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Petroleum refining and petrochemical sector decarbonization: Chemistry, constraints, and compliance in India

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Abstract
The petroleum refining and petrochemical sectors are cornerstone drivers of India's industrial economy, yet they concurrently represent some of the most stubborn hard-to-abate sources of greenhouse gas (GHG) emissions. As India marches toward its ambitious Nationally Determined Contributions (NDCs) target of achieving Net-Zero emissions by 2070, deep decarbonization of these downstream hydrocarbon segments is no longer optional. This comprehensive review article explores the intricate chemical landscapes, systemic operational constraints and evolving regulatory compliance structures governing the Indian refining and petrochemical landscape. Chemically, the sector relies heavily on carbon-intensive processes, including steam methane reforming (SMR) for hydrogen production, high-severity fluid catalytic cracking (FCC), and fossil-fueled steam cracking for olefins. Mitigation vectors require radical process alterations, shifting from grey to green hydrogen via water electrolysis, deploying carbon capture, utilization, and storage (CCUS) technologies, electrification of high-temperature cracking furnaces and transitioning to bio-based and plastic waste-derived circular feedstocks. However, scaling these solutions in India faces multi-dimensional constraints. These include high capital expenditures (CAPEX), nascent domestic supply chains for electrolyzers, land-use barriers for localized solar or wind integration, and an absence of a mature downstream CO_2 transport network. Concurrently, statutory landscapes are shifting rapidly. Regulatory compliance frameworks, including the Bureau of Energy Efficiency's (BEE) Perform, Achieve, and Trade (PAT) scheme, the newly instituted Carbon Credit Trading Scheme (CCTS), and green hydrogen mandates, are exerting structural pressure on operators. This review synthesizes these chemical paradigms, operational roadblocks and statutory mandates into a strategic roadmap, providing a holistic baseline for engineers, policy architects and corporate strategists navigating India's energy transition.

Keywords: Petrochemical decarbonization, refining chemistry, industrial constraints, regulatory compliance, India energy transition

Introduction
The downstream hydrocarbon sector, encompassing petroleum refining and petrochemical manufacturing, forms the backbone of modern industrial economies, supplying crucial liquid transportation fuels, polymers, synthetic fibers, and industrial chemicals. In India, the rapid pace of urbanization, infrastructural growth and expanding middle-class demographics have catalyzed an unprecedented expansion in refining capacity, positioning the country as a major global refining hub. However, this economic cornerstone is inherently carbon-intensive and its sustained growth stands in direct conflict with environmental sustainability goals. At the 26th United Nations Climate Change Conference of the Parties (COP26), India committed to an ambitious climate pledge, achieving Net-Zero greenhouse gas emissions by 2070, reducing the carbon intensity of its economy by 45% by 2030 and installing 500 GW of non-fossil fuel energy capacity [1]. Accomplishing these targets demands an immediate, profound restructuring of hard-to-abate industrial sectors.

The refining and petrochemical industries are categorized as hard-to-abate primarily because carbon is not merely an energy source but a foundational chemical building block embedded within the raw feed stocks. High-temperature process heat above 800°C, required for endothermic catalytic cracking and steam cracking, cannot be easily serviced by standard low-voltage electrical heating systems. Furthermore, standard refinery configurations generate massive streams of byproduct carbon dioxide from hydrogen production facilities and fluid catalytic cracking regenerators. Decarbonizing these facilities requires interventions that span the entirety of chemical engineering thermodynamics, plant economics and regulatory compliance paradigms [2]. This review provides a deep dive into the specific chemical mechanisms behind emissions, analyzes the structural constraints unique to the Indian operating environment, and evaluates the legislative compliance pathways shaping the future of the industry.

The Carbon Footprint of Indian Refining and Petrochemicals
To effectively mitigate emissions, it is imperative to dissect the specific nodes of carbon generation within a standard refinery and petrochemical configuration. Indian refineries typically operate complex, high-conversion setups to maximize the yield of middle distillates (diesel, kerosene) from heavy, sour crudes, which intrinsically demands higher energy and hydrogen intensity [3]. Emissions within these complexes are broadly classified into three scopes: Scope 1 (direct emissions from on-site combustion, process vents, and flaring), Scope 2 (indirect emissions from imported electricity and steam), and Scope 3 (indirect emissions across the value chain, primarily dominated by end-user fuel combustion).

Within Scope 1, the primary emissions centers are process furnaces, utility boilers, Steam Methane Reforming (SMR) blocks, and Fluid Catalytic Cracking (FCC) regenerators. Process heaters, which burn refinery fuel gas, fuel oil, or natural gas to provide the thermal energy required for crude distillation and secondary conversions, account for roughly 45% to 50% of a facility's direct emissions. The SMR unit, utilized to generate the massive quantities of hydrogen required for hydro treating and hydro cracking sour crudes, represents another major point source, yielding approximately 9 to 11 tons of CO_2 per ton of hydrogen produced due to both the stoichiometry of the reaction and the combustion of fuel to heat the reformer tubes [4]. FCC regenerators, where coke deposited on the catalyst during cracking is burned off to restore catalytic activity, emit substantial, continuous streams of CO_2 blended with nitrogen and trace oxides. Understanding the point-source topology of these emissions is essential for designing targeted carbon capture or process substitution frameworks.

Chemical Paradigms of Decarbonization

Decarbonizing downstream assets requires fundamental innovations in process chemistry, catalysts and alternative energy inputs. The core chemical interventions revolve around four pillars, green hydrogen integration, carbon capture and chemical conversion, process electrification, and alternative circular feed stocks.

Green Hydrogen Paradigm

Currently, Indian refineries consume millions of tons of 'grey' hydrogen produced via SMR of natural gas or naphtha, represented by the highly endothermic reaction [5].

$$\mathbf{CH_4 + H_2O \rightleftharpoons CO + H_2}$$

Followed by the water-gas shift reaction:

$$\mathbf{CO + H_2O \rightleftharpoons CO_2 + H_2O}$$

Transitioning to 'green' hydrogen eliminates this chemical process footprint entirely by utilizing renewable electricity to split water molecules via Proton Exchange Membrane (PEM) or Alkaline Water Electrolysis (AWE):

$$\mathbf{2H_2O \longrightarrow 2H_2 + O_2}$$

Integrating green hydrogen into existing hydro treating networks requires no modifications to downstream hydro-processing reactors, making it a highly attractive 'drop-in' decarbonization solution. Chemical research is now focused on optimizing electrolyzer efficiency, reducing noble metal catalyst dependency (such as iridium and platinum in PEM cells), and managing the intermittent purity fluctuations of hydrogen tied to variable solar and wind power regimes [6].

Carbon Capture, Utilization, and Storage (CCUS) Chemistry

For process streams where carbon generation is unavoidable such as the FCC regenerator flue gas CCUS chemistry offers a direct abatement mechanism. Post-combustion carbon capture traditionally utilizes liquid chemical solvents like Monoethanolamine (MEA) or advanced Piperazine formulations to capture CO_2 via reversible carbamate formation [7]. However, the thermal energy required for solvent regeneration (stripping the CO_2 out at high temperatures) represents a severe energy penalty.

Next-generation chemical research focuses on non-aqueous solvents, Metal-Organic Frameworks (MOFs) for pressure swing adsorption and enzymatic membranes that mimic carbonic anhydrase to accelerate capture kinetics. On the utilization front, converting captured CO_2 into valuable petrochemical intermediates like methanol, dimethyl ether, or synthetic polyols via catalytic hydrogenation represents a promising frontier in circular carbon chemistry [8].

Electrification of Thermal Processes

Steam cracking of hydrocarbons to produce ethylene and propylene requires furnace temperatures exceeding 850°C, sustained entirely by fossil fuel combustion. Chemically replacing these gas-fired furnaces with electric resistance heating or plasma-arc technologies completely decouples process heat from fossil energy, provided the electricity source is fully decarbonized [9]. The primary chemical and material science challenges involve developing furnace alloys capable of withstanding extreme localized electrical flux and managing altered radiant heat profiles to prevent premature catalyst and tube coking.

Bio-based and Circular Feedstocks

Transitioning from fossil crude to bio-crude, Used Cooking Oils (UCO) and plastic waste pyrolysis oils alters the baseline stoichiometry of the refinery. Co-processing bio-feedstocks within existing fluid catalytic crackers or hydrocrackers requires novel catalyst designs capable of handling highly oxygenated molecules and processing contaminant metals like alkali and phosphorus inherent in biomass [10]. Deoxygenation chemistry, via hydrodeoxygenation (HDO) or decarboxylation, must be precisely controlled to optimize the yield of sustainable aviation fuels (SAF) and green diesel without depleting the facility's hydrogen balance.

Constraints Impeding Decarbonization in India

While the chemical pathways are scientifically sound, their deployment at an industrial scale within the Indian geopolitical and economic landscape is hindered by deep-seated technical, economic and systemic constraints.

Economic and Financial Barriers

The capital expenditures (CAPEX) required to re-engineering existing refineries for deep decarbonization are extraordinary. Replacing an active SMR block with utility-scale electrolyzers and associated renewable energy infrastructure requires billions of dollars in capital injection, which directly depresses refining margins in a highly price-sensitive market [11]. Furthermore, green hydrogen production costs in India currently hover around \$3.5 to \$5 per kilogram, compared to roughly \$1.5 to \$2 per kilogram for grey hydrogen. This price disparity creates a severe operational expenditure (OPEX) penalty that cannot be easily passed on to consumers at the fuel pump without triggering broader inflationary pressures.

Infrastructural and Supply Chain Deficiencies

The scalability of green hydrogen and electrification is fundamentally dependent on India's power grid infrastructure. Refineries require an ultra-reliable, continuous base load power supply, a single voltage dip can trigger emergency plant shutdowns, costing millions. Integrating highly intermittent solar and wind energy into the refinery grid requires massive, grid-scale energy storage systems (BESS) or pumped hydro storage, both of which are in short supply domestically [12]. Additionally, India possesses limited domestic manufacturing capacity for high-efficiency PEM electrolyzers, creating a heavy reliance on global supply chains subject to geopolitical trade barriers.

Geological and Geographical Limitations for CCUS

Unlike North America or the North Sea region, India possesses highly constrained and poorly mapped geological formations suitable for permanent carbon sequestration. Most Indian refining clusters are located along the coastline i.e., Jamnagar, Paradip, Kochi or deep within inland consumption hubs i.e., Mathura, Panipat. Transporting captured CO_2 from inland refineries to prospective offshore basalt formations or depleted oil fields involves constructing thousands of kilometers of dedicated high-pressure CO_2 pipelines, a proposition fraught with land acquisition challenges, regulatory delays and immense public safety concerns [13].

Operational Complexities and Refit Challenges

Most Indian refineries are highly integrated brownfield assets with optimized thermal networks (Pinch Analysis setups). Modifying one node of the facility, such as substituting steam from a cogeneration plant with an electrical heater, disrupts the entire steam-power balance of the refinery. Furthermore, brownfield retrofitting is constrained by physical space limitations within congested plant layouts, preventing the installation of massive amine scrubbing towers or localized electrolyzer yards [14].

Regulatory Compliance and Policy Landscapes in India

The speed of decarbonization is heavily driven by the stringency and execution of government mandates. The Government of India has rolled out an intricate web of policy mechanisms designed to push and pull the sector toward lower carbon intensity.

Perform, Achieve, and Trade (PAT) Scheme

Administered by the Bureau of Energy Efficiency (BEE), the PAT scheme is a regulatory mechanism that sets mandatory Specific Energy Consumption (SEC) reduction targets for energy-intensive sectors, including petroleum refineries. Facilities that exceed their targets are awarded Energy Saving Certificates (ESCerts), which can be traded with underperforming units [15]. While the PAT scheme has successfully driven incremental energy efficiency enhancements, it is fundamentally an efficiency tool rather than a deep decarbonization mechanism; it encourages optimization but does not mandate absolute fuel or feedstock switching.

The Indian Carbon Market (ICM) and Carbon Credit Trading Scheme (CCTS)

To address the limitations of efficiency-only schemes, India has initiated the development of the Carbon Credit Trading Scheme (CCTS) under the Energy Conservation (Amendment) Act. The CCTS aims to establish a national compliance carbon market, placing hard caps on absolute GHG emissions across industrial sectors, including refining and petrochemicals. Companies will be required to align with declining carbon allowances or purchase carbon credits to achieve compliance. This structural market mechanism effectively puts a price on carbon, internalizing the environmental externality and altering the financial calculations for decarbonization investments [16].

National Green Hydrogen Mission (NGHM)

Launched with an outlay of over ₹19,000 crores, the NGHM targets the production of at least 5 million metric tons (MMT) of green hydrogen per annum by 2030. For the refining sector, the government is formulating mandatory green hydrogen consumption targets, legally requiring refiners to substitute a specific percentage of their grey hydrogen consumption with green variants. While these mandates guarantee a domestic market for green hydrogen, they place a direct regulatory compliance burden on refiners to secure adequate supply in a nascent market.

Fuel Blending Mandates and Alternative Standards

The Ministry of Petroleum and Natural Gas (MoPNG) has aggressively pursued the National Policy on Biofuels, achieving a 20% ethanol blending target in petrol (E20) ahead of schedule and pushing for a 5% biodiesel blending mandate. Furthermore, upcoming mandates for Sustainable Aviation Fuel (SAF) blending will force refiners to rapidly build out bio-refining capacities, introducing operational and logistical compliance challenges across the downstream distribution network [17].

Strategic Decarbonization Roadmap for Indian Operators

Navigating the intersection of chemical possibilities, harsh economic constraints, and tightening compliance mandates requires a multi-tiered, phased operational strategy for Indian refiners. Operators must avoid binary choices and instead implement a blended roadmap characterized by short-term optimizations and long-term structural transformations.

In the short term (2026–2030), the focus must remain squarely on aggressive energy efficiency improvements, digital twin optimizations and early-stage green hydrogen blending. Implementing AI-driven predictive maintenance and thermodynamic optimizations can squeeze additional 2-3% efficiency out of process heaters and distillation trains. Concurrently, refiners should deploy small-scale (10-20 MW) pilot electrolyzers to master the operational nuances of handling variable-pressure green hydrogen and to satisfy early-stage compliance mandates under the NGHM without destabilizing the facility’s macro-economics.

In the medium term (2030–2040), as domestic electrolyzer manufacturing matures and solar or wind paired with energy storage costs decline, refiners must transition to utility-scale green hydrogen replacement i.e., targeting 30-50% substitution. This period must also see the initial deployment of commercial-scale post-combustion carbon capture units specifically on high-purity point sources such as SMR process vents and FCC regenerators. Captured CO_2 during this phase should be diverted primarily to utilization pathways, such as chemical synthesizing of methanol or mineralization into building materials, bypassing the near-term absence of national storage pipelines.

In the long term (2040–2070), deep abatement technologies must take center stage. This involves complete electrification of steam cracking furnaces using high-temperature electrical coils and shifting feedstocks completely toward plastic pyrolysis oils, bio-crudes and captured CO_2 to olefins chemical routes. By building an integrated ecosystem where renewable energy, circular feedstocks and regional CCUS hubs interact seamlessly, India's refining and petrochemical sectors can successfully transition from carbon-intensive liabilities into sustainable, circular chemical engines aligned with the nation's 2070 Net-Zero destination.

Conclusion

The decarbonization of the petroleum refining and petrochemical sectors in India represents one of the most complex engineering and economic challenges of the modern era. While process chemistry offers clear technical routes ranging from green hydrogen substitution and process electrification to advanced CCUS frameworks the practical implementation of these systems is closely bounded by severe financial risks, infrastructural gaps, and geographical limitations unique to India. Moving forward, the transition cannot rely on isolated innovations, it demands a synchronized approach where technological breakthroughs are supported by robust, predictable market-based regulations like the CCTS and financial de-risking mechanisms from the state. By successfully navigating these chemical paradigms, systematically resolving local operational constraints and aligning with evolving statutory compliance frameworks, Indian refiners can safeguard their long-term viability, ensuring that India's path to industrial development remains inherently tied to global climate resilience.

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