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Decarbonizing Hard-to-Abate Industry

A Process Engineering Perspective on Hydrogen-Based Reduction, Industrial Heat Electrification, CCUS, and Low-Clinker Materials

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Abstract: Heavy industry — steel, cement, chemicals, and refining — accounts for roughly a quarter to a third of global CO_2 emissions, and its high process temperatures and reaction chemistry (calcination, ore reduction) resist simple electrification or fuel-switching. This paper surveys four decarbonization pathways from a process-engineering standpoint: hydrogen-based direct reduction and combustion, direct electrification of low- and medium-temperature process heat, carbon capture, utilization and storage (CCUS), and clinker substitution or CO_2 mineralization in cement manufacture. Current technoeconomic benchmarks are compiled for each pathway, including green hydrogen and H_2-DRI-EAF steel cost trajectories, heat pump abatement-cost ranges, capture-route selection criteria, and supplementary cementitious material (SCM) substitution limits, with India-specific policy context under the National Green Hydrogen Mission. A six-point screening framework is proposed to sequence efficiency, electrification, hydrogen, materials substitution, and CCUS investment for a given plant or process line.

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I. INTRODUCTION

Roughly 25-30% of global CO_2 emissions originate from heavy industry — iron and steel, cement, chemicals, and refining — where process heat above 400°C, chemical reduction reactions, and calcination chemistry make simple electrification or fuel-switching insufficient. Industrial decarbonization requires re-engineering the core unit operations: reactors, kilns, furnaces, and separation trains. This write-up surveys four technology families relevant to a decarbonization retrofit or greenfield design: hydrogen-based reduction chemistry, industrial heat electrification, carbon capture, utilization and storage (CCUS), and materials substitution in cement. Each section includes current technoeconomic benchmarks relevant to plant-level implementation.

II. HYDROGEN AS A REDUCING AGENT AND HIGH-TEMPERATURE FUEL

Green hydrogen, produced by electrolysis using renewable power, serves two roles in industry: as a chemical reductant replacing carbon monoxide in ore reduction, and as a combustion fuel for high-temperature process heat.

➢ *Hydrogen Direct Reduced Iron (H_2-DRI)*

The dominant near-commercial pathway for primary steel decarbonization is hydrogen-based direct reduction of iron ore pellets, followed by melting in an electric arc furnace (H_2-DRI-EAF), replacing the blast furnace-basic oxygen furnace (BF-BOF) route that relies on coke as both reductant and heat source. Hydrogen reduces iron oxides to metallic iron in the DRI shaft reactor, but the off-gas is water vapor rather than CO_2. Existing NG-DRI plants can blend up to roughly 30% hydrogen without major reactor modification, giving a phased retrofit pathway before committing to 100% hydrogen operation[1].

[1]MDPI, Modelling Future Pathways for Industrial Process Heat Decarbonisation, 2025. https://www.mdpi.com/2071-1050/17/23/10812

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Whether this pathway pencils out at plant scale is almost entirely a function of delivered hydrogen price. Using an India-specific bottom-up model with a near-term hydrogen price of USD 3.0/kg, one recent techno-economic study puts H_2-DRI-EAF crude steel at roughly USD 562/tonne, only about 5% costlier than a new-build BF-BOF line — and that gap is expected to close further as electrolyzer capital costs fall, with the same study projecting sub-USD 500/tonne green steel once hydrogen reaches USD 2.5/kg[2]. A separate factsheet frames the same trade-off from the fuel-cost side: absent any carbon price, H_2-DRI-EAF reaches parity with BF-BOF at a hydrogen price near USD 1.4/kg, a threshold that relaxes to roughly USD 2.7/kg once a USD 50/tCO_2 carbon price is layered in[3]. Table 1 lays out an indicative line-item comparison between the two routes.

Table 1. Indicative Production Cost Comparison, Conventional BF-BOF vs. Green H_2-DRI-EAF Steel (illustrative, USD/tonne crude steel).

Cost component	Conventional BF-BOF	Green H_2-DRI-EAF
Iron ore feedstock	~$90/t	~$90/t
Reduction agent (coal vs. H_2)	~$80/t	~$180/t
Electricity/energy	~$40/t	~$60/t
Capex, labour, overhead	~$250/t	~$260/t
Total (indicative)	**~$460/t**	**~$590/t**

India is pursuing three parallel steel decarbonization pathways: increasing scrap-based secondary (EAF) production, transitioning to hydrogen-based DRI, and deploying CCUS on existing BF-BOF assets where retrofit is cheaper than replacement[4]. A DRI-EAF conversion should size the electrolyzer and renewable supply as a coupled system — hydrogen storage buffering is essential given solar/wind intermittency, and shaft-furnace turndown must accommodate variable H_2 delivery unless a firm renewable-plus-storage PPA is secured.

➢ *Hydrogen for High-Temperature Process Heat*

Beyond metallurgical reduction, hydrogen combustion can directly substitute natural gas in high-temperature burners for ceramics, glass, and non-ferrous metals. A 2025 industrial trial demonstrated 100% hydrogen combustion sustaining temperatures up to 1550°C with minimal burner modification. Hydrogen thermal routes remain most competitive above roughly 400-500°C, where electrification is constrained by achievable heating densities and where combustion characteristics (flame speed, NOx formation, burner design) require re-validation rather than full equipment replacement.

III. ELECTRIFICATION OF INDUSTRIAL PROCESS HEAT

For low- and medium-temperature heat (below roughly 200-300°C), direct electrification via industrial heat pumps (IHPs), electric boilers, induction heating, and mechanical vapor recompression (MVR) is generally the most efficient and lowest-cost lever, and does not depend on hydrogen supply-chain buildout[5]. Five technologies — heat pumps, induction heaters, MVR, e-boilers, and turbo heaters — can address more than 80% of electrifiable industrial heat demand outside the highest-temperature applications such as electric arc furnaces and cement kilns[6].

- Heat pumps: can achieve coefficients of performance (COP) well above 1, cutting source energy use by up to 32% versus direct-fired alternatives, and are especially attractive where usable waste heat streams exist for upgrading.
- Economic threshold: CO_2 abatement costs for industrial heat pump retrofits fall in the range of USD 49-161/tCO_2 by 2050 across studied process types, generally below the social cost of carbon used in recent regulatory analyses.
- Temperature ceiling: above roughly 80-200°C, heat pump COP degrades and capital cost per unit heat rises sharply, which is where hydrogen combustion or CCUS-equipped fossil combustion become the more economical options.

The standard retrofit workflow is to build a temperature-demand curve (a heat cascade of process streams by temperature band), then match each band to the lowest-cost option — typically heat pumps below 100-150°C, hybrid electric/hydrogen in the 150-400°C band, and hydrogen, biomass, or CCUS-equipped combustion above 400°C[7].

[2]IECC / Berkeley GSPP, Economic Case for Green Steel Production in India, May 2026. https://iecc.gspp.berkeley.edu/wp-content/uploads/2026/05/IECC-Economic-Case-for-Green-Steel-Production-in-India-Report-May26.pdf
[3]Transition Asia, Green Steel Economics - US Factsheet, 2024 (updated 2025). https://transitionasia.org/green-steel-economics-us-factsheet/
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[5]CPUC, Decarbonizing Low-Temperature Industrial Heat in the US, 2026. https://docs.cpuc.ca.gov/PublishedDocs/SupDoc/A2209006/8694/585485908.pdf
[6]McKinsey & Company, Tackling Heat Electrification to Decarbonize Industry, December 2024. https://www.mckinsey.com/industries/industrials/our-insights/tackling-heat-electrification-to-decarbonize-industry

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IV. CARBON CAPTURE, UTILIZATION, AND STORAGE (CCUS)

Where chemical reactions themselves are the CO_2 source — limestone calcination in cement, coke oxidation in blast furnaces, natural gas reforming in ammonia production — CCUS is often the only near-term abatement route, since no feedstock substitution eliminates the reaction stoichiometry. The IEA estimates CCUS must deliver 38% of required emissions reductions in the chemical subsector and 15% each in cement and iron/steel to meet net-zero pathways[8].

➢ *Capture Technology Routes*

Three capture configurations are used commercially. Post-combustion capture separates CO_2 from flue gas via amine absorption-desorption, is retrofit-compatible with existing kilns and furnaces, and achieves capture rates above 90%. Pre-combustion capture converts fuel into syngas (H_2 + CO) before combustion, separating CO_2 ahead of the power/heat cycle. Oxy-fuel combustion burns fuel in near-pure oxygen, producing a concentrated CO_2/H_2O stream that simplifies separation but requires an air separation unit. Amine scrubbing remains the most mature retrofit route for existing cement kilns and steel plant off-gas.

➢ *Transport, Storage, and Utilization*

Captured CO_2 is compressed or liquefied and moved by pipeline (dominant for large volumes) or ship, then injected into deep saline aquifers or depleted hydrocarbon reservoirs for permanent storage, or routed to utilization: enhanced oil recovery, methanol synthesis, or mineralization into construction materials.

V. MATERIALS SUBSTITUTION: LOW-CLINKER AND CO_2-MINERALIZED CEMENT

Cement clinker production causes roughly 7-8% of global CO_2 emissions, split between kiln fuel combustion and unavoidable process emissions from limestone calcination ($CaCO_3 \rightarrow CaO + CO_2$). Since calcination emissions cannot be eliminated by fuel switching alone, materials-side substitution is the primary lever available without a full CCUS retrofit.

➢ *Supplementary Cementitious Materials (SCMs) and Clinker Substitution*

Of all the levers available to a cement plant, swapping out a portion of Portland clinker for supplementary cementitious materials (SCMs) — slag, fly ash, calcined clay, silica fume, or ground limestone — requires the least new capital and the most existing process knowledge, and studies of blended-cement adoption report footprint reductions approaching 50% relative to ordinary Portland cement when the mix design is optimized correctly[9]. One specific blend, limestone calcined clay cement (LC3), brings the clinker factor down to roughly 0.50 while still meeting CEM I strength benchmarks from the first week of curing onward; independent assessments put its carbon intensity 25-40% below conventional cement, generally at a lower delivered cost given how widely available clay and limestone feedstocks are[10]. Further along the substitution curve, blends combining calcined clay, slag, and rice husk ash have been reported at 44-56% clinker content, and laboratory-scale work on ground calcium carbonate blends has demonstrated clinker cuts as steep as 75% without sacrificing comparable strength[11].

➢ *CO_2 Mineralization in Concrete*

A second, increasingly commercially available route skips the materials-substitution question entirely and instead sequesters CO_2 directly inside the concrete itself, dosing captured gas into the mix during batching. Calcium ions in the fresh mix react with the injected CO_2 to precipitate stable calcium carbonate nanocrystals — the carbon stays locked in permanently, early compressive strength actually improves, and plants can typically trim cement dosage slightly as a result[12]. Because the carbonation reaction tolerates dilute CO_2 concentrations, kiln flue gas can often be fed in directly, sidestepping the cost of a dedicated high-purity capture unit altogether[13]. Scaled across the construction sector the opportunity is sizeable — published estimates put sequestration potential in aggregates at 0.1 to 1.4 Gt of CO_2 by 2050, tied to a market opportunity on the order of USD 400 billion[14]. From an implementation standpoint, a ready-mix or precast batching plant generally needs nothing more than a CO_2 dosing and injection skid bolted onto its existing mixer line, making this one of the cheapest CCU retrofits available today.

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[8]IEA, Transforming Industry through CCUS, 2024. https://www.iea.org/reports/transforming-industry-through-ccus

[9]GCCA / ICBC, Country Action on Blended Lower Carbon Cements and SCMs, 2026. https://gccassociation.org/wp-content/uploads/2026/03/ICBC-Country-Action-on-Blended-Cements-and-SCMs-to-Reduce-Clinker-Content-updated.pdf

[10]PatSnap Eureka, Low Carbon Cement Technology 2026, April 2026. https://www.patsnap.com/resources/blog/rd-blog/low-carbon-cement-technology-2026-patsnap-eureka/

[12]WRI, 5 Things to Know About Carbon Mineralization, 2023 (updated 2026). https://www.wri.org/insights/carbon-mineralization-carbon-removal

[13]University of Glasgow (eprints), Journal of CO2 Utilization 65, 2022. https://eprints.gla.ac.uk/280136/1/280136.pdf

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VI. INDIA POLICY CONTEXT AND DEPLOYMENT STATUS

India's National Green Hydrogen Mission (NGHM), backed by an outlay exceeding INR 19,000 crore, targets 5 million tonnes per annum (MMT) of green hydrogen capacity by 2030, alongside roughly 125 GW of associated renewable capacity, aiming to abate approximately 50 MMT of CO_2-equivalent emissions annually across refining, fertilizer, steel, cement, and mobility[15]. As of February 2026, approximately 8,000 tonnes per annum of capacity had been commissioned — an early step toward the 2030 target, with incentives such as the SIGHT scheme aiming to secure long-term offtake for domestic industrial consumers[16].[17]

For process engineers designing plants in India today: (1) green hydrogen supply remains capacity-constrained and price-uncertain through the late 2020s, favoring phased hydrogen-blending over single-shot 100% H_2 commitments; (2) SCM-based clinker substitution is immediately deployable using domestic fly ash, slag, and calcined clay without waiting on hydrogen infrastructure; and (3) electrification of low-temperature heat via heat pumps offers the fastest payback as grid decarbonization progresses, independent of the hydrogen mission timeline.

VII. DESIGN AND SELECTION FRAMEWORK

When screening decarbonization options for a plant or process line, the following sequence is a practical starting framework:

- Build a temperature-demand profile of all process heat and reduction/reaction duties, segmented by temperature band and stream availability for heat integration.
- Exhaust efficiency and heat-recovery options first — pinch analysis, waste heat recovery, and process intensification reduce the base energy demand before any fuel or feedstock substitution is evaluated.
- Electrify what can be electrified — heat pumps and resistive/induction heating for demand below roughly 150-200°C, where COP and capital cost remain favorable.
- Evaluate hydrogen for high-temperature and reduction duties where electrification is not thermodynamically or economically viable, sizing electrolyzer and storage capacity against renewable power availability.
- Apply materials substitution (SCMs, alternative binders, scrap-based feedstocks) wherever product specifications permit, since this is typically the lowest-capital lever.
- Retrofit CCUS on the residual, chemically unavoidable emissions stream (calcination, coke oxidation) where capture, transport, and storage/utilization infrastructure is accessible.

VIII. CONCLUSION

No single technology decarbonizes hard-to-abate industry; the economically rational pathway matches temperature and reaction stoichiometry to a combination of efficiency measures, targeted electrification, hydrogen for genuinely hydrogen-appropriate duties, materials-side clinker reduction, and CCUS for residual unavoidable emissions. Cost curves for green hydrogen and electrolyzers continue to compress — India-specific modelling puts green H_2-DRI-EAF steel within single-digit percentage points of conventional cost by 2030 and below parity by the mid-2030s — while SCM-based cement substitution and CO_2 mineralization are already commercially deployable at limited incremental capital cost. Engineers scoping new plants or retrofits should treat this as a staged deployment problem, sequencing efficiency and electrification ahead of hydrogen and CCUS investment, and tracking feedstock and policy signals that shift the relative economics year over year.

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