF-BOF in 2020. An exception forms the BF-BOF, whose efficiency stagnates in the 1.5 °C scenario. The lowest emission intensity is achieved by the electricity-based technologies of secondary production (scrap-EAF) and EW in 2060, both almost reaching net-zero, *i.e.*, 0.12 kg CO_2-eq. per kg of steel. However, this strongly depends on the emission intensity of electricity, which is by far the most prominent contributor (78% for EW in 2020). In some instances, electricity can have a net negative contribution due to biomass use combined with CCS (BECCS, see ESI,† Section S1.2.5).

For the conventional processes (BF-BOF, TGR-BF-BOF, and NG-DRI), the largest contributors are direct emissions from iron production (red; 33–60%) and iron sinter and pellet production (orange; 3–32%), with smaller contributions from indirect emissions due to the supply of coke and coal (1–13%), electricity (1–33%) and natural gas (1–13%).

The impacts of electrified or novel steelmaking technologies like H2-DRI, EW, and scrap-EAF are primarily driven by indirect emissions from hydrogen, electricity, natural gas, and biomass supply. Thus, in 2020, if operated with the current electricity and hydrogen mix, the emission intensity of EW would be 62% higher and of H2-DRI only 1% lower than that of the BF-BOF. These technologies achieve their maximum emission reductions of −95% and −83%, respectively, only with a decarbonized energy supply under ambitious climate scenarios.

This is because, in the IMAGE scenarios, hydrogen production relies mainly on natural gas or natural gas with CCS (see ESI,† Section S1.2.5), with renewable hydrogen playing a minor role, contributing less than 15% by 2060 in the 1.5 °C scenario. This underscores the importance of a systems perspective and explains why H2-DRI and EW are not deployed in the IMAGE 3.5 °C scenario (see hatched bars). However, using green hydrogen (*via* electrolysis powered by wind energy) can drastically lower H2-DRI's emissions by 33–42%, reducing its intensity from 0.38 to 0.25 kg CO_2-eq. per kg steel by 2060 (green crosses in Fig. 5).

CCS technologies can reduce the net emission intensity of BF-BOF, TGR-BF-BOF, and NG-DRI by 15–46%, capturing 0.42–0.77 kg CO_2-eq. per kg steel. Among them, NG-DRI-CCS achieves the lowest emission intensity by 2060 of 0.32 kg CO_2-eq. per kg steel. Nevertheless, EW and green H2-DRI offer greater emission reduction potentials of −95% and −89%, respectively, than the CCS technologies, which achieve a maximum of −49% (BF-BOF-CCS), −55% (TGR-BF-BOF-CCS), and −86% (NG-DRI-CCS).

For all technologies, direct emissions from the steel production process in the BOF or EAF are almost negligible.

Efficiency improvements are applied only to iron and steel production processes (red and black areas in Fig. 4), whose emissions decrease marginally over time. The benefits of efficiency improvements are thus minor compared to the effect of the overall climate mitigation scenario, which considerably lowers the impacts of multiple sectors, and especially those of electrified technologies, *i.e.*, their upstream emissions.

The share of impacts from iron sinter and iron ore pellets, *i.e.*, the iron-bearing materials for iron production, differs considerably among the routes, with high shares (17–38%) for BF-based and TGR-BF-based routes. The reason is that their iron production processes primarily use iron sinter, while the others use iron ore pellets (apart from EW, which directly uses iron ore concentrates). Iron sinter production has a

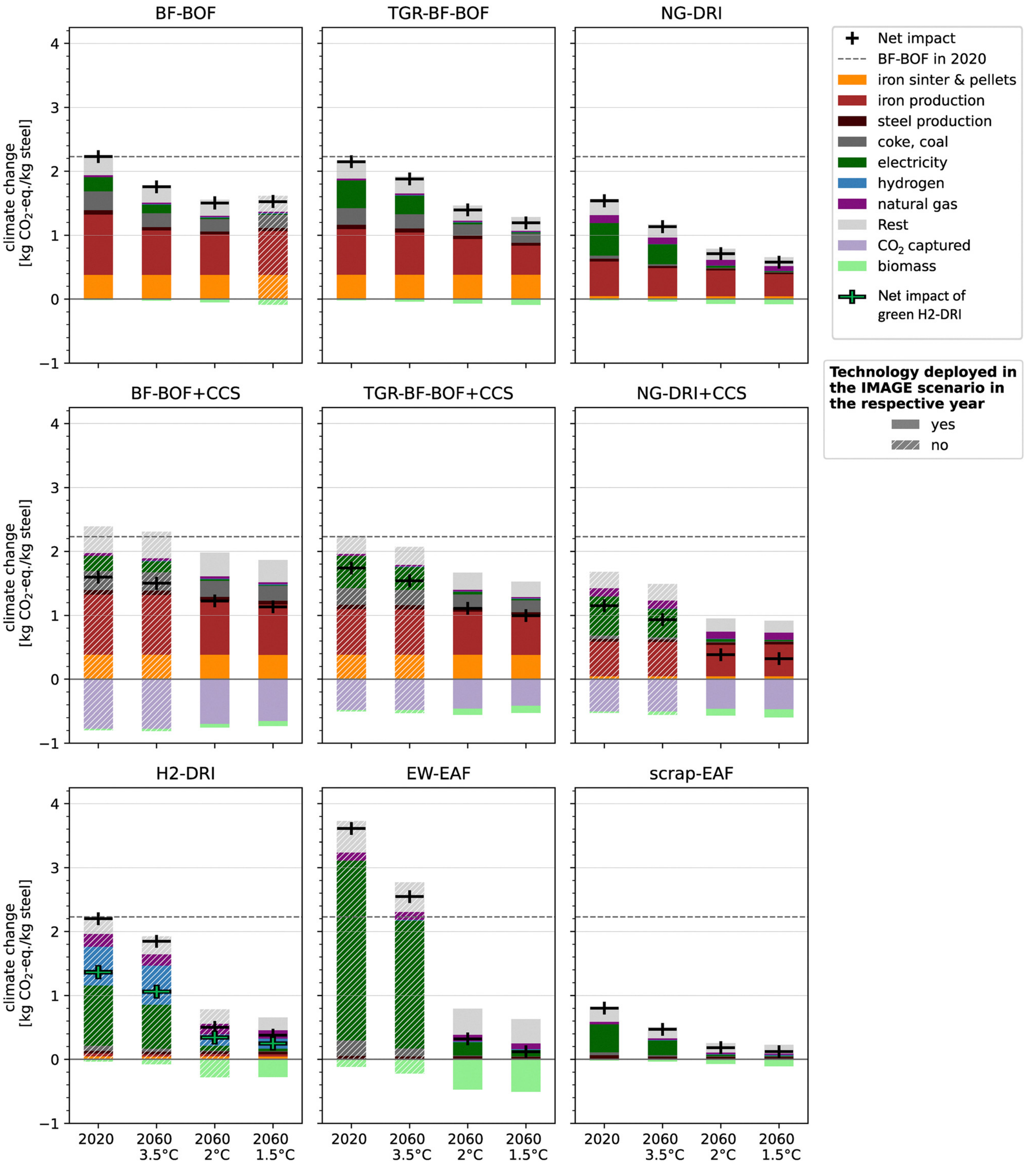

Fig. 5 Climate change impacts for nine steel production routes per kg steel in 2060 compared to 2020 under different climate goal scenarios. The hatching indicates that the technology is not part of the steel production mix in that specific scenario and scenario year of the IMAGE scenarios. H2-DRI: green crosses denote net impact of green H2-DRI compared to H2-DRI which sources hydrogen from the average hydrogen mix (black crosses). Functional units: world datasets for unalloyed steel, apart from scrap-EAF, which is low-alloyed steel; scenarios: SSP2; *premise*: all sectors updated; contribution cut-off at 0.1%, contributors are aggregated by reference product and were partly manually grouped. Biomass: biogenic CO_2, *i.e.*, CO_2 uptake during biomass growth; BF-BOF: blast-furnace and basic-oxygen furnace; CCS: carbon capture and storage; EW: electrowinning; H2-DRI: hydrogen-based direct reduction; NG-DRI: natural gas-based direct reduction; scrap-EAF: scrap-based electric arc furnace; TGR-BF-BOF: top gas recycling blast-furnace and basic-oxygen furnace.

considerably higher emission intensity than iron pellets (about a factor of 5) due to higher direct and indirect emissions (see ESI,† Section S2.1).

3.2 Future climate change impacts of global steel production

3.2.1 Impact by steel types and regions per kg of steel. Fig. 6(a) illustrates the climate change impacts per kilogram of steel across various steel types and the global average (represented by the black line), which aggregates data from all six types (refer to Section 2.2.2 and Section S1.4.3, ESI†). As anticipated, more ambitious climate scenarios lead to higher reductions in emissions. Under the 3.5 °C scenario, impacts decrease by 33%, from 2.1 to 1.41 kg CO_2-eq. per kg of steel (black line). While the 2 °C scenario achieves a 56% reduction lowering emissions to 0.93 kg CO_2-eq. per kg of steel, the 1.5 °C scenario realizes the most substantial reduction of 79% to 0.44 kg CO_2-eq. per kg of steel.

The trends are consistent across different steel types (*e.g.*, low-alloyed, reinforcing, chromium steel), with only minor deviations. However, chromium steel stands out with significantly higher climate change impacts, exceeding the average by more than a factor of two (2.3–5.2 kg CO_2-eq. per kg steel). This is primarily due to the energy-intensive production of its alloying elements, ferronickel and ferrochromium, which account for 56% and 25% of chromium steel's emissions in 2020, respectively. Hot rolling increases emissions by up to 14%, but its impact decreases under stricter climate goals from 0.27 to 0.06 kg CO_2-eq. per kg of steel.

Fig. 6(b) illustrates the regional differences in GHG emissions using the example of unalloyed steel and the top ten steel-producing regions. These originate from the region-specific steel production mixes (ESI,† Section S1.2.3), efficiency improvements (Section S1.2.4, ESI†), and regionalised scenarios for the upstream sectors, such as electricity or fuel supply.

3.2.2 Impacts of global steel production. Fig. 7 illustrates annual climate change impacts of global steel production, with a +61% increase in production by 2060 in our scenarios.

Fig. 7(a) shows that annual GHG emissions strongly depend on the scenario. In the Base scenario, they rise by 8% in 2060 compared to 2020, *i.e.*, from the current 3.4 Gt CO_2-eq. per year to 3.7 Gt CO_2-eq. per year (Fig. 7b). Under stricter decarbonization measures the declining GHG emission intensity is sufficient to compensate for growing demand: total GHG emissions decrease by −29% (to 2.5 Gt CO_2-eq. per year) under the 2 °C- and by −67% (to 1.2 Gt CO_2-eq. per year) under the 1.5 °C scenario by 2060. The substantial reductions in emission intensities achieve absolute decoupling of GHG emissions from demand growth. However, reaching net-zero emissions by 2050 or 2060 remains very challenging.

Unalloyed steel production accounts with 65–77% for the majority of global GHG emissions over time, provided its constant market share of 83% (Section 2.2.2). The other steel types contribute roughly equally between 3.8–9.9% (Fig. 7b).

Most emissions of unalloyed steel are currently associated with steel production *via* the BF-BOF (87%) (Fig. 7c). They decline considerably only with the introduction of new technologies in the 2 °C scenario and are eliminated in the 1.5 °C scenario. The residual emissions are primarily caused by the alternative technologies of TGR-BF-BOF in the 2 °C scenario, and the TGR-BF-BOF-CCS in the 1.5 °C scenario. The electrified technologies of EW and scrap-EAF have very low emissions in 2060 despite their high production shares in the 1.5 °C scenario, which demonstrates their high emission reduction potential. In contrast, the insufficient benefit of mere efficiency improvements and the risk of a lock-in effect with fossil-fuel-based technologies like the BF-BOF, but also TGR-BF-BOF

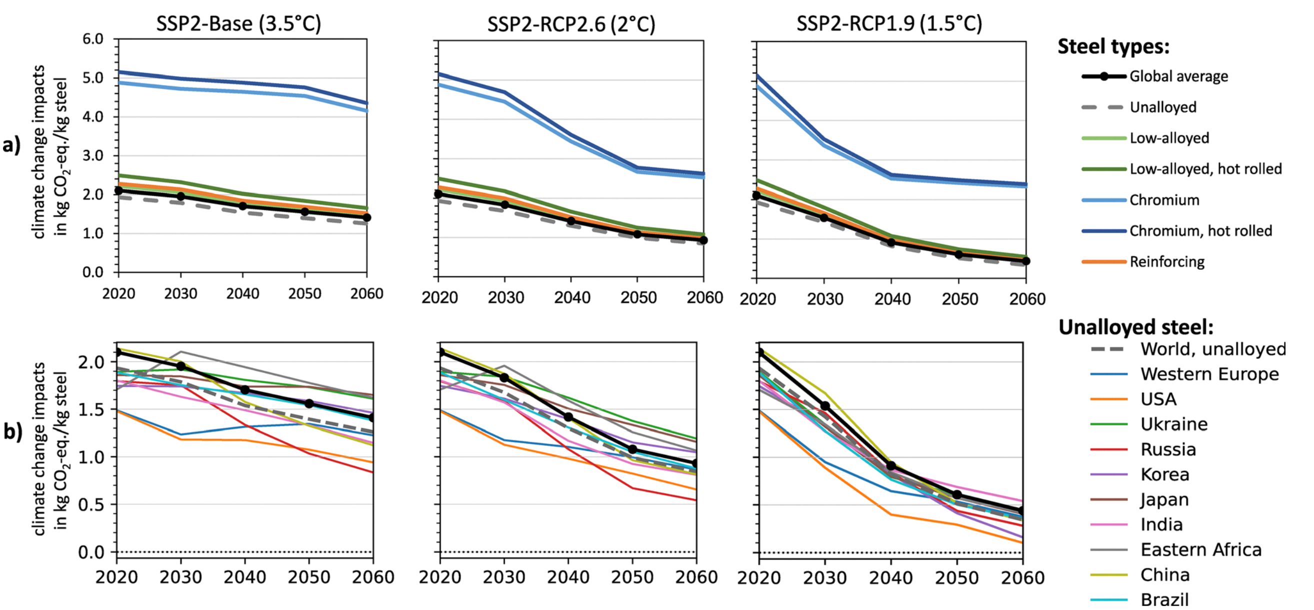

Fig. 6 Specific climate change impacts of global steel production under the three scenarios: (a) by steel type; (b) for unalloyed steel for the top 10 producing regions. The global average steel (black line) represents the impacts of global steel supply summarizing the six steel types (*e.g.*, low-alloyed, reinforcing steel, *etc.*, ESI,† Section S1.4.3). RCP: Representative Concentration Pathways; SSP: Shared Socioeconomic Pathways.

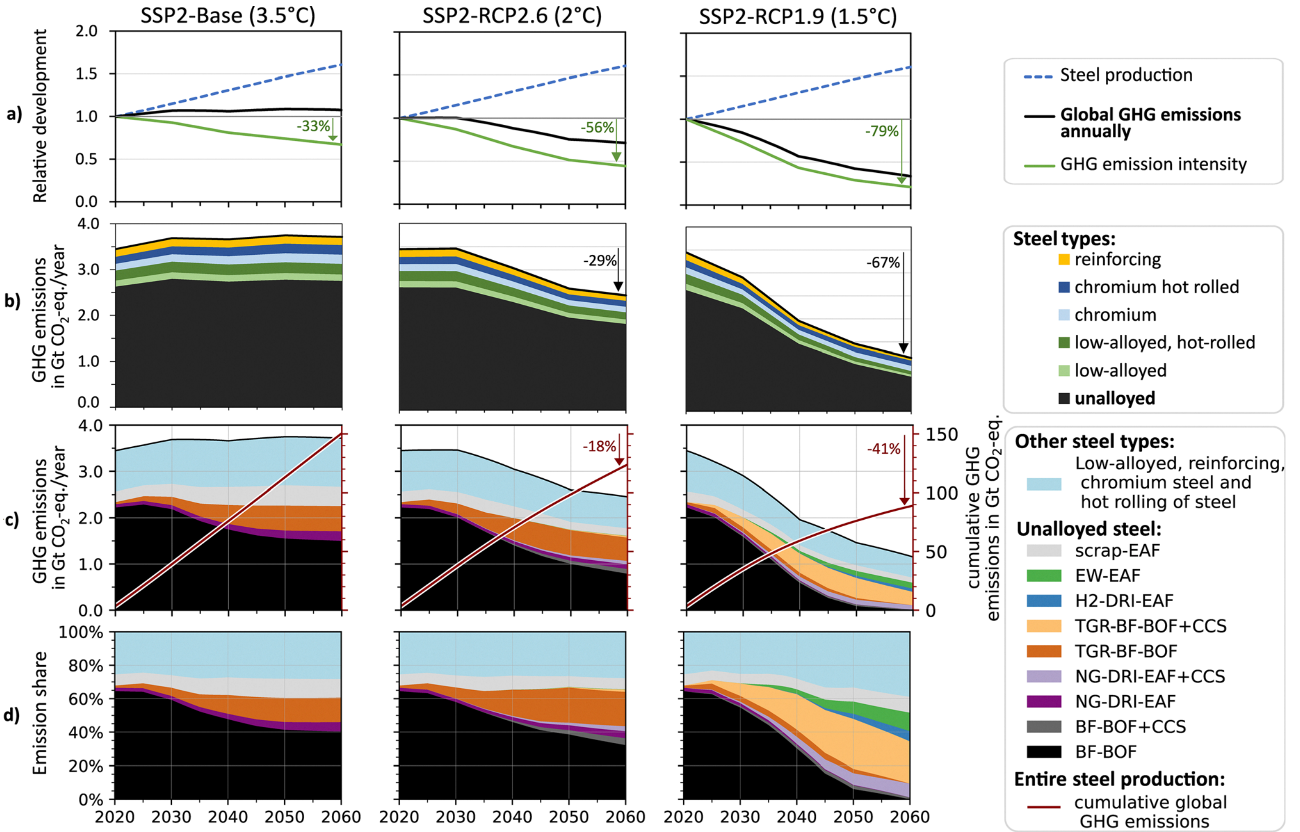

Fig. 7 Annual and cumulative climate change impacts of global steel supply if future production amounts are considered; (a) development relative to 2020; (b) distinguished by steel type; (c) distinguished by production technology for unalloyed steel with cumulative global GHG emissions (right *y*-axis); (d) relative by production technology for unalloyed steel. Functional unit: global steel production from the global market group for steel; *premise*: all background scenarios are incorporated. BF-BOF: blast-furnace and basic-oxygen furnace; CCS: carbon capture and storage; EW: electrowinning; H2-DRI: hydrogen-based direct reduction; NG-DRI: natural gas-based direct reduction; RCP: Representative Concentration Pathways; scrap-EAF: scrap-based electric arc furnace; SSP: Shared Socioeconomic Pathways; TGR-BF-BOF: top gas recycling blast-furnace and basic-oxygen furnace.

and TGR-BF-BOF-CCS becomes apparent. By the time the world should have realised net-zero emissions, such technologies would still emit 0.3 Gt CO_2-eq. per year in the 1.5 °C- and even 1.4 Gt CO_2-eq. per year in the 2 °C scenario in 2060 for unalloyed steel alone.‖

By 2060, the cumulative GHG emissions (red line in Fig. 7c) of the Base scenario (151 Gt CO_2-eq. in 2060) can only marginally be reduced through the decarbonization scenarios by −18% to 124 Gt CO_2-eq. (2 °C) and by −41% to 89 Gt CO_2-eq. (1.5 °C). The Intergovernmental Panel on Climate Change (IPCC) provides remaining global carbon budgets from 2020 to the end of the century of 900–1350 Gt CO_2-eq. and 300–500 Gt CO_2-eq. for the 2 °C and 1.5 °C scenarios and 50–83% likelihoods.[65] The steel industry would thus consume between 9–14% (2 °C scenario) and 18–30% (1.5 °C scenario) of these global end-of-the-century carbon budgets by 2060.

3.3 Future non-climate environmental impacts of global steel production

3.3.1 Environmental impacts per kg of steel. Fig. 8(a) illustrates the projected changes in environmental impacts per kilogram of steel produced for 16 impact categories in 2060 under the 1.5 °C scenario relative to 2020. It highlights potential burden shifting, where reductions in climate change impacts (−79%) may come at the cost of increasing impacts in other categories. These are carcinogenic human toxicity (+25%), water use (+27%), land use (+79%), material resource depletion (+100%), ionising radiation (+241%), and ozone depletion (+275%).

The drivers of these impacts vary by category. Mining contributes to ecotoxicity and freshwater eutrophication, steel production processes drive human toxicity, water use, and ozone depletion, while upstream energy, especially electricity-generating processes dominate ionising radiation, material resource depletion and land use impacts (ESI,† Sections S2.2–S2.3). Transport contributes to marine and terrestrial eutrophication.

Higher electricity demand for electrified steel production intensifies ionising radiation impacts (+241%) caused by the assumed nuclear power generation, especially the uranium tailings treatment due to radon emissions to the air or chemicals leaking into groundwater.[70,71] These emissions may be lowered, for instance, by covering tailings with clay[71] or installing lining membranes and water management systems for tailing deposits. Carbon-14 is released from the treatment of spent nuclear fuel.

‖ Emission sums for BF-BOF, BF-BOF-CCS, TGR-BF-BOF and TGR-BF-BOF-CCS for unalloyed steel.

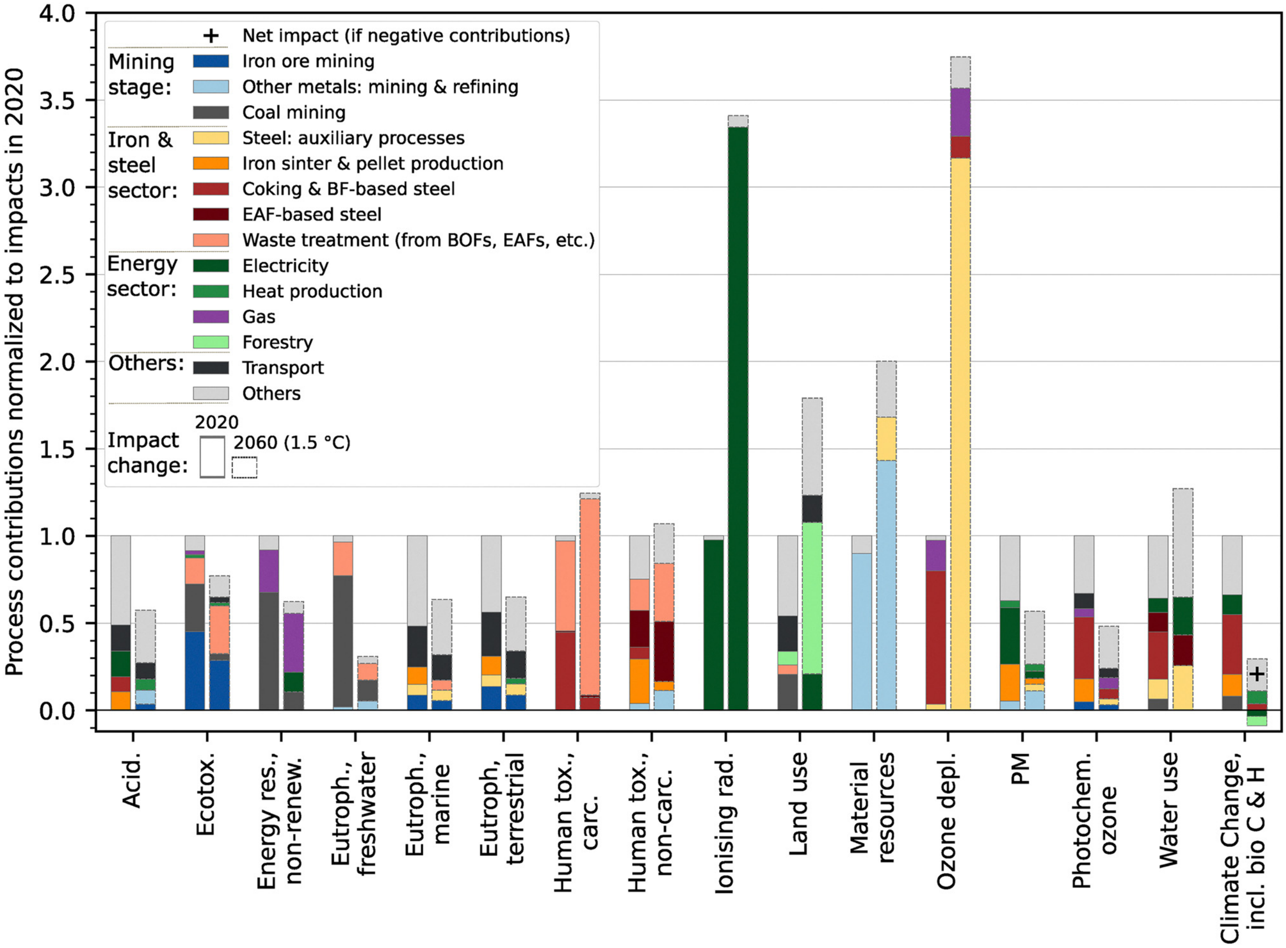

Fig. 8 Impact development and contribution analysis of impacts in 2060 relative to 2020 per kg steel for 16 impact categories. Values are given for 2060 in the 1.5 °C scenario (right bar) relative to 2020 (left bar). The top 5 contributors were selected, aggregated by process name, and partly manually grouped. Functional unit: 1 kg of steel from the global market group for steel, *premise*: all background scenarios are incorporated. Further results are provided in the ESI,† Section S2.2 and S2.3. Acid.: acidification; Ecotox.: ecotoxicity; Energy res., non-renew.: non-renewable energy resources; Eutroph., freshwater: freshwater eutrophication; Eutroph., marine: marine eutrophication; Eutroph, terrestrial: terrestrial eutrophication; human tox., carc.: carcinogenic human toxicity; human tox., non-carc.: non-carcinogenic human toxicity; ionising rad.: ionising radiation; ozone depl.: ozone depletion; PM: particulate matter; photochem. ozone: photochemical ozone formation; incl. bio C & H: including biogenic carbon and hydrogen.

Likewise, land use impacts (+79%) increase due to biomass-based power generation which is controversial as it competes with food production, nature conservation,[72–74] and biomass-based fuels for other sectors, such as cement.[46] Holistic assessments across sectors are needed to evaluate the availability of renewable electricity and sustainable biomass supply, considering natural limits.

The increase in material resource depletion (+100%) is driven by a higher demand for metals required for more electrified steel and more renewable power systems (*e.g.*, for PV and wind turbines) by 2060, such as tellurium, copper, gold and silver, and sodium chloride for sodium hydroxide (for EW). Chromium for chromium steel has a high contribution (21–40%), but its impact stays about constant. Metal depletion could be reduced by more sustainable metal cycles, limiting primary metal extraction. Generally, the energy transition is expected to decrease overall mining activity globally.[75]

The future impacts of ozone depletion and carcinogenic human toxicity might be overestimated. Ozone depletion (+275%), currently driven by coke production, may rise due to sodium hydroxide production, the alkaline electrolyte required for EW. However, the impacts caused by refrigerant gas leaks are likely lower in the future due to ongoing phase-outs of ozone-depleting gases under the Montreal Protocol.[76,77] Carcinogenic human toxicity (+25%) stems from two main processes: (i) chromium emissions into water due to landfilled EAF slag, which has also been reported by previous studies using current ecoinvent processes;[7,78] and (ii) benzo(a)pyrene emissions from coke production. Landfilling EAF slag will probably decline with stricter regulations and when reusing and recovering materials from slag becomes more common. Since slag treatment was modelled based on scrap-EAFs due to a lack of primary data for EAFs used for primary production, slag-related impacts might be overestimated. Nevertheless, the use

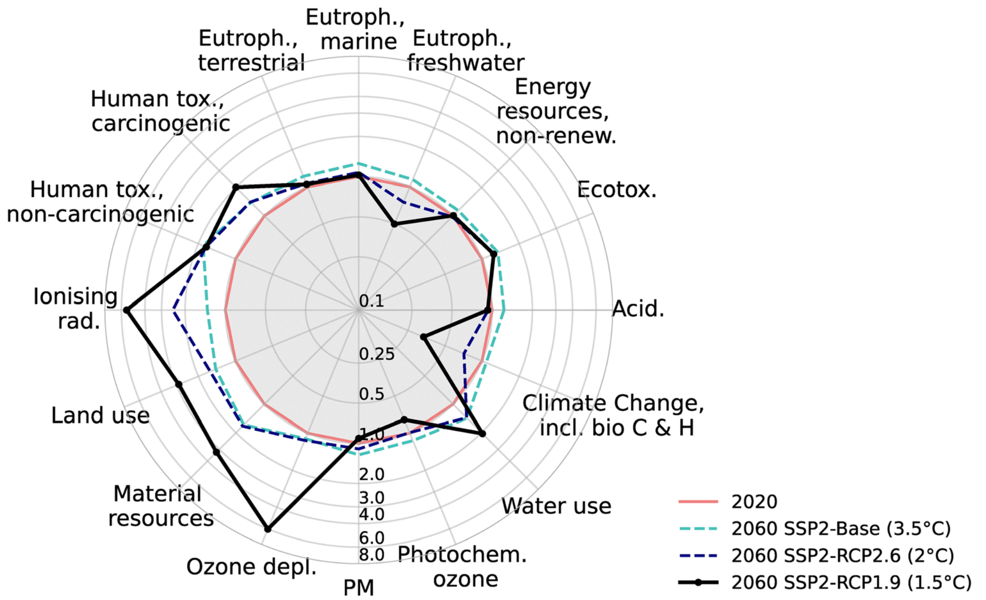

Fig. 9 Impact development of global steel production in 2060 compared to 2020 for total impacts considering annual global steel production. Values are relative to the impacts in 2020 on a logarithmic scale. Functional unit: global annual steel production from the global market for steel; *premise*: all background scenarios are incorporated. For results per steel type, see ESI,† Section S2.2. Acid.: acidification; Ecotox.: ecotoxicity; energy res., non-renew.: non-renewable energy resources; Eutroph., freshwater: freshwater eutrophication; Eutroph., marine: marine eutrophication; Eutroph, terrestrial: terrestrial eutrophication; human tox., carc.: carcinogenic human toxicity; human tox., non-carc.: non-carcinogenic human toxicity; ionising rad.: ionising radiation; ozone depl.: ozone depletion; PM: particulate matter; photochem. ozone: photochemical ozone formation; RCP: Representative Concentration Pathways; SSP: Shared Socioeconomic Pathways; incl. bio C & H: including biogenic carbon and hydrogen.

of EAFs for primary and secondary production will increase in the future, highlighting the need to improve slag management.

For some categories, such as water use (+27%), multiple processes contribute without a dominant source.

On the other hand, several impacts are expected to decline in the future since they co-benefit from the phase-out of coal- and coke-based processes, along with BF-BOFs: ecotoxicity (−23%), eutrophication (−35 to 69%), acidification (−42%), particulate matter (−43%), and photochemical ozone formation (−52%). Their primary contributors include coal mining, coke production, production of iron sinter, and, for example, the treatment of spoil from coal mining and BOF slags in landfills (*e.g.*, freshwater eutrophication).

3.3.2 Environmental impacts of global steel production. Fig. 9 shows the change of annual impacts by 2060, when rising future global steel production is considered (+61% by 2060). It demonstrates that impacts may increase in most impact categories. Impacts per kg of steel would need to decline by at least −38% by 2060 to compensate for the effect of rising demand. Thus, the impact reduction on a per kg steel basis is insufficient to compensate for growing demand, *e.g.*, for ecotoxicity. While the decarbonization scenarios can achieve a decoupling for climate change impacts, an absolute decoupling cannot be observed for many other impact categories.

Impact categories benefitting from the BF-BOF phase-out exhibit a different trend, showing approximately constant or decreasing impacts. These are acidification (−7%), eutrophication (−50%), particulate matter (−8%), and photochemical ozone formation (−22%). However, they decline to a lesser extent than climate change (−67%).

4 Discussion

4.1 The cumulative GHG emission reduction is insufficient

Even under the most ambitious 1.5 °C scenario, the steel sector's cumulative GHG emissions are reduced by only −41% by 2060 compared to the 3.5 °C Base scenario. The 2 °C scenario achieves a modest reduction of cumulative GHG emissions of −18%. As a result, steel production would consume a substantial share of the remaining carbon budget—up to 30% for the 1.5 °C scenario and 14% for the 2 °C scenario by 2060, a conclusion in line with previous research for the steel sector.[1,3,22] For other hard-to-abate sectors, such as cement,[46] similar results were found: Müller *et al.* (2024)[46] estimated cumulative GHG emissions for cement production ranging from 56 to 129 Gt CO_2. This suggests that cement and steel production combined would account for 29–48% of the 1.5 °C or 14–21% of the 2 °C end-of-the-century carbon budget by 2060.

Neither the steel nor the cement sector achieves net-zero emissions by 2060, and hence will claim additional portions of the remaining carbon budget beyond this timeframe. Even electrified technologies like EW and scrap-EAF have remaining emissions of 0.12 kg CO_2-eq. per kg of steel by 2060.

For steel production, particularly the lock-in created by coke-based and CCS technologies (BF-BOF-CCS and TGR-BF-BOF-(CCS) is problematic. Our analysis shows these can reduce emissions in the short term with CCS enabling retrofitting of modern existing plants. However, their emission reduction potential is insufficient in the long term. Investments in CCS will create significant sunk costs for new and long-term infrastructure for CO_2 capture and storage facilities, leading to an incentive to use this infrastructure for decades.

If primary production were to shift entirely to green H2-DRI to replace BF-BOFs, which are phased out as described in the 1.5 °C scenario, cumulative GHG emissions could be further reduced by approximately 15% by 2060 compared to the 1.5 °C scenario, based on estimates for unalloyed steel (ESI,† S3.1). Yet, this represents only a marginal improvement. Thus, the sector needs to realise faster and more drastic decarbonization and emission reduction that exceed those projected in our scenarios.

4.2 System-wide reduction options beyond our projections must be found

Options to further reduce emissions include:

• Reducing demand, particularly for emission-intensive primary steel production, through means such as a circular economy, material substitution, or by increasing life-times and material efficiencies;

• Accelerating technological development and large-scale implementation of green technologies with the highest emission reduction potential, namely, H2-DRI and EW, while simultaneously scaling-up infrastructure for green electricity and hydrogen;

• Accelerating the decommissioning of inefficient and emission-intensive facilities of BF-BOFs, while also avoiding constructing new capacities for them;

• Replacing BF-BOFs with NG-DRI soon, as it is a mature technology of lower emission intensity than BF-BOFs. The advantage of this strategy is that NG-DRI furnaces can switch to near zero-emission H2-DRI when sufficient green hydrogen becomes available, which avoids the lock-in effects of CCS described above.

Next to demand-side reduction strategies, these options essentially imply an ambitious (indirect) electrification of the steel sector and its supply chains. Impacts will shift away from the direct steel production (like BF-BOF) to indirect sources, especially electricity and hydrogen supply, *e.g.*, for H2-DRI and EW, a finding consistent with previous research.[47] The benefit of ambitious electrified steel scenarios becomes effective only if the electricity sector is also decarbonized, as demonstrated by an analysis in the ESI† (Section S2.4). The multi-sector perspective and life-cycle-based approach applied here is hence essential to identify optimal solutions.

The suggested strategies may not be readily adopted without additional economic incentives because of high investment and energy costs, *e.g.*, for hydrogen, natural gas or green electricity. Moreover, green hydrogen and electricity will likely be limited in the future, with other sectors competing for them.[6,22,79] Further research is needed to assess the effect and feasibility of such measures, and to identify suitable policies.

4.3 Potential trade-offs of decarbonisation require multi-sectoral measures

Electrifying the steel sector with decarbonized power cannot mitigate impacts in all categories. Hotspots depend on the impact category (see Section 3.3.1 and Section S2.4, ESI†).

Our life cycle assessment of IMAGE scenarios revealed both co-benefits and burden-shifting of decarbonisation measures. The 1.5 °C scenario changes impacts the most, albeit in either direction, which demonstrates potential trade-offs of future decarbonization strategies, as explained below.

On a per-kg steel basis decarbonizing steel supply can achieve co-benefits in key impact categories for air quality, like particulate matter (−43%) or photochemical ozone formation (−52%). This is vital since air pollution, a global problem, is considered the leading environmental threat to human health.[80] Moreover, it can lower harm to ecosystems through reduced ecotoxicity (−23%), water eutrophication (−35 to 69%), and acidification (−42%), which are pressing issues near mines or industrial sites.[7,81–83]

Impacts may shift to non-climate impact categories, *i.e.*, ionising radiation (+241%), metal resources (+100%), land use (+79%), carcinogenic human toxicity (+25%), and water use (+27%), on a per-kg steel basis (Fig. 8). Rising impacts in these categories were also identified for decarbonization scenarios of other sectors, *e.g.*, cement,[46] hydrogen[56] or ammonia.[84] The absolute values of these rising impacts are subject to uncertainty due to data limitations and the lack of scenario data in the background database, as explained earlier (Section 3.3.1). While impacts in carcinogenic human toxicity (+25%) and ozone depletion (+275%) are likely overestimated, the trend of increasing impacts in ionising radiation, metal depletion, and land use is plausible as they are driven by electricity supply. It is thus understandable that these impacts will rise with higher electricity demand for a more electrified steel production. However, they are determined by the assumed electricity supply mix, which here includes, *e.g.*, nuclear power, and may thus be reduced under a different electricity mix.

When considering future growth in global steel production, our scenarios indicate that the impacts of total steel production globally will rise in most categories. Impacts may decline only for GHG emissions, acidification, freshwater eutrophication, particulate matter, and photochemical ozone formation.

A tentative normalisation and weighting exercise show that the steel sector's non-climate impacts could play a non-negligible role compared to climate change (ESI,† Section S2.5). Despite the uncertainty inherent to normalisation and weighting,[85] this underscores the importance of considering impacts beyond climate change for future steel production, as also emphasized in previous research.[4,7]

4.4 Understanding environmental impacts at the global and local scale is crucial

In sum, our scenarios do not achieve an absolute decoupling across all impact categories from a global perspective. Such absolute decoupling is generally required to sustain ecosystem quality.[86] Our finding aligns with historic trends, where absolute decoupling was only partially observed, *e.g.*, for certain emissions to air but not for all environmental impacts,[86] as well as with scenario assessments for other metals, such as nickel or zinc.[3,87]

While this emphasizes the urgency of minimizing future primary production and the relevance of impact assessments with a global scope, regional assessments are equally crucial. Certain impacts are particularly relevant locally, such as freshwater use, particulate matter or water eutrophication.[7,88] For instance, the rise in water use (+105%) for steel production may be considered minor at the global level, where the primary freshwater consumer is the agricultural sector, requiring about 70% of water globally.[89] Yet, mining and industrial activities can be highly problematic in regions of water scarcity.[7,81]

Future research should identify process- and impact-category-specific emission prevention measures and targeted policies to minimize trade-offs, avoid unwanted side-effects and achieve decoupling.[90] To better prioritise such interventions, we recommend assessing the relevance of each impact category at both global and local levels, *e.g.*, using frameworks like planetary boundaries[7,88] or regionalized impact assessment.[91] Defining and allocating the respective impact threshold is subject to future research. Comprehensive models with a sufficient spatial resolution are essential to link demand and supply scenarios and to account for future emissions of other sectors.

4.5 Limitations and future research

When interpreting shares of carbon budgets, the approach emissions were calculated needs to be considered: (i) we quantified life cycle emissions, which includes indirect emissions of upstream processes, *e.g.*, from electricity or hydrogen supply, while the accounting system of the IPCC differentiates between more sectors; (ii) although we integrated scenarios for several sectors *via premise*, background scenarios for other sectors and supply chains are still lacking in the LCA model, *e.g.*, for chromium steel, electrolyte or generally chemicals production. The latter may lead to overestimating future impacts, but could be addressed by including scenarios for additional sectors.

Utilizing large global integrated assessment models as a guide for future change has proven fruitful for global impact assessment. However, the formulations of such modelling frameworks imply various general limitations and uncertainties inherent to scenario assessments (as discussed in detail in the ESI,† Section S3.2.1). As such, the scenarios should not be interpreted as accurate predictions but as exploratory, *i.e.*, what-if scenarios, providing insights into directions of future developments, their consequences, and venues for further research:

• **Need for ex-ante socio-technical analysis on diffusion and adoption patterns of technologies:** the model framework uses multiple abstracted representations of sectors and an exhaustive portfolio of incumbent and novel technologies, which are parameterised according to empirical analysis or expert consultations (as demonstrated in prior studies[29,92,93]). Model results depict the outcome of the interaction of these portfolios under specific constraints and rule-sets, which may lead to counterintuitive results, such as the scenarios' reliance on CCS, nuclear power and negative GHG emissions for bio-based electricity generation. Similarly, EW, characterised by a low technology readiness level (TRL 4–5[94]), outcompetes (blue) H2-DRI (TRL 6–8[94]) under stringent emission targets, as illustrated in the 1.5 °C scenario, since the assumed increasing carbon tax creates a landscape that advances this more expensive technology due to its lower GHG footprint than H2-DRI (Fig. 5). Although this drastic transition to EW may seem counterintuitive, it reveals the limited GHG emission reduction potential even under such an ambitious scenario. Further ex-ante analyses on the socio-technical development pathways for various production systems (*e.g.*, *via* green H2, EW) could help underpin specific (regional) adoption and diffusion patterns.

• **Focus beyond CO_2:** as steel demand growth primarily drives the presented impacts, additional production and consumption pathways should be explored to gain deeper insights into future emissions. Options to consider are, *e.g.*, scenarios with higher shares of secondary production and green H2-DRI, exploring other novel technologies and electricity supply scenarios, or applying multi-objective optimisation considering impact categories beyond CO_2.

• **Focus beyond aggregated production systems:** more detailed metal scenarios are needed, *e.g.*, accounting for the demand for emission-intensive steel types and alloys alongside decarbonization options for energy-intensive alloying elements,[95,96] such as chromium and ferronickel, the suitability of novel production routes for certain steel types, the effect of mixed inputs of primary iron and scrap into BOFs and EAFs, or considering trade, *e.g.*, of green primary iron from H2-DRI or EW.[97]

Expanding the scope of the scenarios and assessment could be achieved by integrating other modelling frameworks, *e.g.*, offering higher technological, regional or economic resolution.

Likewise, the LCIs of steel production technologies could be further refined to increase data quality, considering, *e.g.*, the scale-up effects of electrowinning potentially lowering sodium hydroxide requirements, a shift to green sodium hydroxide production, improving waste treatment processes, detailed emissions of electric arc furnaces operated with primary material from H2-DRI or EW, or generally the effect of emission mitigation measures. Further modelling assumptions and associated limitations are provided in the ESI,† Section S3.2. We published our data and Python code openly in a repository to facilitate future studies.[98]

5. Conclusions

This study assessed a broad spectrum of the future life-cycle-based environmental impacts of global steel production. We coupled state-of-the-art LCA models of current and future steel production routes with multi-sectoral, internally consistent scenarios for future energy and steel supply from the integrated assessment model IMAGE for three climate targets: 3.5 °C, <2 °C, and 1.5 °C. Our assessment considers nine steel production routes, including CCS options and novel technologies for hydrogen- and electricity-based iron production (H2-DRI and EW). The main outcomes of this study are:

Net-zero steel production unlikely to be reached by 2060

Compared to the current coke-based BF-BOF route, specific life-cycle-based GHG emissions can be minimized by up to 95% by the electrified technologies of H2-DRI, EW and secondary production if green power is used. These technologies still have residual emissions, but outperform CCS technologies for BF-BOFs. However, even in the most optimistic 1.5 °C scenario, electrified technologies are unlikely to fulfil the global steel demand by 2060. Hence, global steel production's average life-cycle GHG emission intensity decreases by only 79% by 2060 in this scenario, falling short of climate neutrality. Considering the 61% increase in global steel production from 2020 to 2060, annual global steel-related GHG emissions may be reduced by at most 67% by 2060. Cumulative emissions are 41% lower in the 1.5 °C than in the Base scenario (Sections 3.1 and 3.2).

Faster action and lower steel demand are needed in light of remaining carbon budgets

The steel sector's transition in the scenarios assessed is overall too slow and may still contribute 89–151 Gt CO_2-eq. until 2060, which represents 9–14% (2 °C scenario) and even 18–30% (1.5 °C) of the respective end-of-the-century global carbon budgets (Section 3.2.2). Hence, faster technological development and large-scale implementation of green technologies are required, *e.g.*, for H2-DRI and EW, while simultaneously lowering steel demand and ramping up the supply infrastructure for renewable electricity and green hydrogen. Deploying CCS to (TGR-)BF-BOF plants poses the risk of a lock-in effect, as the emission reduction potential is insufficient and may delay the transition to steel production of lower emission intensity.

Decarbonizing steel production may shift burdens to other processes that enhance non-climate change impacts

An electrification of steel production is likely to increase impacts (per ton of steel) on land use, material resource depletion, and ionising radiation, which are driven by the assumed future electricity mix (Section 3.3.1). If steel demand continues to rise, the global impacts of decarbonized steel production may increase in more categories, such as human toxicity and water use (Section 3.3.2).

However, certain impact categories also benefit from the phase-out of coke-based processes and may therefore decrease overall. These are acidification, freshwater eutrophication, particulate matter, and photochemical ozone formation (Section 3.3.2).

As the emission hotspots of steel production are diverse and depend on the impact category, targeted interventions across the entire supply chain are required to further decrease emissions (Section 3.3.1). Measures include responsible sourcing of energy carriers and materials, such as electricity, green iron, or sodium hydroxide, and improving slag and mining waste management practices.

Further insights into additional emission reduction levers required

Future research is required to identify additional options to reduce GHG emissions of iron and steel production faster, while also avoiding burden shifting to other categories. This includes exploring potential emission mitigation technologies, alternative steel and energy supply scenarios, additional levers for impact reduction, such as minimising primary steel production, and assessing the relevance of adverse side effects at global and regional levels, *e.g.*, using frameworks like planetary boundaries. Our study can provide a basis for such future works.

Author contributions

Carina Harpprecht: conceptualization, methodology, validation, formal analysis, investigation, data curation, software, writing – original draft, writing – review & editing, visualization, project administration. Romain Sacchi: conceptualization, methodology, software, writing – review & editing. Tobias Naegler: conceptualization, methodology, writing – review & editing, visualization, Mariësse van Sluisveld: data curation, writing – review & editing. Vassilis Daioglou: data curation, writing – review & editing. Arnold Tukker: writing – review & editing. Bernhard Steubing: conceptualization, writing – review & editing.

Conflicts of interest

There are no conflicts of interest to declare.

Abbreviations

Acid.	Acidification
BECCS	Biomass energy with carbon capture and storage
BF-BOF	Blast-furnace and basic-oxygen furnace
BG	Background
CCS	Carbon capture and storage
CO	Carbon monoxide
Ecotox.	Ecotoxicity
Energy res., non-renew.	Non-renewable energy resources
ESI	Electronic supplementary information
Eutroph., freshwater	Freshwater eutrophication
Eutroph., marine	Marine eutrophication
Eutroph, terrestrial	Terrestrial eutrophication
EW	Electrowinning
GHG	Greenhouse gas
GWP	Global warming potential
H2-DRI	Hydrogen-based direct reduction of iron
Human tox., carc.	Carcinogenic human toxicity
Human tox., non-carc.	Non-carcinogenic human toxicity
IAM	Integrated assessment model
IMAGE	Integrated model to assess the global environment

Ionising rad.	Ionising radiation
IPCC	Intergovernmental Panel on Climate Change
LCA	Life cycle assessment
LCI	Life cycle inventory
MEA	Mono-ethanolamine
NaOH	Sodium hydroxide
NG-DRI	Natural gas-based direct reduction of iron
Ozone depl.	Ozone depletion
PM	Particulate matter
Photochem. ozone	Photochemical ozone formation
premise	PRospective EnvironMental Impact assessment
RCP	Representative Concentration Pathways
scrap-EAF	Scrap-based electric arc furnace
SR-BOF	Smelting reduction and basic-oxygen furnace
SSP	Shared socioeconomic pathways
TGR-BF-BOF	Top gas recycling blast-furnace and basic-oxygen furnace
TRL	Technology readiness level
VPSA	Vacuum pressure swing adsorption.

Data availability

The Python code is published in a repository[98] at **https://doi.org/10.5281/zenodo.14968094**, alongside the non-proprietary data.

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