New Political Economy

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/cnpe20

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To cite this article: Jack Copley (2024) Green Vulcans? The political economy of steel decarbonisation, New Political Economy, 29:6, 972-985, DOI: 10.1080/13563467.2024.2373051

To link to this article: https://doi.org/10.1080/13563467.2024.2373051

Published online: 07 Jul 2024.

NEW POLITICAL ECONOMY
2024, VOL. 29, NO. 6, 972–985
https://doi.org/10.1080/13563467.2024.2373051

Routledge
Taylor & Francis Group

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Green Vulcans? The political economy of steel decarbonisation

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ABSTRACT
Studies of the political economy of decarbonisation have begun to move beyond the price-centrism of neoclassical economics to explore the role of profits in propelling, or failing to propel, a green transformation. This article pushes this argument further, claiming with Marx that the focus on profits is useful insofar as it leads us to a broader analysis of the capitalist dynamics of competition, overaccumulation, and crisis that any green transition will have to reckon with. This is illustrated through an historical study of the steel industry – a prodigious carbon emitter that must be urgently greened. This article traces the interwoven patterns of crisis and technological change in steelmaking through the nineteenth and twentieth centuries, before drawing out certain core themes that then serve as a lens through which to analyze the prospects of steel decarbonisation today. Since its modern birth, technological revolutions in steelmaking have generated and in turn been conditioned by crises of overaccumulation and restructuring. These same forces are shaping the drive to decarbonise the industry today, as vital green investments are obstructed by reoccurring cycles of overcapacity and weak profitability. Greening steelmaking, and capitalism more generally, means wrangling with this boom-and-bust logic and its political ramifications.

ARTICLE HISTORY
Received 5 February 2024
Accepted 18 June 2024

KEYWORDS
Decarbonisation; climate change; steel; Marx; crisis; overcapacity

Observers of steelmaking have long reached for mythological imagery to capture its drama. To workers, Winant (2021, p. 26) writes, the mill appears as ‘an elemental force, like a Greek god’. In the nineteenth century, foundries sprang up in Britain and the US named after Vulcan, the god of fire (Gwyn 2023, p. 188, Misa 1995, p. 28). An early American union of iron puddlers called themselves the Sons of Vulcan. Such workers earned their wages, one attested, ‘standing with our faces in the scorching heat while our hands puddled the metal in its glaring bath’ that burned ‘as hot as the fiery lake in Hades’ (Davis 1922, p. 91, 104). ‘It is a little hell’, Landes (2003, p. 255) said of the Bessemer converter in his classic study – a technology that inaugurated the ‘Age of Steel’ by blowing air through molten iron in eruptions of searing heat and light.

These infernal metaphors have assumed a new meaning in view of climate change. A prodigious greenhouse gas emitter, the steel sector is actively dragging us into a hotter, more hostile world – a world in its image. This industry contributes 7–9 per cent of global anthropogenic CO^2 emissions and uses more coal than any other industry except electricity generation (Kim *et al.* 2022, pp. 1–2). However, it cannot simply be shuttered. Steel will undergird any feasible green transition: it is, for example, a core component of electric vehicles, solar arrays, and wind turbines

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(Kim *et al.* 2022). Steelmaking must therefore be decarbonised – an imperative that is increasingly recognised by states, international organisations, and industry associations (IEA 2020, WSA 2021b).

The complexities of carbon-neutral metallurgy and the scale of contemporary steelmaking operations make this a classic 'hard-to-abate' industry. Yet while such technical obstacles are significant, they are greatly amplified by their interaction with the crisis dynamics of the steel industry – an industry that has witnessed 'at least one crisis … every decade since the 1970s' (Silva and de Carvalho 2017, p. 17). These crisis tendencies are pronounced in steel, but not unique to it. In fact, this article contends that the case of steel decarbonisation brings into relief the knotted relationship between technological change of the sort vital for a green transition, on the one hand, and the dynamics of global competition, uneven accumulation, and crisis and restructuring that mark capitalist production, on the other.

For the neoclassical tradition, which has largely guided political responses to climate change, the question of the relationship between decarbonisation and capitalism's crisis tendencies is meaningless. This is because neoclassical economics abstracts from the crisis-marked history of capitalist development so as to better construct formal models of price determination (Clarke 1991). For green neoclassicals, global warming constitutes a towering market failure, whereby the utility-maximizing actions of private agents result in an unpriced harm for the planet at large (Jacobs 1997). The key to effecting decarbonisation is first to hang a price on this environmental harm such that it enters into agents' calculations. Second, this price must be manipulated through market mechanisms and/or limited state intervention such that agents are incentivized to minimise environmental harm by reorganising their production processes.

Against such 'price-oriented theories' of decarbonisation, Christophers (2024) has advocated the 'profit-sideism' of Marx. Through an exploration of the trajectory of the renewable electricity market, he argues that the key determinant of investment decisions is expected profitability. Capital will be incentivized to green itself only when it becomes profitable to do so, and not before. Christophers is not alone in making this point. For example, scholars have examined the profit-logics underpinning Environmental, Social, and Governance investing (Parfitt 2020), while 'derisking' literature explores how states seek to alter the profitability (risk/return) profiles of green investments in order to attract private capital (Gabor and Braun 2023).

Yet recentring the profit question is only the starting point of an adequate account of decarbonisation. Marx's work is not distinguished by an emphasis on profits, but rather by his demonstration that the profit imperative generates a unique form of historical development (Marx 1976). The relentless churn of competition drives productivity-enhancing technological change, resulting in globally uneven spurts of breakneck accumulation that culminate in overaccumulation, crisis, and restructuring or stagnation. Technological advancements, which are required for a green transition, are fundamental to Marx's theory. But they are both conditioned by, and productive of, periods of boom and slump. The challenge of decarbonisation is to rapidly and completely transform the energetic basis of a system that is not only profit driven but marked by this jolting and imbalanced form of economic locomotion (Alami *et al.* 2023, Copley 2023, Keil and Steinberger 2024).

This article illustrates these dynamics by analyzing the contemporary prospects of steel decarbonisation in the context of the long-run history of technological change within the sector. Three key points are made. First, the major technological revolutions in steelmaking have been those that have delivered massive productivity gains – yet the diffusion of these technologies has been surprisingly gradual and internationally uneven. This is largely because, second, technological change is intimately bound up with the industry's crisis tendencies: the adoption of revolutionary technologies is conditioned by reoccurring crises of overaccumulation, and the diffusion of these new technologies contributes to new overaccumulation crises. Third, these technological changes and the crisis tendencies that they birth give rise to pressures for global industrial restructuring that involve the traumatic reorganisation of the geography and labour relations of production. This restructuring stokes class conflict and international tensions, and these political ramifications rebound back upon the process of technological diffusion, warping its progress.

The coming decarbonisation of steel displays certain similarities and differences with this historical pattern. As before, the industry faces a protracted crisis of overaccumulation, rendering a zero-emissions overhaul of production an unprofitable business proposition. Unlike previous technological shifts, however, it is not clear that green steel innovations offer momentous productivity advances. Further, even if state interventions render steel decarbonisation a financially viable strategy for firms – an uncertain prospect – this will likely herald another traumatic global restructuring of the sector that is difficult to reconcile with notions of a Just Transition. Indeed, such restructuring will generate political reactions that are likely to impact the decarbonisation process itself.

This article begins by tracing the interwoven patterns of crisis and technological change in modern steelmaking. Next, this historical narrative is distilled into core theoretical themes, drawing upon Marx's account of capitalist development. This theoretical discussion then serves as a lens through which to analyze the prospects of steel decarbonisation today.

Two revolutions

The birth of cheap steel

The spell of remarkable economic dynamism that followed the defeat of the 1848 revolutions and lasted until 1873, despite several interruptions, swept the iron industry up along with it (Hobsbawm 1988, pp. 43–63). Iron was the predominant industrial metal at this point, rather than steel, due to the relative cheapness of its manufacture. By the mid-nineteenth century Britain completely dominated the industry, producing more iron than every other country combined (Landes 2003, p. 95). As iron output increased, much of it went to furnish the great railway expansion of the era. The most spectacular extensions occurred in the Americas, as thousands of miles of new track branched out with the advancing frontier in young republics like the US and Argentina, facilitated by and in turn hastening the extermination of the indigenous nations of the plains and pampas alike (Wright 1974, Karuka 2019). The demand for iron and steel created by this conquest – this 'fever for westward expansion' – 'surpassed the dreams' of Europe's producers (Misa 1995, p. 15). Britain alone saw its exports of railroad iron and steel grow from around 1.3 million tons in 1945–49 to more than four million tons in 1970–75 (Hobsbawm 1988, p. 54).

It was during these years that the first revolutionary cluster of steel technologies was introduced. The most famous was the Bessemer process for refining pig iron into steel, invented in England in 1856. This innovation allowed metallurgists to produce three to five tons of steel in just ten to twenty minutes, compared to roughly 24 h via the old puddling process (Landes 2003, p. 255). Bessemer steel was well suited for railway tracks, and it was this industry that it chiefly served. The second was the open-hearth furnace (OHF), created in 1864 by German and French engineers. Although slower than the Bessemer converter, the OHF could produce higher grade steel – required by industries like shipbuilding – while achieving great energy savings (Wengenroth 1994, pp. 25–30). By allowing for the mass production of cheap steel, these technologies together set the stage for steel to displace wrought iron as the premier material of late nineteenth and twentieth century capitalism.

However, the revolution was slow going. The new technologies had technical limitations that frustrated early licensees. For instance, the Bessemer converter could only be used with non-phosphoric iron ores, which were distributed unequally across the globe, or else it produced steel that was too brittle to mould (Wengenroth 1994, pp. 17–24). The OHF faced similar chemical hurdles. This would not be overcome until 1879, when the Gilchrist-Thomas process made it possible, using a Bessemer converter or OHF, to produce steel from more abundant phosphoric ores (Wengenroth 1994). Another major obstacle was the first Great Depression. The bursting of a speculative bubble centred on overzealous railway investments in 1873 revealed a global crisis of overaccumulation (Clarke

1988, pp. 165–8). With supply dwarfing demand, the industry witnessed a dramatic fall in prices that crashed profitability. As '21,000 miles of American railroads collapsed into bankruptcy', Hobsbawm (1988, p. 62) writes, 'almost half the blast-furnaces in the main iron-producing countries of the world stopped'. In the US, rail-producing steel mills were operating at one third of their capacity by early 1874 (Misa 1995, p. 31). While the depression dragged on until the 1890s, the fortunes of iron and steel revived in the late 1870s on the back of renewed railway building (Burn 1961, p. 73, Misa 1995, p. 16, 31). Yet the industry saw several more bouts of overcapacity before World War One, including slumps in the early-to-mid 1880s, early 1890s, and early 1900s (Burn 1961, pp. 77–94).

The pace of adoption of the new steelmaking innovations was conditioned by these overaccumulation crises, and the new technologies intensified such crises by enabling a tremendous growth of steel output. Bessemer and open-hearth steel continued to grow through the rhythm of these cycles. Nevertheless, for many firms, periods of depressed prices and profits encouraged the rationalisation of existing production processes, rather than major investments to employ the novel technologies at scale. As a German steel manager commented in 1877: 'Given the extraordinarily low sales prices it was, if one did not want to pack in the whole concern, only possible to drive production costs down and to limit losses as far as possible' (quoted in Wengenroth 1994, p. 62). Indeed, although Britain had made major advances in adopting Bessemer and open-hearth methods in the 1860s (Landes 2003, pp. 257–9), it was not until after the 1870s depression that 'American and German entrepreneurs began to make investments that fully utilised the cost advantages of the new technologies' (Chandler 1990, pp. 282–3). Steel output only overtook iron – its chief rival – in Britain after 1885, Germany in 1887, and France in 1894 (Landes 2003, p. 260). And in Japan, already among the world's most industrialised economies, the first Bessemer converter was installed in 1901 – almost half a century after its invention (Howe 1996, p. 249).

Once this technological revolution was in train, though, it transformed the global distribution of steel production, with jarring political effects. The Germans gained several advantages over the British after the 1870s, including their early embrace of the Gilchrist-Thomas method, their vertical integration and mechanisation, and their superior management structures (Chandler 1990, pp. 488–92). The US steel industry also surpassed Britain's in many of these areas, but above all else it achieved unprecedented scale and concentration. By 1900, Andrew Carnegie's three plants – combining Bessemer and open-hearth processes – could produce close to four million tons of steel a year (Warren 2001, p. 14). And Carnegie's was just one of many steel enterprises, large and small, that were merged to form the gargantuan US Steel Corporation in 1901 – the world's largest industrial company (Warren 2001, p. 7). British firms began ceding export markets to the foreign giants. Burn (1961, p. 94) puts it in distinctly martial terms: 'Competition could no longer be regarded as a series of frontier skirmishes: outlying provinces were the objects of massed invasion, and there were attacks on the capital'. The travails of British steelmaking were a stimulus to Joseph Chamberlain's early twentieth century Tariff Reform League, which called for protectionism and imperial preference against the prevailing Free Trade ideology (Clarke 1988, p. 191). Perceived foreign steel dumping was an important feature of this campaign, which in the years leading to 1914 included 'hostile depictions of "Herr Dumper"' and presented 'Anglo-German trade competition as a kind of war to the death' (Searle 2004, p. 516).

Even in the countries that most successfully adopted the new technological paradigm, the process was not without significant social upheaval. As suggested above, US steel plants employed the Bessemer, open-hearth, and Gilchrist-Thomas processes with awesome efficiency, with mechanisation advancing in leaps and bounds (Brody 1960, pp. 29–30). This upended existing industrial relations. The Amalgamated Association of Iron and Steel Workers was entrenched in certain key plants, like Carnegie's Homestead works, and carefully controlled its members' conditions of work through a mass of rules and regulations (Brody 1960, pp. 52–3). For the steel magnates, this was unacceptable. To fully exploit the productive potential of the new technological cluster, they required 'complete freedom from union interference' (Brody 1960, p. 52). The result was class war, in the most literal sense. In 1892, Homestead's management encircled the waterfront mill with a barbed wire fence, locked the union out, and shipped in Pinkerton detectives on barges to break the striking workers' picket (Brody 1960, p. 55). 'While the Pinkertons fired through gun slits in the armor plating of their barges', Montgomery (1987, p. 37) writes, 'the populace of Homestead hastily erected steel barricades of their own and assaulted the invaders with rifle fire, dynamite, flaming oil, cannon fire, and fireworks left over from the Fourth of July'.

Reinventing steel post-war

1914–45 were difficult years for steel as for the global economy generally. Steelmaking lurched from wartime mobilisation to the 'black decade' of overcapacity in the 1920s to the protectionism of the 1930s to wartime mobilisation again (Burn 1961, Chandler 1990). After the Second World War, the industry experienced an historically unparalleled recovery. Output was carried continually higher by the updraft of the Golden Age boom, with global steel production increasing six-fold from 1946 to 1974 (Hudson and Sadler 1989, p. 16). At the boom's outset, the US occupied the position of Britain in the mid-nineteenth century, boasting roughly 45 per cent of worldwide crude steel output in 1949 (Messerlin 1987, p. 114). The technical character of production had shifted too, without any epochal innovations. In the preceding decades, Bessemer steel had gone the way of iron before it and accounted for just 2.8 per cent of US steel production by 1956 (US Congress 1968, p. 733). In its place, the OHF predominated, given its energy efficiency and the superior quality of its product. US producers pushed open-hearth steelmaking to its efficiency limits: colossal integrated mills sprawled around increasingly bigger furnaces, manned by tens of thousands of employees, working day and night (Smil 2016, pp. 74, 98–9).

As the post-war boom gathered pace, the second revolutionary cluster of steel innovations became available. The Basic Oxygen Furnace (BOF) saw its first commercial application in Austria in 1952. The BOF perfected the Bessemer method by blowing pure oxygen through molten iron – a process that had become lucrative by the 1950s when the cheap production of pure oxygen was achieved (Smil 2016, pp. 99–101). The BOF constituted a giant leap in productivity. By the 1960s, two BOFs could substitute for at least eight OHFs while reducing the time of a production cycle from six to twelve hours down to just forty-five minutes (Herrigel 2010, p. 92). Continuous casting was similarly transformative. It allowed molten steel to be directly cast into various shapes and then rolled without the need for repeated cooling and reheating, resulting in large energy savings (Herrigel 2010, p. 91). This process was increasingly adopted in the steel sector from the 1950s onwards.

Yet like the Bessemer and open-hearth processes, diffusion was gradual and globally uneven. As Herrigel (2010) has shown, Japan and West Germany pioneered the mass adoption of BOFs and continuous casting in the 1950s and achieved economies of scale that surpassed even the American integrated works. By 1970, BOFs produced 95 per cent of Japanese steel[1] (D'Costa 1999, p. 111). US steelmakers, by contrast, were still constructing new OHFs in the 1950s, and in 1960 produced only 3.7 per cent of their steel with BOFs (D'Costa 1999, p. 38, 111). US firms were not ignorant of the new technologies' superiority. By the mid-twentieth century steelmaking was an extremely capital-intensive affair, requiring huge upfront investments that would only pay off after many years of continuous operation. To write off fleets of OHFs and the infrastructure that supported them, in order to make way for new technologies, was an unattractive proposition (D'Costa 1999, p. 38). It was only begrudgingly accepted by US firms when the drawn-out 1959 steel strike reduced output so much that cheap Japanese and German products began to penetrate the US market (D'Costa 1999, p. 41). Consequently, the US started to invest in earnest in the new innovation cluster in the 1960s (D'Costa 1999, p. 111).

The 1960s also saw the rise of 'minimills' in the US, which began to wrest market share away from integrated mills by achieving higher productivity and lower costs (D'Costa 1999, pp. 33, 140–68, Herrigel 2010, pp. 100–38). This was done through the downscaling of operations, disintegration of iron and steelmaking, and regressive reorganisation of labour relations. Crucially, minimills used electric arc furnaces (EAFs), which have lower capital costs and can respond more flexibly to changing demand conditions. EAFs produce 'secondary' steel by melting and purifying scrap steel, instead of creating 'primary' steel through the reduction of iron ore. They were introduced into the steel industry in 1901 and by the mid-1970s minimills made up almost a fifth of total US raw steel output, placing further pressure on the harried integrated mills to modernise or fail.[2]

Nevertheless, this post-war technological progress was soon impeded by the global economy's transition from prosperity to stagnation. The expansion of productive capacity across a range of sectors during the post-war boom had by the early 1970s culminated in a generalised crisis of over-accumulation (Clarke 1988, pp. 341–51). In steel, the downturn was deep and enduring. The tremendous output enabled by the new technological cluster, alongside continuing production by obsolete plant, combined to overwhelm steel demand and sink prices and profit rates (D'Costa 1999). In Europe, steel capacity utilisation dropped from 87 per cent in 1974 to 57 per cent in 1982, dragging profitability down with it (Hudson and Sadler 1989, pp. 30–2). The crisis persisted through the 1980s. By 1993, global steel output was less than 5 per cent higher than it had been in 1973 (Smil 2016, p. 66).

Given the bleak profitability outlook, firms were wary of making large investments in new technologies (D'Costa 1999, p. 16). The pace of US adoption slowed: the BOF share of total steel production grew just 14.7 per cent from 1975 to 1985, after rising by 54.9 per cent the decade prior (D'Costa 1999, p. 111). It took until 1992 for open-hearth steelmaking to be completely phased out in the US (Smil 2023, p. 16). Beyond the advanced capitalist nations, the pace of technological diffusion was slower still – excepting South Korea, which became a leading steel producer by the 1970s. This gradual technological adoption was conditioned by further cycles of recovery and crisis in steel production during the 1990s and early 2000s (Silva and de Carvalho 2017, pp. 17–18). China shuttered its last OHF in 2001, and Ukraine still produced 19 per cent of its crude steel this way in 2021 (Smil 2023, p. 16, WSA 2021a, p. 10).

Much like in late-nineteenth century Britain, the dimming of American steel hegemony ramified through the US political structure. From the late 1960s, US steel firms, in conjunction with the United Steel Workers of America, appealed to the state for protection against foreign competition. Their appeals resulted in a series of Voluntary Restraint Agreements, beginning in 1968, that sought to limit steel imports from Japan and Western Europe, and the introduction of a Trigger Price Mechanism in 1977 that set a minimum price for steel imports (D'Costa 1999, pp. 52–3). Rather than solving the problem of overproduction and overcapacity, such measures simply shifted it onto other nations (Hudson and Sadler 1989, p. 48). Steel protectionism continued through the Reagan and Bush Sr. administrations as part of an increasingly chauvinistic trade dispute with Japan.

These trade measures were not meant to substitute for restructuring but to facilitate it. By protecting US firms from outright extinction, the state granted them the breathing room to gradually liquidate underperforming assets and modernise/rationalize remaining plant. The results were no less brutal for being state guided: US steel employment fell from 521,000 in 1974 to 204,000 in 1990 (Herrigel 2010, p. 102). Restructuring elsewhere was similarly dramatic and politically directed. The European Economic Community responded to the overproduction crisis by pressing member states to undertake a managed reduction in capacity (Moraitis 2020). France's steel employment fell by more than 70 per cent from 1974 to 1990, and the UK's by close to 75 per cent (Herrigel 2010, p. 102). The '[u]nemployment statistics were almost anaesthetising, so great were they', one account observes (Mény and Wright 1987, p. 27). Because of their superior competitiveness, this traumatic process was somewhat delayed in Japan and (West) Germany. Nevertheless, Japan's steel employment fell by almost half in the period 1974–96, and Germany's declined by considerably more (Herrigel 2010, p. 102).

Technology, crisis, and restructuring

Taking stock of the history of technological development in steelmaking, it is possible to conceptually map the relationship between capitalist accumulation, technical change, and patterns of crisis and restructuring.

Technology and productivity

Changes in production are propelled by the 'coercive law of competition' (Marx 1976, p. 436). They take the form of continuous drips of efficiency gains, from bigger furnaces to the mechanisation of rolling, and once-a-century flash floods of technological revolution that quickly antiquate existing plant. The revolutionary innovations that stick are those that deliver tremendous leaps in labour productivity, allowing early adopters to secure higher profits. These innovations have generally led production to take place on a greater scale, requiring greater up-front investments, and thus often with a greater concentration of ownership.[3] This pattern is so familiar to modern industrial development that Marx (1976) termed it the 'general law of capitalist accumulation'.

Productivity and overaccumulation

The speed of technological adoption is set by various factors. As Perez (2010) argues, certain technical/infrastructural hurdles must be overcome for new innovation clusters to become generalised, such as the invention of the Gilchrist-Thomas process. Further, as each cluster is generally accompanied by an expanding scale of production, sunk investments in existing technology tend to pose a growing barrier to further technological revolutions.[4] This results in what Marxist scholars have identified as a gradual and globally 'stratified' form of technical change (Reuten 1991). Despite the proliferation of cutting-edge producers, many backwards firms reject the option of 'immediately liquidating their capital to restore the balance between supply and demand' (Clarke 1990, p. 455). They instead continue to produce until the possibility of squeezing further profits from their outmoded machinery is finally extinguished – a calculation that is often warped by state support for outmoded mills. The combined *over*accumulation of capital, consisting of plants of varying technological vintages, acts to ratchet up the general output level. Unless demand keeps pace with this heightened supply, which largely depends on the boom-and-bust dynamics of capitalism as a whole, this tends to drive the industry into crisis. Overaccumulation is expressed as overproduction and/or overcapacity. That is, the market is either inundated with product, leading to unsold inventory and declining prices, or firms dial back their capacity utilisation to match demand (Reuten 1991: 90). In both cases, the rate of profit falls, which dampens investment and thus slows the diffusion of the new innovation cluster (D'Costa 1999, p. 16). The industry faces a fork in the road: restructure or stagnate. In accordance with Marx's concept of capitalist development, then, technological change is both moulded by and generative of the industry's crisis tendencies and the crisis tendencies of the wider economy.

Overaccumulation and restructuring

Technological revolutions are not seamless transitions from a lower to a higher plane of industrial sophistication. They are violent reorderings of the geography, geopolitics, and relations of production (Massey 1995, Harvey 2006 , pp. 413–45). Internationally, new innovation clusters have often been adopted most successfully in emerging manufacturing powers, which places fierce competitive pressure on nations that rely upon older technologies, leading to calls for protectionism that can inflame international tensions (Hudson and Sadler 1989, D'Costa 1999, pp. 22–8). Eventually, however, technological diffusion forces obsolete producers to undergo painful restructuring or exit the field. Within the plant, the adoption of new technologies involves both a reorganisation of the labour process and a reduction in the amount of labour required to produce a given volume of product (Braverman 1974). All of this tends to inflame class struggle and risk the social peace. Out of fear of such social dislocation, as well as given the unique importance of steel for arms manufacturing, states regularly offer support to backwards firms, which in turn shapes the pace and form of technological diffusion.

As the next section shows, this conceptual framework is not only apt for retrospective analysis of past technology transformations, but provides an illuminating guide to the challenges of steel decarbonisation today.

Green steel: a third revolution?

Eliminating carbon emissions will require a third technological revolution in steelmaking. The mode of primary steel production that dominates today, namely the reduction of iron ore in coal-fired blast furnaces and conversion of iron into steel in BOFs (the BF-BOF route), must be replaced. There exist several potential technological pathways to achieve this, with varying degrees of feasibility.

Perhaps the most rational option, from a sustainability perspective, is to produce secondary steel with renewables-powered EAFs. This pathway chafes against the logic of capitalist development, however, because EAFs rely on recycled scrap steel, meaning that production may not be able to keep pace with the demands of an expansionary global capitalism (IEA 2020, p. 12). The least disruptive pathway, from the perspective of the status quo, involves outfitting current steel plants with carbon capture technologies. This approach is limited by the fact that carbon dioxide is released at many points during the steelmaking process, making it difficult to capture all emissions (Swalec and Grigsby-Schulte 2023, p. 9). Another possibility is direct electrification, such as the production of liquid metal from iron ore via molten oxide electrolysis – but this technology is at an early stage of development (Kim *et al.* 2022, pp. 16–17). The decarbonisation pathway that has perhaps inspired the most optimism among industry observers involves a combination of two techniques: the direct reduction of iron ore (DRI) using hydrogen that is itself produced by renewables-powered electrolysis, and the conversion of iron (and scrap steel) into steel in renewables-powered EAFs (IEA 2020).

Thus far, however, this green transformation has failed to materialise. Global steel production had a higher CO^2 emissions intensity and energy intensity in 2022 than in 2007 (WSA 2023, p. 4). This reflects the entrenched nature of BF-BOF steelmaking. According to one estimate, 62 per cent of worldwide crude steel capacity today uses BOFs, and just 29 per cent uses EAFs (Swalec and Grigsby-Schulte 2023, pp. 12–13). Of the new steel capacity that has been announced, 52 per cent follows the BF-BOF route and only 39 per cent the EAF route (Swalec and Grigsby-Schulte 2023, p. 18). Global steel decarbonisation, if it is occurring at all, is proceeding at a crawl. This is not simply because of the technical challenges of carbon-neutral metallurgy, significant though they are, but because of the dilemmas posed by the aforementioned dynamics of overaccumulation in steelmaking.

Big investments, low margins

A crucial obstacle to the green transformation of steel is the problem of sunk costs in existing plant. As discussed earlier, the historical trajectory of steelmaking has been towards larger scales of production and capital investment. A slab caster may cost USD$154 million, a hot roll mill USD$506 million – overall, the investments required to construct an integrated steel mill can run into the billions of US dollars (Rimini *et al.* 2020, p. 23). Once in operation, these fixed investments have long life cycles. A single blast furnace lasts for around 40 years and requires relining only every 25 years. In 2020 the global fleet of blast furnaces was just 13 years old on average (IEA 2020, pp. 12, 46–7). Unsurprisingly, firms are wary of abandoning such huge and long-lasting investments, or undertaking green retrofitting that adds to already high costs. 'For the average steel company producing, say, 5 million tons of steel per year', argues Morgan Stanley's Head of Europe Metals and Mining Research, decarbonisation could require 'approximately $6 billion in capital expenditures' (Morgan

Stanley 2023). Overall, the IEA (2020, p. 110) estimates that achieving steel industry sustainability will entail USD$1.39 trillion of cumulative investment from 2021 to 2050 in core process equipment.

Sunk costs would be an impediment to revolutionising steelmaking even in conditions of prosperity, as we saw with US producers' reluctance to scrap OHFs in the face of superior BOFs during the post-war Golden Age. Yet, in recent decades, steelmaking has been a volatile business. After gradually recovering from the doldrums of the 1980s, the industry found itself mired in crisis again in the late-1990s and early-2000s. As former Communist countries underwent economic collapse, their steel producers diverted output to foreign markets; a pattern that was replicated in East Asia following the 1997 financial crash and consequent evaporation of Asian steel demand. Surplus steel flooded the more buoyant European and US markets and the sector was pitched into crisis (Silva and de Carvalho 2017, pp. 17–18). The industry was saved in the mid-2000s by China's spectacular economic expansion, which saw its demand for steel grow by 16 per cent a year from 2000 to 2008, reversing previous price and profit trends (Humphreys 2010, p. 6). Global steelmaking capacity ballooned in response to these stimuli. New production was dominated by mammoth Chinese firms, with China manufacturing 36.4 per cent of the world's crude steel by 2007 (WSA 2008, p. 17). The global contraction in steel demand that followed the 2008 crisis put a stop to this boom and inaugurated yet another spell of overcapacity and depressed profitability (Silva and de Carvalho 2017, pp. 17–18).

Despite a partial and globally uneven recovery in the years that followed, by 2014 the sector was facing a profitability crisis that was 'much more pervasive' than the late-1990s slump, as global steel capacity towered over market demand (Silva and de Carvalho 2017, p. 11). It was estimated that by 2016–17 China's *excess* capacity was around 65 per cent larger than the entire crude steel output of the US (Lu 2017). China enacted significant capacity cuts in response to this downturn, yet global capacity began rising again in 2018 and by 2022 it had exceeded the previous 2014 peak (Nakamizu 2023, p. 7). The pandemic lockdowns led to the idling of great swathes of the global steel production apparatus. The post-pandemic recovery, much of it powered by infrastructure-oriented state stimuli, created a sharp rebound in steel demand that pushed up prices and profit rates in 2021. By 2022, however, demand began to weaken again and profitability along with it, exacerbated by supply chain disruptions (McKinsey 2023). Indeed, in 2022 global steel capacity outstripped actual crude steel production by 627.7 million metric tons (Nakamizu 2023, p. 13).

Several forecasts have pointed towards an 'unevenly distributed slowdown in global steel demand' in the decades to come, though this is necessarily speculative (IEA 2020, p. 59, McKinsey 2023). This may be driven by several factors, including the moderation of Chinese growth and the saturation of advanced economies' steel demand (McKinsey 2023). It could also be influenced by the ongoing stagnation of the global economy more generally, characterised by relatively weak investment and growth trends since the 1970s (Alami *et al.* 2023). In such demand conditions, a continuation of the repeated bouts of overaccumulation and low profitability is likely, unless the industry undergoes a dramatic capacity reduction. ArcelorMittal (2022, p. 24) explained in its 2022 Annual Report: the 'industry has historically suffered from structural overcapacity globally', which 'may continue in the future to weigh on the profitability of steel producers'.

As the Global Forum on Steel Excess Capacity puts it: 'The persisting situation of excess capacity and the resulting lower profitability margins for steel companies hinder the creation of an ecosystem that is needed to facilitate the green transition' (OECD 2022, p. 17). Without sufficient profits, companies 'are not in a favourable position to bear' the 'investments or increase in production costs' associated with green steelmaking, and thus 'excess capacity leads to a harder and more costly transition' (OECD 2021, p. 32). Indeed, in line with the steel industry's volatile profitability in recent decades, investment in general, not simply green investment, has stagnated: capital and R&D expenditure as a share of revenue was lower in 2022 than in 2003 (WSA 2023, p. 4). This dilemma is not new. Crises of overaccumulation are innate to capitalism and previous steel slumps have also postponed the widespread adoption of revolutionary technologies. This was the case with the delay imposed on the global spread of Bessemer and OHF processes by the 1870s depression and the slow diffusion of BOFs and continuous casting during the crisis of the 1970s and 1980s.

Yet there are important differences between past technological revolutions and today. Previous insurgent innovation clusters promised tremendous leaps in productivity and thus profitability for early adopters, and yet were still gradual in their spread. It is unclear, however, whether innovations like green-hydrogen-based DRI can deliver the same competitive advantages as these predecessors. If these innovations do deliver radically higher productivity, this will further contribute to patterns of overaccumulation in the sector, more urgently necessitating a painful restructuring process. If they do not deliver such massive productivity gains, which appears more likely, their adoption will be difficult to financially justify in the first place. And certainly these technologies will not be a feasible option for firms without a massive expansion in green hydrogen infrastructure that would lower hydrogen costs, in the same way that it took the development of the mass production of pure oxygen to facilitate broad adoption of BOFs (Hoffman *et al.* 2020).

The chief barrier to steel decarbonisation is therefore the following. Massive upfront investments and the large-scale scrapping of still-functional plant will be required to replace BF-BOF steelmaking with green alternatives – alternatives that may not offer eye-watering leaps in productivity. And the possibility that these green investments will yield even adequate profits is jeopardised by the cycles of overaccumulation that have characterised the industry since its nineteenth century birth.

What kind of transition?

A range of policy initiatives have been floated to overcome these formidable obstacles, some of which have begun to be rolled out (see ResponsibleSteel 2023). These include carbon pricing, sustainable steel investment criteria, state subsidies for green operational and/or capital expenditure, public-private financing initiatives, and instruments that offer green steelmakers premium prices for their output (Climate Bonds Initiative 2022, Graham *et al.* 2023). It is unclear whether such measures, even if fully implemented, would be sufficient to effect a comprehensive and timely decarbonisation of steel – in fact a growing literature critiques the 'derisking' logic that underpins many of these measures (Cooiman 2023). Yet, assuming that these policies were successful, the question remains as to what form this green shift might take. The concept of 'Just Transition' has entered mainstream discussions of industrial decarbonisation in recent years. The EU's Just Transition Platform, for instance, envisions a 'sustainable steel sector which provides good jobs, adds to the local economy, and supports local communities' (European Commission 2022, p. 10). If past revolutions in steelmaking are any guide to the future, however, the process of steel decarbonisation will not automatically align with principles of worker or community justice. Two key points are worth emphasising.

First, decarbonisation is unlikely to straightforwardly reinforce the hegemony of incumbent steel powers. In terms of steel production in general, the fastest capacity growth from 2016 to 2021 occurred in Algeria, Vietnam, Indonesia, Iran, Malaysia, and Pakistan (Nakamizu 2023, p. 16). India will also be a major growth centre in coming decades, with Indian steel production expected to quadruple between 2020 and 2050 (IEA 2020, p. 118). However, these countries may not necessarily be the first to dominate *green* metallurgy. The global distribution of zero-carbon steel capacity will be partly determined by the availability of cheap renewable electricity. The Middle East and North Africa region may potentially take a leading position in green ironmaking, given its already strong DRI sector combined with abundant solar resources, although this is far from certain (Basirat and Nicholas 2023, p. 5). This could signal a historic disintegration of iron and steel production, as regions rich in renewable energy export green iron to other steel production hubs (Basirat and Nicholas 2023). Decarbonisation can thus be expected to involve a significant geographical reallocation of iron and steel capacity.

Second, if steel decarbonisation is to align with the profit imperative, it will likely require a global wave of restructuring to shutter excess and outmoded capacity, similar to that which accompanied past technological revolutions (OECD 2021). Such restructuring would be unevenly distributed in space, with the heaviest burden falling on regions that lag in the adoption of green steel technologies (While and Eadson 2022). In any case, this would involve a reorganisation of labour relations and an intensification of class struggle. Given the slow progress of steel decarbonisation, the shape of this process has yet to come into focus. However, the 2024 announcement of Tata Steel's restructuring of its Port Talbot plant may foreshadow the larger changes to come: 2,800 jobs are to be eliminated, as the remaining blast furnaces are replaced by EAFs, with trade unions pledging to resist these changes (Davies 2024). The social dislocation and security concerns arising from a global reorganisation and restructuring of production could spark neo-mercantilist state interventions in a sector already marked by acrimonious trade disputes that increasingly revolve around green steel (Alami and Dixon 2023, Manak 2023). Such disputes would in turn shape the decarbonisation process.

Conclusion: beyond profit

In 1982, David Roderick, the CEO of US Steel, stated a basic fact about his business: 'our primary objective is not to make steel, but to make steel profitably' (Maranville 1989, p. 58). This insight – the centrality of 'the question of profitability' – has been increasingly emphasised by scholars writing on the political economy of climate change (Christophers 2024, p. 374). Yet while foregrounding profit is crucial for transcending the green neoclassical perspective, it is not a skeleton key that unlocks the secrets of decarbonisation. Instead, this article argued, it should serve as an entry point into a broader account of the intertwined dynamics of technological change, crisis and restructuring, and social struggle that animate capitalist development – and the manner in which these dynamics condition the possibility of a green transformation (Copley 2023; Alami *et al.* 2023; Keil and Steinberger 2024).

Indeed, as Roderick knew, speaking during the worst steel slump since the interwar period, the 'primary objective' of profit-making cannot always be met. This is because the imperative to accrue profits is self-undermining. To ensure their survival, firms introduce productivity-boosting technological advancements, the general result of which is the reoccurrence of crises of overaccumulation and dwindling profitability – followed by restructuring or prolonged stagnation. This article demonstrated that, since the nineteenth century, the steel industry has exemplified this cyclical pattern, as the introduction of new production technologies has been propelled and at the same time delayed by the forces of competition and crisis. These same forces are shaping the drive to decarbonise the industry today. Greening steelmaking, and capitalism more generally, means wrangling with this geographically-uneven, boom-and-bust logic and the political backlash that it stirs.

It is not inevitable that steel decarbonisation will mirror prior technological revolutions in the sector. Steel production need not continue to be organised as a capitalist enterprise at all. Of course, those struggling to subordinate steelmaking to social and environmental needs face an uphill battle against the arrayed forces of steel capital and states whose reproduction is tied to the profitability of capital in general. Nevertheless, steel has a rich history of working-class environmentalism upon which future struggles can build (Dewey 1998, Barca and Leonardi 2018). These bonds of solidarity will need to grow in geographical scope in line with the global character of climate change. Further, disarming the logic of competition, profit-seeking, and crisis that is restraining decarbonisation will require an ambition and militancy that surpasses the current steel unions' understandably defensive position. It would require steel workers to forge deliberative coordination mechanisms not only with environmentalist groups, but with steel end users too, such as workers in wind turbine plants, bringing the production and consumption of this metal under greater democratic direction and in line with planetary limits (see Special Issue: Rethinking Economic Planning in *Competition and Change*).

This would place steel workers and their collaborators in direct conflict with private property and thus with the forces of law and order – a situation that steel workers have found themselves in at various points in the industry's history (Brody 1960, Montgomery 1987). As the climate crisis worsens, and as capital continues to prove unable to deliver both environmental and social justice, the possibility of such radical confrontations will be raised again and again.

Notes

1. That is, non-electric arc furnace steel.
2. However, EAFs are unlike the revolutionary steel innovations discussed earlier in that they have not rendered past steelmaking processes obsolete, ultimately because they cannot make certain higher grades of (primary) steel required for sectors like the automobile industry.
3. Minimills are an exception, illustrating an important counter-tendency to this dynamic.
4. The adoption of BOFs exerted contradictory pressures on capital costs: BOFs were cheaper than OHFs, but they were increasingly installed as part of more massive integrated mills (D'Costa 1999, pp. 36–41).

Acknowledgements

I would like to thank Maria Eugenia Giraudo, Alexis Moraitis, Lorenzo Feltrin, and Thomas Da Costa Vieira for their helpful comments on earlier drafts of this paper. I would also like to thank the anonymous reviewers for their guidance.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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