THE GREEN SHIFT IN METALLURGY: A PATH TO SUSTAINABILITY OR ACCELERATED DEPLETION?

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Abstract

Decarbonization is essential – and it must begin immediately. As one of the leading global producers of CO_2, the metallurgical industry must contribute its share to mitigating the climate crisis. However, alongside the development and implementation of low- and zero-carbon technologies, we must ask a fundamental question: will the "green label" not merely create an illusion of sustainability? There is a real risk that under the banner of technological efficiency, total resource consumption will increase and industrial activity will shift toward a more sophisticated form of planetary destruction. This paper highlights the dangers of rebound effects, the neglect of planetary boundaries, and the emergence of "green" industry as a form of moral alibi. It also considers a broader context: the historical responsibility of industrialized nations, the imperative of climate justice, the geopolitical consequences of carbon policies, and the need for a systemic transformation. In conclusion, the paper calls on the academic community to actively engage in these debates, to ask uncomfortable questions, and to seek responsible answers.

Keywords: decarbonization, green steel, rebound effect, planetary boundaries, sustainable transformation

1. INTRODUCTION

The metallurgical industry is one of the largest producers of greenhouse gases, contributing approximately 7 to 9% of global CO_2 emissions [2]. Decarbonizing this sector is therefore a crucial part of the global effort to reduce CO_2 emissions. The development of low-emission technologies, such as hydrogen-based direct reduced iron (H-DRI), the increased use of electric arc furnaces (EAF), and carbon capture and storage (CCS), offers a technical pathway to reducing the carbon footprint [1]. Green steel is thus becoming a symbol of sustainable transformation [3].

Scientists have been pointing out the link between increased atmospheric CO_2 concentrations and climate change for more than a hundred years. A pioneer in this field was Swedish chemist Svante Arrhenius, who as early as 1896 hypothesized that the burning of fossil fuels could lead to planetary warming. Since the 1970s, a scientific consensus has been forming, which today confirms that the rise in greenhouse gases is altering the Earth's energy balance and accelerating global warming [7, 9].

The international community has also responded to these findings. UN climate conferences have been held annually since 1995, with major milestones including the Kyoto Protocol (1997), the Paris Agreement (2015), and the most recent commitments from the COP28 conference (2023). Countries are pledging to reduce emissions, develop sustainable technologies, and ensure a just transition. These commitments also affect the metallurgical sector—mainly due to its emissions and high energy demands [4,6].

The aim of this article is to critically assess whether technological decarbonization is sufficient as a response to the complex environmental crisis. We start from the premise that even with a significant reduction in emissions, a so-called rebound effect may occur—where increased production efficiency leads to expansion, and thus to greater extraction of natural resources [8]. Moreover, green technologies themselves require new materials, energy inputs, and extensive new infrastructure [1,3].

If decarbonization is not accompanied by a reduction in overall material demand, a fair distribution of environmental costs, and support for global equity, we risk achieving only the illusion of progress. The carbon footprint per unit of production may decline, but if total production and consumption continue to grow, the ecological burden will not be reduced—it will merely change in form and geographic distribution. Such a "green" transformation would be little more than a façade, beneath which the unsustainable exploitation of the planet continues [5,6,9].etc).

2. TECHNOLOGICAL DECARBONIZATION OF THE METALLURGICAL INDUSTRY

2.1. Current State and Technological Trends

Steel is currently produced using either the BF-BOF route (blast furnace + basic oxygen furnace), which is among the most emission-intensive technological pathways, or the EAF (electric arc furnace), which - when powered by renewable energy - enables a significant reduction in carbon footprint [1]. The most notable technological advancement in recent years is the development of hydrogen-based direct reduced iron (H-DRI), which replaces carbon as the reducing agent in the production of crude iron [1,3].

Many global metallurgical corporations are already actively developing their own decarbonization strategies (**Table 1**). For example Swedish company SSAB is collaborating with Vattenfall and LKAB on the HYBRIT project, which combines hydrogen-based iron reduction with EAF technology and aims to be commercially operational by 2030. ArcelorMittal is implementing its Smart Carbon and XCarb strategies, which integrate multiple approaches including CCUS, EAF, biomass, and hydrogen. Germany's Thyssenkrupp is launching the tkH2Steel project, utilizing H-DRI and electrolyzers. Tata Steel is testing the HIsarna technology, based on plasma reduction without the need for agglomeration. South Korea's POSCO is developing the HyREX project, which combines H-DRI and EAF. Chinese giant Baowu Steel is experimenting with hydrogen metallurgy as part of national climate plans [1,3].

Table 1 Overview of strategic approaches by selected major global steel producers.

Company	Project/Product	Technological Pathway	Implementation Status
SSAB (Sweden)	HYBRIT	H-DRI (hydrogen + EAF)	Pilot line, commercial by 2030
ArcelorMittal	Smart Carbon / XCarb	CCUS, EAF + bio-carbon, hydrogen	Various pilot projects, some in commercial phases
Thyssenkrupp	tkH2Steel	H-DRI, electrolyzers + EAF	Construction of pilot plant
Tata Steel	HIsarna	Plasma ore reduction without agglomeration	Advanced development, pilot phase
POSCO	HyREX / Hydrogen Steel	H-DRI, direct reduction + EAF	Pilot plant in Korea, commercial development planned
Baowu Steel	Hydrogen Metallurgy Program	Hydrogen reduction, CCS, electrification	Multiple pilot lines, in cooperation with the government

3. NEW INDUSTRIAL ECOSYSTEMS AND THE RISKS OF GROWTH UNDER THE GUISE OF SUSTAINABILITY

These initiatives may give the impression of a shift toward sustainability. However, a fundamental question arises: will only the carbon intensity per unit of product decrease, while the overall volume of production and consumption continues to grow? If technological efficiency improves but there is no systemic change in the scale of demand, consumption, and material flows, there is a risk that the overall environmental pressure will remain the same—or even increase [8].

This phenomenon is known as the Jevons paradox, or the rebound effect: while technological efficiency reduces costs or emissions per unit of production, it can simultaneously lead to increased consumption, as it makes the good or service more accessible and economically attractive [8,9]. In the context of steel, this would mean that cheaper and "greener" production could lead to even more widespread use—across construction, transportation, infrastructure, and industry.

If these technologies are implemented in developing and emerging countries—which is both desirable and necessary—global demand for steel and raw materials could increase dramatically. Moreover, the development of such technologies itself requires new types of raw materials, energy inputs, and large-scale infrastructure [1,6].

This brings us to the concept of planetary boundaries, which define a safe operating space for humanity on Earth. These boundaries encompass not only climate, but also land-use change, the nitrogen and phosphorus cycles, biodiversity, and chemical pollution [7]. If decarbonization is reduced solely to lowering CO_2 emissions, but is accompanied by growth in all other areas, we risk crossing other critical thresholds of ecological stability—bringing us closer to collapse scenarios in domains beyond CO_2 and climate change.

For these reasons, it is essential that technological transformation is not separated from value-based and societal transformation. It is not enough to produce in a "green" way—which today is often narrowly viewed as low in CO_2 emissions—we must also consider lower, more mindful, and more equitable consumption [5,6].

4. THE GLOBAL DIMENSION AND THE RISKS OF A "MORAL ALIBI"

4.1. Historical Responsibility and Global Asymmetry

While Europe and other Global North countries are adopting ambitious plans to decarbonize industry, their historical contribution to climate change cannot be overlooked. The industrialization of these nations took place over decades without environmental constraints, laying the foundation for their current prosperity—often at the expense of countries in the Global South [5,9]. Today, European steelmaking contributes roughly 1% to global emissions, but historically it has been among the largest CO_2 producers [2].

If these countries now expect developing nations to industrialize "cleanly" using more expensive and technologically demanding solutions, it presents an ethical dilemma. Many emerging economies—such as India (approx. 1.4 billion people) and China (also approx. 1.4 billion)—are striving to improve their standard of living, which naturally requires increased energy and material consumption. Since the beginning of the 21st century, China has experienced significant economic growth and has become the world's largest steel producer, primarily relying on the BF-BOF technology [2]. Despite investments in modernization, the carbon intensity of China's metallurgical sector remains high. India, which is rapidly industrializing, may become another major producer in the coming decades. While both countries are engaging in the development of low-carbon technologies, their absolute growth in steel demand and infrastructure will have a massive impact on global raw material use, energy consumption, and CO_2 emissions [1,2].

4.2. CBAM, ETS, and Questions of Climate Justice

An example of a potentially controversial policy is the EU's proposed carbon border tax—CBAM (Carbon Border Adjustment Mechanism), designed to prevent so-called carbon leakage and ensure a level playing field for both domestic and foreign producers [4]. While this mechanism supports Europe's climate ambitions, it may also disadvantage exporters from developing countries who lack equal access to low-carbon technologies, technical know-how, or investment capital [4,6].

If this approach is not accompanied by technology transfer, financial support, and climate reparations, there is a risk that the climate policies of the wealthy Global North will be perceived as a protectionist strategy rather than a gesture of solidarity and cooperation [5,6].

4.3. CBAM, ETS, and Questions of Climate Justice

In this context, “green steel” (steel produced using low-carbon or even carbon-free technologies) takes on a symbolic dimension: it is not only a technical product but also a moral statement. However, if decarbonization is not accompanied by a reduction in the overall volume of production and a redefinition of economic growth, it may amount to little more than a cosmetic adjustment of the existing system—rather than a fundamental transformation [5,8,9].

This phenomenon is known as the rebound effect: while technological efficiency reduces emissions per unit of production, growth in overall output can lead to an absolute increase in emissions [8]. Green technologies may thus become a moral alibi—a tool that soothes the collective conscience but does not truly halt the exploitation of natural resources; it merely makes that exploitation more “efficient” [5,8].

5. THE GLOBAL DIMENSION AND THE RISKS OF A “MORAL ALIBI”

The decarbonization of the metallurgical industry is technically feasible—we know how to reduce CO_2 emissions, we are familiar with the technologies that make it possible, and there is political will to implement them [1,3,4]. However, no technology is inherently “green.” Every technology requires resources, space, energy, and has both direct and indirect impacts [8]. So-called “green” solutions like H-DRI or EAF may have a lower carbon footprint, but they demand massive amounts of renewable energy, increased consumption of other natural resources, expanded infrastructure, and often introduce new types of geopolitical dependencies [1,3].

There is a risk that under the pretext of “clean” production, environmental pressure will not be eliminated—only transformed. The planet does not respond solely to CO_2 emissions, but also to mining, biodiversity loss, land use change, hydrological disruptions, and toxic waste [7,9]. Reducing the carbon footprint is therefore a necessary, but not sufficient, condition for sustainability.

This brings us to the need to think green—not just produce green. It means asking questions about the purpose and scale of consumption, about the fairness of access to resources, about responsibility for the consequences of production, and about redefining prosperity. It also means recognizing planetary boundaries as the fundamental framework within which all human activity must take place [7,9].

Green steel can become a symbol of a new era—but only if it is part of a deeper transformation of our economic and value systems: from growth to balance, from extraction to circularity, from efficiency to moderation. Otherwise, we risk merely softening the symptoms of a system that is fundamentally unsustainable through technological means [6,9].

6. CONCLUSION

The decarbonization of the metallurgical industry is essential—not only from a technological standpoint but also from an ethical one. As one of major emitters of greenhouse gases, the steel sector has a responsibility to contribute to mitigating climate change. Technological advances in iron and steel production—including H-DRI, EAF, and CCS—offer real opportunities to reduce emissions [1,3]. New ecosystems of collaboration and investment are emerging, signaling a strong commitment to transforming the industry [3,4].

However, this article highlights the risk that technological decarbonization may become a moral alibi: a means by which society legitimizes the continuation of resource-intensive production and consumption without addressing their overall scale and impact [5,6,8].

Even if CO_2 emissions were reduced to zero today, atmospheric concentrations would persist for centuries. The climate system has already triggered self-reinforcing processes—such as permafrost thawing, forest loss, and the decreasing ability of oceans to absorb carbon—that could lead to further irreversible increases in greenhouse gases [7,9]. This makes the issue extraordinarily urgent. It is not a long-term goal, but a crisis that demands immediate and decisive action.

Decarbonization alone—however necessary—cannot be the ultimate goal. It must be part of a broader transformation of the economic model, one that respects planetary boundaries [7,9], reduces overall consumption, and ensures fair access to resources [5,6]. Without this value-based and systemic reflection, green steel will remain merely a symbol of good intentions—without real impact on the sustainability of life on Earth.

The academic role in metallurgy is not limited to optimizing technologies. We must also be able to ask uncomfortable questions, reflect on consequences, and seek responsible answers to the issues we raise. It is not enough to simply follow current technological developments—we must ask where these developments may lead, what consequences they might bring, and what tensions and challenges they may create in terms of resources, social stability, climate security, and justice. We must begin thinking about, naming, and preparing for these "end scenarios" today—not just as co-creators of technology, but as co-responsible participants in the future of this planet. If we are indeed standing at a civilizational crossroads, then metallurgical science cannot remain on the sidelines. On the contrary—it must become an active part of the dialogue about our shared future.

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