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CARBON FOOTPRINT IN THE STEEL INDUSTRY: HURDLES AND OPTIONS TO MITIGATE

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***ABSTRACT*:**

The iron and steel industry is one of the largest industrial sources of greenhouse-gas emissions because conventional ironmaking depends on carbon-intensive reduction chemistry and high-temperature energy. This paper reviews the carbon footprint of major steelmaking routes and evaluates practical and emerging mitigation pathways, with particular attention to carbon capture, utilization and storage (CCUS), top-gas recycling, hydrogen-based direct reduction, electric arc furnaces (EAFs), molten oxide electrolysis (MOE), circular scrap use, and membrane-based separation of blast-furnace gas (BFG). The manuscript consolidates route-level emission characteristics and discusses the trade-offs among energy demand, carbon intensity, technology readiness, infrastructure, and cost. Recent evidence indicates that BF–BOF remains the dominant route globally, while scrap-EAF and hydrogen-DRI-EAF can substantially reduce emissions when electricity and hydrogen are low-carbon. Membrane separation, particularly zeolite-based membranes, is identified as a promising modular option for CO2/H2 separation, although defect control, durability, gas pretreatment, scale-up, and economics remain major barriers. The review concludes that no single technology is sufficient: near-term reductions should combine efficiency, scrap optimization, process integration, and CCUS where appropriate, while long-term deep decarbonization requires abundant low-carbon electricity, hydrogen, and commercially mature alternative ironmaking.

***Keywords**: Steel industry, carbon footprint, BF–BOF, electric arc furnace, hydrogen direct reduction, carbon capture, CCUS, blast-furnace gas, membrane separation, zeolite membrane, green steel.*

INTRODUCTION

Steel is fundamental to infrastructure, transportation, energy systems, manufacturing, and construction, but its production remains highly carbon intensive. Current global evidence places the sector at roughly 7–8% of anthropogenic greenhouse-gas emissions, with worldsteel reporting about 4.1 Gt CO2e in 2024 and an average footprint of 2.18 t CO2e per tonne of steel when Scopes 1–3 are considered. [1], [2]

The principal reason is the dominance of the blast furnace–basic oxygen furnace (BF–BOF) route, in which carbon is simultaneously an energy source and a chemical reductant. The BF–BOF route accounts for about 70% of global production, while scrap-based EAF production has a substantially lower direct carbon intensity when supplied with low-emission electricity. [2], [3], [4]

Decarbonization therefore requires a portfolio approach. Short-term options include energy efficiency, waste-heat recovery, higher scrap utilization, process integration, and carbon capture. Longer-term options include hydrogen direct reduction (H2-DRI), electrified ironmaking, and other electrochemical routes. [5], [6], [7]

OBJECTIVES

• Quantify and compare the carbon intensity of major steelmaking routes.
• Identify the dominant sources of emissions across the steel production cycle.
• Review CCUS, top-gas recycling, membrane separation, hydrogen reduction, and electrified ironmaking as mitigation options.
• Assess technical, energy, infrastructure, and economic barriers to large-scale deployment.

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• Outline a practical pathway toward low-carbon and near-zero-emission steel.

CARBON FOOTPRINT OF STEELMAKING

The carbon footprint of steel depends on the production route, raw-material mix, fuel and reductant, electricity source, plant efficiency, and system boundary. Ore-based steelmaking carries most of the emissions burden because oxygen must be removed from iron ore, whereas scrap-EAF avoids the primary ore-reduction step. [1], [3], [4]

Route	Main process	Indicative CO2 intensity (t CO2/t steel)
BF–BOF	Ore-based integrated route	~1.8–2.3
Scrap-EAF	Melting recycled steel	~0.3–0.7
NG-DRI–EAF	Natural-gas direct reduction + EAF	~1.0–1.4
H2-DRI–EAF	Hydrogen direct reduction + EAF	Potentially near-zero at process level; system footprint depends on H2/electricity

TABLE I. REPRESENTATIVE CARBON-INTENSITY RANGES OF MAJOR STEELMAKING ROUTES. Values are indicative literature ranges; boundaries and electricity assumptions differ among studies.

A. BF–BOF ROUTE

In the BF, iron oxide is reduced using carbon monoxide and hydrogen generated from coke, coal, and injected fuels. A simplified overall representation is $Fe_2O_3 + 3C \rightarrow 2Fe + 3CO$, followed by oxidation reactions that ultimately form CO_2. The BF is the principal emission source in an integrated works, with additional emissions from coking, sintering, pellet preparation, and downstream steelmaking. [3], [8]

Because BF–BOF emissions are partly process emissions rather than only combustion emissions, efficiency improvements alone cannot deliver deep decarbonization. Carbon capture, top-gas recycling, increased scrap use, alternative reductants, and eventual replacement of the reduction step are therefore required for very large reductions. [8], [9], [14]

B. SCRAP-EAF ROUTE

EAF steelmaking melts scrap using electricity and therefore avoids most primary iron reduction. Its footprint is strongly dependent on the carbon intensity of electricity, scrap availability, and the need for virgin iron units such as DRI or pig iron. System-level analyses identify scrap reuse and efficiency as among the least-cost early decarbonization measures. [4], [5], [7]

A high-recycled-content EAF supplied by renewable electricity can therefore provide a low-carbon route, but scrap supply and quality constrain how much global steel demand can be met by secondary production.

C. DRI–EAF ROUTES

Natural-gas DRI reduces iron ore without a conventional blast furnace and can substantially lower emissions compared with coal-based BF–BOF. The deeper pathway is H2-DRI, where hydrogen replaces carbon as the reductant: $Fe_2O_3 + 3H_2 \rightarrow 2Fe + 3H_2O$. The process is attractive only when hydrogen and electricity are produced with sufficiently low lifecycle emissions. [6], [7], [17]

The feasibility of hydrogen reduction has been demonstrated at pilot scale. The HYBRIT initiative reported hydrogen-reduced sponge iron in 2021 and subsequently produced fossil-free steel, establishing an important proof of concept for hydrogen-based ironmaking. [20]

PRIMARY SOURCES OF EMISSIONS

Chemical reduction: carbon-bearing reductants in BF ironmaking generate process CO_2. [3], [8]
Energy consumption: high-temperature furnaces, coking, sintering, reheating, and auxiliary systems require substantial energy. [4], [5]

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Electricity: EAF and hydrogen production can shift emissions from Scope 1 to Scope 2 or upstream Scope 3 depending on the power source. [3], [17]

Raw materials and logistics: ore preparation, coal/coke production, and transportation contribute additional lifecycle emissions. [1], [6]

GLOBAL AND INDIAN CONTEXT

Steel emissions remain broadly stable at a global scale, and the transition is not yet aligned with a net-zero trajectory. The IEA reports that BF–BOF remains dominant and that the pipeline of near-zero-emission capacity is still small relative to global production. [2]

India faces a particularly important transition because steel demand is expanding while new capacity can lock in coal-based production for decades. Recent modelling finds that strategic investment in hydrogen-ready direct-reduction plants can avoid substantial future emissions in India, highlighting the importance of technology choice at the investment stage. [18], [19]

The literature also emphasizes that decarbonization is not purely a technology problem. Financing, infrastructure, industrial coordination, electricity availability, policy design, and market demand for low-carbon products all influence deployment. [6], [18], [19]

CARBON CAPTURE, UTILIZATION AND STORAGE

CCUS is particularly relevant for existing BF–BOF assets because a large fraction of their emissions arises from concentrated process and off-gas streams. A systematic review of 188 studies found that chemical absorption, physical adsorption, oxy-blast-furnace concepts, calcium looping, and membrane separation are among the principal pathways being investigated. [8]

Conventional amine scrubbing can achieve high CO2 removal but requires significant regeneration energy and can suffer from solvent degradation, corrosion, and impurity sensitivity. Cryogenic separation is capable of high-purity CO2 but is energy intensive. Pressure-swing adsorption (PSA) can be effective where pressure and gas composition are favourable. [8], [9], [14]

For existing blast furnaces, top-gas recycling can recover CO and H2 after CO2 removal and return these reducing gases to the furnace. This can reduce the need for fresh carbon and improve resource efficiency, but the process requires substantial gas conditioning, oxygen supply, capture equipment, and integrated process control. [8], [10]

MEMBRANE-BASED CO2 SEPARATION

Membrane separation offers a compact and potentially energy-efficient alternative to some thermally driven separation processes. Reviews of steel-sector gas separation identify membranes as promising for moderate-purity CO2 recovery and for H2 recovery from steelworks gases, while also noting challenges associated with multicomponent gas feeds and impurities. [9], [11]

For BFG treatment, the gas must first be cooled and cleaned to remove dust and other contaminants. A membrane unit can then be arranged as a single- or multi-stage process, with recycle and compression used to achieve the required recovery and purity. [11]

Zeolite membranes are particularly attractive because of their defined microporous structures and high thermal and chemical stability. SAPO-34 has been investigated extensively for CO2 and H2 separations; reported studies demonstrate high CO2 permeance/selectivity and improved H2 selectivity after suitable membrane modification. [12], [13], [14]

The principal engineering challenge is the permeability–selectivity trade-off together with defect formation. Large-area, thin, defect-minimized membranes must maintain performance under pressure, temperature, water vapour, CO, CO2, and acidic impurities. These issues become more important during scale-up from laboratory coupons to industrial modules. [12], [13]

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PROPOSED MEMBRANE-BASED SYSTEM

A practical BFG membrane system should include: (1) dust removal, (2) wet or dry gas cleaning, (3) cooling and moisture management, (4) compression to the membrane feed pressure, (5) a selective membrane stage, (6) recycle of unseparated reducing gases, and (7) CO2 compression for utilization or storage.

Stage	Function	Key design issue
Pretreatment	Remove dust, water, acid gases	Protect membrane
Compression	Provide driving force	Energy penalty
Membrane stage	Separate CO2/H2/CO/N2	Selectivity and permeance
Recycle	Return CO/H2-rich stream	Process integration
CO2 handling	Utilization or storage	Purity, compression and logistics

TABLE II. CONCEPTUAL CONFIGURATION OF A MEMBRANE-BASED BFG CO2-SEPARATION SYSTEM.

Recent studies show that BFG valorization can combine capture with conversion to fuels or chemicals, but the additional hydrogen and energy requirements can shift environmental burdens to other parts of the system. Consequently, membrane separation should be evaluated using integrated techno-economic and life-cycle assessment rather than membrane performance alone. [15], [16]

HYDROGEN DIRECT REDUCTION AND GREEN STEEL

H2-DRI replaces the carbon-based reduction chemistry of the BF with hydrogen. Hydrogen is generated by electrolysis, supplied to a shaft furnace, and reacts with iron oxide to produce DRI and water vapour. The DRI is subsequently melted in an EAF. The route can deliver very low process emissions when powered by low-carbon electricity. [6], [7], [17]

Pilot-scale industrial experience has already demonstrated hydrogen-reduced sponge iron and steel. However, large-scale deployment requires high-grade iron ore, very large quantities of low-carbon electricity, hydrogen production and storage infrastructure, and substantial capital investment. [2], [4], [20]

Aspect	BF–BOF	H2-DRI–EAF	MOE
Reductant	Coke/coal	Hydrogen	Electricity
Main product of reduction	CO/CO2	H2O	O2
Primary energy carrier	Fossil fuels	Low-carbon electricity + H2	Low-carbon electricity
Maturity	Commercial	Pilot/early commercial scale	Pilot/early commercial scale
Main constraint	CO2 process emissions	H2, electricity and ore quality	Electricity, materials and scale-up

TABLE III. QUALITATIVE COMPARISON OF POST-COAL IRONMAKING PATHWAYS.

MOLTEN OXIDE ELECTROLYSIS

Molten oxide electrolysis is an electrochemical route in which iron oxide is reduced in a high-temperature molten electrolyte. It has the potential to bypass coke, conventional reduction furnaces, and hydrogen production, but it remains less mature than H2-DRI and faces challenges involving electrode durability, materials compatibility, electricity demand, and industrial scale-up. [4], [7], [20]

The technology is therefore best considered a longer-term pathway rather than a near-term universal replacement for existing BF–BOF capacity.

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CIRCULARITY, SCRAP AND PROCESS EFFICIENCY

Increasing scrap use is one of the most immediate ways to reduce primary iron production. EAF recycling can avoid ore reduction and therefore eliminate a large portion of the upstream carbon footprint. However, scrap availability, contamination, residual elements, collection systems, and electricity supply constrain the global potential. [4], [5], [7]

For existing integrated plants, energy efficiency, waste-heat recovery, top-gas recovery, process optimization, and improved raw-material preparation can provide early emissions reductions while deeper technologies are developed. [5], [8]

TECHNO-ECONOMIC AND IMPLEMENTATION HURDLES

Barrier	Impact on deployment	Priority response
Green electricity	Raises operating cost and limits H2 production	Renewable generation, grid expansion, long-term PPAs
Hydrogen cost	Dominates H2-DRI economics	Electrolyzer scale, storage, transport and low-cost power
Iron-ore quality	H2-DRI favours high-grade feed	Ore beneficiation, agglomeration and flexible reduction
Capital cost	New plants require high upfront investment	Blended finance, guarantees and policy support
CCUS infrastructure	Capture alone does not solve transport/storage	Shared CO2 hubs and standardized infrastructure
Membrane scale-up	Defects and durability reduce performance	Thin-film fabrication and module engineering
Market demand	Low-carbon steel may carry a premium	Green procurement and product standards

TABLE IV. PRINCIPAL DEPLOYMENT BARRIERS AND RESPONSES.

Recent global modelling indicates that the least-cost pathway differs by plant and region. Efficiency and scrap reuse are often favourable before 2030, while hydrogen reduction, carbon capture, and other deep-decarbonization technologies become increasingly important later. This reinforces the need for plant-specific transition plans rather than a single technology prescription. [5], [18]

DISCUSSION

The review indicates three complementary horizons. First, existing plants should pursue efficiency, material optimization, gas recovery, and selective CCUS. Second, new primary capacity should avoid long-lived coal lock-in by considering hydrogen-ready DRI and low-carbon electricity. Third, advanced technologies such as MOE and advanced membranes should be developed in parallel to broaden the future technology portfolio. [2], [5], [18] Membrane technology has a particularly useful role where gas separation can be integrated with top-gas recycling or CO2 utilization. Its advantages—compact equipment, modularity, and potentially lower thermal energy demand—must be balanced against compression work, pretreatment requirements, selectivity/recovery trade-offs, and module lifetime. [9], [11], [12]

No single route is universally optimal. The appropriate solution depends on existing assets, scrap availability, iron-ore quality, renewable-resource availability, hydrogen cost, CO2 infrastructure, and policy conditions. A robust transition should therefore combine technology portfolios with lifecycle assessment and plant-level techno-economic analysis. [3], [4], [6]

RECOMMENDED DECARBONIZATION ROADMAP

• 2026–2030: maximize energy efficiency, scrap use, waste-heat recovery, process integration, and low-cost emissions monitoring; identify capture-ready streams.

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• 2026–2035: deploy demonstration and early commercial H2-DRI–EAF projects in regions with low-carbon electricity and suitable iron ore; develop shared hydrogen and CO2 infrastructure.
• 2030–2040: scale CCUS for suitable existing BF–BOF assets, expand low-carbon EAF capacity, and industrialize membrane-based gas separation where techno-economic assessment is favourable.
• Beyond 2040: progressively retire unabated coal-based primary ironmaking and expand hydrogen/electrochemical routes as their costs and material constraints improve.

CONCLUSION

Steel decarbonization is technically possible but requires coordinated changes in reduction chemistry, energy supply, materials management, gas separation, and industrial infrastructure. BF–BOF remains the major source of steel-sector emissions, making efficiency and CCUS important for existing assets, while scrap-EAF and H2-DRI–EAF offer lower-carbon production routes when supported by low-carbon electricity. Membrane separation, especially zeolite-based membranes, offers a promising route for modular CO2/H2 management in BFG systems but requires continued research on defect control, durability, impurity tolerance, module scale-up, and integrated economics. Emerging electrochemical routes such as MOE may provide additional long-term options. The most credible pathway is therefore a staged portfolio that combines immediate efficiency and circularity measures with deployment of H2-DRI, CCUS, advanced separation, and electrification. [1], [2], [3], [4], [5], [7], [8], [9]

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