GREEN STEEL –
Viable Pathway or Costly Mirage?

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INTRODUCTION

The rise and fall civilizations shows that human mastery of metals and metallurgy have repeatedly served as technological inflection points. While the Stone Age relied on stone, bone, and wood, the Bronze Age (ca. 3300–1200 BCE) introduced copper–tin alloys that enabled durable tools, weapons, and trade goods, underpinning the first urban civilizations in Mesopotamia, Egypt, and the Indus Valley.[1] The subsequent Iron Age, beginning around 1200 BCE, dramatically lowered entry barriers because iron ores are widely distributed. Wrought iron and, later, deliberate steel-making techniques (e.g., the Wootz process in India) multiplied agricultural productivity, military reach, and construction scale. The 19th-century breakthroughs, such as the Bessemer Converter (1856) and eventually the integrated mill, dropped steel prices by more than 80% in real terms and launched the modern industrial era.[11]

The global steel industry has become the linchpin of modern infrastructure and economic activity. Due to its high production energy intensity, it currently accounts for 7 – 9% of human CO_2 emissions, which is comparable in scale to the total CO_2 emissions from global cement production. In 2024 conventional steel-making released approximately 4.1 billion tonnes of CO_2 equivalent.[2] These figures place steel among the harder-to-abate sectors as some governments and companies pursue long-term decarbonization objectives.

The dominant production route remains the blast furnace + basic oxygen furnace (BF-BOF) process, which relies on *metallurgical coke* to reduce iron oxide (e.g., Fe_2O_3) into what is called pig iron. The core chemistry is governed by the exothermic mass action relationship in the reduction zone:

$$FE_2O_3 + 3CO \rightleftharpoons 2FE + 3CO_2 \quad \Delta H^\circ_{298K} = -230 \text{ MJ PER TONNE FE}$$

Carbon monoxide (CO), generated in situ from coke via the Boudouard reaction ($C + CO_2 \rightleftharpoons 2CO$), performs the actual oxygen removal (aka iron oxide reduction). Equilibrium favors reduction above ~900 °C, and precise control of gas composition and temperature is essential for efficient iron yield and low impurity carry-over.[3]

Metallurgical coals are defined by low-to-medium volatile matter (usually 15–32 wt%), strong caking properties, low sulfur (<1 wt%), low phosphorus (<0.05 wt%), and ash content targeted below 10 wt% after beneficiation (i.e., impurities extraction).[5] These properties enable the coal to soften, swell, and re-solidify into a coherent, high-strength coke when heated in the absence of air.

High-quality metallurgical coal is first crushed and washed in cyclones or jig plants to remove inorganic sulfur, ash-forming minerals, and rock. Ash content must typically be reduced below 9–10 wt% to avoid excessive slag volume and refractory wear in the blast furnace. The cleaned coal is then charged into coke ovens and heated to 1,000–1,200 °C in the absence of air. Volatile hydrocarbons are driven off, leaving a strong, porous carbonaceous residue with 88–92 wt% fixed carbon.

This unique dependence on a narrowly defined subset of coal deposits underscores its strategic importance, where metallurgical coal has recently been designated a critical mineral. On November 7, 2025, the U.S. Department of the Interior finalized its 2025 Critical Minerals List, adding metallurgical coal alongside copper and uranium.[8] The decision, directed by Executive Order 14261 (April 8, 2025), reflects assessments that domestic steel production, which is vital for infrastructure, defense, and emerging industries, faces supply-chain risks from concentrated global reserves and recent export disruptions. The designation unlocks permitting fast-tracks, funding eligibility, and procurement preferences, reinforcing near-term production capacity while alternative iron oxide reduction technologies mature.[9]

Today, annual crude steel production exceeds 1.9 billion tonnes.[12] Affordable steel is woven into virtually every facet of contemporary life. Developing economies depend on it for basic infrastructure, while advanced economies rely on high-performance grades for aerospace and power generation hardware.

This white paper asks a straightforward but consequential question:

Is so-called green steel, defined here as hydrogen-based direct reduction of iron (H_2-DRI), followed by melting in renewable-powered electric arc furnaces (EAF), a viable route to large-scale low-carbon primary steel production, or does its promise rest primarily on demonstration projects, policy momentum, and naive optimism?

The analysis is scoped to the H_2-DRI + EAF pathway, currently the most discussed alternative to the coke fired blast furnace. In this route, green H_2 replaces CO as the reducing agent, producing H_2O instead of CO_2, and electricity supplies the melting energy. Pilot and demonstration plants have proved technical feasibility at modest scale.[14] Yet scaling to tens or hundreds of millions of tonnes per year introduces new variables: H_2 and renewable electricity availability, capital intensity, operating cost differentials, supply-chain reconfiguration, and trade dynamics.

II. THE PROMISE OF GREEN STEEL: A TECHNICAL PRIMER

Traditional blast furnace + basic oxygen furnace (BF-BOF) routes rely on metallurgical coal both as a chemical reductant and energy source, releasing roughly 2.0–2.3 tons of CO_2 per ton of crude steel produced. Green steel produced via hydrogen-based direct reduction of iron ore (H_2-DRI) followed by melting in an electric arc furnace (EAF) powered by renewable electricity has emerged as a potential, yet hotly debated decarbonization pathway over the past decade. When both the hydrogen and the electricity are sourced from low emitting sources such as wind, solar PV, hydroelectric and nuclear, life-cycle emissions can fall by up to 95% compared to the conventional route.[16]

In the classic blast furnace, coke reacts with iron oxide to form pig iron and CO_2. In H_2-DRI, high-purity H_2 performs the same oxygen-removal role. The core chemistry is governed by the endothermic mass action relationship in the reduction zone:

$$H_2 + FE_2O_3 \rightarrow 2FE + 3H_2O \qquad \Delta H^\circ_{298K} = +900 \text{ MJ PER TONNE FE}$$

The large endothermic reaction enthalpy requires an applied external heat source to drive the H_2-DRI reaction. This is opposite to the BF-BOF process, which due to its exothermic nature, is almost always paired with a superheated steam cogeneration step and used to produce electricity.

The only by-product of the H_2-DRI reaction is water vapor and the resulting product, DRI or "sponge iron", is continuously fed into an EAF along with recycled scrap. Modern EAFs already achieve 70 – 100% scrap-based production in some regions. Pairing them with virgin H_2-DRI allows steelmakers to maintain metallurgical quality while eliminating nearly all process emissions.[17]

The viability of this nascent supply chain hinges on the rapid scale-up of green hydrogen production via water electrolysis. Electrolyzer capital costs have fallen dramatically, from roughly $1,000–1,200/kW in 2020 to $500–700/kW in 2024, with industry road-maps projecting $300–400/kW by 2030 at gigawatt-scale manufacturing.[23] BloombergNEF's 2024 Hydrogen Economy Outlook claims that levelized cost of hydrogen from solar-rich regions could or may drop below $1.5/kg by 2030, making H_2-DRI competitive with BF-BOF even before carbon pricing is fully factored in.[24]

The remaining barriers are economic and infrastructural, which specifically are: securing multi-gigawatt renewable power purchase agreements (a), building hydrogen pipelines or dedicated electrolyzer clusters near mines and steelworks (b), and managing the higher capital and energy intensity (c) of this alternative route.

III. THE ILLUSION EXPOSED: TECHNICAL AND ECONOMIC HURDLES

The iron and steel industry's decarbonization via hydrogen-based direct reduction (H_2-DRI) followed by electric arc furnace (EAF) melting is widely presented as the cornerstone of "green steel." Yet a rigorous examination reveals a far more precarious pathway than policy documents and corporate net-zero pledges typically admit. Scaling H_2-DRI+EAF to displace even a fraction of the world's 1.9 billion tonnes of annual crude steel production would require energy inputs, mineral supply chains, and grid transformations that are currently unrealistic without sustained multi-trillion-dollar interventions.

HYDROGEN'S ENDURING COST PENALTY

Green hydrogen produced by electrolysis currently costs $3–6/kg ($21 – $42/GJ) in most markets, with the most optimistic 2030 forecasts still above $2/kg ($14/GJ) in sun-rich regions.[26] Grey hydrogen from steam methane reforming (SMR) remains well below $2/kg ($14/GJ), and in some gas-rich jurisdictions falls to $1.2 – $1.5/kg ($8.5 – $10.7/GJ).[27] By comparison, premium hard coking coal traded at approximately $191/tonne in late 2025, is worth $9.55/GJ or $1.3/kg as a reductant.[29] Natural gas used in existing gas-based DRI plants costs roughly $0.05–$0.1/kg ($1– $2/GJ) on an energy-equivalent basis.[30] Electrolysis consumes 50–60 kWh per kg of H_2 produced, pushing the electricity bill alone to $150–300 per tonne of DRI when power costs $50/MWh.[28]

THERMODYNAMIC EFFICIENCY AND EROEI

Two metrics called *Thermal Efficiency* (TE, process-level) and *Energy Return on Energy Invested* (ERoEI, system-level sustainability) are introduced to compare the performance of green and grey H_2-DRI + EAF steel versus by conventional BF-BOF steel production. First, some basic definitions are in order.

1. A high TE implies less energy is lost as wasted heat and more useful energy (i.e., chemical, electrical) is delivered to society by a given conversion process. In the case of steel production, this useful energy is chemically stored in reduced iron and or includes waste heat recovery if applicable.
2. ERoEI is a *cradle-to-grave* measure of the useful energy produced over the life-cycle of a conversion facility relative to the amount of energy invested in creating and maintaining the energy conversion infrastructure over is life-span. ERoEI does not factor in energy consumption (e.g., electricity consumed by an electrolysis unit) and is analogous to productivity. When ERoEI drops below 3 : 1, it indicates that the process may not produce enough useful energy over its lifetime to limit energy inflation.

Table 1 compares both the TE and ERoEI of steel produced using the coke BF-BOF process versus H_2-DRI + EAF processes fed by either grey (SMR) and green (electrolysis) hydrogen. Note that grey hydrogen is produced using natural gas in an SMR, and the assumption is there is no carbon capture sequestration. Additionally, as both the coke BF-BOF and grey H_2-DRI + EAF processes produce high temperature gas streams, the TE calculations assume there is steam generation through waste heat recovery, which improves overall TE.

Table 1. Thermal Efficiency and Energy Return on Energy Invested (ERoEI) for differing modes of steel production.

Metric	Coke BF-BOF	Grey H_2-DRI + EAF	Green H_2-DRI + EAF
Thermal Efficiency (%)	40 to 45	50 to 65	58 to 65
ERoEI	20 : 1 to 80 : 1	4 : 1 to 8 : 1	0.5 : 1 to 2 : 1

COKE BF-BOF AND GREY H_2-DRI + EAF INCLUDE WASTE HEAT RECOVERY.

The application of ERoEI in the context of these three steel production processes is intended to be specific to the associated energy conversion infrastructure alone and not the steel production facilities. For example, the life cycle analysis (LCA) done for the coke BF-BOF extends from the mine to the steel plant, while for the green or grey H_2-DRI + EAF process, the LCA is focused on the unit processes associated with power generation (green), hydrogen production and storage.

The much higher ERoEI of the infrastructure feeding the coke BF-BOF process is noteworthy. This demonstrates that on a craddle-to-grave basis, the BF-BOF's coke related infrastructure produces 20x to 80x times more energy than was used in building and maintaining this portion of the BF-BOF facility over its life-span. Conversely, the ERoEI of the green H_2-DRI + EAF process's energy infrastructure is so low, that on average, it is barely break-even over its lifetime. This should not be surprising, given the intermittency of wind and solar PV generation and the high steel use intensity of capturing highly diffuse energy sources, act to reduce the ERoEI ratio over the relatively short life-span of this infrastructure. These are physics fundamentals and not economics; therefore, no economies of scale or manufacturing efficiencies can change these metrics.

The implications are profound and suggest that a coke BF-BOF process will produce steel in great excess relative to the steel used in powering its production over its life-span, whereas the very opposite is true for a green H_2-DRI + EAF process. Thus, it can be expected that the whole scale adoption of green steel production will have an inflationary impact on steel prices.

Finally, the lower TE values reported for the coke BF-BOF process, is largely due to the production of slag or the higher molten impurities fraction that functions as a source of sensible heat loss that is not found in the grey or green H_2-DRI + EAF process's.

RENEWABLE POWER AND GRID BASE-LOAD CONSTRAINTS

A modern EAF melting DRI, using scrap steel consumes 400–600 kWh of electricity per tonne of steel, but the upstream electrolysis step in green hydrogen production dominates the electricity demand, where approximately 3,000–3,500 kWh per tonne of steel when 55 kg of H_2 are required to reduce a tonne of iron oxide.[35] Multi-billion-dollar green steel plants are designed for 2 – 5 M tonne/year and demand true 24/7 base-load power. Intermittent wind and solar cannot supply this without either (a) massive overbuild plus gigawatt-hour-scale battery or pumped-hydro storage, or (b) dispatchable hydroelectric or nuclear firming capacity.

A fundamental head-wind for full scale adoption of intermittent power generation is increasing grid instability that comes with a greater dependence on inverter based generation resources. Regions with limited expandable hydroelectricity, such as most of Europe outside Scandinavia, the U.S. Midwest, and Japan, face escalating grid-stability risks as inverter-based generation exceeds 30–40% of instantaneous supply.[36] This points to the need to maintain significant capacity of dispatchable synchronous generation assets connected to the grid in order to provide frequency and voltage control. Whether this need is ultimately going to be satisfied by nuclear or increased hydroelectric capacity, only time will tell.

The ultimate head wind acting to limit wide scale adoption of green steel production is the sheer capacity of new emissions free generation required for these new facilities. If it takes approximately 4 MWh of electricity to produce a tonne of green steel, it will require at least 5,200 TWh to replace the 1.3-1.4 billion tonnes of BF-BOF per year of steel production. Bear in mind that the United States produced 4200 TWH of electricity in 2023.

SCRAP SUPPLY CEILING

Global steel scrap availability is physically capped at 600 – 650 M tonne/year in 2025 and will grow only gradually as today's new steel enters the use phase and eventually returns as end-of-life material two to five decades later.[39] This hard ceiling means EAFs, even when fed 100% scrap, cannot produce more than roughly one-third of world demand. High-quality flat products for automotive and appliance sectors require low residual elements (copper, tin, etc.), forcing dilution with virgin DRI. Without vastly expanded primary iron units, the global steel industry remains structurally dependent on carbon-intensive blast furnaces.[40]

SUPPLY-CHAIN AND GEOPOLITICAL VULNERABILITIES

Water electrolyzers rely on critical minerals dominated by a handful of producers. Alkaline electrolyzers require high-purity nickel (Russia ~20% of Class-1 supply); PEM electrolyzers need iridium and platinum-group metals (80–90% of processing in China); solid-oxide systems use rare-earth-doped ceramics again largely refined in China.[41] China also controls 70% of solar PV manufacturing, 80% of wind-turbine components, 90% of utility-scale battery production, and over 85% of global electrolyzer manufacturing capacity in 2025.[42] Aggressive G7 adoption of green steel therefore represents a massive transfer of economic rent and strategic leverage to Beijing.

FUGITIVE HYDROGEN LOSSES AND HIDDEN GLOBAL-WARMING POTENTIAL

Recent peer-reviewed studies reveal that electrolyzers operated at partial load, which is inevitable when paired with variable renewables, suffer significantly higher hydrogen leakage and venting losses than manufacturers' nameplate figures. Measured fugitive losses range from 1 – 3% at steady state to 5 – 10% during frequent ramping and depressurization cycles.[43] These fugitive emissions are highly relevant, as hydrogen is a potent indirect greenhouse gas with a 100-year global warming potential (GWP) of 11 - 12 and a 20-year GWP of 33 - 40. This indirect potential arises from the fact that hydrogen emissions cause methane and ozone concentrations to rise by acting to deplete the tropospheric hydroxyl radical concentrations.[44] This also implies that an air-shed receiving extensive hydrogen fugitive emissions will suffer from reduced air quality as pollutant levels rise as hydroxyl radical concentrations fall.

Factors that influence whether a modern H_2-DRI-EAF plant emitting zero stack CO_2 will have a lower, neutral or higher climate warming influence than conventional BF-BOF steel are as follows:

1. The upstream CO_2e intensity per MWh if the H_2-DRI-EAF plant is grid connected versus truly operating on non-emitting electricity.
2. How the plant is operated (e.g., intermittent versus continuous).
3. How the plant is maintained.
4. The short versus long term environmental response to large scale hydrogen emissions.

When operating solely on non-emitting electricity, the climate benefits relative to a conventional BF-BOF plant, depends strongly on the level of leakage. These benefits range from more than a 95 % reduction in CO_2 emissions relative to a BF-BOF plant, to 65 % over the first 10 years, for total leakage rates of 1 % and 10 %, respectively[45]. At the higher short-term GWP and realistic upstream grid emission intensities, the break-even leakage rate, where a H_2-DRI-EAF equals a BF-BOF plant in terms of emissions, falls. As economics favor full time or high availability modes of operation, green hydrogen steel plants will be under immense pressure to operate in a grid connected scenario and climate-neutrality quickly resembles the grid's CO_2e intensity and a H_2-DRI-EAF plant quickly looses its climate appeal.[46]

IV. REAL-WORLD CASE STUDIES: FROM LAB TO LIMBO

The promise of green steel has moved from laboratory triumph to industrial-scale disappointment faster than most forecasts predicted. Three flagship projects illustrate the gap between pilot success and commercial reality; Sweden's HYBRIT, Nucor's stalled U.S. initiative, and China Baowu's pragmatic coal-hydrogen hybrid.

Sweden's HYBRIT project delivered the world's first green steel in August 2021 and remains the poster child for the technology.[47] By 2025 the consortium had operated a 1 t/h pilot plant continuously and stored hydrogen underground. Yet the planned 2.5 M tonne/year commercial plant, originally scheduled for 2026 start-up, has been repeatedly delayed. Construction was paused in October 2024, then fully halted in March 2025 after the Swedish centre-right government withdrew key funding.[48]

In the United States, Nucor, the country's largest and most profitable steelmaker, announced in 2022 a $1.7 billion greenfield H_2-DRI-EAF complex in Mason County, West Virginia, targeting 800 k tonne/year of near-zero steel by 2026.[50] By mid-2025 the project is mired in permitting delays, litigation and cost overruns.[51] The plant is now explicitly designed to start operations on natural-gas-based syngas ($CO + H_2$) in 2028–2029 before gradually increasing green hydrogen substitution as electrolyzers and dedicated renewables come online post-2030.[52] This "grey-first, green-later" strategy reflects both the immaturity of the U.S. green hydrogen supply chain and the reality that natural gas remains $1–2/GJ versus green H_2 at $21–42/GJ. Nucor's own filings acknowledge that pure green operation is not economically viable without the full $3/kg 45V tax credit and additional state incentives.[53]

China Baowu, the world's largest steel producer (132 Mt in 2024), has taken a markedly different path. Its flagship "near-zero" demonstration in Zhanjiang incorporates hydrogen injection into blast furnaces and a 1 M tonne/year DRI-EAF line, but the hydrogen is derived from coke-oven gas reforming and coal-gasification by-products and not by electrolysis.[54]

These cases share structural weaknesses. Green steel currently commands a market price of $800–1,200 per tonne versus $400–600 for conventional hot-rolled coil.[57] Capital-cost estimates reveal that a new greenfield integrated BF-BOF plant costs $600–800 million per million tonnes of annual capacity, whereas a comparable H_2-DRI-EAF plant ranges from $1.5–2.5 billion per million tonnes; 2 – 3× higher and driven by electrolyzers, hydrogen storage, and dedicated renewable power contracts.[58] H2 Green Steel's 5 M tonne/year Boden project in Sweden, often cited as the benchmark, has a total budget of €6.5 billion (€1,300/t-year), triple the cost of a conventional Asian mill.[59]

V. CONCLUSION

The global steel industry stands at a crossroads, but the path marked "green steel via H_2-DRI + EAF" is not the superhighway that net-zero road-maps portray. After stripping away the rhetoric, the numbers are unforgiving: replacing just half of today's 1.9 billion tonnes of blast-furnace steel with fully green hydrogen would require roughly 4,000 TWh of dedicated zero-carbon electricity annually, more than forty percent of China's entire 2024 consumption. No credible forecast shows renewable capacity or electrolyzer manufacturing scaling by those multiples before mid-century without planetary-scale resource mobilization and sustained subsidies measured in trillions of dollars.

The thermodynamic and ERoEI evidence is even more damning. While the blast furnace route returns 20–80 joules of useful energy for every joule invested in its energy conversion infrastructure over its lifetime, the green hydrogen route struggles to break even (0.5 : 1 to 2 : 1). This is not an engineering problem that learning curves will solve; it is a consequence of harvesting diffuse, intermittent solar and wind energy with steel-intensive infrastructure that must itself be replaced every 20–30 years. In energy terms, green steel risks becoming a monumental exercise in energy cannibalization rather than decarbonization.

Real-world projects confirm the theory. Flagship initiatives—HYBRIT, H2 Green Steel, Nucor's West Virginia plant, are either indefinitely delayed, scaled back, or openly pivoting to natural-gas-based syngas as a bridge that may never be crossed. Even in jurisdictions with the strongest political will and deepest subsidies, pure green operation remains economically unviable without permanent public support. Meanwhile, steel demand continues to grow in Asia on the back of low-cost, coal-based capacity that no carbon border adjustment mechanism has yet proven capable of neutralizing. None of this implies that steel decarbonization is impossible. Scrap-based EAF production is already low-emission and will grow as more post-war steel enters the recycling pool. But pretending that the H_2-DRI vision, as currently constituted, can displace the blast furnace at global scale by 2050 is not ambition; it is self-deception.

The blast furnace, powered by a narrowly defined subset of the earth's metallurgical coal deposits, has delivered abundant, affordable steel for 170 years and still enjoys profound thermodynamic and energetic advantages. Its continued dominance is not an accident of history or policy failure, it is the predictable outcome of physics, geology, and economics. Until a demonstrably superior primary-iron technology emerges at competitive cost and colossal scale, policymakers, investors, and societies must plan on the world continuing to make most of its steel the way it always has: with coke, carbon, and coal. Green steel, in its current form, is not the destination. It is a cautionary tale of what happens when ideological ambition outruns material reality.

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