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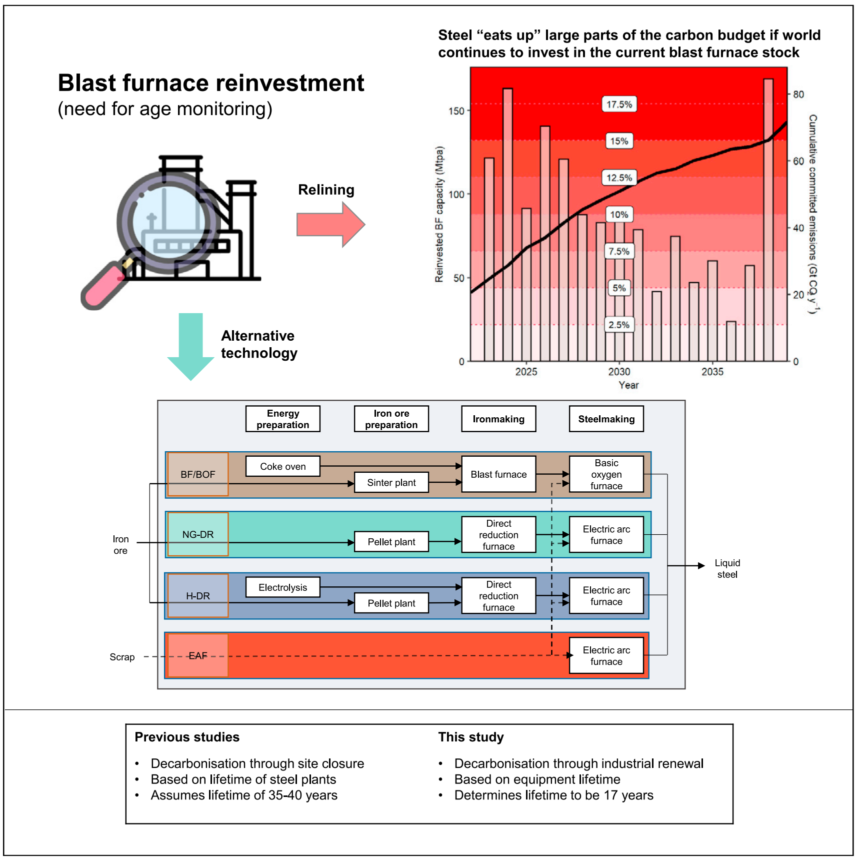
Phasing out the blast furnace to meet global climate targets



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Highlights

First estimation of committed emissions based on actual industry equipment data

The median historic blast furnace campaign length is 17 years

CO_2 emissions of 21 Gt to be expected for immediate blast furnace phase-out case

10 years of inaction and steel consumes 12% of the remaining 1.5°C carbon budget

Iron and steel production accounts for 7% of anthropogenic greenhouse gas emissions. We estimate expected future emissions from steel based on an improved approach to committed emissions accounting that uses actual equipment-level data. Without starting to phase out unmitigated blast furnaces soon the operation of current steel production equipment will consume significant amounts of the remaining 1.5°C carbon budget. The age of emission-intensive assets should be better monitored, and research should explore regulatory phaseouts of such assets.

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Phasing out the blast furnace to meet global climate targets

Valentin Vogl,[1,2,4,*] Olle Olsson,[3] and Björn Nykvist[3]

SUMMARY

Iron and steel production is responsible for 7% of global greenhouse gas emissions. Earlier literature finds that the long economic life of steel production equipment impedes decarbonization in line with climate targets. Here, we estimate the cumulative emissions from existing primary steel production equipment if operated as historically observed, based on furnace-level data of historical operating patterns. We find that the emissions commitment of current primary steel equipment is significantly smaller (21 Gt CO_2eq) than previously suggested (52–65 Gt CO_2eq). Consequently, we argue that future emissions from steel are driven not by long-lived capital but by the deployment pace of novel technologies and renewable energy provision, and a reduction of steel and energy demand. Without rapid progress in these aspects, the operation of current steel production equipment is likely to consume significant amounts of the remaining carbon budget. We recommend monitoring of emission-intensive asset aging and regulation of their operation.

Context & scale

Stronger climate policy has pushed the steel sector to start implementing lower-emission technology, but existing large-scale industrial assets have long economic lifetimes that are impeding decarbonization. Furthermore, socio-economic and political considerations such as local jobs and value creation are deterring policy makers to retire polluting production.

We show that the opportunity to reduce such committed emissions is larger than previously estimated if equipment-level analysis is conducted and reinvestments in the coal-based global blast furnace fleet are avoided. This approach can be also applied to other emission-intensive industrial assets and their respective investment cycles. To safeguard a chance to meeting the Paris Agreement target a focus on industrial renewal is thus needed. This includes better data transparency on the age of industrial assets and regulatory measures that co-evolve with a policy also taking into account a just transition, demand reduction, and research, development, and demonstration.

INTRODUCTION

The climate targets of the Paris Agreement require anthropogenic greenhouse gas emissions (GHG) to peak as soon as possible, reaching net-zero around 2050 and becoming negative thereafter.[1–3] In order to limit the reliance on negative emission technologies that are unproven and potentially undesirable on a large scale,[4,5] the steel sector should aim to decarbonize in pace with economy-wide targets and reach climate neutrality around in 2050.

In 2018, steel production was responsible for 7% of global GHG emissions and 10% of total anthropogenic CO_2 emissions.[6,7] These numbers include indirect emissions from the use of electricity and heat but exclude emissions up- and downstream the value chain such as in mining and manufacturing. Meanwhile, the demand for steel is expected to keep increasing, driven by emerging economies mostly in Asia.[6,8] Primary steel production—i.e., steel made from iron ore, unlike "secondary" made from steel scrap—is by far the main source of GHG emissions from the sector due to its reliance on metallurgical coal.[9,10] Decarbonizing the steel sector requires substantial changes to the primary production process, either by redesigning the blast furnace—equipping it with carbon capture and storage (CCS) and using biomass where possible to replace coal and coke[11,12]—or by replacing the blast furnace with a different technology such as the hydrogen direct reduction process,[13–15] an alternative that has gained significant momentum within the industry in recent years.[16,17]

The scientific climate and energy literature commonly refers to steel as a "hard-to-abate"[18–20] or "difficult-to-decarbonize"[21] sector. Steel has earned this label for several reasons. Some of these are purely technical and relate to how the majority of steel industry emissions do not come from simple fossil fuel combustion but from the ironmaking process itself where fossil coke used to reduce iron ore in the blast furnace. Blast furnace technology is a mature production system with literally a thousand-year history and fossil coke has unique desirable mechanical properties which makes it difficult to replace with less emitting alternatives.[22] Another commonly stated reason why steel is seen as difficult to decarbonize is the socio-economic inertia that stems from the view that large industrial capital is long-lived, and once built, tends to cause emissions until its final retirement (cf. Seto et al.[23]). Steel mills and their heavy equipment such as blast furnaces are thought to have long economic lifetimes, and consequently, investment decisions to build new or refurbish existing assets can lock-in a substantial amount of emissions and future climate warming.[24,25]

The impact of long-lived capital on climate warming has been studied quantitatively through the committed emissions accounting method.[24–27] Committed emissions are defined as the cumulative GHG emissions resulting from operating current fossil infrastructure until the end of its expected economic lifetime.[27–31] These emissions are not unavoidable but uneconomic to abate since previous investments in plants and equipment risk becoming stranded.[32–34] However, no study has yet quantified the committed emissions from industry based on the lifetimes of actual industrial equipment that needs to be replaced. The literature on committed emissions accounting has largely focused on the power sector and only a few studies have extended their scope to industrial assets.[6,24,25,35] The studies that do include industrial sectors such as steel do not account for the nature of investment cycles in the respective sectors and model industrial asset retirement akin to power sector infrastructures lifetimes at plant or site level with economic lifetimes of 35–40 years based either on historic survival curves of power plants,[24,35] or other not clearly specified assumptions.[6,25]

In this paper, we estimate the emissions commitment from global primary steel production equipment through a modified approach to committed emissions accounting for industrial assets that is based on actual historic operating patterns of steel production equipment. By doing so, we show that the socio-economic inertia of steel assets is a much smaller obstacle to steel decarbonization than often assumed. Our main argument is that the blast furnace *relining* (the reoccurring investment between furnace campaigns) is the main driver of committed emissions from steel production. In other words, the investment in a blast furnace relining at the end of the campaign represents the junction at which the branching off onto a low-emission technology pathway is most feasible for integrated steel producers. In the following we first develop the argument that decarbonizing industrial assets follows a logic of industrial renewal rather than whole plant retirement. We then analyze historic blast furnace operational patterns based on a global furnace-level dataset and use the results to estimate the emissions commitment of current primary steel production equipment.

Asset reinvestment and carbon lock-in

From its first presentation,[26] the goal of committed emissions accounting (CEA) was to inform public policy and investors on the future emissions of current investments into long-lived fossil infrastructure.[27,30,35] This body of literature has shown that the world is already locked into substantial climate warming from current assets—even if no more GHG emitting equipment is realized. A similar approach investigates the implications of treating the remaining carbon budget for the 1.5°C goal as a hard target, i.e., that all emitting equipment be retired when this budget is exhausted.[29]

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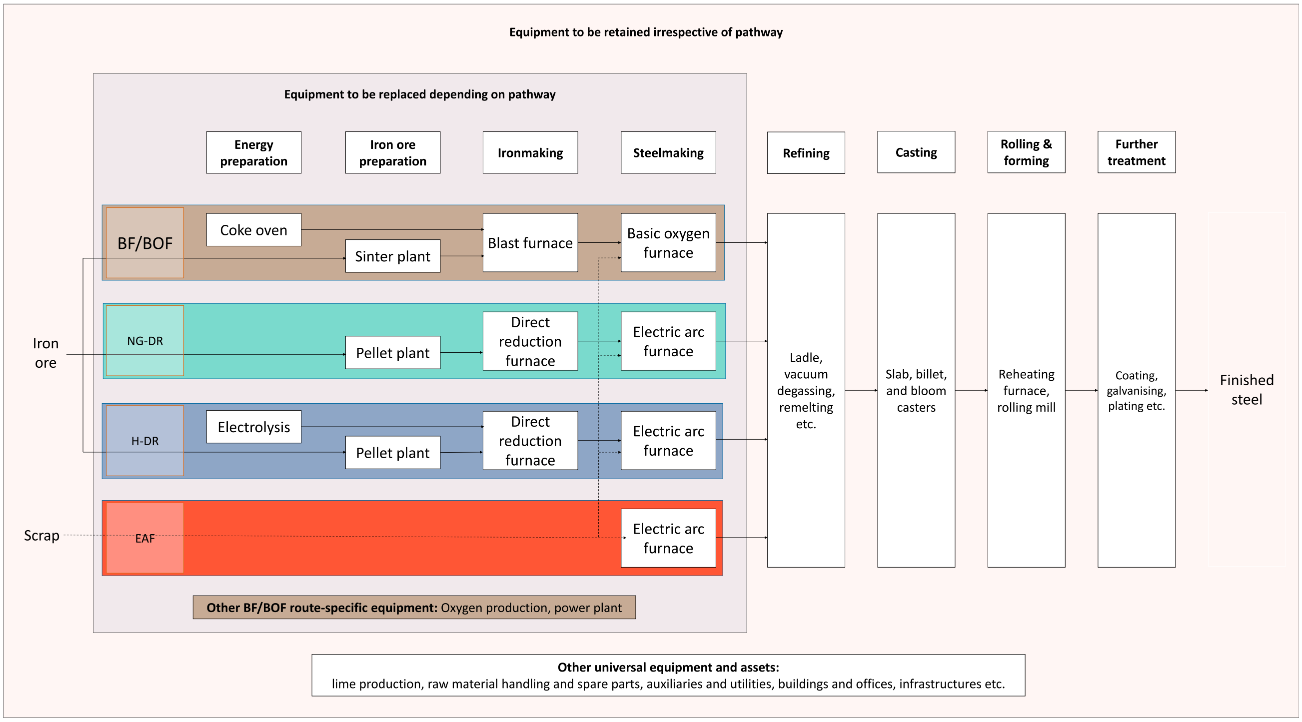

Figure 1. Schematic illustration of typical configurations of selected steel production pathways and associated difference in necessary equipment
BF/BOF, blast furnace/basic oxygen furnace; NG-DR, natural gas direct reduction; H-DR, hydrogen direct reduction; EAF, electric arc furnace.

This would mean that assets are potentially abandoned before the end of their economic lifetimes[26] and before they have generated the expected returns and recouped investments. These assets are then referred to as impaired or stranded.[32–34]

A key input to committed emissions accounting is the expected economic lifetime of an investment.[27] Most CEA studies have so far focused on the power sector and assumed that the economic lifetime of assets such as coal power stations entails the retirement of all the equipment at the site in question. Although this may be a reasonable assumption for the power sector—for example when a coal power plant is retired—we argue that a different approach is needed to quantify the emissions commitment of industrial sectors. Industrial sites such as steel mills can be over one hundred years old and will have undergone multiple cycles of repair and reinvestment during this time. As CEA was designed to “inform public policy by quantifying future emissions implied by current investments” (Davis and Socolow[27]: p.1), an analysis concluding that steel mills will be emitting until the end of the industrial site will not be of much service of climate policy makers wanting to act quickly. What is needed, instead, is a choice of expected economic life that takes into account the timing and economics of the asset reconfigurations that are needed to bring the steel sector onto a low-emission pathway.

Decarbonizing steel and other industries require the replacement or significant redesign of *certain equipment* in existing plants but does not necessarily mean that all current production sites need to be abandoned (see Figure 1). While it is probable that decarbonization of the global steel sector will entail the retirement of old steel plants and the establishing of new, greenfield steel mills, in the short term the conversion of existing sites are likely to dominate. This is due to large sunk costs in downstream equipment and the presence of skilled and knowledgeable workers and staff as well as political interests in sustaining jobs and value creation locally. Steel plants are part of an established value chain, with both upstream suppliers of iron ore that will remain also in a decarbonized future and with significant value in downstream assets—such as casting and rolling—that are often located close to main customers and that can be retained in all low-emission technology pathways for the steel sector. As shown in Figure 1, a transition from the traditional integrated route to, for example, steel production based on the hydrogen direct reduction process,[14] will require the replacement of equipment in the process stages of energy and iron ore preparation, ironmaking, and steelmaking, while up- and downstream assets as well as auxiliary equipment at the production site can be repurposed and thus their value retained. A detailed techno-economic assessment by the IEAGHG,[36] for example, has found the value of retainable assets (1,817 million USD as defined in Figure 1) to be close to half of total investment costs for a greenfield integrated steel mill.

The major capital expenditure that drives investment cycles in a steel mill is the so-called *relining* of the blast furnace.[36] During a relining, production at the steel mill is halted, and the refractory material that separates the furnace walls from its hot contents is repaired or replaced. The production outage distinguishes the relining from the maintenance of other equipment at the steel mill, which does not require halting production. During relining production typically ceases for several months before production can be resumed, starting a new *campaign*, i.e., the productive time period between relinings. The combination of investments of a magnitude of several hundred million USD[36,37] and the absence of revenues during the production stoppage make the blast furnace relining the single most important reinvestment in steel production. To illustrate, a typical relining of 3 months for a large blast furnace (4 Mtpa capacity) would result in foregone revenues of one billion USD. Capital expenditures for relining lie in the order of one-third to one-half of constructing a new blast furnace (USD 280–300 million, adjusted for inflation).[36,37]

At the same time, ironmaking in blast furnaces is the main source of GHG emissions in steel production. All low-emission pathways for steel require the replacement or at least significant modifications to the blast furnace, which can only be implemented once the furnace is shut down (even for CCS technology that necessitates complex integration with the blast furnace). The moment just before a relining is the time in the investment cycle when the blast furnace is relatively most depreciated, and thus, the investment decision is most likely to favor alternative technology. As production will be halted any way, the regular interval of blast furnace relining constitutes the most suitable and most probable timing for an integrated steelmaker to shift to a low-emission steel production pathway. In the case of a Northern European steelmaker, for example, "[t]he blast furnace was fully refurbished as recently as 2011 […] to last until the conversion to electric arc furnace in 2025." [38]

The choice to reline an existing blast furnace, on the other hand, will lead to a lock-in into carbon-intensive steel production for the next blast furnace campaign. We therefore argue that the blast furnace campaign is an appropriate proxy for the lifetime in CEA for steelmaking, as it represents the most probable investment timing for a technology shift. The fundamental difference between CEA in the power and industry sectors is thus one of discontinuation of fossil power plants versus industrial renewal. In the following we will apply this principle to quantify the committed emissions of the global steel sector. Based on a furnace-level dataset, we first determine the median length of historic blast furnace campaigns and then deploy it as the lifetime input for an analysis of committed emissions. By doing so, we hope to open up a

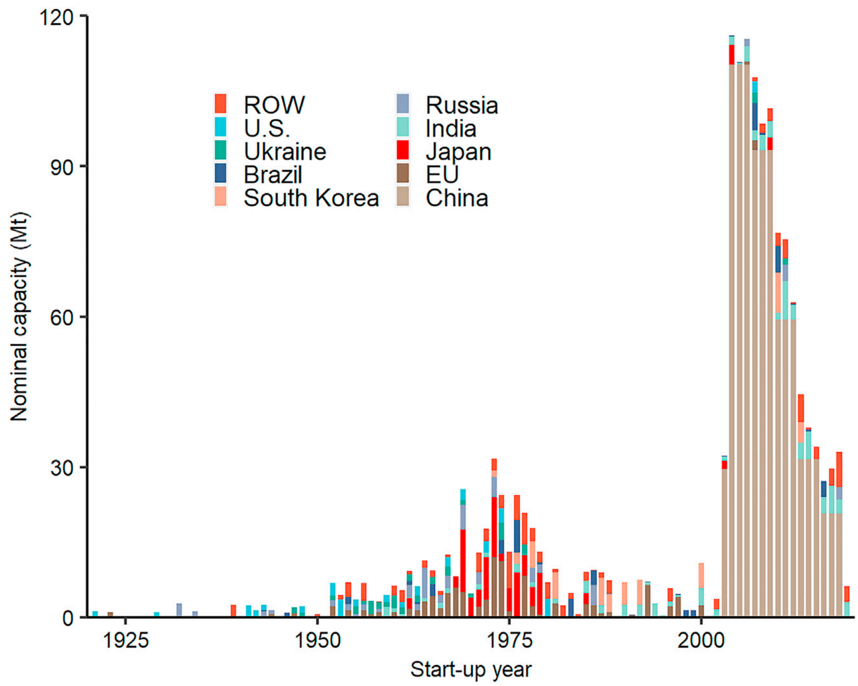

Figure 2. Age structure of currently (2019) operating global blast furnace equipment per country
(ROW, rest of the world)
Columns show the yearly capacity additions for furnaces that are still in operation. Two waves of capacity addition are apparent: a global expansion period in the 1970s and the great Chinese acceleration after 2000 (see also Tables S1 and S8). Data for China between 2004 and 2018 is presented as a three-year average due to data confidentiality.

path for further applications of this approach, for example, in other industry sectors, and enable more detailed equipment-level assessments in integrated assessment modeling work.

RESULTS

Blast furnace campaign life

The currently operating blast furnace fleet (Figure 2) dates to two waves of expansion: a first in the 1970s with large European and Japanese additions, the second after 2000 with massive capacity additions in China, but also significant industry growth in India. As a result, today's blast furnace capacity (1.6 Gtpa) is heavily concentrated in China (0.98 Gtpa). China has completed a rapid expansion of steel production after the year 2000 and made up 51% of total steel production and 64% of production through the blast furnace route in 2018.[39] Chinese-integrated still mills also have the second highest emission intensity of the countries regarded (India has highest, see Table S9).[9]

We quantified the duration of historic blast furnace campaigns by analyzing a unit-level dataset of global blast furnaces built after 1,897 (n = 858, see experimental procedures). Based on information on historic blast furnace campaigns in our dataset (n = 243) including both currently operating and shutdown furnaces (see experimental procedures), we determine the median historic blast furnace campaign life to be 17 years (Figure 3A). This is significantly lower than the lifetime assumptions made in previous studies of committed emissions in industry (35–40 years),[6,24,25,35] which were based on the economic life of whole plants or unstated assumptions.

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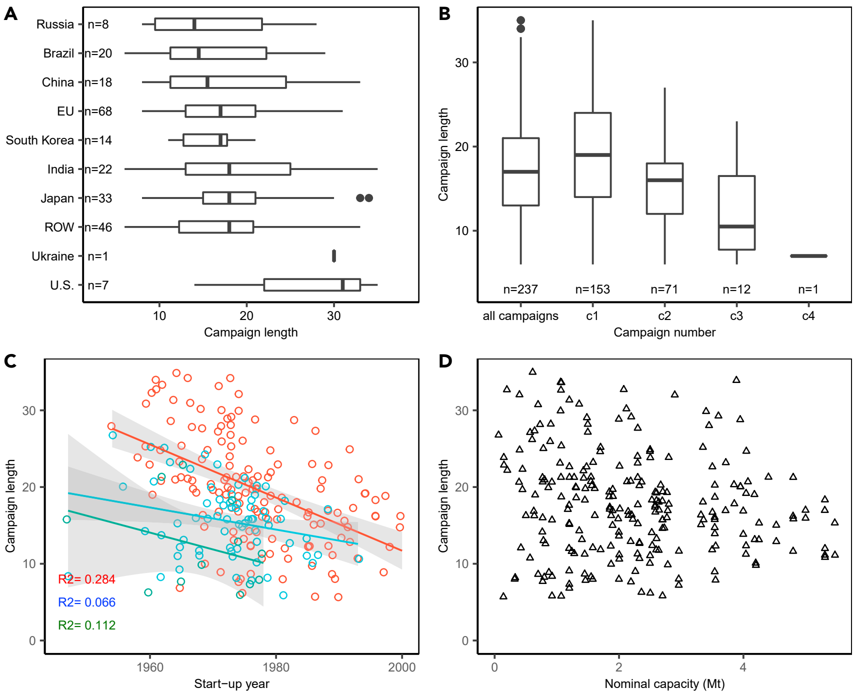

Figure 3. Summary of historical blast furnace campaign data sample

(A) Historical blast furnace campaign life per country (ROW, rest of the world).

(B) Campaign life for all, first, second, third, and fourth furnace campaigns.

(C) Campaign life over startup year of furnaces for first (red), second (blue), and third (green) furnace campaigns, and (D) campaign life over nominal furnace capacity. Linear regressions are shown with shaded 95% confidence interval.

However, it is in line with the assumptions made in literature on steel decarbonization literature of 15–20 years.[15,36,37,40]

We find an inverse relationship between blast furnace campaigns lives and total age of a furnace. The median for first campaigns is 19 years, while second (16) and third (10.5) campaigns have historically been shorter (Figure 3B). Campaign life distributions look similar for the main steel producing countries, although only limited data were available in the case of Ukraine. Counter to our expectations, no statistically significant time trend was found that would indicate longer campaigns of more modern blast furnaces (Figure 3C). One explanation for this finding could be that while the technical lifetime of a blast furnace has increased in recent decades,[41] more blast furnaces are relined early due to changing economic circumstances, including potentially accelerated technological innovation cycles. Campaign life was also found to be largely independent from furnace size (Figure 3D). Finally, again it is important to note that all these figures refer only to investments and reinvestments in the blast furnace, not the steel mill as a whole. The latter consists of many different assets (see Figure 1), of which however the blast furnace is arguably the most important in determining the economic life of the steel mill.

Committed emissions of primary steel assets

In the following we employ equipment campaign life as the expected lifetime to determine the committed emissions of the current global blast furnace production route. We find committed emissions of 21 Gt CO_2eq, which is significantly lower

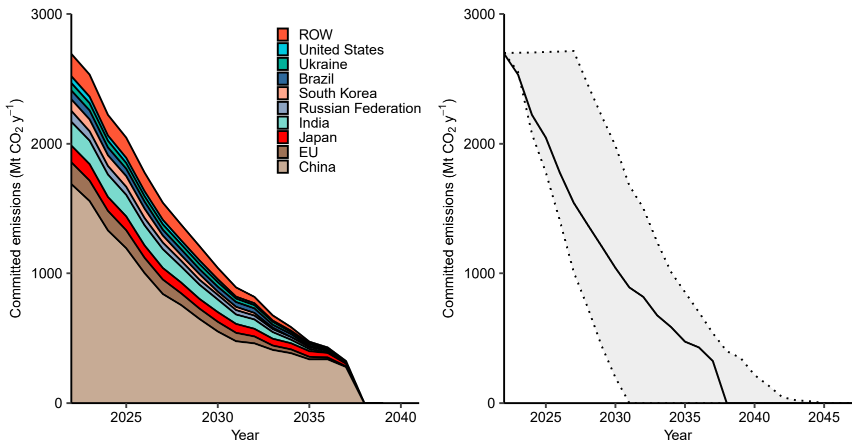

Figure 4. Committed emissions from existing global blast furnace equipment
(A) Committed emissions in main steel producing countries. Areas represent cumulative committed emissions.
(B) Committed emissions based on median historic blast furnace campaign life (17 years, black line, 21 Gt CO_2eq) and range of plus/minus one standard deviation (10–24 years, dotted lines, 13 and 32 Gt CO_2eq, respectively; see also Tables S2–S4).

compared with what was previously reported (52–65 Gt;[6,24] sectoral commitment retrieved through personal communication with author of Tong et al.[24]). Owing to the large variability of historic campaign lengths discussed before, the emissions commitment ranges from 13 to 32 Gt CO2eq in the interval of one standard deviation from the median (see Figure 4).

Figure 4 shows the capacity retirement and resulting yearly emissions if global blast furnace equipment ceases to be relined from 2022 onward. This implies that existing furnaces are either retired completely or replaced by zero-emission alternatives. Our calculation is based on two core assumptions. First, we defined a trajectory for future steel demand in line with the IEA's sustainable development scenario.[19] Second, we conservatively assumed that a capacity utilization level of 85% is required for investments into new capacity to occur (see experimental procedures for a justification and Figure S1). Below this threshold, once a furnace is due for relining it will be closed and the idled production volumes will be taken up by other producers, thereby increasing average global capacity utilization. With this approach, we are able to include how the current global excess capacity in steel production influences committed emissions.

Methodologically, the approach to capacity utilization presented here differs from previous studies of committed emissions, which have applied historically observed capacity utilizations of power generators in the range of 35%–61%[24,27,30] to industrial assets. Assuming power sector capacity factors for industry has two shortcomings in our view. First, blast furnaces have historically been operated more intensively than power generators. Between 2000 and 2018, despite the often lamented size of global excess capacity, global average capacity utilization in the global steel industry has been 78%, with global overcapacity for all steel producing assets at 520 Mtpa in 2018.[39,42] Second, and more importantly in our view, prescribing capacity utilization rather than future demand could de-link the calculation from real-world steel production volumes. Consequently, we chose to assume future steel demand, which then translates into capacity utilization depending on the state of global overcapacity in a given year.

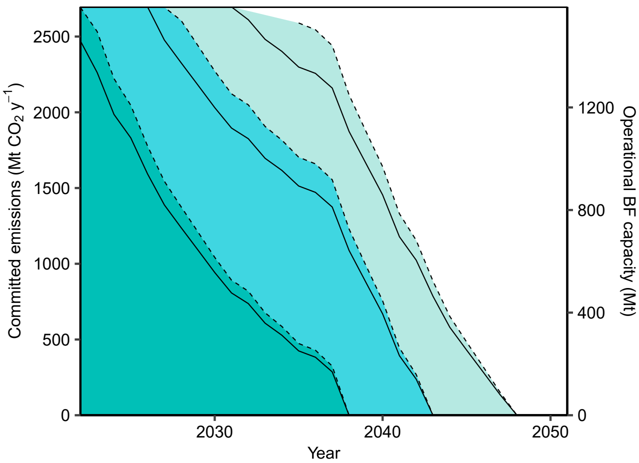

Figure 5. Committed emissions under delayed phase-out

Committed emissions (colored areas) from global blast furnace equipment varied for the starting year of calculations in 2022, 2027, and 2032 (left axis). Solid lines show capacity phase out of the blast furnace stock (right axis). Emission reductions trail behind capacity retirement due to global overcapacity (see results for explanation and Table S5 for data).

Phase-out delays put climate targets at risk

These results suggest that the technological carbon lock-in[23] in the steel system is actually smaller than often assumed in the literature. Future emissions from steel are driven not by long-lived and difficult-to-retire capital, but by the pace of demonstration, scale-up, and deployment of novel primary steel production processes with radically lower carbon footprint, as well as progress in reducing steel demand and the rollout pace of renewable energy generation. Branching points at which a switch onto a low-emission pathway is possible occur more frequently than previous research results imply, and intervals between branching points are characterized by a very large variability. We concur with Worrell and Biermans[43] that specific equipment, in this case the blast furnace, cannot be regarded to have a fixed lifetime. Furthermore, the economic lifetimes of large assets are affected not least by political and economic conditions as well as public acceptance. This means that policy makers, market actors, and civil society all have some power to accelerate the decarbonization of the steel sector by tilting investment decisions from carbon-intensive toward low-carbon alternatives.

However, this contribution is limited to estimating the expected emissions realized by current assets and the actual future emissions from primary steel production could significantly exceed this emissions commitment. Several reasons for this can be named. First, zero-emission alternatives to the blast furnace for primary steel production have yet to be tested on industrial scale. Despite recent industry advances and initial investments, it seems unlikely that zero-emission primary steel technologies will be available and widely substitute blast furnaces within the next 5 years. Figure 5 illustrates the impact of delaying the retirement of unmitigated blast furnaces on the emissions commitment. If blast furnaces continue to be relined according to historically observed lifetimes, 5 and 10 years of inaction increase total committed emissions to 40 and 53 Gt CO2eq, respectively. As a consequence, the steel sector in these two cases consumes 9% and 12% of the remaining carbon budget for a 50% probability of limiting global warming to 1.5°C,[44] compared with the current 7% share in global GHG emissions.

Second, while theoretically feasible,[12] a shift to fully zero-emissions technology seems unlikely. Current industry plans seem to favor conservative approaches such as using natural gas or the stepwise blast furnace retirement that lasts over decades.[16] Third, the benefits of retiring furnaces in one jurisdiction could be compromised be the building of new blast furnace equipment in others. Fourth, the deployment of technologies with radically lower carbon emissions hinges on the availability and buildout of large amounts of renewable electricity generation and delivery.[45] Progress in the electricity transition thus co-determines the decarbonization of the steel industry.

Figure 5 further illustrates the effect on global excess steel capacity on committed emissions, as emissions reductions (solid lines) lag behind capacity closures (dashed lines). In other words, even though capacity is reduced as blast furnaces are being phased out, initially, global capacity utilization is too low to warrant the replacements of these assets. As a consequence, vacant production is taken up in other blast furnaces, instead of motivating investments into zero-emission technologies. In our base case (not relining from 2022, as in Figure 4), emissions do not decline in first year (2022) even though 133 Mtpa of blast furnace capacity are retired. The size of the lag depends on the pace which with capacity is retired in the first years of the calculation. A sensitivity analysis for both the 85% capacity utilization threshold and for future steel demand development are presented in Figure S1.

DISCUSSION

Retiring unmitigated blast furnaces does not have to be delayed until zero-emission technologies are fully commercialized. Intermediate steps that are aligned with a long-term zero-emission strategy that limits further carbon lock-in can be implemented already today.[46] The diversity of steel mills in terms of assets and sizes allows for varying and often intermediate and stepwise technological pathways, influenced by the specific geographic and economic context in which a site is embedded. For example, a recent refurbishment of a main asset might be a reason to prefer one technological path over another. The electric arc furnace in particular seems to be a promising technology that is compatible with several technological pathways (see Figure 1). In regions reliant on natural gas such as Germany, steelmakers have announced plans to replace blast furnaces with direct reduction technology and replace natural gas with renewable hydrogen incrementally.[16] The same firms and some other operators of large steel mills with several blast furnaces at one site have communicated strategies to replace them one by one with direct reduction furnaces according to their next relining dates (see also Agora Energiewende and Wuppertal Institute[17]). Sites without access to natural gas can retire the blast furnace and switch to electric arc furnace operations that are supplied with a mix of scrap and direct reduced or hot-briquetted iron.[47] Such a strategy would retain most assets and jobs at the mill but outsource the most energy-intensive part of the production process to locations that can produce iron with a lower carbon footprint, while being able to guarantee product quality by using virgin material.

Overcapacity reduction represents a further reason for immediate blast furnace phaseouts. While in 2021 in response to built-up demand from the COVID-19 pandemic global steel production has peaked and capacity utilization increased sharply, the last decade was one of large global overcapacity and associated small margins for steel producers.[48,49] Global excess capacity for steel production can be said, as shown above, to have a delaying effect on emission reductions. As long as the global overcapacity remains high, blast furnace phase outs will not lead to significant emission reductions, but to the increased utilization of previously idle capacity. However, this delay in effective emission reductions can be mitigated if zero-emission steel technologies that replace current assets are able to capture green premium markets.[46] This would allow zero-emission alternatives to scale independently from the state of global blast furnace capacity and outcompete carbon-intensive steel production methods. In other words, demand previously served through the blast furnace route becomes demand for "green" steel, leading to emission reductions in line with blast furnace retirements and retaining the low-capacity utilization in the emission-intensive segment of steel production.

Policy implications

We conclude that research on climate policy and industrial decarbonization should put more effort into investigating the design of policy measures to phase out unmitigated blast furnaces and other Paris-incompatible industrial equipment, although exactly how such a policy should be designed is outside the scope of this contribution. A relining ban, for example, would likely create the perverse incentive to operate existing blast furnaces as long as possible (see also Davis and Socolow[27]); hence, careful policy design will be needed. Crucially, an effective ban on unmitigated blast furnaces requires much improved monitoring, data availability, and transparency. Open access to information about the age and status of the global blast furnace fleet would allow for more impactful research on steel transitions and help to avoid further carbon lock-in and promote proactive steps toward a just transitions for steel regions.[50] In particular, the relining of existing blast furnaces and the construction of new steel production capacity should be monitored more closely.

A policy plan for the blast furnace phase out must be integrated with a broader policy mix for the decarbonization of the steel industry that contains measures on market creation, subsidies, material efficiency improvements, and a just transition for its stakeholders.[51] Large potentials exist today when it comes to increasing use of recycled steel[52,53] and more efficient use and substitution of steel in construction.[54] These demand-side measures can reduce emissions immediately and reduce the steel sector's energy and resource use in the long term but depend on measures to avoid the contamination of steel scrap with impurities such as copper.[55] Many strategies to mitigate and adapt to climate, for example, renewable energy, railways, and other infrastructure and flood protections, are inherently steel intensive. Furthermore, not all currently existing steel mills have equally good opportunities to switch from metallurgical coal to renewable energy carriers, and for some of these, a blast furnace retirement will likely mean the end of the whole mill. Policy makers should early on facilitate dialogs for a just transition for workforces and communities. By integrating the abovementioned strategies into a coherent policy mix, we hold that steel can help rather than hold back the building of a fossil-free society.

Limitations

Using historically observed lifetimes of equipment in estimating future emissions from existing assets has several limitations in our view. Inferring campaign lives based on the historical economic conditions into the future is a prediction fraught with uncertainties. While past technological change in the steel industry was carried primarily by productivity gains, climate policy is arguably becoming one of the main drivers of current technological change. Furthermore, two-thirds of global blast furnace capacity are currently concentrated in China, where economic lifetimes of capital investments can follow patterns quite different from those observed historically in market economies.[56] While the use of observed historic lifetime in CEA is a useful tool to illustrate the climate impact of today's investment decisions, we should pay attention when the longevity of capital assets is primarily used as a discourse of climate delay[57] to kick the can down the road.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information questions should be directed to the lead contact, Valentin Vogl (corresponding author to this paper).

Materials availability

This study did not generate new unique materials.

Data and code availability

The two main data sources used are the Plantfacts database[58] and data on Chinese blast furnace capacity additions between 2000 and 2018, provided by Tong et al.[24] via personal communication (23 November 2020). All data to reproduce the study are made available in the Table S8 file, except for the data on China, for which the authors of Tong et al. [24] should be contacted. The OECD steelmaking capacity database[42] was used to take account of recent capacity developments as well as for the validation of Plantfacts data.

The Plantfacts dataset[58] was developed by the German steel institute VDEh until 2018 and contains detailed information on steel production equipment in global steel production sites. The dataset includes, among other things, information about nominal capacities, geographical locations, startup, and relining years on equipment level, e.g., for blast furnaces, BOF shops, coke ovens, etc. For every piece of equipment, several data sources are available to cross-check the information in the database. The same dataset has previously been used in the 2020 IEA Iron and Steel Roadmap.[6] Plantfacts is currently under private ownership by world steel dynamics (https://gsis.worldsteeldynamics.com).

Plantfacts is the most complete dataset on global blast furnace capacity to date. In order to evaluate the quality of the data, it was compared with total steelmaking capacity data from the OECD[42] and production data for oxygen-blown converters,[59] which are linked to blast furnaces in most cases except some open hearth furnaces that are still operating in Ukraine and Russia (see Table 1). OECD national steelmaking capacity, which covers both primary and secondary steel production, was adjusted to reflect the BF/BOF route by multiplying with the share of steel production that occurs in oxygen-blown converters to approximate steel capacity in the BF/BOF route.[39] Plantfacts capacity lies within $\pm$20% of the adjusted OECD capacity in all countries except India and Ukraine. For these two countries capacity seems to be lacking in the OECD dataset, however, as data from Global Energy Monitor[61] closely mirrors Plantfacts (India: 87 Mtpa, Ukraine: 42 Mtpa). Resulting capacity utilization factors derived from world steel production and OECD capacity data, reasonably lie between 58%–96% in all cases except Ukraine (37%), where capacity utilization is known to have been low, and which still operates 4.8 Mtpa of open hearth furnace capacity.

Approach

We determined the emissions commitment of the global blast furnace stock based on historically observed blast furnace campaigns and following assumed future steel demand projections. This section details our approach to data preparation, determining historical campaign lives and committed emissions calculations. We use *campaign life* to denote the lifetime of the asset in-between major reinvestments, which we refer to as *relinings*.

Table 1. Capacity data comparison: Plantfacts, OECD steelmaking capacity, and crude steel production in oxygen-blown converters

	Plantfacts capacity 2019[58] (Mtpa)	OECD capacity 2019[39,42] (Mtpa)	OBC Production 2017–2019[39] (Mt/year)
Brazil	41.0	38.5	26.2
EU	103.3	120.0	96.8
India	82.7	56.4	48.1
Japan	88.2	98.2	77.5
Russian Federation	62.8	55.7	47.4
South Korea	49.9	55.6	48.2
Ukraine	40.5	27.7	15.0
United States	34.1	33.3	26.7
ROW	102.9	100.1	59.5

OECD steelmaking capacity was adjusted according to the share of production in oxygen-blown converters in each country. ROW, rest of the world.

Scope

Emission intensities

We focus only on the blast furnace—basic oxygen furnace (BF/BOF) production route and do not consider direct reduction plants (8% of global iron production[39]) or secondary steelmaking. By doing so we capture more than 90% of 2018 direct emissions from steel.[6,12,39] This approach also covers indirect emissions from steel off-gas combustion in the BF/BOF route but does not consider indirect emissions from electricity use in secondary steelmaking. Our perspective is justified as the blast furnace is the part of the steel production process that is most difficult to decarbonize due to its reliance on fossil coke (see e.g., IEA and Vogl et al.[6,46]), and thus represents the prime obstacle to decarbonization and main reason for carbon lock-in[23] in the steel sector. The other two main iron and steel production methods—direct reduction and secondary steelmaking—can be decarbonized more incrementally through power grid decarbonization and the blending in of renewable fuels and/or hydrogen into existing direct reduction plants and thus are less prone to asset stranding and locked-in emissions due to asset longevity.

For Chinese blast furnace capacity, we relied on the more complete data used in Tong et al.24 which was generously made available to us by the authors. These data contain Chinese blast furnace capacity additions between 2000 and 2018 and was originally provided by the Chinese Ministry of Ecology and Environment (MEE). A comparison with other possible sources as well as Plantfacts showed that the MEE data provide the most accurate picture of the current Chinese blast furnace stock. A partial explanation of the lack of available data on Chinese steel assets could be the difficulty to keep track of the rapid changes in capacity since 2000, with several dozens of steel mills having opened and/or closed each year. Due to recent capacity closures of several hundred million tons in China,[48] we corrected the MEE data by scaling it according to the OECD steel capacity database.[42] Our core assumption states that Chinese blast furnace capacity was 975 Mtpa in 2018, which is in close range of production data[39] and recent reports on Chinese blast furnace capacity developments.[60] We then corrected the abovementioned Chinese blast furnace data[24] assuming that recent capacity closures affected the oldest furnaces in the data.

National emissions intensities (Table S9) for the BF-BOF production route were adopted from Hasanbeigi and Springer.[9] While for most major steel producing countries data were available, we had to assume that the emission intensity if Ukraine is equal the Russian. For the EU we used the capacity-weighted average emission intensity from the EU countries reported (Spain, France, Germany, Italy, and Poland).[9] For the ROW, we assumed a value of 2 tons CO_2 per ton of crude steel. We follow Davis et al.[21] and assume that emission intensities remain constant over the whole asset lifetime, which resonates with the common claim that optimization potentials are largely exhausted in today's integrated steel mills.[6] It needs to be stressed that the used emission intensities cover emissions of the whole integrated steel mill and not just those arising from blast furnaces. This is in line with our argument that the blast furnace campaign is the main driver of committed emission from steel mills (see main text).

Historic campaign life

Based on historic data from Plantfacts, we analyzed the distribution of historic campaign lives of blast furnaces. The database contains 858 blast furnaces (BFs). This includes Chinese assets, which are used to determine the historical median campaign life but are later replaced by more complete data on Chinese blast furnaces (see above). Out of the 339 blast furnaces that started operating before 2000, reliable information about relining dates was found to be available for 129 furnaces, many of which have been relined more than once. For some data points, additional relining information had to be retrieved from the comment fields to the respective data points and incorporated into the analysis.

For some older plants, only information about last relinings, but no intermediate refurbishments were available. In order to not misrepresent several campaigns as one in the determination of historic campaign lives, we decided to dismiss data points with historic campaigns longer than 35 years in the analysis. This is in line with reports on world record blast furnace campaigns of 30–35 years.[41,62] For reported campaigns between 30 and 35 years, we tried to find relining information through a web-based search. Through this, we could find additional relining dates that were missing in the data for four furnaces. Furthermore, a few data points reported partial relinings, which we considered as full relinings.

Some furnaces in the dataset were idled and later restarted. Although start-and-stop operations can have a detrimental effect on plant lifetimes,[63] long idle times prolong campaign lives. One plant, for example, was held idle for 12 years before restart. Here, we considered idle times part of campaign lives.

The data quality on historic relinings was generally better for EU countries, Japan, and Brazil (Figure 2), and slightly poorer for Russia, Ukraine, China, and India. More data points were available for newer blast furnaces and less for older units, for example, in the United States and Ukraine.

The median campaign life was determined to be 17 years. This result compares well to typical assumptions made in the steel decarbonization literature. Schneider et al.[40] assumes a blast furnace technical lifetime of 20 years for both the first and subsequent campaigns. Fischedick et al.[15] assumed investment cycles of 20 years, while Wörtler et al.[37] assumed 15 years. IEAGHG[64] assumes a relining in the 15th year after the operational start of a greenfield integrated steel mill. However, a complete dataset on all blast furnace relinings does not exist today. Because of this, we might have missed past relinings and respectively counted of two past campaigns as one, thereby overestimating historic campaign life. Our findings for historical lifetime should thus be understood as a conservative estimate, with the real historic lifetime possible being even shorter, which supports our methodological approach in the paper.

Committed emissions

The result from the campaign life calculation was used as the asset lifetime to calculate the committed emissions of current blast furnace-related infrastructure.

$$CE = \sum_{f} \sum_{y_0}^{y_{i,\,end}} C_f * cuf_y * EI_c \qquad \text{(Equation 1)}$$

Committed emissions (CEs) were calculated according to Equation 1 as the sum of yearly (y) emissions based on capacities (C) of each furnace (index f) until the end of its campaign ($y_{i,end}$), using country-specific emission intensities (EI_c) and assuming global average yearly capacity utilizations (cuf_y).

In our base case the calculation begins 2022 and uses a campaign life of 17 years. Future iron demand follows the IEA's sustainable development scenario (SDS) scenario and a capacity utilization value of 85% needed for the industry to make new investments. This approach is detailed below under "capacity utilization."

Next relining date

In determining the next relining date for all non-Chinese furnaces, several decisions were made due to differing data quality. First, assets listed as shut down or mothballed were sorted out (17 furnaces). For the remaining assets, all furnaces with available last relining dates were considered to be relined every 17 years until the resulting date passed the starting date of our calculation (2022 in the base case). If no last relining date was available (50% of furnaces, 34% of total capacity of the sample), the startup date of the furnace was used. If neither date was available (4% of furnaces, 6% of sample capacity), it was assumed that the next relining would be due in the first year of the calculation.

Capacity utilization

This paper approaches the capacity utilization differently than previous literature.[22] Instead of assuming a constant utilization factor, here, we assume the development of future steel production and derive the capacity utilization from it. We conservatively assume that a capacity utilization of 85% is necessary for the industry to make new investments. If the capacity utilization in a given year is lower than this threshold, a reduction of capacity does not lead to a reduction in emissions, but to increased production in the remaining operational capacity. In line with the literature on CEA capacity replacing the phased out blast furnaces is assumed to be zero-emission technology.[24,27] Our assumption of 85% is at the upper end of observed capacity utilizations over the last 20 years,[42,49] when rapid capacity additions led to large global excess capacities. Our base case can thus be understood as one of a thriving steel industry that has overcome the overcapacity dilemma. A sensitivity analysis for this capacity utilization threshold is provided in Figure S1.

We assume that global iron production develops in line with the IEA's SDS,[6,18] resulting in a 0.28% reduction of iron production per year globally. The SDS scenario assumes that known material efficiency potentials such as building lifetime extension and the direct reuse of steel without remelting are realized. Consequently, while global steel demand continues to increase, iron production slightly decreases as additional demand is covered through increased secondary steel production. This compares to a linear annual 1.7% demand increase in the IEA's Stated Policies Scenario (see Figure S1 for a sensitivity analysis).

To determine global capacity utilization for year one of our calculation we further assume blast furnace steel production in 2022 to equal the last reported value for steel production in oxygen-blown converters by Worldsteel.[39] This necessary simplification means that our model treats the share of BF and other iron production methods as constant in the future, although direct reduction grew more rapidly than BF ironmaking in the last decade.

Future onset dates

The starting date for the CEs calculation is varied to illustrate the effects of global overcapacity and climate inaction on the result. For the two cases (2027 and 2032), blast furnaces are assumed to be relined according to their identified next relining dates until the respective onset years, and iron demand follows the SDS scenario as explained above. In these cases, CEs denote the cumulative emissions from the base year of the paper (2022) until the entire retirement of blast furnace capacity.

Limitations

Focusing on blast furnaces only is a useful simplification of real-world industry investment situations. The actual assets to be replaced in the decarbonization of a steel mill depend on the technological path chosen for a given site. Most alternatives to the blast furnace such as direct reduction processes or direct electrification would also require the phase out of other assets than the blast furnace, in particular sinter plants, coke ovens, and basic oxygen furnaces. The different technical and economic lifetimes and relative economic values of these assets in a steel mill influence the optimum investment window and could cause stranded assets even in case of ideal investment timing. However, this does not change our argument that the fact that the blast furnace relining is the main reinvestment for integrated steel mills and thus represents the window of opportunity for zero-carbon investments.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.joule.2021.09.007.

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AUTHOR CONTRIBUTIONS

All authors participated equally in conceptualization, methodology design, validation and investigation of results, article writing, and proofreading. V.V. took the lead on formal analysis and visualization. O.O. and B.N. were leading on review and editing.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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REFERENCES

1. Rogelj, J., Huppmann, D., Krey, V., Riahi, K., Clarke, L., Gidden, M., Nicholls, Z., and Meinshausen, M. (2019). A new scenario logic for the Paris Agreement long-term temperature goal. Nature *573*, 357–363. https://doi.org/10.1038/s41586-019-1541-4.

2. Rogelj, J., Luderer, G., Pietzcker, R.C., Kriegler, E., Schaeffer, M., Krey, V., and Riahi, K. (2015). Energy system transformations for limiting end-of-century warming to below 1.5 °C. Nature Clim. Change *5*, 519–527. https://doi.org/10.1038/nclimate2572.

3. Rogelj, J., Shindell, D., Jiang, K., Fifita, S., Forster, P., Ginzburg, V., Handa, C., Kheshgi, H., Kobayashi, S., Kriegler, E., et al. (2018). Mitigation pathways compatible with 1.5°C in the context of sustainable development. In Global Warming of 1°C. An IPCC Special Report on the impacts of global warming of 1.5°C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty, V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, and R. Pidcock, et al., eds.. https://www.ipcc.ch/site/assets/uploads/sites/2/2019/05/SR15_Chapter2_Low_Res.pdf.

4. Smith, P., Davis, S.J., Creutzig, F., Fuss, S., Minx, J., Gabrielle, B., Kato, E., Jackson, R.B., Cowie, A., Kriegler, E., et al. (2016). Biophysical and economic limits to negative CO_2 emissions. Nature Clim. Change *6*, 42–50. https://doi.org/10.1038/nclimate2870.

5. Carton, W., Asiyanbi, A., Beck, S., Buck, H.J., and Lund, J.F. (2020). Negative emissions and the long history of carbon removal. WIREs Clim. Change *11*, e671. https://doi.org/10.1002/wcc.671.

6. IEA (2020). Iron and Steel Roadmap (International Energy Agency).

7. European Commission (2020). Emissions database for global atmospheric research (EDGAR). http://edgar.jrc.ec.europa.eu/overview.php?v=431.

8. Watari, T., Nansai, K., and Nakajima, K. (2021). Major metals demand, supply, and environmental impacts to 2100: a critical review. Resour. Conserv. Recy. *164*, 105107. https://doi.org/10.1016/j.resconrec.2020.105107.

9. Hasanbeigi, A., and Springer, C. (2019). How clean is the U.S. steel industry? An international benchmarking of energy and CO2 intensities (Global Efficiency Intelligence). https://www.globalefficiencyintel.com/us-steel-industry-benchmarking-energy-co2-intensities.

10. Wang, P., Ryberg, M., Yang, Y., Feng, K., Kara, S., Hauschild, M., and Chen, W.Q. (2021). Efficiency stagnation in global steel production urges joint supply- and demand-side mitigation efforts. Nat. Commun. *12*, 2066. https://doi.org/10.1038/s41467-021-22245-6.

11. Mandova, H., Patrizio, P., Leduc, S., Kjärstad, J., Wang, C., Wetterlund, E., Kraxner, F., and Gale, W. (2019). Achieving carbon-neutral iron and steelmaking in Europe through the deployment of bioenergy with carbon capture and storage. J. Cleaner Prod. *218*, 118–129. https://doi.org/10.1016/j.jclepro.2019.01.247.

12. Tanzer, S.E., Blok, K., and Ramírez, A. (2020). Can bioenergy with carbon capture and storage result in carbon negative steel? Int. J. Greenhouse Gas Control *100*, 103104. https://doi.org/10.1016/j.ijggc.2020.103104.

13. Kushnir, D., Hansen, T., Vogl, V., and Åhman, M. (2020). Adopting hydrogen direct reduction for the Swedish steel industry: a technological innovation system (TIS) study. J. Cleaner Prod. *242*, 118185. https://doi.org/10.1016/j.jclepro.2019.118185.

14. Vogl, V., Åhman, M., and Nilsson, L.J. (2018). Assessment of hydrogen direct reduction for fossil-free steelmaking. J. Cleaner Prod. *203*, 736–745. https://doi.org/10.1016/j.jclepro.2018.08.279.

15. Fischedick, M., Marzinkowski, J., Winzer, P., and Weigel, M. (2014). Techno-economic evaluation of innovative steel production technologies. J. Cleaner Prod. *84*, 563–580. https://doi.org/10.1016/j.jclepro.2014.05.063.

16. Vogl, V., Sanchez, F., Gerres, T., Lettow, F., Bhaskar, A., Swalec, C., Mete, G., Åhman, M., Lehne, J., Schenk, S., et al. (2021). Green steel tracker. 27/4/2021 edition (LeadIT). https://www.industrytransition.org/green-steel-tracker/.

17. Agora Energiewende; Wuppertal Institute (2021). Breakthrough strategies for climate-neutral industry in Europe: policy and technology pathways for raising EU climate ambition. https://www.agora-energiewende.de/en/publications/breakthrough-strategies-for-climate-neutral-industry-in-europe-study/.

18. ETC (2018). Mission possible: reaching net-zero carbon emissions from harder-to-abate sectors by mid century (Energy Transition Commission). https://www.energy-transitions.org/publications/mission-possible/.

19. IEA (2020). Energy Technology Perspectives (International Energy Agency).

20. Bataille, C.G.F. (2019). Physical and policy pathways to net-zero emissions industry. WIREs Clim. Change *11*, e633. https://doi.org/10.1002/wcc.633.

21. Davis, S.J., Lewis, N.S., Shaner, M., Aggarwal, S., Arent, D., Azevedo, I.L., Benson, S.M., Bradley, T., Brouwer, J., Chiang, Y.-M., et al. (2018). Net-zero emissions energy systems. Science *360*. https://doi.org/10.1126/science.aas9793.

22. Suopajärvi, H., Kemppainen, A., Haapakangas, J., and Fabritius, T. (2017). Extensive review of the opportunities to use biomass-based fuels in iron and steelmaking processes. J. Cleaner Prod. *148*, 709–734. https://doi.org/10.1016/j.jclepro.2017.02.029.

23. Seto, K.C., Davis, S.J., Mitchell, R.B., Stokes, E.C., Unruh, G., and Ürge-Vorsatz, D. (2016). Carbon lock-in: types, causes, and policy implications. Annu. Rev. Environ. Resour. *41*, 425–452. https://doi.org/10.1146/annurev-environ-110615-085934.

24. Tong, D., Zhang, Q., Zheng, Y., Caldeira, K., Shearer, C., Hong, C., Qin, Y., and Davis, S.J. (2019). Committed emissions from existing energy infrastructure jeopardize 1.5 degrees C climate target. Nature *572*, 373–377. https://doi.org/10.1038/s41586-019-1364-3.

25. Erickson, P., Kartha, S., Lazarus, M., and Tempest, K. (2015). Assessing carbon lock-in. Environ. Res. Lett. *10*. https://doi.org/10.1088/1748-9326/10/8/084023.

26. Davis, S.J., Caldeira, K., and Matthews, H.D. (2010). Future CO_2 emissions and climate change from existing energy infrastructure. Science *329*, 1330–1333.

27. Davis, S.J., and Socolow, R.H. (2014). Commitment accounting of CO_2 emissions. Environ. Res. Lett. *9*, 084018. https://doi.org/10.1088/1748-9326/9/8/084018.

28. Davis, S.J., and Caldeira, K. (2010). Consumption-based accounting of CO_2 emissions. Proc. Natl. Acad. Sci. USA *107*, 5687–5692. https://doi.org/10.1073/pnas.0906974107.

29. Pfeiffer, A., Millar, R., Hepburn, C., and Beinhocker, E. (2016). The '2°C capital stock' for electricity generation: committed cumulative carbon emissions from the electricity generation sector and the transition to a green economy. Appl. Energy *179*, 1395–1408. https://doi.org/10.1016/j.apenergy.2016.02.093.

30. Pfeiffer, A., Hepburn, C., Vogt-Schilb, A., and Caldecott, B. (2018). Committed emissions from existing and planned power plants and asset stranding required to meet the Paris Agreement. Environ. Res. Lett. *13*, 054019. https://doi.org/10.1088/1748-9326/aabc5f.

31. Cui, R.Y., Hultman, N., Edwards, M.R., He, L., Sen, A., Surana, K., McJeon, H., Iyer, G., Patel, P., Yu, S., et al. (2019). Quantifying operational lifetimes for coal power plants under the Paris goals. Nat. Commun. *10*, 4759. https://doi.org/10.1038/s41467-019-12618-3.

32. Johnson, N., Krey, V., McCollum, D.L., Rao, S., Riahi, K., and Rogelj, J. (2015). Stranded on a low-carbon planet: implications of climate policy for the phase-out of coal-based power plants. Technol. Forecasting Soc. Change *90*, 89–102. https://doi.org/10.1016/j.techfore.2014.02.028.

33. Caldecott, B. (2017). Introduction to special issue: stranded assets and the environment. J. Sustain. Finan. Invest. *7*, 1–13. https://doi.org/10.1080/20430795.2016.1266748.

34. Sen, S., and von Schickfus, M.-T. (2020). Climate policy, stranded assets, and investors' expectations. J. Environ. Econ. Manag. *100*, 102277. https://doi.org/10.1016/j.jeem.2019.102277.

35. Smith, C.J., Forster, P.M., Allen, M., Fuglestvedt, J., Millar, R.J., Rogelj, J., and Zickfeld, K. (2019). Current fossil fuel infrastructure does not yet commit us to 1.5 degrees C warming. Nat. Commun. *10*, 101. https://doi.org/10.1038/s41467-018-07999-w.

36. IEAGHG (2013). Iron and Steel CCS Study (Techno-Economics Integrated Steel Mill).

https://ieaghg.org/publications/technical-reports/reports-list/9-technical-reports/1001-2013-04-iron-and-steel-ccs-study-techno-economics-integrated-steel-mill.

37. Wörtler, M., Schuler, F., Voigt, N., Schmidt, T., Dahlmann, P., Lungen, H.B., and Ghenda, J.-T. (2013). Steel's contribution to a low-carbon Europe 2050. https://www.bcg.com/publications/2013/metals-mining-environment-steels-contribution-low-carbon-europe-2050.

38. Moggridge, M. (2018). SSAB shuts down blast furnace ops in Oxelösund. Steel Times International, 30th August, 2018. https://www.steeltimesint.com/news/ssab-shuts-down-blast-furnace-ops-in-oxeloesund.

39. Worldsteel. (2019). Worldsteel Statistical Yearbook 2019 (Worldsteel). https://www.worldsteel.org/en/dam/jcr:7aa2a95d-448d-4c56-b62b-b2457f067cd9/SSY19%2520concise%2520version.pdf.

40. Schneider, C., Lechtenböhmer, S., and Höller, S. (2014). Re-industrialisation and low carbon economy – can they go together? Results from transdisciplinary scenarios for energy intensive industries. ECEEE Industrial Summer Study Proceedings. https://www.eceee.org/library/conference_proceedings/eceee_Industrial_Summer_Study/2014/4-undertaking-high-impact-actions-the-role-of-technology-and-systems-optimisation/re-industrialisation-and-low-carbon-economy-can-they-go-together-results-from-transdisciplinary-scenarios-for-energy-intensive-industries/.

41. Lüngen, H.B., and Schmöle, P. (2020). Comparison of Blast Furnace operation modes in the world. steel Res. Int. *91*, 2000182. https://doi.org/10.1002/srin.202000182.

42. OECD (2021). Steelmaking capacity. http://www.oecd.org/sti/ind/steelcapacity.htm.

43. Worrell, E., and Biermans, G. (2005). Move over! Stock turnover, retrofit and industrial energy efficiency. Energy Policy *33*, 949–962. https://doi.org/10.1016/j.enpol.2003.10.017.

44. Damon Matthews, H., Tokarska, K.B., Rogelj, J., Smith, C.J., MacDougall, A.H., Haustein, K., Mengis, N., Sippel, S., Forster, P.M., and Knutti, R. (2021). An integrated approach to quantifying uncertainties in the remaining carbon budget. Commun. Earth Environ. *2*. https://doi.org/10.1038/s43247-020-00064-9.

45. Arens, M., Åhman, M., and Vogl, V. (2021). Which countries are prepared to green their coal-based steel industry with electricity? - Reviewing climate and energy policy as well as the implementation of renewable electricity. Renew. Sustain. Energy Rev. *143*, 110938. https://doi.org/10.1016/j.rser.2021.110938.

46. Vogl, V., Åhman, M., and Nilsson, L.J. (2020). The making of green steel in the EU: a policy evaluation for the early commercialization phase. Clim. Policy *21*, 78–92. https://doi.org/10.1080/14693062.2020.1803040.

47. Gielen, D., Saygin, D., Taibi, E., and Birat, J.P. (2020). Renewables-based decarbonization and relocation of iron and steel making: a case study. J. Ind. Ecol. *24*, 1113–1125. https://doi.org/10.1111/jiec.12997.

48. Chen, L., Ding, D., and Mano, R.C. (2018). China's Capacity Reduction Reform and Its Impact on Producer Prices (International Monetary Fund).

49. Chalabyan, A., Mori, L., and Vercammen, S. (2018). The Current Capacity Shake-Up in Steel and How the Industry Is Adapting (McKinsey & Company).

50. Grubert, E. (2020). Fossil electricity retirement deadlines for a just transition. Science *370*, 1171–1173. https://doi.org/10.1126/science.abe0375.

51. Nilsson, L.J., Bauer, F., Åhman, M., Andersson, F.N.G., Bataille, C., de la Rue du Can, S., Ericsson, K., Hansen, T., Johansson, B., Lechtenböhmer, S., et al. (2021). An industrial policy framework for transforming energy and emissions intensive industries towards zero emissions. Clim. Policy, 1053–1065. https://doi.org/10.1080/14693062.2021.1957665.

52. Milford, R.L., Pauliuk, S., Allwood, J.M., and Müller, D.B. (2013). The roles of energy and material efficiency in meeting steel industry CO_2 targets. Environ. Sci. Technol. *47*, 3455–3462. https://doi.org/10.1021/es3031424.

53. Pauliuk, S., Milford, R.L., Müller, D.B., and Allwood, J.M. (2013). The steel scrap age. Environ. Sci. Technol. *47*, 3448–3454. https://doi.org/10.1021/es303149z.

54. IRP (2020). Resource Efficiency and Climate Change: Material Efficiency Strategies for a Low-Carbon Future (United Nations Environment Programme).

55. Daehn, K.E., Cabrera Serrenho, A., and Allwood, J.M. (2017). How will copper contamination constrain future global steel recycling? Environ. Sci. Technol. *51*, 6599–6606. https://doi.org/10.1021/acs.est.7b00997.

56. Myllyvirta, L., Zhang, S., Shen, X., and Bi, Y. (2020). Political Economy of Climate and Clean Energy in China: Opportunities and Limits of International Influence on the Chinese Emissons Pathway (Heinrich Böll Foundation).

57. Lamb, W.F., Mattioli, G., Levi, S., Roberts, J.T., Capstick, S., Creutzig, F., Minx, J.C., Müller-Hansen, F., Culhane, T., and Steinberger, J.K. (2020). Discourses of climate delay. Glob. Sustain. *3*, E17. https://doi.org/10.1017/sus.2020.13.

58. VDEh (2018). Plantfacts database.

59. Worldsteel. (2020). 2020 World Steel in Figures (World Steel Association).

60. Global, Mysteel (2020). Mysteel global (Mysteel global. Newsletter). https://www.mysteel.net/.

61. Global energy Monitor (2021). Steel Plants. 17/4/2020 edition. https://globalenergymonitor.org/projects/global-steel-plant-tracker/.

62. Kerkhoven, F., Stuurwold, J., Tijhuis, G., Nugteren, B., and Laar, R.v. (2020). 30+ year campaign of IJmuiden blast furnace No. 6. Millenium Steel *2020*, 46–53.

63. IspatGuru. (2015). Operation practices and campaign life of a blast furnace. https://www.ispatguru.com/operation-practices-and-campaign-life-of-a-blast-furnace/.

64. IEAGHG (2013). Overview of the current state and development of CO2 capture technologies in the ironmaking process. http://www.ieaghg.org/docs/General_Docs/Reports/2013-TR3.pdf.