



## Decarbonising coal locally: Reviewing gasification pathways for affordable blue hydrogen in India

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DOI: <https://doi.org/10.66856/ijard.2025.10.2.11074>

### Abstract

India faces a complex trilemma of energy security, economic affordability, and aggressive decarbonisation targets. While green hydrogen remains the ultimate long-term frontier, high electrolyser capital costs and renewable intermittency limit its immediate scalability. This review article evaluates local coal gasification as a pragmatic, transitional bridge toward a low-carbon economy through the production of affordable "blue" hydrogen. India's domestic coal reserve base, characterized by high ash content, low sulfur and low calorific value, presents distinct thermochemical challenges. This paper comprehensively reviews primary gasification technologies including moving-bed, fluidized-bed, and entrained-flow systems assessing their techno-economic viability and operational compatibility with high-ash Indian coal run-of-mine variants. We systematically evaluate syngas conditioning pathways, focusing on advanced Water-Gas Shift (WGS) kinetics, acid gas removal (AGR) units, and commercial carbon capture and storage (CCS) or utilization (CCUS) technologies. Techno-economic models reveal that combining local coal gasification with carbon capture can deliver blue hydrogen at a levelized cost of hydrogen (LCOH) substantially below current green hydrogen pathways, making it highly competitive with imported liquefied natural gas (LNG) reforming. Finally, we map out the regional infrastructure requirements, geological storage potential in depleted oil/gas fields and deep saline aquifers, and the critical policy frameworks necessary to de-risk investments and integrate blue hydrogen into India's National Green Hydrogen Mission ecosystem.

**Keywords:** Blue hydrogen, coal gasification, carbon capture (CCUS), techno-economic analysis, Indian Coals

### Introduction

India is currently navigating one of the most critical energy transitions in modern history. The nation must simultaneously support rapid macroeconomic industrialization, ensure energy security for over 1.4 billion citizens, and meet its international climate commitments, including the target of achieving net-zero greenhouse gas emissions by 2070. Historically, India's industrial progress has been powered by domestic coal, which continues to account for over 55% of the country's primary energy mix and more than 70% of its utility electricity generation.<sup>[1]</sup> However, the heavy reliance on conventional coal combustion exacerbates localized air pollution and conflicts with national carbon mitigation trajectories.

To decouple industrial growth from carbon emissions, the Government of India launched the National Green Hydrogen Mission.<sup>[2]</sup> This framework aims to transform India into a global hub for hydrogen production, utilization, and export. Hydrogen (H<sub>2</sub>) is widely recognized as a versatile energy carrier capable of decarbonising hard-to-abate sectors such as steelmaking, oil refining, chemical fertilizer manufacturing, and heavy-duty long-haul transport.<sup>[3]</sup>

Despite the immense strategic focus on green hydrogen (produced via water electrolysis powered by renewable energy), significant deployment bottlenecks persist. These include the high capital expenditure (CAPEX) of Proton Exchange Membrane (PEM) and Solid Oxide Electrolyser Cells (SOEC), constrained supply chains for critical rare-earth minerals, and the massive geographical footprint required to deploy dedicated solar and wind farms.

Furthermore, the levelized cost of green hydrogen (LCOH<sub>green</sub>) in India remains prohibitively high for immediate wholesale adoption without heavy subsidies.

This structural reality highlights the need for a diversified, multi-pathway hydrogen roadmap.<sup>[4]</sup> "Blue" hydrogen produced from fossil fuel feedstocks coupled with carbon capture, utilization, and storage (CCUS) offers a scalable, continuous, and cost-effective alternative that can utilize existing industrial infrastructure. While steam methane reforming (SMR) of imported Liquefied Natural Gas (LNG) is a common pathway for blue hydrogen globally, India's high reliance on volatile foreign natural gas imports creates severe balance-of-payments challenges and exposes the economy to international geopolitical shocks.

Consequently, gasifying indigenous coal assets and capturing the resulting carbon dioxide (CO<sub>2</sub>) emerges as a highly strategic alternative. This approach, termed "local coal decarbonisation," transforms an abundant domestic liability into a clean energy asset. It ensures reliable base-load hydrogen production independent of weather conditions, supports domestic energy security, and leverages local supply chains.

This review article provides a comprehensive evaluation of coal-to-blue-hydrogen pathways tailored specifically to the unique mineralogical and chemical profiles of Indian coal feedstocks. By analyzing gasification kinetics, syngas purification mechanics, CCUS integration options, and techno-economic variables, this paper outlines a clear framework for establishing a viable domestic blue hydrogen sector.

**Characterization of Indian Coal Feedstocks: Technical Obstacles to Gasification**

The success of any coal gasification facility depends heavily on the intrinsic chemical and physical properties of the input feedstock. Indian coals, predominantly mined from Gondwana deposits located across regions such as Jharkhand, Odisha, Chhattisgarh and West Bengal, differ significantly from the premium bituminous coals found in the United States, Europe, or Australia. Effectively processing Indian coal requires specialized engineering configurations due to several distinct characteristics.<sup>[5]</sup>

**High Ash Content:** Run-of-mine (ROM) coal from Indian deposits regularly exhibits extraordinarily high ash content, typically ranging from 35 wt% to as high as 50 wt%. In contrast, international traded coals generally contain less than 10-15 wt% ash. This massive inert mineral load demands higher energy inputs to melt or fluidize the ash, accelerates mechanical erosion inside the gasifier and decreases the overall cold gas efficiency (CGE) of the reactor.<sup>[6]</sup>

**High Ash Fusion Temperature (AFT):** The mineral ash in Indian coal is rich in silica (SiO<sub>2</sub>) and alumina (Al<sub>2</sub>O<sub>3</sub>), while containing lower concentrations of fluxing agents like iron oxide (Fe<sub>2</sub>O<sub>3</sub>), calcium oxide (CaO) and magnesium

oxide (MgO). This composition leads to an exceptionally high Ash Fusion Temperature (AFT), often exceeding 1350°C to 1500°C under reducing conditions. Operating a slagging gasifier above these extreme temperatures requires substantial thermal energy, which increases oxygen consumption and challenges the thermal stability of refractory linings.

**Low Calorific Value and High Volatile Matter:** Indian coals are generally classified as sub-bituminous to lower-grade bituminous variants (typically graded from G7 down to G17 under the Ministry of Coal's Gross Calorific Value system). Their useful heat value varies between 3,000 and 5,000 kcal/kg. The high volatile matter content requires precise control of the oxygen-to-coal ratio to prevent tar formation during low-temperature processing.

**Beneficial Low Sulfur Profile:** On the positive side, Indian Gondwana coals generally feature low sulfur content, frequently below 0.5 wt% (with the exception of specific Tertiary coals in the northeastern regions like Assam, which can exceed 3 wt% sulfur). This low sulfur baseline reduces the upfront burden on acid gas removal (AGR) units and mitigates the risk of early catalyst poisoning in downstream synthesis stages.

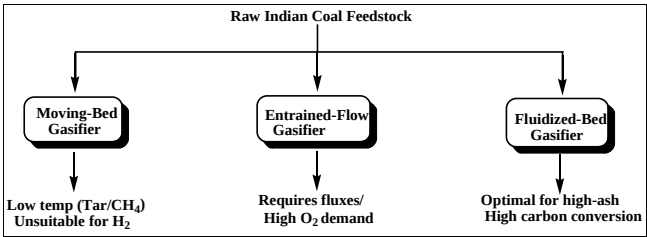
**Table 1:** Comparison of Coal Feedstocks

| Coal Parameter                   | Typical Indian Gondwana Coal (Sub-bituminous) | Typical US/Euro Bituminous Coal (Illinois No. 6 / Hunter Valley) |
|----------------------------------|-----------------------------------------------|------------------------------------------------------------------|
| Ash Content (wt%, dry basis)     | 35.0% – 50.0%                                 | 8.0% – 12.0%                                                     |
| Fixed Carbon (wt%, dry basis)    | 30.0% – 42.0%                                 | 50.0% – 60.0%                                                    |
| Volatile Matter (wt%, dry basis) | 20.0% – 30.0%                                 | 30.0% – 38.0%                                                    |
| Sulfur Content (wt%, dry basis)  | 0.3% – 0.6%                                   | 1.5% – 4.0%                                                      |
| Ash Fusion Temperature (AFT, °C) | 1350°C – >1500°C                              | 1150°C – 1300°C                                                  |
| Gross Calorific Value (kcal/kg)  | 3,200 – 4,800                                 | 6,200 – 7,500                                                    |

Processing feedstocks with these characteristics requires careful technology selection. Applying standard international gasification blueprints directly to high-ash Indian coal without modification can lead to operational issues, including incomplete carbon conversion, excessive slag viscosity, and unscheduled plant shutdowns.

**Comparative Evaluation of Gasification Pathways for High-Ash Indian Coal**

Gasification involves the partial oxidation of carbonaceous material at high temperatures and pressures to generate syngas a mixture primarily composed of carbon monoxide (CO), hydrogen (H<sub>2</sub>), carbon dioxide (CO<sub>2</sub>), and water vapor (H<sub>2</sub>O)<sup>[7]</sup>. Commercial gasifiers generally fall into three main design categories, each interacting differently with the high ash content and high AFT of Indian coal.



**Moving-Bed Gasification Systems**

Moving-bed (or fixed-bed) counter-current reactors, such as the classic Lurgi design, operate by feeding lump coal (10-50 mm) through the top while injecting steam and oxygen from the bottom. The coal moves slowly downward through distinct drying, devolatilization, gasification, and combustion zones.

The primary advantage of moving-bed systems is their long fuel residence time, which enables high carbon conversion efficiency even for less reactive coals. Because the escaping syngas exits at relatively low temperatures (450°C-600°C), these systems achieve high cold gas efficiency.

However, moving-bed configurations possess severe drawbacks for large-scale blue hydrogen production. The low exit temperature leads to the generation of substantial volumes of tars, oils, and heavy liquid hydrocarbons, as well as significant methane (CH<sub>4</sub>) bypass. Reforming this bypassed methane and treating the contaminated process wastewater adds significant capital cost and complexity to downstream operations. Furthermore, these units require carefully sized lump coal, making them less compatible with the high proportion of fine coal particles generated by modern mechanized mining in India.

### Fluidized-Bed Gasification Systems

Fluidized-bed gasifiers, including High-Temperature Winkler (HTW) and fluidized-bed designs developed by domestic entities like BHEL,<sup>[8]</sup> suspend pulverized coal particles (1-6 mm) in an upward-flowing stream of oxygen and steam. The reactor operates under highly turbulent, back-mixed conditions at temperatures typically maintained between 850°C and 1050°C. This temperature range is intentionally kept safely below the ash softening point to avoid clinkering and agglomeration.

For high-ash Indian coals, fluidized-bed gasification offers several key processing advantages:

**Excellent Solid-Gas Mixing:** The turbulent bed ensures uniform temperature profiles and high tolerance for varying feed ash concentrations (up to 45%).

**Non-Slagging Operation:** By operating below the AFT, the system avoids the need to melt the minerals into liquid slag, saving significant thermal energy and reducing oxygen consumption.

**Feed Flexibility:** The system easily handles fine coal fractions that would clog a moving-bed reactor.

The main limitation of fluidized-bed systems is lower carbon conversion efficiency compared to entrained-flow systems. This occurs because char particles can be carried out of the bed prematurely with the exiting syngas, requiring cyclone separation and char recycling. Additionally, minor amounts of methane and light hydrocarbons remain in the syngas, requiring subsequent secondary reforming stages to maximize hydrogen yield.<sup>[9]</sup>

### Entrained-Flow Gasification Systems

Entrained-flow gasifiers, such as those from Siemens, Shell, E-Gas, or General Electric (GE), process finely atomized coal slurry or pneumatic dry coal dust. They operate at high temperatures (1300°C-1600°C) and elevated pressures (30-80 bar) with short residence times. The mineral matter is intentionally melted into an inert, glassy liquid slag that drains continuously from the bottom of the reactor.

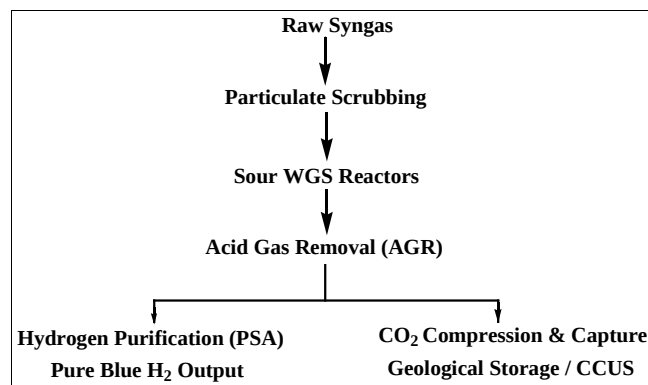
Entrained-flow systems provide distinct benefits for hydrogen production, including high carbon conversion efficiencies (frequently >99%) and a syngas stream that is completely free of tars and heavy hydrocarbons. The high operating temperatures ensure that methane bypass is virtually eliminated, maximizing the production of CO and H<sub>2</sub>. However, processing high-ash Indian coal in an entrained-flow system presents major technical challenges:

**High Oxygen and Thermal Demand:** Melting coal with 40% ash content requires substantial amounts of pure oxygen, which increases the capital and operating costs of the Air Separation Unit (ASU).

**Refractory Wear:** The high flow of liquid slag accelerates the chemical erosion and mechanical wear of the inner refractory lining, leading to more frequent maintenance shutdowns and higher operational costs.

**Fluxing Agent Requirements:** To lower the high ash fusion temperature (AFT) of Indian coal down to an operational window of 1250°C-1300°C, fluxing agents like limestone (CaCO<sub>3</sub>) must be continuously added to the feed. This addition increases the overall solid handling requirements of the plant.

### Advanced Syngas Conditioning & Water-Gas Shift (WGS) Kinetics



To maximize the production of affordable blue hydrogen, the raw syngas from the gasifier must undergo multiple conditioning stages. This processing converts the carbon monoxide (CO) fraction into additional hydrogen while preparing the carbon dioxide (CO<sub>2</sub>) for efficient capture. The core sequence includes particulate removal, syngas cooling, water-gas shift reactions, and acid gas clean-up.

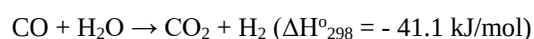
### Particulate Removal and Gas Cooling

The raw syngas contains significant quantities of fly ash, soot, and volatile trace elements. Particulate removal is performed using a combination of high-efficiency cyclones and water scrubbers, reducing particle concentrations to sub-milligram levels per cubic meter to protect downstream catalytic beds.

Thermal management is accomplished either via high-pressure radiant syngas coolers that generate valuable high-pressure steam, or through direct water quenching. For hydrogen production, direct water quenching is highly effective because it saturates the syngas with the water vapor required for the subsequent Water-Gas Shift reaction, eliminating the need for external steam injection.

### Water-Gas Shift (WGS) Reactor Engineering

The fundamental chemical reaction used to increase hydrogen yields is the Water-Gas Shift (WGS) reaction, an exothermic equilibrium reaction:



Because the reaction is exothermic, lower temperatures favor higher equilibrium carbon monoxide conversion, whereas higher temperatures accelerate reaction kinetics. Consequently, industrial facilities typically employ a multi-stage configuration:

**High-Temperature Shift (HTS):** Operating between 350°C and 450°C, the HTS stage rapidly reduces the bulk CO concentration from roughly 40-50% down to 5-8%.

Traditional HTS catalysts are iron-chromium based ( $\text{Fe}_3\text{O}_4\text{-Cr}_2\text{O}_3$ ), though newer formulations incorporate copper promoters to enhance activity.

**Low-Temperature Shift (LTS):** Operating between 200°C and 250°C, the LTS stage drives the thermodynamic equilibrium forward, lowering the remaining CO concentration to less than 0.5-1.0%. Standard LTS systems use highly active copper-zinc oxide-alumina catalysts ( $\text{Cu/ZnO/Al}_2\text{O}_3$ ).

**Sour vs. Sweet Shifting:** A key engineering choice is whether to position the shift reactors before or after the sulfur removal stage:

**Sweet Shifting:** Requires cleaning the syngas of all sulfur species ( $\text{H}_2\text{S}$  and  $\text{COS}$ ) prior to the shift reactors. This setup allows the use of standard, less robust catalysts but requires reheating the syngas stream, which reduces thermal efficiency.

**Sour Shifting:** Processes raw syngas directly before sulfur removal using sulfur-tolerant cobalt-molybdenum ( $\text{Co-Mo/Al}_2\text{O}_3$ ) catalysts. These catalysts require a minimum threshold of hydrogen sulfide ( $\text{H}_2\text{S}$ ) in the gas stream to maintain their active sulfided state. Given that Indian coal has low but stable sulfur levels, sour shifting is often preferred.<sup>[10]</sup> This approach avoids early gas cooling and reheating loops, maximizing the moisture content of the gasifier exit stream.

### Acid Gas Removal (AGR) and Hydrogen Purification

Following the WGS reactors, the syngas contains mainly  $\text{H}_2$ ,  $\text{CO}_2$ , water vapor and small amounts of  $\text{H}_2\text{S}$ ,  $\text{COS}$  and  $\text{N}_2$ . This stream must be split into three separate outputs: clean hydrogen, a concentrated  $\text{CO}_2$  stream ready for storage, and sulfur byproducts.

This separation is typically performed using an Acid Gas Removal (AGR) unit operating via physical or chemical absorption.<sup>[11]</sup>

The two leading commercial technologies are:

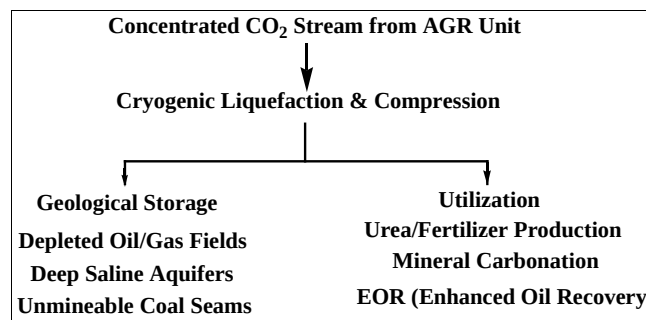
**Selexol:** Uses a physical solvent composed of dimethylether of polyethylene glycol (DMPEG). It operates efficiently at high partial pressures and low temperatures, allowing for the selective, sequential absorption of  $\text{H}_2\text{S}$  and  $\text{CO}_2$  into separate streams.

**Rectisol:** Uses cold methanol (typically between -30°C and -60°C) as a physical solvent. Rectisol offers high trace purity, removing organic sulfur compounds, carbonyls, and trace heavy metals alongside bulk  $\text{CO}_2$  and  $\text{H}_2\text{S}$ . This makes it well-suited for applications requiring high-purity syngas, though it carries higher capital and refrigeration costs.

Following AGR processing, the hydrogen-rich stream (around 95-98%  $\text{H}_2$ ) undergoes final purification in a Pressure Swing Adsorption (PSA) unit. The PSA system uses multi-bed zeolites and activated carbon layers to remove remaining trace gases ( $\text{CO}$ ,  $\text{CO}_2$ ,  $\text{CH}_4$ ,  $\text{N}_2$ ), delivering a final hydrogen stream at 99.999% purity, meeting ISO 14687 standards for fuel cell and industrial applications.

### Carbon Capture, Utilization, and Storage (CCUS) Integration

To classify hydrogen produced from coal as "blue," carbon dioxide emissions must be captured and permanently isolated from the atmosphere, rather than released. Because coal gasification operates at high pressures, the partial pressure of  $\text{CO}_2$  in the shifted syngas stream is relatively high, which makes carbon capture significantly more efficient and cost-effective than post-combustion capture from conventional power plant flues.



### Carbon Capture Mechanisms

The AGR units described above yield a high-purity  $\text{CO}_2$  gas stream (often >98 vol% on a dry basis). To prepare this captured  $\text{CO}_2$  for transport, it is compressed through multi-stage centrifugal compressors with intercooling to a supercritical state (typically above 110-150 bar). At these pressures,  $\text{CO}_2$  behaves with the density of a liquid but the viscosity of a gas, making it highly efficient to transport via pipeline or specialized shipping vessels.

### Sequestration Opportunities within the Indian Subcontinent

Permanent geological storage requires appropriate deep subsurface formations. India's geological storage opportunities can be categorized into three primary options:<sup>[12]</sup>

**Depleted Oil and Gas Reservoirs:** Formations such as the Cambay Basin in Gujarat, the Krishna-Godavari (KG) offshore basin, and fields in Assam offer well-understood geology, existing structural traps, and legacy seismic data. These reservoirs are excellent candidates for early blue hydrogen deployment and can also support Enhanced Oil Recovery (EOR) operations to improve project economics.

**Deep Saline Aquifers:** These formations offer the largest theoretical storage capacity in India. Extensive sedimentary basins, including the Indo-Gangetic foreland basin, the Mesozoic basins in Kutch and Rajasthan, and various coastal margins, contain deep saltwater layers that can store significant volumes of injected  $\text{CO}_2$  through dissolution and mineral trapping.

**Unmineable Coal Seams:** Deeply buried coal beds that cannot be mined safely or economically can absorb injected  $\text{CO}_2$ . The coal matrix preferentially adsorbs  $\text{CO}_2$  while releasing trapped methane, a process known as Enhanced Coal Bed Methane (ECBM) recovery. This approach provides an additional revenue stream while securing long-term carbon storage.

### Industrial Utilization Pathways

Given that large-scale geological storage infrastructure is still developing in India, commercial utilization pathways offer an important near-term option for captured CO<sub>2</sub>.<sup>[13]</sup>

**Urea and Fertilizer Manufacturing:** India is a major consumer of nitrogenous fertilizers and relies heavily on imported urea. Integrated coal-to-blue-hydrogen facilities can react captured CO<sub>2</sub> directly with ammonia NH<sub>3</sub> produced on-site, supporting agricultural supply chains while avoiding emissions.

**Mineral Carbonation:** Disposing of CO<sub>2</sub> by reacting it with industrial alkaline solid wastes, such as steel slag, fly ash, or recycled concrete fines, creates stable solid carbonates. These materials can be safely used as aggregate components in the construction sector.

### Techno-Economic Analysis: Decarbonised Gasification vs. Competitors

The commercial viability of coal-to-blue-hydrogen pathways depends on their Levelized Cost of Hydrogen (LCOH) compared to alternative production methods.<sup>[14]</sup> The LCOH represents the net present cost of electricity, fuel, capital equipment, and operations divided by the total hydrogen produced over the facility's economic lifetime:

$$\text{LCOH} = \frac{\sum_{t=0}^N \frac{\text{CAPEX}_t + \text{OPEX}_t + \text{Fuel}_t + \text{CO}_2\text{Tax}_t - \text{Byproduct}_t}{(1+r)^t}}{\sum_{t=0}^N \frac{\text{Hydrogen Output}_t}{(1+r)^t}}$$

### Cost Structure Breakdown

To evaluate the economics of blue hydrogen production from domestic high-ash coal in India, we assess a representative utility-scale facility producing 100,000 metric tonnes of hydrogen per annum. The financial assumptions incorporate an 8% weighted average cost of capital (WACC) and a 25-year operational lifetime.

**Table 2:** Levelized Cost of Hydrogen (LCOH) Comparison (\$/kg H<sub>2</sub>)

| Process                         | Cost            |
|---------------------------------|-----------------|
| Coal Gasification + CCUS (Blue) | \$1.65 - \$2.10 |
| Imported LNG Reforming (Grey)   | \$2.20 - \$2.80 |
| Renewable Electrolysis (Green)  | \$3.80 - \$5.50 |

**Capital Expenditure (CAPEX):** Coal gasification plants require significant initial investment due to the need for advanced air separation units, high-pressure gasifiers, multi-stage shift reactors, acid gas clean-up systems, and CO<sub>2</sub> compression trains. The addition of CCUS infrastructure typically increases base plant CAPEX by 15-25%. However, localized engineering, procurement, and construction (EPC) services and domestic fabrication can significantly reduce these capital costs compared to Western or Middle Eastern baselines.

**Operational Expenditures (OPEX) and Fuel Feedstock Costs:** A key economic advantage of this pathway is the

low cost of local high-ash coal. While international liquefied natural gas (LNG) prices often fluctuate significantly (\$10–\$25/MMBtu), domestic Indian coal remains highly affordable and price-stable, typically ranging from \$25 to \$55 per metric tonne depending on the specific GCV grade and mine-mouth proximity. This low feedstock cost helps insulate operators from international energy market volatility.

**Carbon Capture and Compression Penalties:** Integrating carbon capture introduces an energy penalty, as steam and electrical power must be diverted from the plant's auxiliary systems to regenerate solvents and run the CO<sub>2</sub> compressors. This reduces the net cold gas efficiency of the complex by approximately 4-7 percentage points. Additionally, transport and geological injection costs add an estimated \$10 to \$25 per tonne of captured CO<sub>2</sub>.

### LCOH Sensitivity to Coal Price, Ash Content, and Carbon Taxes

Techno-economic models indicate that blue hydrogen can be produced from local coal within an estimated cost window of \$1.65 to \$2.10 per kg of H<sub>2</sub>. This compares favorably to alternate pathways:

**Imported LNG SMR (Grey/Blue):** Costs vary from \$2.20 to \$2.80/kg, driven by volatile international gas prices.

**Renewable Electrolysis (Green):** Currently ranges from \$3.80 to \$5.50/kg, limited by electrolyser capital costs and low renewable capacity factors.

Sensitivity analyses highlight three primary variables that influence the economic competitiveness of the coal-to-blue-hydrogen pathway:

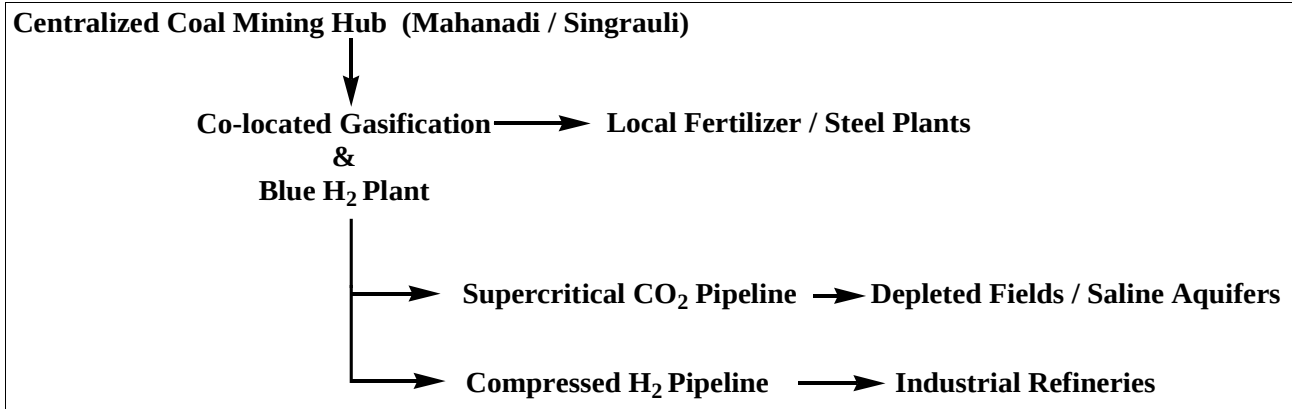
**Ash Concentration:** Increasing ash levels from 35% to 48% reduces carbon conversion efficiency and increases oxygen consumption, raising the LCOH by roughly \$0.15/kg due to higher specific coal throughput and ash disposal costs.

**Mine-Mouth Proximity:** Locating production facilities near mine mouths eliminates long-distance rail freight costs, which can otherwise double the delivered cost of coal. Co-locating the gasifier with the mine significantly improves project economics.

**Carbon Pricing and Policy Support:** Implementing a domestic carbon tax or a cap-and-trade market would penalize unmitigated grey hydrogen facilities. With high-efficiency CCUS capturing over 90% of process emissions, blue hydrogen remains cost-competitive even under modest carbon pricing structures (\$20–\$40 per tonne of CO<sub>2</sub> equivalent).

### Infrastructure Development, Logistical Corridors, and Geological Storage Mapping

Deploying a national blue hydrogen network requires matching centralized production hubs with long-term carbon storage sites and industrial end-users. Developing these connections efficiently is essential for keeping hydrogen affordable.



### Hydrogen Logistical Corridors

Because hydrogen has a low volumetric energy density at ambient conditions, long-distance transport can add significant cost. This review proposes establishing integrated industrial clusters, or "Hydrogen Valleys," located near major coal fields and heavy industrial users:

**The Eastern Corridor (Odisha-Jharkhand-West Bengal):** This region contains major coal deposits (Mahanadi, Jharia, Raniganj) alongside a high concentration of primary steel plants, chemical manufacturers, and heavy industries. Producing blue hydrogen locally allows for direct delivery via short-distance, high-pressure pipelines, minimizing transportation costs.

**The Central Corridor (Madhya Pradesh-Chhattisgarh):** Centered on the Singrauli and Korba coal fields, this corridor can supply clean hydrogen directly to regional fertilizer plants and chemical facilities, reducing their reliance on imported natural gas feedstocks.

### Carbon Dioxide Transport Networks

Transporting captured CO<sub>2</sub> from inland gasification plants to suitable geological storage sites requires dedicated infrastructure. While truck or rail transport can support small-scale pilot projects, a mature blue hydrogen industry will require high-pressure steel pipelines to transport supercritical CO<sub>2</sub> continuously.

Designing these networks requires careful routing to avoid highly populated areas and complex terrain. Engineers must also manage specific thermodynamic risks, such as preventing phase changes within the pipeline and mitigating the risk of ductile fractures by maintaining constant operating pressures above the critical point of CO<sub>2</sub> (73.8 bar, 31.1°C).

### Geological Storage Assessment

To validate long-term storage viability, detailed site characterization is required across India's primary sedimentary basins. These assessments focus on measuring porosity, permeability, and the structural integrity of overlying caprocks (such as thick shale formations) to prevent any upward migration of injected CO<sub>2</sub>.

**Table 3:** Geological Storage Assessment

| Target Geological Basin           | Primary Storage Type           | Estimated Capacity Potential | Key Technical Risk Parameters                              |
|-----------------------------------|--------------------------------|------------------------------|------------------------------------------------------------|
| Cambay Basin (Gujarat)            | Depleted Reservoirs / Aquifers | Moderate-High                | Complex faulting networks, high geothermal gradients       |
| Krishna-Godavari (KG) Basin       | Deep Offshore Formations       | Very High                    | Deepwater operations, high injection pressure requirements |
| Indo-Gangetic Foreland Basin      | Deep Saline Aquifers           | Extensive                    | High structural variability, proximity to seismic zones    |
| Mahanadi Basin (Onshore/Offshore) | Saline Formations / Coal Seams | Moderate                     | Low permeability in certain deep strata                    |

### Policy Frameworks, Strategic Roadmaps, and Environmental Lifecycle Assessments

Developing a viable local blue hydrogen industry requires a combination of supportive government policy, clear regulatory frameworks, and thorough environmental lifecycle assessments to ensure real net emissions reductions.

#### Aligning with the National Green Hydrogen Mission

While India's National Green Hydrogen Mission focuses primarily on renewable pathways, incorporating affordable blue hydrogen into the national strategy can accelerate the transition of hard-to-abate sectors. Blue hydrogen can

supply immediate, high-volume clean energy to refineries and fertilizer plants, helping establish hydrogen transport infrastructure, storage facilities, and utilization standards while green hydrogen production scales up and reduces in cost.

#### Recommended Policy Mechanisms

To attract private capital and lower investment risk for large-scale blue hydrogen projects, several policy mechanisms should be considered:

**Carbon Intensity Standards:** Implementing a technology-neutral framework that defines and certifies hydrogen based

on its lifecycle carbon intensity (e.g., kg CO<sub>2</sub> e/kg H<sub>2</sub>). This approach encourages adoption by focusing on net emissions reductions rather than specific production technologies.

**Production Tax Credits (PTCs) and Viability Gap Funding (VGF):** Providing target financial incentives or capital subsidies for early-stage integrated gasification and CCUS projects to offset initial (CAPEX) penalties.

**Concessionary Coal Linkages:** Offering stable, long-term coal supply agreements at concessional pricing for gasification facilities that achieve verified carbon capture rates above 90%, improving long-term operational predictability.

#### Lifecycle Environmental and Sustainability Assessments

To ensure that coal-to-blue-hydrogen pathways deliver genuine climate benefits, projects must be evaluated using full Lifecycle Assessments (LCA) from mine to end-use. This evaluation must account for:

**Upstream Methane Fugitive Emissions:** Methane leakage during coal mining and transportation must be minimized, as methane has a high global warming potential that can erode the carbon benefits of downstream capture.

**Verified Carbon Capture Efficiency:** Ensuring that the AGR and storage systems maintain high capture rates (>90-95%) under continuous operating conditions.

**Sustainable Ash Management:** Developing clear frameworks for recycling the high volumes of gasifier slag and ash into stable construction materials, preventing local soil and water contamination.

#### Conclusion

Decarbonising domestic coal through high-efficiency gasification coupled with CCUS offers a pragmatic and affordable pathway for accelerating India's transition to a low-carbon economy. By leveraging abundant indigenous coal assets, India can produce blue hydrogen at a levelized cost (LCOH) that is highly competitive with imported fossil fuels and significantly lower than current green hydrogen pathways.

While high ash content and high ash fusion temperatures present real technical challenges for processing Indian coal, advanced gasification systems particularly optimized fluidized-bed and modified entrained-flow reactors offer proven technical solutions. When paired with sour water-gas shift kinetics, modern acid gas removal systems, and permanent geological storage, this approach can deliver reliable, base-load hydrogen while mitigating greenhouse gas emissions. As India balances its energy trilemma, developing a dedicated blue hydrogen infrastructure can bridge the gap between fossil-fuel dependence and a renewable-energy future.

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