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Averting the steel carbon lock-in through strategic green investments

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A new wave of steel capacity additions in emerging economies threatens to lock in coal-based production for decades. By combining detailed steel production modelling with plant-level data in an integrated assessment model, we estimate that existing and planned coal-based steel plants could commit the world to nearly 60 $GtCO_2$. If current policy and investment trends continue beyond current plans, committed emissions reach 114 $GtCO_2$, consuming 20% of the remaining carbon budget for limiting peak warming to 1.7 °C. We show that 60% of this lock-in risk can be avoided at moderate average abatement costs of US\$100–150 tCO_2^{-1}. In India alone, 22 $GtCO_2$ of future emissions could be avoided by leveraging climate finance to redirect US\$50 billion this decade towards hydrogen-ready direct reduction steel plants. Near-term investment decisions on new steelmaking capacity represent a critical opportunity to avert the carbon lock-in and align the sector with climate targets.

Global primary steel production, made from virgin iron ore rather than recycled scrap[1], has expanded in distinct historical 'waves', first in the Global North after the Second World War, and later in China during the early 2000s (Fig. 1a). Both waves were dominated by coal-based blast furnace with basic oxygen furnace (BF-BOF) steelmaking, which still accounts for roughly 70% of global steel production[2]. Due to the high emissions intensity of this route, the steel sector was responsible for 7% of global CO_2 emissions in 2023[3].

A third wave of steel production is now starting in emerging economies, driven by rapid industrialization and increasing material demand[4]. The outcome of this wave will be critical for climate targets: around half of all planned projects are BF-BOF plants[5], which will likely operate for several decades once built. Investment decisions made today could therefore commit the world to substantial CO_2 emissions in the long term or lead to costly early retirements and stranded assets if climate action accelerates. This carbon lock-in[6–9] (Methods) impedes cost-effective mitigation and jeopardizes climate targets.

Several technological options can decarbonize steel production: existing BF-BOF plants can be partially decarbonized through post-combustion carbon capture retrofits (CCS)[10–12] or coal substitution with biomass[13,14]. New capacity additions could shift towards gas- or hydrogen-based steel[15–18] or scrap recycling[19–22]. Prior studies highlight clear trade-offs[23,24]: scrap recycling has the lowest abatement cost, CCS can be cost-competitive[23–25] and hydrogen-based steel is the most mature deep decarbonization option for primary steelmaking. However, these alternatives generally remain costlier than BF-BOF steelmaking and compete for resources needed by other sectors, such as carbon storage capacity and infrastructure, sustainable biomass, green hydrogen or natural gas. Assessing their potential to reduce the steel lock-in therefore requires an energy-system-wide perspective that captures intersectoral trade-offs.

Near-term investment choices will determine whether the steel sector transitions to lower-emission alternatives or further locks in coal-based production. Studies on committed emissions show how long-lived assets can constrain future mitigation efforts[26,27] and plant-level analyses extend this to BF-BOF reinvestment decisions[28,29]. Integrated assessment models have also begun exploring long-term steel transition pathways using process-explicit representations[30–34].

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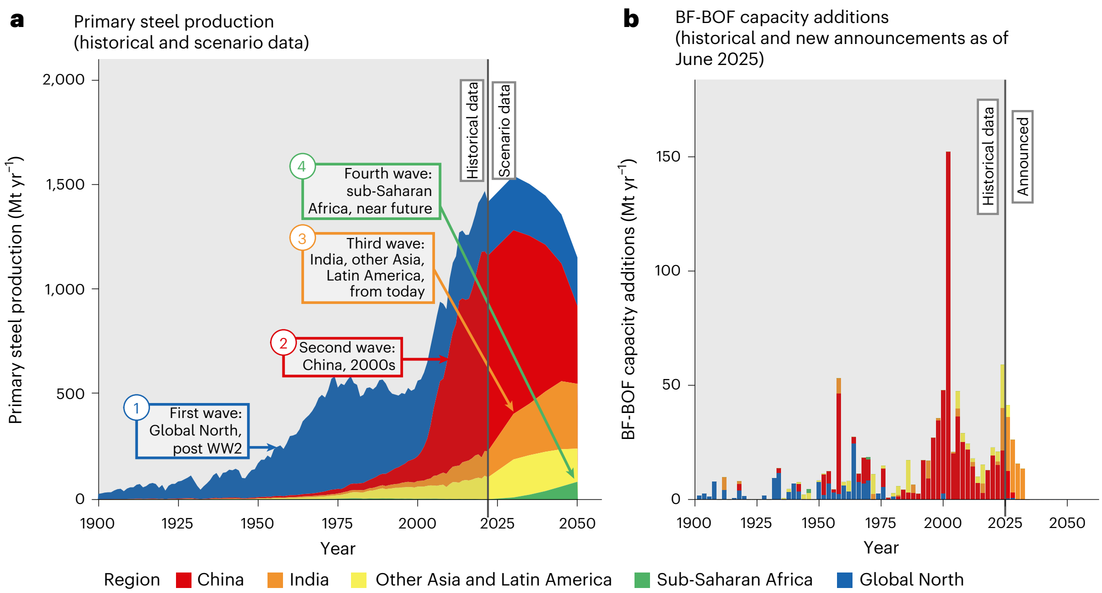

Fig. 1 | Primary steel production and BF-BOF capacity additions by region. **a**, Successive waves of steel production, identified by combining historical primary steel production data (1900–2022) from the World Steel Association with scenario data from the SSP2 Current Policies Implemented REMIND scenario (2023–2050; Methods). WW2, World War II. **b**, Historical and planned BF-BOF capacity additions, derived from the GEM Iron and Steel plant tracker data[35]. The regional groups are defined in Methods.

However, none of these studies incorporate the rapidly expanding pipeline of announced BF-BOF projects and therefore cannot quantify how near-term investment decisions could deepen or help avert a long-term carbon lock-in. Addressing this gap requires a modelling approach that accounts for system-wide resource constraints and intersectoral mitigation trade-offs in 1.5 °C mitigation pathways.

In this study, we quantify the magnitude and implications of the steel carbon lock-in and assess how targeted near-term investment decisions can avert it in 1.5 °C overshoot scenarios that limit peak warming to approximately 1.7 °C. We extend the global integrated assessment model REMIND with a new process-based steel sector implementation and represent near-term investment trends by integrating recent plant-level data from the Global Energy Monitor[35]. We evaluate alternative scenarios in which planned BF-BOF capacity is either built or redirected towards lower-emission routes and in which existing plants are either reinvested in or retired early. By comparing these pathways, we identify the technological, temporal and regional determinants of committed emissions, as well as the scale of redirected investments and additional system costs required to minimize them. This analysis shows how early investment shifts—particularly in rapidly growing economies such as India—can substantially reduce future emissions at comparably low costs, making early action in steel a high-leverage climate mitigation opportunity.

Quantifying the lock-in from operating and planned plants

The current capacity of long-lived BF-BOF steel plants already creates a substantial lock-in, which upcoming investment decisions threaten to extend for decades (Fig. 2). This risk stems from two main sources: the large fleet of young BF-BOF plants (<20 years), primarily in China, that are approaching relining decisions and the sizable pipeline of planned BF-BOF additions, mostly in India (Fig. 1b). BF-BOF plants typically operate for 35–40 years, with blast furnaces requiring a first major refurbishment, known as a 'relining', after approximately 20 years[29]. While such relinings have been discussed as opportunities to retire or retrofit plants[29], their relatively low cost (around 10% of the initial total investment)[10] makes them financially attractive. Without strong policy signals, relinings will probably extend steel plant lifetimes, meaning that plants built over the next decade would lock in emissions well into the 2060s.

This long-lived capacity creates a substantial lock-in of up to 58 $GtCO_2$ if the full pipeline of new projects is built and young blast furnaces are relined (Fig. 2, red line). The current operating fleet already commits nearly 40 $GtCO_2$ by 2070 (grey line) if plants operate for their full lifetimes. The pipeline of new BF-BOF projects, with both under construction and announced plants, could add 19 $GtCO_2$ (5 $GtCO_2$ and 14 $GtCO_2$, respectively), yielding a total of 58 $GtCO_2$. This lock-in would already deplete approximately 10% of the remaining carbon budget for limiting global warming to 1.7 °C (from 2025, at 50% likelihood)[36].

Two near-term investment decisions could substantially reduce these committed emissions. First, most new capacity additions are still at the announcement stage, with fewer projects under construction. This leaves an opportunity to replace announced projects in high-demand growth regions, such as India or Southeast Asia, with lower-emissions plants. Second, the relining of young blast furnaces (<20 years) opens another window of opportunity to avert deepening the lock-in. Around 57% of BF-BOF plants had been operating between 8 and 24 years in 2023, placing them within their relining window[28]. In markets with excess capacity and slowing demand, such as China or parts of Europe, relinings become economically uncertain, creating opportunities to retire BF-BOF plants or replace them with more cost-effective scrap-based steel plants. Together, avoiding both the planned new BF-BOFs and the relining of young furnaces could almost halve committed emissions to 31 $GtCO_2$.

Global steel transition pathways and the need for early action

To assess how these investment decisions influence the global steel transition, we implement them in three scenarios using the REMIND integrated assessment model (Table 1 and Methods). Alongside a Current Policies baseline scenario, which preserves currently implemented national policies without additional mitigation efforts, we design two mitigation scenarios consistent with a 1.5 °C target with overshoot (corresponding to C2 category in the Intergovernmental Panel on Climate Change framework[37]). Both achieve the climate target but

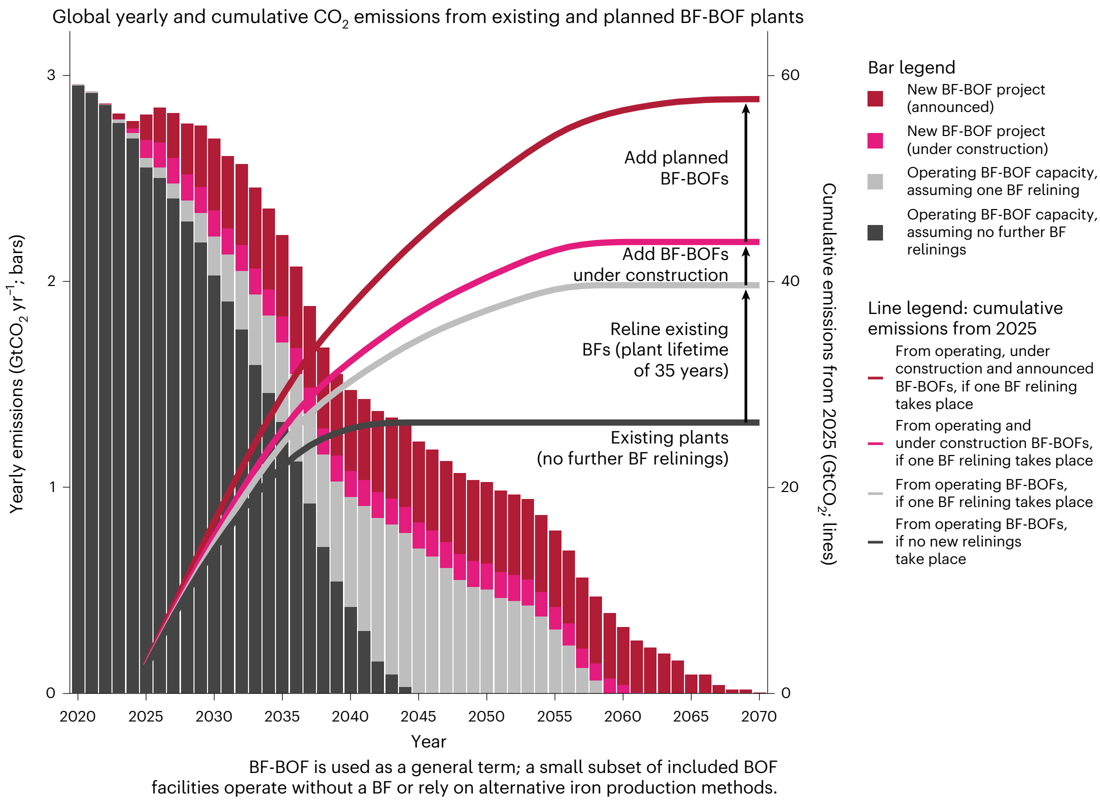

Fig. 2 | Global yearly CO_2 emissions from existing and planned BF-BOF plants and the corresponding cumulative CO_2 emissions. Annual and cumulative global CO_2 emissions are calculated from the GEM Steel and Iron Plant Tracker data[35] (Methods, 'Steel plant data analysis') and shown as bars on the left-hand *y* axis, distinguishing emissions from operating steel plants without (black) and with one relining (grey), new steel plants that are already under construction (pink) and announced steel plants (red). The lines of corresponding colours (right-hand *y* axis) show the resulting cumulative emissions.

Table 1 | Scenario set-up

Scenario name	Climate ambition	BF-BOF plant mean lifetime	BF-BOF project pipeline	Peak carbon budget
Current Policies	Status quo	35 years	All announced and under construction plants are built.	Not applicable
Transition with Lock-in	Returning to 1.5 °C warming by 2100 (50% likelihood)	35 years	All announced and under construction plants are built.	820 $GtCO_2$ from 2020 (corresponding to peak warming of 1.75 °C)
Fast Transition	Returning to 1.5 °C warming by 2100 (50% likelihood)	20 years in China and Global North countries, 35 years in all other regions	Only plants that are currently under construction are built; announced plants can be cancelled.	820 $GtCO_2$ from 2020 (corresponding to peak warming of 1.75 °C)

model different outcomes for the steel sector. The Transition with Lock-in scenario assumes all announced BF-BOF projects are built, and all plants undergo a relining and operate for a mean lifetime of 35 years (Methods). The Fast Transition scenario assumes that BF-BOFs in the Global North and China retire after 20 years, before the first relining. In emerging steel-producing regions (Latin America, Southeast Asia, India and sub-Saharan Africa), announced BF-BOF projects can be cancelled, but plants already built operate for 35 years, as one relining is economically likely given growing steel demand. This scenario design assumes broadly stable steel trade patterns (Limitations) and highlights regional differences in steel investment dynamics and their impact on alternative mitigation options, such as carbon capture or direct reduction of iron (DRI) scale-up.

In the Current Policies baseline, global steel production shifts towards increased scrap steel recycling, but primary steel remains almost entirely coal based (Fig. 3a). The lower cost of secondary steelmaking using scrap steel with an electric arc furnace (scrap-EAF) enables the share of secondary steel to increase to more than 50% of total steel production by 2070. However, without rising carbon prices or similar policies, primary steel continues to rely on BF-BOF, accounting for over 1,000 Mt of steel in 2070. This contrast reveals an important distinction regarding steel as a 'hard-to-abate' sector[38,39]: while secondary (scrap-based) steel is relatively inexpensive, decarbonizing primary steel production remains difficult in the absence of strong policy signals.

Both the Fast Transition and the Transition with Lock-in scenarios agree on three robust features for the global steel transition (Fig. 3a).

(1) Phasing out coal-based steel. Coal-based steel declines from almost 75% of production in 2025 to under 25% in 2055. CCS retrofits, previously identified as key components of the steel transition[30,33], are only marginally used. This reflects the model's preferential allocation of limited carbon storage capacity to bioenergy with CCS (BECCS), which offers lower system-wide mitigation costs in our scenario set-up. BF-BOF-CCS becomes more

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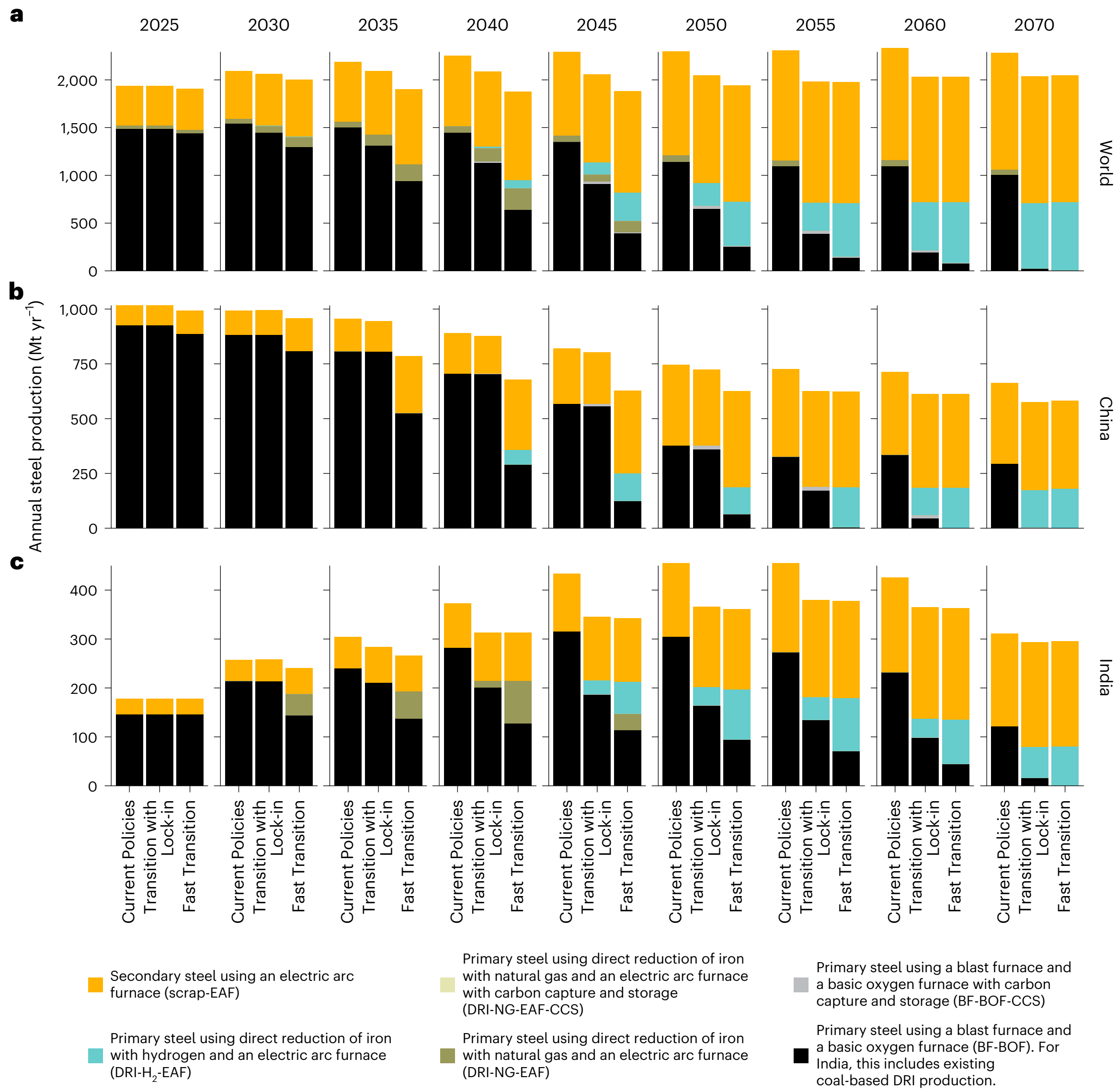

Fig. 3 | Annual steel production by technology for different scenarios. In each panel, we show scenario results for the Current Policies, Transition with Lock-in and Fast Transition scenarios. **a**, Global annual steel production. **b**,**c**, Annual steel production in China (**b**) and India (**c**). Note: in India, the BF-BOF category includes a small share of legacy coal-based DRI capacity. These plants cannot be retrofitted to operate fully on hydrogen and are therefore grouped with coal-based steelmaking in the model (Methods).

relevant in scenarios with lower bioenergy availability, higher CO_2 storage potential or stronger climate ambition (Supplementary Notes 1 and 2 and Supplementary Figs. 1 and 3).

(2) Switching to DRI-EAF production, making full use of a fossil gas bridge. DRI plants initially operate with fossil gas until 2040–2050 before switching to hydrogen (Extended Data Fig. 1). This gas bridge allows capital-intensive DRI-EAF plants to be built today while postponing reliance on low-emission hydrogen, which remains scarce and costly in the near future[40].

(3) Accelerating the transition to secondary steel (scrap-EAF production). Secondary steel production increases from 20% in 2025 to become the dominant route by 2050 in both scenarios. This confirms previous findings highlighting the importance of secondary steelmaking in the second half of the century[19–22], especially for countries in the first and second waves of steel production with growing scrap stocks.

Despite these common features, the pace of the transition away from coal-based steel is much slower in Transition with Lock-in. In 2050, the majority of primary steel is still produced through this pathway (500 Mt yr^{-1}), whereas limiting the lock-in in Fast Transition halves it to 250 Mt yr^{-1}. Notably, China and India dominate the global dynamics of the Fast Transition scenario (Fig. 3b,c) driven by their near-term BF-BOF investments, which far exceed those of other regions (Extended Data Fig. 2).

In China, avoiding further BF relinings in Fast Transition accelerates the shift to hydrogen- and scrap-based production. Compared to Transition with Lock-in, BF-BOF output declines by more than half by 2040, while scrap-EAF and H2-DRI-EAF production rises from 170 Mt yr^{-1} to 390 Mt yr^{-1} combined (Fig. 3b). This faster shift temporarily reduces total steel output by approximately 100 Mt yr^{-1} compared to Current Policies between 2035 and 2050. This results from the model's endogenous price elasticity of steel demand: as rising carbon prices increase steel prices, demand temporarily falls compared to the baseline (Methods). While politically challenging, this aligns with observed trends of slowing demand and persistent overcapacity in China[4,41,42]. Whether Chinese steel production remains high in the short term (as in Transition with Lock-in) or declines more

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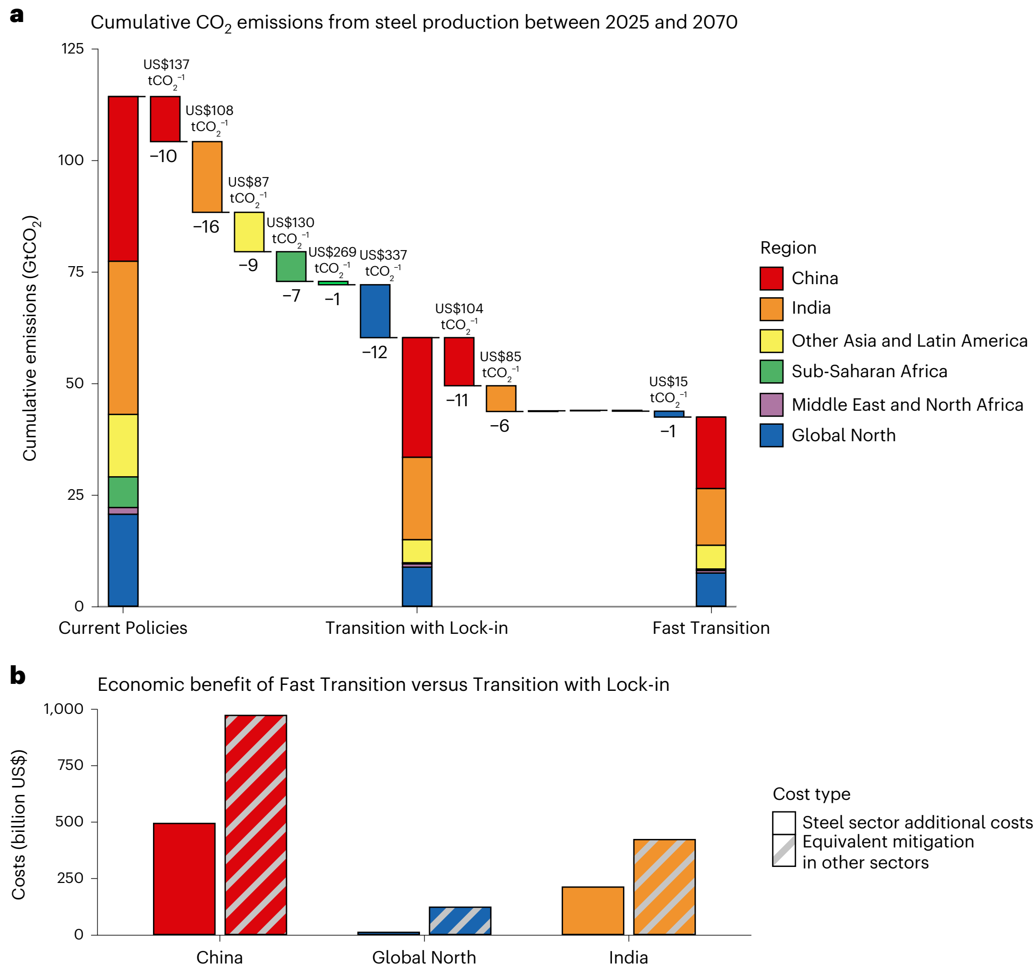

Fig. 4 | Cumulative CO_2 emissions from steel production and the economic benefit of avoiding the steel lock-in. a, Cumulative CO_2 emissions from steel production for Current Policies, Transition with Lock-in and Fast Transition, with regional breakdowns. The connecting segments between scenarios represent the CO_2 emissions reductions achieved in each region, with numerical values shown below each bar in black (in $GtCO_2$). Average abatement costs for these reductions are given above each segment. **b**, Economic benefit of avoiding the steel lock-in, comparing the additional costs for transforming the steel sector in Fast Transition relative to Transition with Lock-in (solid bars) with the equivalent cost of achieving the same level of mitigation in other energy sectors (hatched bars). Methods provides details.

rapidly will depend on how industrial and trade policies evolve in response to changing domestic demand and increasing trade barriers on Chinese steel exports.

In India, redirecting investments away from new BF-BOF projects enables an early shift to NG-DRI-EAF and avoids a full coal lock-in. In Fast Transition, recently announced BF-BOF plants are replaced by NG-DRI-EAF capacity (Fig. 3c). Without this early shift, BF-BOF plants built in 2030 would operate until 2065, locking in about 70 Mt yr^{-1} of coal-based steel exposed to rising carbon prices (Supplementary Note 3 and Supplementary Fig. 4). Seizing this narrow investment window limits stranded asset risk and aligns new capacity with long-term decarbonization goals.

The economic benefit of averting the steel carbon lock-in

By 2070, cumulative steel sector emissions exceed 110 $GtCO_2$ in Current Policies (Fig. 4a), around half of which is already committed by existing and planned BF-BOF capacity (58 $GtCO_2$; Fig. 2). The Fast Transition scenario shows this can be avoided: cumulative emissions are reduced by 73 $GtCO_2$, a 60% decrease relative to Current Policies. China and India together account for 43 $GtCO_2$ of avoided emissions, reflecting the impact of their near-term investment decisions.

Transition with Lock-in shows that a 1.5 °C-consistent pathway remains achievable despite continued coal-based steel investments. In this scenario, cumulative emissions are reduced by 50 $GtCO_2$ at moderate average abatement costs below US\$150 tCO_2^{-1} in most regions. The Global North is an exception, with average abatement costs of US\$337 tCO_2^{-1} mainly driven by higher energy costs (Extended Data Fig. 3 and reflected in the shadow prices shown in Supplementary Figs. 5–8).

Early action in Fast Transition delivers an additional 18 $GtCO_2$ of reductions at an average abatement cost below US\$110 tCO_2^{-1}, reducing cumulative emissions to 42 $GtCO_2$. Avoiding further coal-based investments therefore both limits the lock-in and reduces economic costs, as deeper steel sector decarbonization is achieved more economically per ton of CO_2 abated.

The case for early action strengthens further when comparing steel sector decarbonization costs to the costs of alternative mitigation options (Fig. 4b). Using the carbon price as a measure of the marginal abatement cost available in other sectors (Methods), we find that achieving comparable emission reductions in other sectors (primarily through additional BECCS; Extended Data Fig. 4) would cost nearly US\$1 trillion and US\$400 billion in China and India—almost twice the additional steel sector costs. Early action in steel

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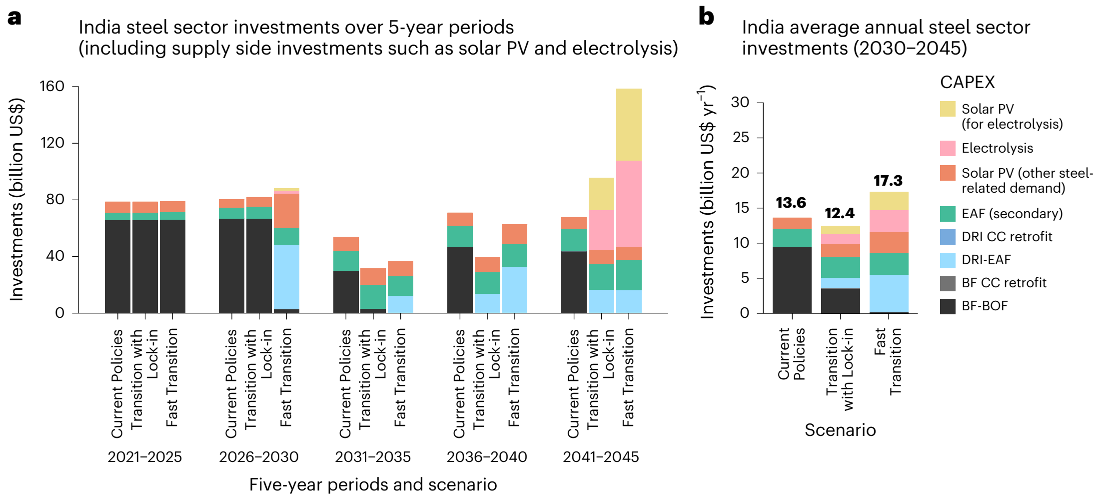

Fig. 5 | Indian steel sector investment needs. a, Steel sector investments per 5-year model period in Current Policies, Transition with Lock-in and Fast Transition. The breakdown of bars shows the fraction of investments required for different types of steel plant and for other supply-side investments: solar PV and electrolysers. **b**, The nominal (non-discounted) arithmetic average of annual investments for each scenario. CAPEX, capital expenditure; CC, carbon capture.

decarbonization is therefore a cost-effective strategy for achieving a 1.5 °C-consistent pathway.

India's early-action window for redirecting steel investments

India faces the most consequential near-term investment decisions of any steel-producing region. Early action in Fast Transition reduces India's cumulative steel sector emissions by 22 $GtCO_2$ compared to Current Policies (Fig. 4a).

Most announced BF-BOF projects have not yet begun construction, creating a narrow window this decade to redirect investments towards lower-emission technologies. Fast Transition seizes this opportunity by redirecting US$50 billion of near-term investments (2026–2030) from planned BF-BOF capacity towards NG-DRI-EAF (Fig. 5a). Total investments over this period reach US$80–90 billion across scenarios, but the allocation differs substantially. In Fast Transition, new capacity investments shift almost entirely towards DRI-EAF plants and scrap-EAF, whereas this window is missed in Transition with Lock-in, delaying the steel sector transition and locking in additional coal-based capacity.

Achieving the full 22 $GtCO_2$ emissions reductions requires a second investment phase, transitioning DRI production from natural gas to hydrogen. As carbon prices rise, low-emission hydrogen DRI becomes cost-competitive with NG-DRI, requiring around US$160 billion between 2041 and 2045 in Fast Transition, dominated by electrolysers and solar photovoltaic capacity for green hydrogen production (Fig. 5a). This concentration represents an upper bound, as the model assumes DRI plants operate on either natural gas or hydrogen exclusively. In practice, DRI plants can blend an increasing fraction of hydrogen with fossil gas, enabling a gradual transition as low-emission hydrogen availability and costs improve, which would spread investment needs more evenly over time.

Annual steel sector investments averaged over 2030–2045 therefore provide a more realistic indicator of finance requirements (Fig. 5b). Fast Transition requires US$17.3 billion yr^{-1}, compared with US$12.4 billion yr^{-1} in Transition with Lock-in and US$13.6 billion yr^{-1} in Current Policies. The additional US$3.7 billion yr^{-1} stems primarily from hydrogen production infrastructure investments (electrolysers and solar photovoltaics (PV)) needed to switch DRI operations from fossil gas to hydrogen. Accounting for operating costs of solid and gaseous fuels does not affect this cost comparison substantially (Extended Data Fig. 5). Combined with the early redirection of US$50 billion towards new DRI-EAF capacity, these investments could place India's steel sector on a cost-effective pathway consistent with the 1.5 °C target.

However, the feasibility of a rapid DRI transition in India is highly sensitive to financing conditions. As in many emerging economies, higher weighted average costs of capital (WACC) than in the Global North[43–45] can increase the annual costs to service capital-intensive investments in steel plants, electrolysers and associated PV capacity (Extended Data Fig. 6). Increasing the WACC from 5% to 12% nearly doubles peak annual financing costs to US$35 billion yr^{-1} by 2050 in Fast Transition, compared to US$24 billion yr^{-1} in Current Policies. These annual financing requirements are comparable in magnitude to the total financing support mobilized under India's green hydrogen policy framework (approximately US$60 billion) (ref. 46).

Financing conditions become especially important if the NG-DRI bridge is bypassed in favour of hydrogen DRI: the large upfront investments in electrolysers and PV capacity increase peak financing costs to nearly US$50 billion at a WACC of 12%, highlighting the trade-off between reduced fossil dependence and higher near-term financing needs. These results suggest financing conditions are a key constraint for early steel decarbonization, and reinforce the need for climate finance instruments that reduce WACC by de-risking these capital-intensive investments in emerging economies.

Discussion

If current investment trends in coal-based steel capacity continue, the steel sector risks consuming up to 20% of the remaining carbon budget for limiting warming to 1.7 °C. However, this outcome is far from inevitable: a large share of this lock-in risk can be avoided through timely investment shifts.

Across our mitigation scenarios, three robust features characterize the steel transition: (1) a phase-out of coal-based primary steelmaking, (2) an early scale-up of DRI-EAF production and (3) increasing scrap-based production, although its maximum market share remains subject to uncertainty (Methods). These features persist under a stricter 1.5 °C and a 2 °C-compatible trajectory (Supplementary Note 1) and when increasing BF-BOF mean lifetime to 40 years (Supplementary Note 4 and Supplementary Fig. 9). By contrast, CCS retrofits for both NG-DRI-EAF and BF-BOFs play a limited role. This divergence from some previous integrated assessment models[30–33] and bottom-up studies[24,47] is discussed in detail in Supplementary Note 5 and arises from a system-wide trade-off between CCS deployment and negative emissions under limited carbon storage capacity (Supplementary Fig. 3 and Supplementary Notes 1 and 2), as well as the limited capture rates of 73% for BF-BOF-CCS (Supplementary Table 1).

The regional distribution of the potential steel carbon lock-in is highly uneven. Of the 73 $GtCO_2$ difference between the Current Policies and Fast Transition scenario, 43 $GtCO_2$ originate from India and China, reflecting their dominance in recent and planned BF-BOF investments. Avoiding the lock-in in these regions could deliver valuable emission reductions, particularly in a 1.5 °C overshoot scenario.

In India, Fast Transition hinges on redirecting US$50 billion this decade from BF-BOF towards hydrogen-ready NG-DRI-EAF. However, the feasibility of a rapid shift towards DRI-EAF steelmaking faces three important obstacles: technology scale-up, financing conditions and energy supply constraints. First, few DRI-EAF plants operate today, and they are concentrated in Europe, the USA, the Middle East and North Africa. Scaling DRI at the pace envisioned in Fast Transition (nearly 50 Mt yr^{-1} produced in 2030) would require substantial technology transfer and industrial cooperation with these regions, and anticipating potential bottlenecks, such as skilled worker shortages or manufacturing capacity.

Second, DRI-EAF plants are more capital-intensive than BF-BOF plants[48] and require upfront investment commitments of billions of dollars[10,49]. Increasing the WACC from 5% to 12% nearly doubles peak annual financing costs to US$35 billion yr^{-1}, further increasing to US$50 billion yr^{-1} if India leapfrogs directly to H_2-DRI (Extended Data Fig. 6).

Finally, India specifically has limited fossil gas resources and relies on imported liquefied natural gas (LNG), which is currently expensive[50]. While price uncertainty remains high, NG-DRI adoption could be uneconomical without sustained lower gas prices or targeted policy support.

Emerging economies may be able to leapfrog directly to hydrogen-based DRI, avoiding the NG-DRI transition altogether. In India, recent auctions under the National Green Hydrogen Mission hinted at lower-than-expected prices for green hydrogen-based ammonia[51] suggesting that hydrogen-based steelmaking could become a viable option earlier than previously anticipated. A direct transition to hydrogen would additionally reduce the risk of stranded natural gas infrastructure and avoid delaying hydrogen supply chain development and learning effects[52–54]. Trade policies such as the EU's Carbon Border Adjustment Mechanism (CBAM) could further reshape incentives. By raising the cost of emissions-intensive steel exports, CBAM would improve the relative competitiveness of DRI-EAF production—particularly hydrogen based[48]—while strengthening the economic case for avoiding further lock-in of coal-based steel capacity for emerging economies. Whether individual countries can seize this opportunity will depend on the pace of renewable deployment, financing conditions and country-specific barriers (for example, India's cross-subsidy system in the power sector[55,56]) that determine the feasibility of this transition.

International climate finance and technology transfers could play a decisive role in diffusing DRI-EAF technologies to the wider Global South. Multilateral climate funds, such as the Clean Technology Fund, or green development programmes such as the Just Energy Transition Partnerships[57,58] can de-risk DRI-EAF investments through concessional loans, grants or guarantees. Clean technology transfers are equally essential[59] as most patents for key technologies (DRI shaft furnaces, EAF, electrolysers) remain concentrated in a few industrialized countries. A dedicated steel 'climate club' could facilitate such transfers[60–62]. Over the medium term, instruments such as green hydrogen contracts for difference[63] can support the scale-up of green hydrogen-based steelmaking.

The coming decade is a decisive window for global steel decarbonization. A pathway remains open to avoid locking in a new generation of coal-based steel plants, but this investment window is narrowing as new capacity comes online and existing plants undergo relinings. Our findings suggest that steel is less a 'hard-to-abate' sector than a sector facing a 'hard-to-abate barrier' that can be overcome at relatively moderate costs through timely investment decisions. With a lock-in risk of 58–114 $GtCO_2$ at stake, establishing DRI-EAF as the dominant primary route for new capacity additions this decade is one of the highest-leverage climate policy opportunities available.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41558-026-02635-8.

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Methods

REMIND model

In this study, we extend the integrated assessment model REMIND with a technology-explicit steel production model (below). This allows us to explore cost-efficient transformation pathways for the steel sector, assessing how different technological options could contribute to the transformation of the sector.

We use a version of the REMIND model[64] based on the release version 3.5 (https://github.com/clarabachorz/remind/tree/steel-LockIn). REMIND is a global model which divides the world into 12 regions and uses a Ramsey-type macroeconomic growth model combined with a detailed and technology-rich energy system. The model maximizes intertemporal welfare for each region based on a nested CES (constant elasticity of substitution) production function in a tree structure ('CES tree'), with a detailed representation of the three energy demand sectors: buildings, transport and industry. Each demand sector translates final energy inputs to energy services outputs, which in turn, together with generic capital and labour, contribute to economic production (gross domestic product).

Emissions from both energy and non-energy processes are tracked and penalized with an endogenous carbon price implemented as a tax. In climate policy scenarios, the carbon price is iteratively adjusted so that cumulative emissions meet prescribed carbon budgets compatible with certain levels of global warming.

Scenarios

The service demand trajectories for the buildings, transport and industry sectors rely on scenario assumptions on global political and economic development. Those are synthesized in narratives called the shared socio-economic pathways (SSPs)[65] and commonly used in the integrated assessment model community. All scenarios in this study are based on the SSP2 scenario. The policy scenarios we develop to explore the steel lock-in use the Current Policies baseline scenario, where only currently implemented climate policies are preserved, and no further efforts are made to mitigate climate change: there are no additional climate policies and no prescribed carbon budget.

Country groups

REMIND models 12 regions in this study, but we group some of them for simplicity in these results. Global North refers to the United Nations Framework Convention on Climate Change (UNFCCC) Annex 1 countries grouped with the other countries of the former Soviet Union. Other Asia refers to the grouping of Southeast Asian countries, South Korea and North Korea but excludes China and India, which are modelled as individual regions.

Cost basis

All costs reported in this paper, if not indicated otherwise, are in 2017 US dollars.

REMIND steel implementation

The novel REMIND steel production model is a technology explicit, linear model. It connects to the energy-system module of REMIND, which provides final energy used by steel production processes, and to the CES (constant elasticity of substitution production function) tree (Supplementary Fig. 10), which determines material demand, that is, the amount of material produced by the model. This means that the steel sector presents an exception with respect to the CES tree: its primary production factors are not final energy demands, but material demands and the translation of final energy demands to material demands is calculated outside of the nested CES function.

Steel demands

Steel demand from the CES tree. The 'steel' node is one of four CES production factors contributing to the 'industry' node of REMIND, next to the 'cement', 'chemicals' and 'other industry' nodes, with an elasticity of substitution. To represent the substitution dynamics between primary and secondary steel, the 'steel' node is itself the output of a CES function, with the inputs 'primary steel' and 'secondary steel'. These nodes are linked to the outflows of the processes in the steel model. Steel demands are therefore price sensitive and react to changes in production prices.

Baseline steel demands. The CES tree is calibrated to meet prescribed steel demands over time in the Current Policies scenario. The methodology for deriving these prescribed demand trajectories is described in detail in Pehl et al.[66]. Historical demands are based on historical production data from the World Steel Association. Projections into the future are based on a simple stock-and-flow model, which regresses future per capita in-use steel stocks as a logit function of time in each region, following the methodology in Pauliuk et al.[22]. A lifetime model derives inflows and outflows into/from the in-use stock. Steel trade is included as an exogenous assumption in this model, with historical relative trade shares assumed to remain constant into the future, with corrections ensuring global market clearing.

Secondary steel constraints. Two upper bounds constrain the amount of secondary steel production in each region.

First, the amount of secondary steel production must not exceed the amount of available scrap in each region. For this, 90% of the outflow of the in-use stock is assumed to be collected and available for recycling[67,68].

Second, the share of secondary steel in the total steel production must not exceed 70%, due to quality constraints of recycled steel. This limit aligns with the share of secondary steel observed in the USA today[69]. This upper limit additionally reflects current quality constraints associated with the accumulation of tramp elements in steel scrap, in particular copper[21,70]. Sectors requiring high-quality steel sheets, such as the automobile industry, are therefore limited in their ability to rely on scrap steel[21]. Improved scrap segregation and recycling practices may relax this constraint in the longer term[71], but it remains binding today, supporting the use of a 70% upper bound in this study.

Process-based production model

Technology graph. The main current and future technologies in steel production are represented in a multi-stage production model. The layout is depicted in Supplementary Fig. 10, including each technology's material inputs and outputs. The model includes an integrated steel plant technology representing the blast furnace-basic oxygen furnace (BF-BOF) route and an electric arc furnace, and the precursory direct reduction furnace, resolved as individual technologies. Some technologies can switch between operation modes, which differ in terms of material and energy inputs, without changing the capacity stock: electric arc furnaces can be fed with scrap or with direct reduced iron, while direct reduction furnaces can be fed with natural gas or hydrogen. A full list of processes with their techno-economic parameters is given in Supplementary Table 1.

Capacity stock. Each technology's production capacity is represented with a capacity stock model. It is parameterized with specific CAPEX for capacity additions, fixed operational expenditures and a mean lifetime for the stock depreciation model. Specifically, the share of surviving plants at an age x given a mean lifetime L is $1-\left(\frac{x}{1.25L}\right)^4$.

The capacity factor, that is, the ratio of production to production capacity, is fixed and not just an upper bound, such that further unused capacities are not allowed by the model. However, optionally, a given share of the standing capacity can be allowed to retire early.

Energy and material inputs. REMIND differentiates five types of final energy: solid, liquid, gaseous, electricity and green hydrogen. The former three can stem from either fossil, biogenic or synthetic secondary energy sources (except for synthetic solids, which are not represented), but the steel model does not differentiate between secondary energy sources in its use. The prices for the material inputs of iron ore, DRI pellets and scrap are exogenous and constant for all regions and time steps. They are given in Supplementary Table 2.

Energy prices, such as electricity or hydrogen, are endogenous outputs of the REMIND optimization. These values correspond to the shadow prices of the respective energy balance equations and therefore represent the marginal cost of supplying one additional unit of the energy carrier in the optimal solution.

Historical energy demands and energy efficiency improvements. The specific energy demands in Supplementary Table 1 are literature values, usually referring to the best available technology (BAT). Real operating plants have different values and are typically less efficient.

The historical energy demand of steel production is obtained from the International Energy Agency's world energy balances[72]. Historical energy efficiencies are derived by dividing this demand by historical production.

Future energy efficiencies are then assumed to converge towards the literature values given in Supplementary Table 1 at a rate following an exponential decay of base 0.9804 from 2020, such that the excess over BAT is halved by 2055.

All historical capacity for primary steelmaking is assumed to be from the BF-BOF or DRI-EAF-NG route. This is a simplification, especially in India, where primary steel is also produced via coal-based DRI. Coal-based DRI kilns cannot be retrofitted to operate with natural gas or hydrogen and fully rely on coal, making their dynamics similar to the BF-BOF route. In our calibration, we account for the higher energy demand and emissions of coal-based DRI in the historical data, such that the model's 'BF-BOF route' in India should be interpreted as an aggregate of BF-BOF and coal-DRI. This aggregation allows us to capture the lock-in and energy demand associated with coal-based primary steel, even though we do not model coal-DRI as a separate technology. Coal-DRI also plays a minor role in India's planned future capacity additions, such that this simplification only affects the already standing capacity.

The historical efficiency penalty (defined as the ratio of observed energy use to BAT levels) is applied to DRI furnaces at a reduced rate of 60%. This prevents the model from unrealistically achieving large energy efficiency gains by switching from BF-BOF to DRI in regions with low historical efficiency.

Emissions. Emissions accounting is based on final energy use: fossil-based final energy carriers have implied emissions factors given in Supplementary Table 3. For biogenic and synthetic gases/solids/liquids and for electricity and green hydrogen, these emissions factors are zero. Upstream emissions, such as electricity grid emissions and mining emissions, are not accounted for in the steel sector but in other sectors.

Local emissions are needed to derive the carbon capture potential. To this end, the fossil emissions factors are also applied to solids, liquids and gases of biogenic and synthetic origin.

Carbon capture in the steel sector. Carbon capture technology based on amine scrubbing can be retrofitted to blast furnaces and natural-gas-based direct reduction furnaces. This means that the techno-economic parameters in Supplementary Table 1 are given only for the capture technology, excluding the furnaces themselves. No cost distinction is made between greenfield and brownfield technology. All costs and inputs are given per ton of captured CO_2 (the specific CO_2 material input is thus the inverse of the capture rate). The heat input of the reboiler is assumed to be from gas burners, with 90% of the resulting reboiler heating emissions being directly captured in the plant.

Captured carbon is passed to REMIND's carbon management module, which decides endogenously whether to sequester it (carbon capture and storage—CCS) or use it as a feedstock for e-fuels (carbon capture and use—CCU).

Unrepresented technologies. Casting and rolling, and their energy demand, are not explicitly represented in the model, as their energy requirements are independent of the chosen production route.

Technologies with a low technology readiness level are not included, as their techno-economics are too uncertain for a comparative analysis. This applies in particular to molten oxide electrolysis.

Locked-in and committed emissions. In this study, we define 'locked-in' or 'committed' emissions by building on the initial definitions used by Davis et al.[73] and Tong et al.[26]. Specifically:

(1) We define emissions as 'committed'/'locked-in' when they arise from existing or already planned CO_2-emitting assets and can only be avoided through (1) early retirement or (2) substantial additional investments outside normal investment cycles or conventional operation (including CCS retrofits or feedstock substitution). These typically entail significant additional costs.
(2) We further distinguish this from an additional 'lock-in risk', which refers to emissions that are not yet committed but may become committed through continued investments in fossil technologies in a given policy scenario.

The definitions are summarized in Supplementary Table 4.

Steel plant data analysis. We use plant-level data from the Global Iron and Steel Plant Tracker from the Global Energy Monitor (June 2025 version)[35]. The dataset reports unit-level data for both steel plants and iron plants (DRI furnaces and BFs) and includes information on production route, operating status, steel and iron capacity, start dates, retirement dates and, if available for blast furnaces, relining dates.

For the analysis in Fig. 1, we use the steelmaking dataset to derive historical and announced BF-BOF capacity additions by region. The announced capacity additions data are also used to constrain near-term capacity additions in REMIND by setting lower bounds on BF-BOF capacity additions: depending on the scenario design, this lower bound is either set to all new plants (announced and under construction) or only under construction plants (Supplementary Table 1). According to GEM, plants are classified as 'announced' rather than 'under construction' if they are 'Capacity that has been announced in corporate or governmental planning documents but has not begun construction'.

Figure 2 combines the steelmaking and ironmaking datasets to estimate the magnitude of the potential carbon lock-in from existing and planned capacity. Using a custom analysis code (Code availability), we match each BOF steel plant to its respective blast furnace(s). If a plant has multiple blast furnaces, the total steel capacity is distributed among blast furnaces in proportion to their respective iron production capacity.

Using the reported last relining date (or if not available, the start date of the steel plant or of the blast furnace), we estimate blast furnace-specific end dates under different relining assumptions (no further relining or relining for young BFs). From this, we can calculate what fraction of steel capacity is retired at what time. We follow Vogl et al.[29] for blast furnace campaign life assumptions: 20 years before the first relining and an additional 15 years before the second.

From this projected retirement estimation, we can calculate the standing BF-BOF capacity over 2020–2070 for each relining case. This is then translated to CO_2 emissions by assuming a capacity factor of 0.8 and an emissions factor of 2.3 tCO_2 per t steel for existing plants, and

2 tCO_2 per t steel for new plants. The resulting annual and cumulative emissions from BF-BOF plants are shown in Fig. 2.

Average abatement cost calculation. We calculate the average abatement cost from the ratio of the net-present value (NPV) difference in cumulative steel system costs to the NPV of avoided emissions. This metric also adjusts for steel demand changes between scenarios.

The average abatement cost for moving from a higher-emissions scenario (1) to a lower-emission scenario (2), over a total period of T years, is defined in equation (1):

$$\mathrm{AAC} = \frac{\mathrm{NPV}\left(\mathrm{Cost}_2^{\mathrm{adj}}(t) - \mathrm{Cost}_1(t)\right)}{\mathrm{NPV}\left(\mathrm{Emissions}_1(t) - \mathrm{Emissions}_2(t)\right)}, \quad (1)$$

with

$$\mathrm{NPV}(x(t)) = \sum_{t=0}^{T} \frac{x(t)}{(1+r)^t},$$

where t is time in years and r, the discount rate, is assumed to be 5% in this study, in line with market interest rates[74]. $\mathrm{Emissions}_n(t)$ are the steel sector CO_2 emissions of scenario n in year t, while $\mathrm{Cost}_n(t)$ is the total steel system cost of scenario n in year t. $\mathrm{Cost}_n^{\mathrm{adj}}(t)$ is the total steel system cost of scenario n, combined with an additional term accounting for steel production differences between the two scenarios considered, at all (t), as seen in equation (2).

$$\mathrm{Cost}_n^{\mathrm{adj}}(t) = \mathrm{System\ costs}(t) + \Big((\mathrm{Steel\ production}_1(t) - \mathrm{Steel\ production}_2(t)) \times \frac{P_1^{\mathrm{steel}}(t) + P_2^{\mathrm{steel}}(t)}{2}\Big), \quad (2)$$

where $P_n^{\mathrm{steel}}(t)$ is the price of steel in scenario n and in year t, and $\mathrm{Steel\ production}_n(t)$ the steel produced in scenario n in year t.

Value of avoided emissions in Fast Transition. To assess the economic value of avoiding the steel lock-in, we compare the additional costs required in the Fast Transition (FT) scenario, compared to Transition with Lock-in (TwLI), for two different mitigation strategies:

(1) reducing emissions directly in the steel sector by reducing the lock-in and
(2) achieving equivalent emissions reductions in other energy sectors, at the lowest possible cost.

For strategy (1), this cost TC_1 corresponds to the additional cumulative steel system costs in FT compared to TwLi (equation (3)):

$$\mathrm{TC}_1 = \mathrm{NPV}\left(\mathrm{Cost}_{\mathrm{FT}}^{\mathrm{adj}}(t) - \mathrm{Cost}_{\mathrm{TwLI}}(t)\right), \quad (3)$$

with the NPV and all other symbols defined as in the section above.

For strategy 2, the cost TC_2 represents the system-wide cost of compensating the additional emissions in TwLI by abating an equivalent amount of CO_2 elsewhere in the energy system. In REMIND, the carbon price gives the marginal cost of abating an additional ton of CO_2 across all economic sectors covered in a given time step. We therefore estimate TC_2 by multiplying the emissions difference between FT and TwLI by the average carbon price of the two scenarios in the same time step t, as seen in equation (4):

$$\mathrm{TC}_2 = \mathrm{NPV}\left(\mathrm{Cp}_{\mathrm{avg}}(t) \times (\mathrm{Emissions}_{\mathrm{FT}}(t) - \mathrm{Emissions}_{\mathrm{TwLI}}(t))\right), \quad (4)$$

where $\mathrm{Cp}_{\mathrm{avg}}(t)$ is the average carbon price in FT and TwLI. Using the average carbon price corresponds to approximating the marginal abatement cost curve between the two scenarios as linear, reflecting increasing marginal abatement costs as additional emissions reductions are required.

Emissions reductions occurring 'elsewhere in the energy system' are endogenously determined by the model and occur primarily in the energy supply sector and by increasing BECCS deployment (Extended Data Fig. 4).

Limitations. Several modelling assumptions and other uncertainties should be considered when interpreting our results.

The REMIND steel sector implementation does not include endogenous technological learning, so capital costs of steel technologies remain constant over time. However, endogenous learning is represented for other key technologies, including electrolysis, solar photovoltaics and wind turbines. As a result, the cost of, for example, hydrogen-based steel can decline endogenously over time through reductions in low-emission hydrogen cost. In addition, energy efficiency improvements are included for all modelled steel production technologies on a regional basis, based on historically observed trends.

Additionally, relining events are represented as additional investment costs that extend the mean BF-BOF plant lifetime to 35 years, without explicitly capturing potential efficiency upgrades associated with these refurbishments.

We do not model international trade for iron and steel and instead assume broadly stable trade patterns—alternative scenarios with, for example, increased steel exports from China or a reshaping of trade flows with the expansion of hydrogen DRI are not explored.

Finally, our analysis focuses on supply-side mitigation and does not explore demand-side interventions such as material efficiency, substitution or lifetime extension of steel products, which could further reduce investment needs and emissions.

Data availability

The Global Energy Monitor data used for the steel plant-level analysis are available online (https://globalenergymonitor.org/projects/global-iron-and-steel-tracker/). All other data used for this work, including the REMIND scenario data, can be accessed via Zenodo at https://doi.org/10.5281/zenodo.19372559 (ref. 75).

Code availability

The REMIND model version used for this work is available via GitHub at https://github.com/clarabachorz/remind/tree/steel-LockIn. The analysis code, including the scenario data, is available via Zenodo at https://doi.org/10.5281/zenodo.19372559 (ref. 75).

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Author contributions

C.B., J.D., F.U. and G.L. developed the research idea. J.D. developed the model used, with contributions from P.C.V., M.P., C.C.G., F.S. and C.B. C.B. collected and processed the data. C.B. carried out the analysis. C.B. created the figures, with contributions from P.C.V. and J.D. C.B. wrote the paper, with contributions from J.D. A.O., F.U. and G.L. reviewed the paper, with contributions from all authors. F.U. and G.L. jointly supervised this work.

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Competing interests

The authors declare no competing interests.

Additional information

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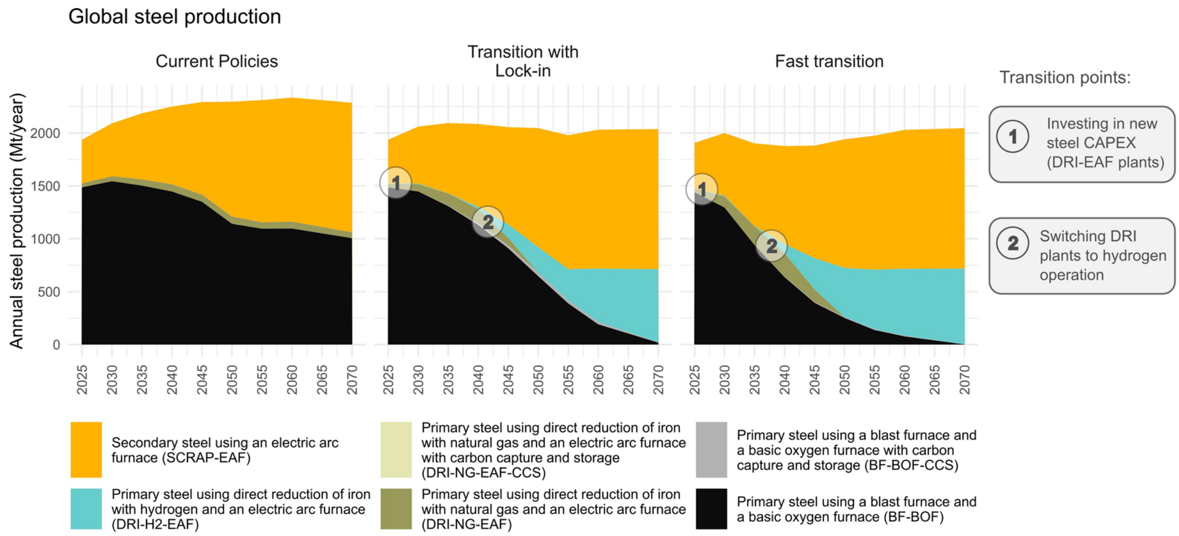

Extended Data Fig. 1 | Global annual steel production. The numbers indicate key transition points in the policy scenarios (*Transition with Lock-in and Fast Transition)*.

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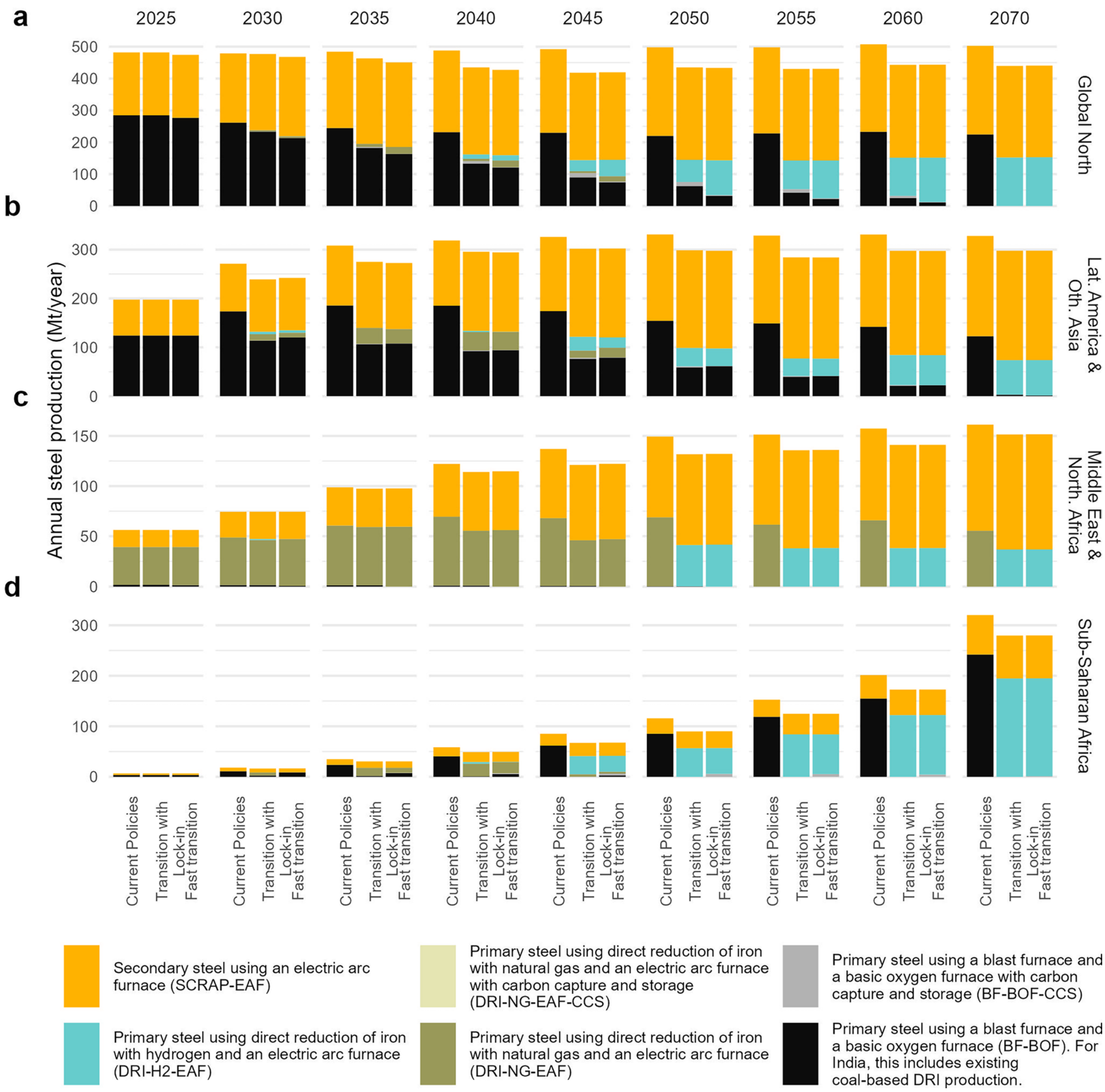

Extended Data Fig. 2 | Annual steel production for the remaining regions. All other regions modelled, which make up the production total in Fig. 3a, are shown here. **a**,**b**,**c**,**d**, Annual steel production in the Global North, Latin America and Other Asia, Middle East and North Africa and sub-Saharan Africa.

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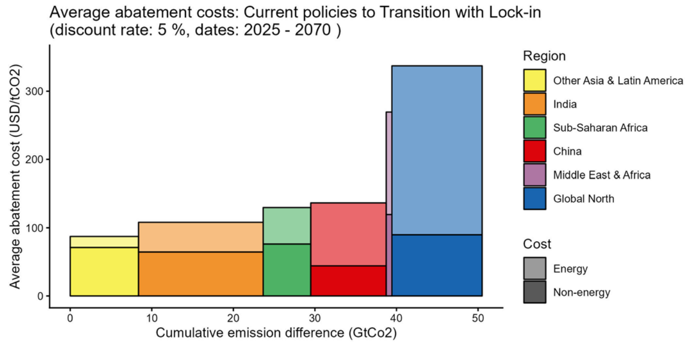

Extended Data Fig. 3 | Average abatement cost for going from Current Policies to Transition with Lock-in. The average cost of abatement over 2025–2070 is given per region and for two cost categories: energy (transparent bars, includes all energy costs for the steel system, such as hydrogen, fossil gas, coal, electricity) and non-energy (solid bars). Details for the average abatement cost calculation are given in Methods.

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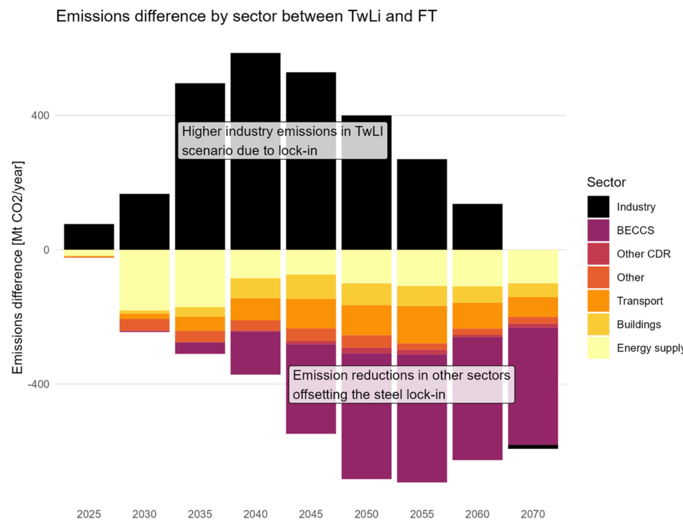

Extended Data Fig. 4 | Emission difference by sector between Transition with Lock-in and Fast Transition. Positive values indicate sectors with higher emissions in *Transition with Lock-in* compared to *Fast Transition*, while negative values indicate sectors that offset these additional emissions.

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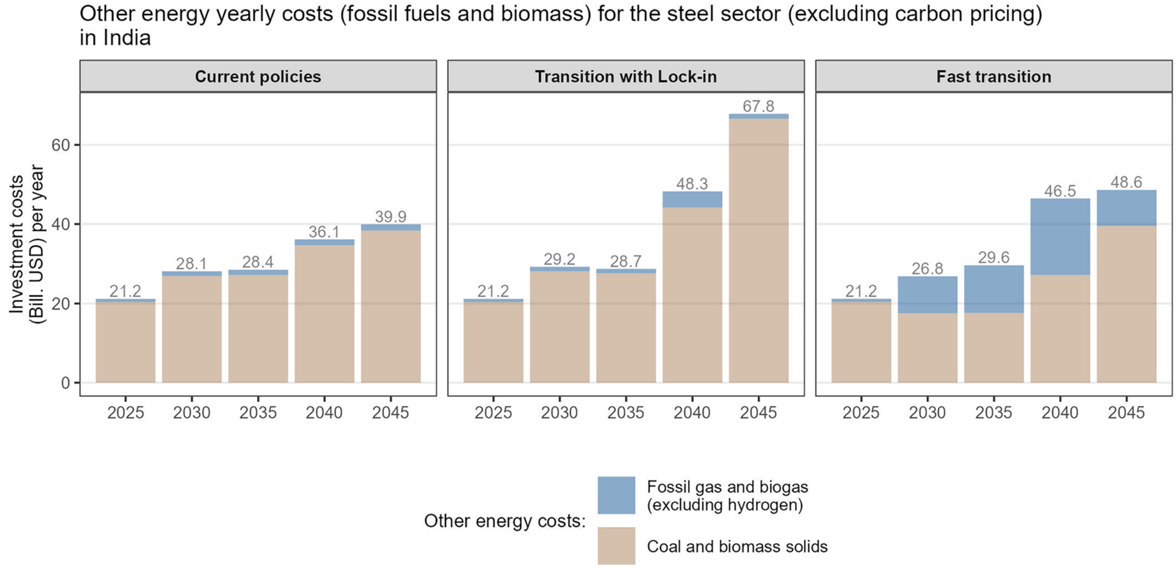

Extended Data Fig. 5 | Additional annual steel sector costs in India from the remaining operational expenditure. The remaining operational expenditure is energy costs from solid and gaseous fuels (there are no liquid fuels used in the steel sector). The colours show the different fuel types for each scenario. The CO_2 pricing is excluded from the costs shown here.

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Extended Data Fig. 6 | Annuity payments required to service primary steel investments in India, for Current Policies and Fast Transition. Annual capital payments are shown for varying weighted average costs of capital, covering investments made between 2026 and 2050 for primary steel production (including blast furnace with basic oxygen furnaces – BF-BOF, direct reduction of iron plants combined with an electric arc furnace – DRI-EAF, and associated infrastructure). This includes investments in electrolysers for hydrogen-based DRI operation, and in solar photovoltaic (solar PV) capacity for electrolysis and other electricity demands. The left-hand column shows annuity payments for *Current Policies*. The middle and right-hand columns show annuity payments for *Fast Transition:* the middle column shows the default results, in which DRI plants are first operated with natural gas before switching to green hydrogen. The right-hand column shows the annuity payments if DRI plants immediately operate with green hydrogen.