Transforming India's fertiliser production with green ammonia

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About Climate Analytics

Climate Analytics is a global climate science and policy institute. Our mission is to deliver cutting-edge science, analysis and support to accelerate climate action and keep warming below 1.5°C.

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Executive summary

India's fertiliser sector is a cornerstone of its food security, but its high import dependence and subsidy burden create significant macro-economic strain. India is the world's second-largest consumer and third-largest producer of fertiliser. However, the sector's foundation is increasingly unstable. The current production model for nitrogenous fertilisers relies heavily on “grey” ammonia, which is produced using primarily imported liquefied fossil gas (LNG). This dependency creates a set of interconnected risks for India:

1. **Economic risk:** Exposure to volatile global energy prices, leading to unpredictable production costs and a massive subsidy burden.
2. **Supply chain risk:** Reliance on imports for a critical agricultural input, which creates balance of payment risks and exposes the food supply chain to geopolitical shocks.
3. **Environmental and climate risk:** The high emissions from production jeopardise India's climate commitments, including its net-zero goal.

This report presents a techno-economic analysis of decarbonisation pathways for India's fertiliser sector. It compares the conventional business-as-usual (BAU) grey ammonia pathway with two alternatives: a carbon abated business-as-usual (CA-BAU) pathway using carbon capture and storage (CCS) to produce blue ammonia, and a real zero pathway that uses renewable electricity to produce green ammonia.

The analysis conclusively demonstrates that the real zero pathway is the most viable, economically advantageous, and strategically sound solution for India's future. Among the outlined pathways, the real zero approach is the only one which addresses all three risk dimensions identified above. Real zero reduces fiscal exposure by decoupling costs (and subsidies) from global gas price volatility, India’s core economic vulnerability in the fertiliser sector. To address the supply chain risk factor, real zero strengthens supply security by lowering dependence on imported LNG and related balance-of-payments/geopolitical risks. And, crucially, real zero is the only pathway that fully cuts process emissions, aligning the sector with India’s net zero ambitions.

Key findings

The analysis reveals that while grey ammonia currently holds a slight cost advantage, a decisive economic and technological shift is underway. The real zero pathway is not a distant aspiration but an imminent reality with clear benefits.

- **Green ammonia is on a clear trajectory to cost less:** The primary driver of this transition is the dramatic and ongoing cost reduction in renewable energy and electrolysis technology. Our quantitative analysis models levelised cost of ammonia (LCOA) for green production in 13 of India's 28 states. By 2034, our modelling indicates that green LCOA falls below grey LCOA in 10 of these 13 states. In states with high renewable potential, such as Gujarat and Rajasthan, this crossover is expected to happen as early as 2030, establishing them as leaders in a decarbonised fertiliser industry.
- **The real zero pathway is economically advantageous:** The blue ammonia pathway, reliant on LNG and CCS, is found to be less efficient and economically less competitive, and given the imminent competitiveness of green ammonia, would not make sense even as a transitional step. It also fails to eliminate the core problem of dependence on volatile fossil gas prices and upstream emissions. The economies of scale of CCS technologies is still to be proven and its capture rates are often far lower than claimed. Furthermore, with no significant government investment or policy push for CCS in this sector, it does not represent a viable path for India.

Green ammonia, by contrast, eliminates emissions and fossil fuel dependency at the source.

- **Multiple co-benefits enhance the economic case:** The transition to green ammonia offers benefits far beyond emissions reduction. It will drastically reduce the nation's import bill for LNG, insulate the agricultural sector from global energy shocks, and alleviate the immense pressure of fertiliser subsidies on the national budget. This creates a more resilient and self-sufficient economy.

  Minimal impact on consumers, maximum impact on sustainability: The analysis shows that even a significant increase in the cost of ammonia would translate to a negligible price increase for the end consumer of food products. This presents a powerful opportunity for food brands and retailers to decarbonise their supply chains at a minimal cost, meeting growing consumer demand for sustainable products.

- **Supportive policies are accelerating the transition:** The Indian government has already laid a strong foundation for this shift. The National Green Hydrogen Mission (NGHM) and its associated incentive schemes, such as the Strategic Interventions for Green Hydrogen Transition (SIGHT) programme, are effectively de-risking private investment and stimulating the development of a domestic green hydrogen ecosystem. These policies are critical enablers that are already yielding results, with competitive bids in recent green ammonia auctions signalling strong market confidence.

India should prioritise and scale investment in states with the strongest renewable resources and existing infrastructure to build large, cost-competitive green ammonia hubs. Policy and financial incentives should be strengthened across the full green hydrogen value chain – from renewable generation and electrolyser manufacturing to storage and transport – including measures to lower the weighted average cost of capital (WACC) for green technologies.

Parallel efforts should foster innovation and domestic manufacturing of next generation electrolysis and other critical components to cut costs, create skilled jobs, and reinforce India's technological leadership. Finally, India could develop green fertiliser markets by encouraging farmer uptake and creating demand for low-carbon food products at home and for export, with corporations playing an important role.

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Background

Of the hard-to-abate sectors, synthetic fertiliser production underpins global food security. Since its introduction in the first half of the 20th century, Haber-Bosch has remained the primary method for producing ammonia, a key input for synthetic nitrogenous fertilisers. Among commercially viable methods, the Haber-Bosch process remains the most energy-efficient large-scale option for producing ammonia at current demand levels (Erfani et al., 2024). It plays a vital role in feeding roughly half of the world's population, accounting for about 0.82% of global annual greenhouse gas (GHG) emissions from production and around 2.1% of total lifecycle emissions (Menegat et al., 2022).

As the production pathway currently exists, process emissions from ammonia production are unavoidable. Ammonia is produced by combining nitrogen and hydrogen in a Haber-Bosch synthesis reactor at high-temperature and pressure. Hydrogen is produced from the steam methane reforming of methane/fossil gas or through coal gasification, producing 9-12 kg of CO_2 for every kg of hydrogen (Comparison of the Emissions Intensity of Different Hydrogen Production Routes, 2023). Globally, nitrogenous fertiliser manufacturing consumes around 3-5% of annual fossil gas demand. Of that amount, 65% is used as feedstock for the synthesis of ammonia used to produce fertiliser (Kayalıoğlu, 2022). Additionally, the overall process is energy intensive, operating at high temperatures and pressures. The contemporary process is designed to operate at continuous and steady outputs to increase efficiency. The continuous demand of energy to maintain the conditions necessary for the Haber-Bosch reaction makes the process challenging to electrify using variable renewable sources (Wang et al., 2023). However, electrification is feasible when paired with renewable hydrogen, electrified utilities, and appropriate buffering (e.g., H_2/NH_3 storage) and flexibility measures, which allow the process to run reliably on renewable power.

India is the second-largest consumer of fertilisers in the world (Ritchie et al., 2023). Over the last decade, domestic fertiliser production has grown at a steady rate, increasing from 38.54 million metric tonnes (mmt) in 2014/2015 to 50.34 mmt in 2023/2024 (Government of India, Press Information Bureau, 2025). Domestic production emits roughly 0.58 tCO_2 per tonne of fertiliser it produces, which resulted in about 29 $MtC0_2$ in FY 2023-2024 (Patidar et al., 2024). The Indian government views the fertiliser sector as a strategic pillar of its domestic food capacity and economic security. Agriculture contributed 18.2% of the nation's GDP in 2024 and has continued to support over 40% of the country's workforce throughout the previous decade (Press Information Bureau, 2024; O'Neill, 2025). Policy moves taken by the federal government reflect the degree of importance placed on maintaining domestic production capacity (Press Information Bureau, 2024a).

India's overall consumption of nitrogenous fertilisers far outpaces its domestic production, with total domestic demand for fertilisers reaching approximately 144% of domestic production capacity in 2022 (World Bank, 2025). To bridge the gap between supply and demand, India has turned to imported fertilisers, costing the country USD 9.84 billion in 2024 (second-largest imported fertiliser value in the world) (Jaganmohan, 2024). However, to meet the ammonia demand of the fertiliser sector, India is reliant on the import of liquefied fossil gas (LNG). The production cost of ammonia, a necessary feedstock for nitrogenous fertiliser, is corelated to the price of fossil gas from which it is derived. The relationship between LNG, ammonia, and the ammonia derived fertiliser urea (the dominant fertiliser in India) is visualised in Figure 1. In 2023, roughly 77% of the fossil gas required for domestically manufactured fertiliser was met by imported LNG, up 21% from 2020 (Kothadiya et al., 2024). As demand for fertiliser is set to increase over the course of the decade, India is forecasted to see a 60% rise in fossil gas demand by 2030 (India Gas Market Report, 2025).

India's reliance on LNG imports to meet the needs of its growing fertiliser demand creates macro-economic strain and undermines the country's food security, while also undercutting its stated climate ambitions. Price volatility within the fossil gas market, particularly since the onset of the Russia-Ukraine war in 2022, has cost the Indian government billions of USD in subsidies to insulate the fertiliser sector from price shocks in the trade of LNG (Shah, 2022).

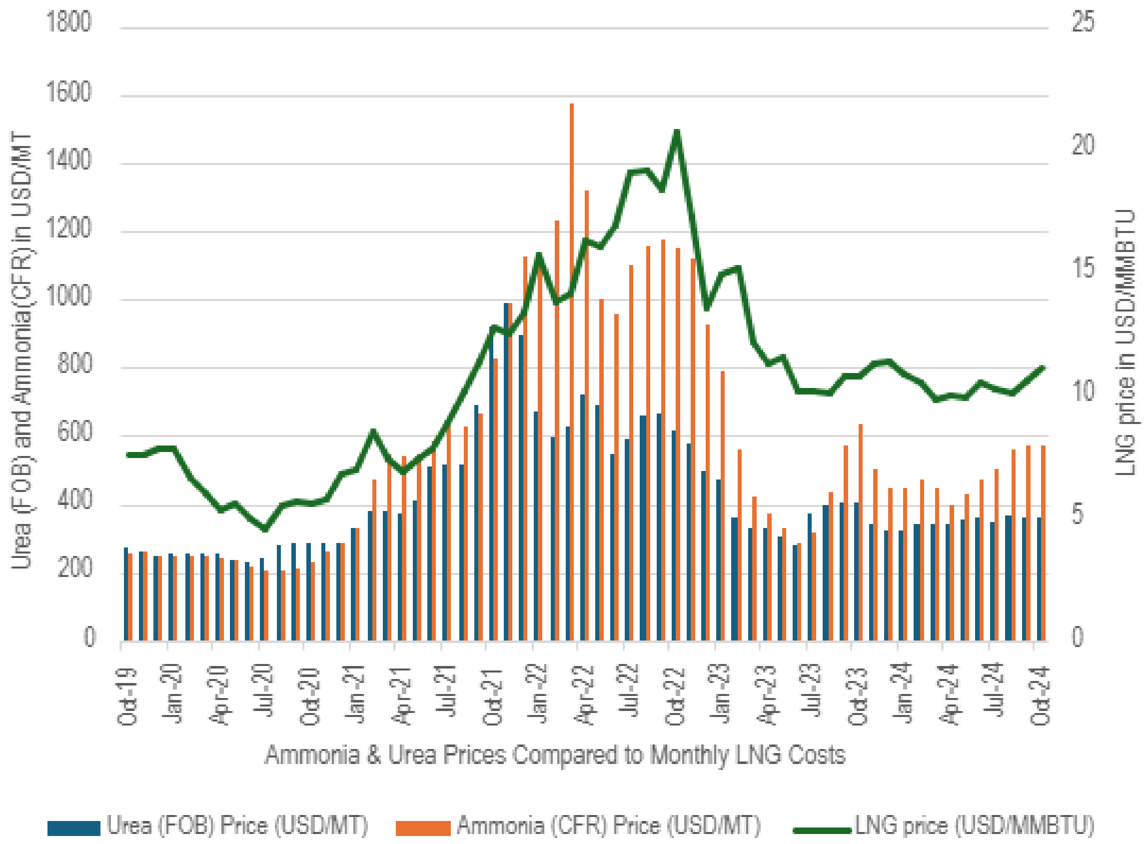


Figure 1: Analysis of LNG prices against the price of ammonia and urea in India, 2019 thru 2024. The fossil gas market shock of 2022 is clearly visible, with domestic ammonia and urea prices also rising Source: Department of Chemicals and Petro-chemicals, 2025; Petroleum Planning and Analysis Cell, 2025.

Meanwhile, annual growth in fertiliser demand and production comes with ever increasing levels of sectoral emissions. In FY 2023-2024, urea production in India reached 31.407 MT per annum, growing from 22.5 MT per annum in FY 2014-2015 (Press Information Bureau “New Investment Policy 2012”, 2024). Estimates of the Indian fertiliser sector determine that ~0.58 tonnes of CO_2 are emitted for every tonne of fertiliser produced, meaning production growth alone added ~5 $MtCO_2$/yr over this timespan (Patidar et al., 2024). Given the growth trajectory of fertiliser demand, with the whole of the domestic market anticipated to grow at a CAGR of 4% between 2025 and 2033 (Lal, 2025), and the emissions intensity of the business-as-usual (BAU) production methods, increases in sectoral emissions could outpace emissions reductions across other sectors, jeopardising India’s stated emissions reduction goals (*Climate Action Tracker - India*, 2025). A BAU approach with ammonia production will cost the sector economically and undo progress made toward India’s stated climate goals.

However, BAU is not inevitable for India. Several factors give India an advantageous route toward a real zero fertiliser sector, where emissions are completely removed from the production of nitrogenous fertilisers at the source. One advantage is the country's ample access to renewable energy which sets India up with a competitive advantage for producing green electricity used in fertiliser production. Additionally, federal ministries have formalised policies focused on enabling domestic green hydrogen and green ammonia production.

Green ammonia itself is not new to India. In fact, electrolysis-based ammonia was prominent in global ammonia production during the first half of the 20th century. By the 1960s, economic conditions and increasing demand contributed to the displacement of the original green ammonia facilities with fossil fuel-based production, particularly fossil gas. Green ammonia production began in India as early as 1958 at a facility in Nangal in the northern part of the country, deriving its electricity from the nearby Bhakra Dam (Rouwenhorst et al., 2022).

Great potential and economic incentive for immediate emissions reductions for fertiliser production in India exists now. This can be accomplished by returning the country's ammonia production back to electrolysis and away from imported LNG. Analysing the long-term trajectory of decarbonisation pathways for ammonia, this case study determines that a transition involving real zero technologies – eliminating all emissions at the sector level – is technically feasible and economically advantageous. This can be achieved through zero-emission ammonia production methods, such as the use of green hydrogen, and has significant momentum to achieve cost parity with grey ammonia production.

The life cycle emissions of synthetic fertilisers and the scope of this study

In 2018, the supply chain of nitrogenous fertilisers accounted for 2.1% of global GHG emissions, with the Indian fertiliser sector the second-largest emitter among producing countries, after China (Menegat et al., 2022). The fertiliser production in India contributes ~25 million tonnes of CO_2 annually, about 1% of the country's total GHG emissions (Patidar et al., 2024). Emissions from nitrogenous fertilisers can be divided into three core phases: emissions resulting from the production of fertilisers, including the production of the hydrogen feedstock and the nitrogen synthesis; the transportation of the finished product to the consumer; and process emissions associated with the application of fertilisers to the soil.

Transportation of nitrogenous fertiliser from production to use sites accounts for the lowest amount of emissions at 2.6% of global lifecycle emissions. The bulk of nitrogenous fertiliser emissions can be attributed to the production and application phases. Application alone accounts for approximately 58.6% of the overall lifecycle emissions (Menegat et al., 2022). When applied to soil, nitrogen fertilisers release nitrous oxide (N_2O), a potent GHG with a global warming potential nearly 300 times that of CO_2.

This case study focuses exclusively on the production-phase greenhouse gas emissions of fertiliser, particularly those arising from ammonia production. The production stage – including both the steam methane reforming (SMR) for hydrogen production and the Haber-Bosch process for ammonia synthesis – accounts for approximately 38.8% of the total lifecycle GHG emissions associated with nitrogenous fertiliser. In conventional systems, this production step is highly emissions-intensive due to both direct emissions from the methane reforming process and significant Scope 2 emissions from the energy required for the Haber-Bosch process.

It is important to emphasise that ammonia is the single most critical leverage point for decarbonizing India's vast agricultural sector. It serves as the fundamental chemical feedstock to produce nearly all nitrogen-based fertilisers. This includes urea and di-ammonium phosphate (DAP), the production of which is currently an energy- and emissions-intensive process reliant on fossil fuels. Therefore, any credible analysis of agricultural decarbonisation must begin by analysing the decarbonisation pathway for ammonia.

Ammonia production pathways: grey, blue, and green

To decarbonise the fertiliser industry, we must first understand the different ways ammonia is produced. Ammonia is the fundamental building block for virtually all nitrogen-based fertilisers and typically represents a significant share of their final production cost. The industry uses a colour-coded system – “grey, blue, and green” – to classify ammonia based on two key factors: how its hydrogen is sourced and what happens to the resulting CO_2 emissions. Each colour corresponds to a different climate scenario in this report: business-as-usual (BAU), carbon abated business-as-usual (CA-BAU), and real zero.

Additionally, real zero strictly equates to the production phase of fertiliser in the context of this paper. The definition does not include GHG emissions resulting from the use of fertilisers. Emissions from the application phase would not be meaningfully mitigated by a shift to green ammonia-based production since nitrogenous fertilisers, whether derived from green or grey ammonia, have comparable emissions profiles at the application stage (Menegat et al., 2022).

Grey ammonia (business-as-usual / BAU)

Grey ammonia is the conventional and most common method used today, representing the industry's standard, high-emissions process. Grey ammonia production starts with fossil gas (methane). In a process called steam methane reforming (SMR), fossil gas is reacted with high-temperature steam to strip away its hydrogen atoms. This process is extremely energy-intensive and uses even more fossil gas as a fuel to generate the required heat.

This method produces a significant amount of CO_2 as a direct by-product. This CO_2 is simply vented into the atmosphere, making grey ammonia a major contributor to GHG emissions.

Blue ammonia (carbon abated business as usual / CA-BAU)

Blue ammonia starts the same way as grey ammonia, using fossil gas to produce hydrogen. However, it adds a critical production step: carbon capture and storage (CCS). Instead of being released, the CO_2 produced during the process is captured.

The captured CO_2 is either permanently stored deep underground or recycled for other industrial uses (with eventual, delayed, release into the atmosphere). For example, in fertiliser production, the captured CO_2 is a key ingredient for synthesising urea. While urea plants in India source the CO_2 needed for production from process emissions generated during ammonia production, this does not meaningfully mitigate overall emissions. Deployed CCS technologies currently operate at efficiency levels far below what would be required for blue ammonia production to become a viable pathway for reducing sectoral emissions in line with India’s climate targets. Proponents of CCS often claim target capture efficiencies of 90% or higher of total CO_2 emissions from the production plant, and government policies often take this at face value (Longden et al., 2022, p. 3). The observable capture efficiency rates at plants outfitted with CCS are often much lower, ranging from <40% to ~70%, dependent on how the plant is outfitted (Schlissel & Juhn, 2023).

The outfitting of CCS touches upon the issue of scope. Hydrocarbon-derived hydrogen production is considered an ideal candidate for CCS because the form of CO_2 emissions, released in a concentrated stream from the facility, is considered optimal for capture. However, Longden et al. (2022) found that applying CCS to this stream only results in potential emissions reductions of around two-thirds from the total emissions. Emissions from fossil gas combustion of methane to provide thermal energy to the SMR process are released via a diluted flue gas stream. This discharge method is considerably more difficult and costly to mitigate (Schlissel et al., 2022).

Blue ammonia's continued reliance on fossil gas feedstock involves upstream and downstream methane emissions inherent to the use of fossil fuels. Per unit of mass, methane is 84-86 times more potent than CO_2 as a greenhouse gas over a 20-year period, and about 35% of all anthropogenic methane emissions are rooted in the continued use of fossil fuels (McSweeney, 2020; United Nations Environment Programme and Climate and Clean Air Coalition, 2021). Fossil gas extraction, transportation to facilities, and process leakage contributes considerable methane emissions that would otherwise not be produced in a green ammonia supply chain (Howarth, 2024).

As of publication, the central government in India is not invested in any meaningful program for the deployment of CCS in the ammonia and fertiliser sectors. There is no indication or evidence that authorities are considering CCS for these sectors in the future.

Green ammonia (real zero)

Green ammonia is the ideal, long-term solution for a truly decarbonised fertiliser industry, achieving real zero by avoiding fossil fuels altogether. Green ammonia completely redesigns the first step. Instead of fossil gas, it starts with water (H_2O) and renewable electricity (from solar or wind) to produce hydrogen. Using a process called electrolysis, the electricity is used to split water molecules into hydrogen and oxygen. This clean hydrogen is then used to produce ammonia.

Since the only inputs are water and renewable energy, the entire process is virtually emissions-free, if electricity is sourced from renewables. This pathway eliminates the production-related GHG emissions at the source.

A closer look at electrolysis

Electrolysis is the core technology for green hydrogen. The two leading approaches are:

1. **Alkaline water electrolysis (AWE):** A mature and cost-effective technology that has been used for nearly a century. It uses a liquid alkaline solution (such as potassium hydroxide) to help conduct the electric current that splits the water.
2. **Proton exchange membrane (PEM) electrolysis:** A newer technology that uses a solid polymer membrane to separate the hydrogen and oxygen. While currently more expensive, it is very responsive, making it well-suited to the fluctuating output of renewable energy sources like wind and solar.

Table 1: The table summarises the key differences and the resulting greenhouse gas (GHG) intensity for each production pathway. Source: Ammonia Technology Roadmap, 2021, p. 33.

Greenhouse gas emissions by ammonia production pathway

Ammonia Type	Production Method	CO_2 Handling	GHG Intensity of Production (tCO_2eq per tonne of Ammonia)
Grey (BAU)	Natural Gas (SMR)	Vented to atmosphere	High (>1.6)
Blue (NZ)	Natural Gas (SMR) + Carbon Capture	Captured and stored/utilized	Low (0.1 - 0.6, with high uncertainty depending on capture rate)
Green (RZ)	Water Electrolysis + Renewable Energy	No fossil-fuel CO_2 produced	Near-Zero (<0.1)

Risks and opportunities for real zero fertiliser production

Staying within the BAU scenario brings with it a number of risks for India. At the same time, the country has a number of opportunities that can help it in transitioning to real zero ammonia production. This section highlights both of these risks and opportunities in more detail.

Risk 1: India's import dependency in BAU

India's fertiliser sector faces a double-edged dependency problem: the country relies heavily on imports for both finished fertilisers and the raw materials needed to produce them locally. For urea, the most widely-used fertiliser in India, the country has a huge domestic industry producing around 28.5 million tonnes per year (Patidar et al., 2024, p. 12). Yet, this is not enough to meet the demand, requiring the import of an additional 9.3 million tonnes in the 2022-23 financial year (Patidar et al., 2024, p. 17). The situation is even more critical for other fertilisers like phosphates and potash, as India lacks its own natural reserves of the key raw materials. Consequently, about 40% of these non-urea fertilisers are imported directly, a share that has been steadily growing (Patidar et al., 2024, p. 13). This reliance on imports supports a massive market, which was valued at over USD 41 billion and is projected to grow to over USD 70 billion by 2032 (Sood, 2025).

The biggest vulnerability, however, is hidden within India's "domestic" production itself. The local urea industry runs almost entirely on fossil gas, and a staggering 77% of this gas was imported in the form of liquefied fossil gas (LNG) in 2022-23. This directly ties the price of locally-made fertiliser to volatile global energy markets. Gas can account for as much as 70-80% of total production costs, depending on feedstock prices and energy efficiency of the plant (Jain, 2022). This complex web of dependencies – importing finished products, raw materials, and the energy to process them – creates significant risks. When global prices spike, as was the case during the Russia-Ukraine war, the cost is ultimately borne by the government to keep fertilisers affordable for farmers.

Risk 2: Rising subsidies linked to grey ammonia

To keep fertilisers affordable for farmers while ensuring stable supply, whether produced domestically or imported, fertiliser subsidies constitute a significant component of India's total subsidy expenditure. The price of urea is regulated in India; the government fixes its maximum retail price (MRP) nationwide and reimburses producers and importers for the difference between this price and the actual cost of production or import plus distribution.

Since the start of the decade, the overall amount India pays to subsidise fertiliser access for its farmers has increased. For the 2025/26 fiscal year, the government has earmarked nearly 70% of its total agricultural budget to finance the fertiliser subsidy programme (Ministry of Finance, Government of India, 2025). From 2010 through 2019, India's average fiscal budget for the fertiliser subsidy was USD 11.4 billion. Since 2020, that amount has doubled to an average of USD 22.5 billion annually.

As can be seen in Figure 2, the price volatility in LNG is highly correlated with fertiliser subsidies. The dependency on LNG exacerbates exposure to volatile global gas markets and foreign exchange risk. Because many urea and ammonia inputs depend on imported LNG or imported ammonia, any spike in global gas or ammonia prices or depreciation of the rupee can sharply raise the true subsidy cost for the state. In response to the global gas price spike, the government spent USD 30.5 billion on fertiliser subsidies in FY2023. Earlier this year, as tensions simmered in the Middle East and the potential closure of the Strait of Hormuz cast a shadow on global LNG trade, India's exposure to the resulting market volatility again made domestic headlines (Reynolds & Jain, 2025; S. Sharma, 2025).

The subsidy regime for fertiliser carries additional environmental and food security risks that extend beyond purely economic implications. A recent study by Sapkota and Bijay-Singh (2025) found that the existing scheme and the guaranteed MRP encourages overuse or misallocation of urea, degrading soil health, increasing leaching and runoff, and reducing marginal yield gains over time (Sapkota & Bijay-Singh, 2025). The overuse of urea also contributes to additional application emissions resulting from ammonia volatilisation, the process where nitrogen is lost from soil to the atmosphere as ammonia gas (NH_3).

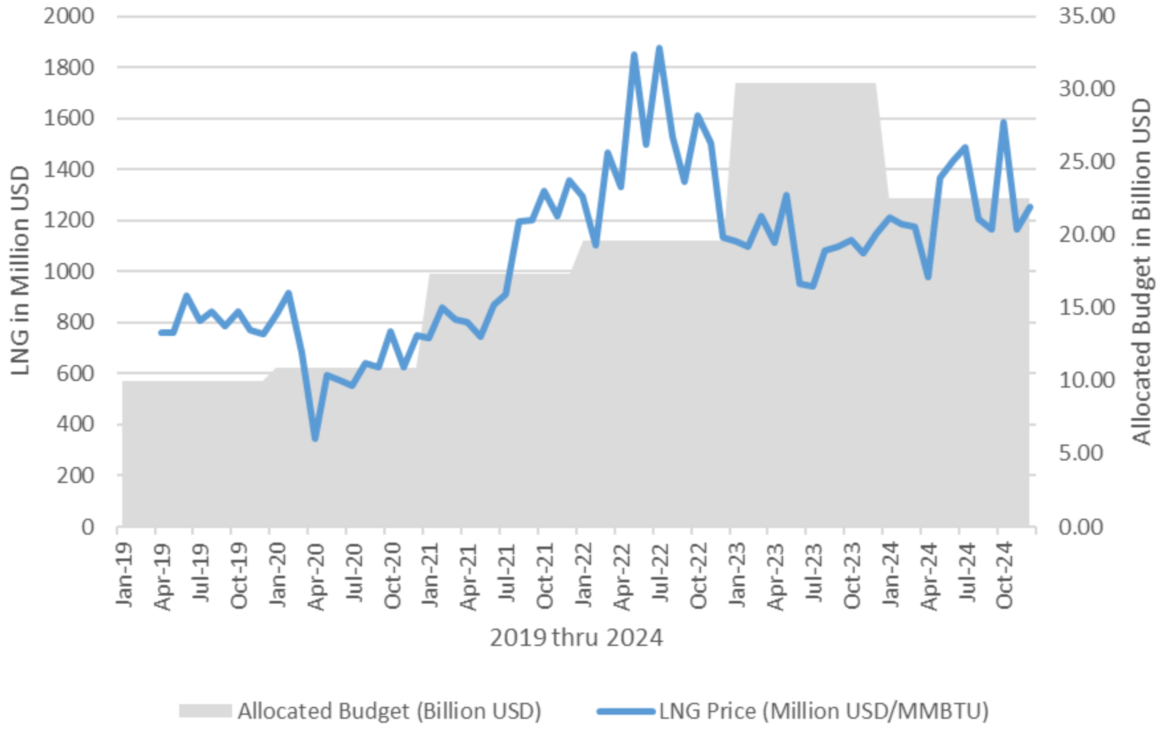


Figure 2: Analysis of LNG spot prices against the annual budget allocation by The Ministry of Chemicals and Fertilisers (Department of Fertilisers) for the fertiliser subsidy (Ministry of Finance, Government of India, n.d.; Petroleum Planning and Analysis Cell, 2025).

As mentioned above, not only are there risks associated with staying in the BAU scenario, but there are also key opportunities for India that can drive it towards a real zero scenario.

These opportunities include rapid cost decline of renewables, declining costs of electrolysis and a welcoming policy environment.

Opportunity 1: Rapid cost decline in the price of renewables

Solar capacity in India, 2000-2024 (GW)

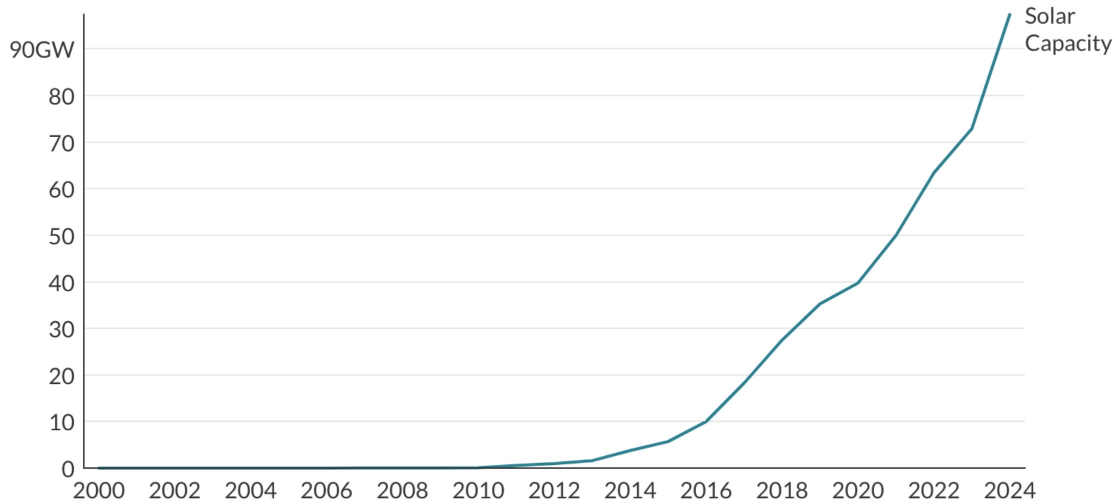


Figure 3 India's cumulative installed solar capacity, measured in gigawatts (Ember, 2025).

Considering India's ambitious renewable capacity target of 600 GW by 2031-32, the falling tariff of renewables, particularly solar, provides ample opportunity to develop a green hydrogen economy. Solar capacity in India has grown significantly over the last 15 years, reaching near 100 GW (2010: <1GW) in 2024 (Ember, 2025). Over the same time period, India's wind capacity has more than tripled, amounting to approximately 48 GW. According to the IEA, India is among the world's leading countries for both solar PV and wind capacity and is projected to have the fastest renewable energy market growth among large economies through 2030 (IEA, 2024b, pp. 8, 45).

To fulfil its growing solar energy capacity, domestic manufacturing of solar modules and cells is expanding in parallel (Sengupta, 2025). In order to offset an import dependency, the Indian government has been aggressively implementing policies to incentivise domestic solar production. This has included lucrative subsidies for locally produced solar cells and batteries and restricting foreign products in certain renewable energy projects. Projections by SolarPower Europe (2025) estimate that the country's photovoltaic module manufacturing capacity is set to increase from 80 gigawatts in 2025 to 160 GW by 2030 (Hemetsberger et al., 2025, Section 4.4 India).

The government has also prioritised growing its domestic wind turbine manufacturing, modelled off of its solar manufacturing policies (Asian Power, 2025). In 2025, the Ministry of New and Renewable Energy adopted measures requiring Indian wind turbine manufacturers to realign their component supply chains toward domestic sources. At least 64% of wind turbine components by cost must be sourced domestically. This buildout of domestic renewable energy manufacturing is a crucial factor in ensuring the country attains greater energy security particularly as a shift to green ammonia brings reduced dependence on imported LNG.

The significant increase in capacity in both utility-scale solar PV and (onshore) wind was accompanied by remarkable cost declines (IRENA, 2022). Solar PV saw the steepest drop, with a global learning rate of 33%, driven by its modular design, rapid manufacturing innovation, and unprecedented scale-up. Solar electricity prices in India dropped from around USD 240/MWh in 2010 to just over USD 30/MWh by 2022 (Garg et al., 2022). Wind (onshore) has also seen similar success, with a learning rate of 20.6% thanks to regional supply chain maturity, advances in manufacturing, and competitive project procurement (IRENA, 2022, p. 56).

As of 2023, the total renewable generation capacity of India is around 175 GW installed, representing 37% of its total generation capacity. This includes 47 GW of hydro, 10 GW of bioenergy, 45 GW of wind, and 73 GW of solar, with about half of its solar capacity installed in just the last three years (Ministry of Power, Government of India, 2025). Over the last five years, India has installed more new annual generation capacity for wind and solar than for coal at an average of 11 GW compared to 3.9 GW respectively (Graham et al., 2025, pp. 43–45).

Opportunity 2: Declining cost of electrolysis

Falling costs of renewables is not the only part of the equation for making green ammonia more cost competitive with grey ammonia, the other key element is falling cost of electrolysis. Though the decline here is not comparable to that of solar and wind, electrolysers have exhibited learning rates of 16-21%, with a typical estimate around 18%, meaning costs fall by about 18% for every doubling of cumulative capacity (IRENA, 2020).

India aims to establish a domestic electrolyser manufacturing capacity of 15 GW by 2030 to meet the projected demand for green hydrogen production (*India | Green Hydrogen Organisation*, n.d.). Recent developments in India exemplify this acceleration, with several world-scale projects reaching Final Investment Decision (FID). Among the most significant is the one-million-ton-per-annum green ammonia project in Kakinada, India under AM Green Ammonia. Announced in August 2024, this project commits to a 1.3 GW electrolyser facility, integrated with an existing fertiliser plant (IEA, 2024a, p. 69).

The Green Hydrogen Transition (SIGHT) programme is an incentive scheme targeting domestic electrolyser manufacturing and green hydrogen production. SIGHT aims to identify and develop regions capable of supporting large-scale production and provide financial support for the development of the necessary infrastructure for these hubs. The scheme was budgeted at USD 2.1 billion at its inception and has been met with enthusiasm from the private sector. Under both the electrolyser manufacturing and green hydrogen production components, SIGHT received bids far exceeding the initial targets (Gulia et al., 2024). Aimed at boosting domestic manufacturing, the Production-Linked Incentive (PLI) scheme extended for electrolysers manufacturing as well, offering subsidies to selected companies.

Both alkaline and PEM technologies have seen substantial global cost declines, with alkaline electrolyser costs falling from about USD 1,500/kW in 2010 to USD 800/kW in 2022, and PEM costs dropping from USD 2,000/kW to USD 1,250/kW until 2020. Projections suggest that with continued large-scale deployment, electrolyser costs could reach as low as USD 200/kW by 2030, making green hydrogen production increasingly competitive (IRENA, 2020; IRENA & European Patent Office, 2022).

Opportunity 3: Policy enabling environment

National policy interest in the domestic production of hydrogen is a key enabler for green ammonia and fertiliser production. Formalised in 2023, India's National Green Hydrogen Mission (NGHM) aims to establish the country as a global hub for the production, usage, and export of green hydrogen. The mission's target is to increase domestic clean hydrogen capabilities to five million MT annually by 2030. As the export market grows, the mission envisions those capabilities scaling to 10 million MT. NGHM has been consistently integrated in the renewable energy policy framework in the country. One of the main components of this policy is to waive the inter-state transmission charge for 25 years for green hydrogen producers, an important step towards ensuring price competitiveness of green hydrogen. The renewable energy tendering process in India is increasingly aligned with the country's goal of scaling up green hydrogen production. In August 2025, Solar Energy Corporation of India (SECI) conducted its inaugural auction for the procurement of green ammonia under the SIGHT scheme (Press Information Bureau, 2025b). This auction achieved a landmark price of INR 55.75/kg (approximately USD 641/MT), marking a substantial decrease from the previous price of INR 100.28/kg (USD 1,153/MT) discovered in the H2Global auction in 2024. This price is also closely competitive compared to the prevailing grey ammonia price of USD 515/MT as of March 2025.

Alongside SIGHT, the NGHM includes complementary measures such as pilot projects in hard-to-abate sectors (steel, shipping, and long-haul transport), the creation of hydrogen storage and transport infrastructure, and standards for safety, purity, and certification to facilitate both domestic use and international trade. The mission is closely linked to India's broader renewable energy expansion, leveraging India's advantageous (but under realised) access to solar and wind generation for electrolysis, and aligns with the nation's net-zero 2070 commitment. By lowering production costs through scale and innovation, and establishing reliable offtake mechanisms, the NGHM is expected to create a competitive green hydrogen ecosystem.

India is also considering the implementation of Hydrogen Purchase Obligations (HPOs), which would require certain industries, such as refineries and ammonia plants, to procure a specified percentage of their hydrogen from green sources (Government of India - Ministry of External Affairs, 2021). This approach, similar to Renewable Purchase Obligations (RPOs) in the electricity sector, aims to stimulate demand for green hydrogen and ensure the country meets its NGHM's targets. The proposed framework could drive significant green hydrogen demand, contributing up to 45% of the mission's 2030 target, while addressing investment risks by providing assured market demand (IH2A, 2025).

India has been engaging in international partnerships, positioning itself as a future hub for green hydrogen production. For example, collaborations with companies like Japan's ENEOS Corporation aim to establish green hydrogen supply chains, further enhancing India's competitiveness in the global hydrogen market (R. Sharma, 2025).

At the sub-national level, states like Gujarat have embraced the NGHM's objectives, with the state targeting the production of three million metric tonnes of green hydrogen by 2030 (GH2, 2024). The state of Uttar Pradesh has adopted the Uttar Pradesh Green Hydrogen Policy 2024 to promote business opportunities for green hydrogen in the state (Invest UP, 2024). These state-level initiatives are paired with localised incentives and policies aimed at fostering green hydrogen production and consumption, further reinforcing the country's transition to a low-carbon economy.

Analysis and results

Aims and objectives of this study

This case study analyses and compares the economics underpinning the adoption and scaling of green and blue ammonia production to replace grey ammonia as a feedstock in India's fertiliser sector. The following framework broadly outlines scenarios for the adoption of each production pathway:

1. **Business-as-usual (BAU):** Continued production and use of grey ammonia as a feedstock for fertiliser production.
2. **Carbon abated business as usual (CA-BAU):** Incorporation of CCS technologies into the SMR process, enabling the production of blue ammonia.
3. **Real zero:** Development and scaling of electrolysis-enabled hydrogen production replacing traditional SMR technology, allowing for the production of green ammonia.

The analysis is solely focused on the production stage of ammonia (Scope 1 and 2 emissions) and does not evaluate the emissions resulting from the use of synthetic fertilisers. Considering the scenarios outlined above, this study hypothesises the following:

1. Under the existing economics behind the adoption of CA-BAU and real zero production pathways, the levelised cost of ammonia (LCOA) of green ammonia demonstrates that real zero is more advantageous than CA-BAU for Indian firms to adopt. When factoring in learning rates for electrolysers and renewable electricity sources over time, real zero maintains and expands its economic edge over CA-BAU.
2. As green ammonia reaches an economy of scale in India and the LCOA of green ammonia continues to decline, it will attain an economical advantage over grey ammonia production. Therefore, it is expected that real zero will surpass BAU – the main question is by when and under which conditions.

Methods employed

This study explores its central hypotheses by employing a techno-economic assessment of the BAU, CA-BAU, and real zero production pathways for ammonia. These results are further corroborated with a review of existing literature on costs associated with ammonia and hydrogen production to inform the overall analysis.

For the quantitative analysis, the Modelling Tool for Production Cost of Green Ammonia in India (developed by MEC Intelligence for Deutsche Gesellschaft für Internationale Zusammenarbeit and the Indo-German Energy Forum) is utilised to estimate the LCOA under different renewable energy and plant design configurations (GIZ et al., 2024). The tool simulates techno-economic performance over the plant lifetime, incorporating capital expenditure (CAPEX), operational expenditure (OPEX), plant utilisation, and financing assumptions.

LCOA is the discounted cost of producing one kg of ammonia via the Haber-Bosch process using green hydrogen. It captures CAPEX and OPEX of the ammonia synthesis unit, the electrolyser system, renewable energy resource, and balancing/storage technologies. It is the final output metric of the tool, combining upstream costs of renewable electricity (LCOE) and hydrogen (LCOH) into the economics of ammonia production.

The three levelised cost indicators are interlinked in a sequential production chain of costs. Under the production pathway, LCOE determines the cost of renewable electricity supplied to the electrolyser stage for hydrogen production. This is built on by LCOH, where the hydrogen production costs are dependent on the price of electricity and electrolyser CAPEX/OPEX. Finally, the cost flow feeds into the LCOA, where ammonia production depends on the cost of hydrogen feedstock, additional CAPEX/OPEX for the Haber-Bosch system, and cost of N2 feedstock for the ammonia synthesis.

The tool uses 25 parameters (including 14 which can be configured to replicate varying conditions of interest) that consider plant utilisation and geography; energy source and gid connectivity; adopted policies; cost of capital; and the capital expenditure and operation expenditure. Using these parameters, LCOE and LCOH are calculated and used to determine an LCOA for green ammonia production in 2026 and 2034.

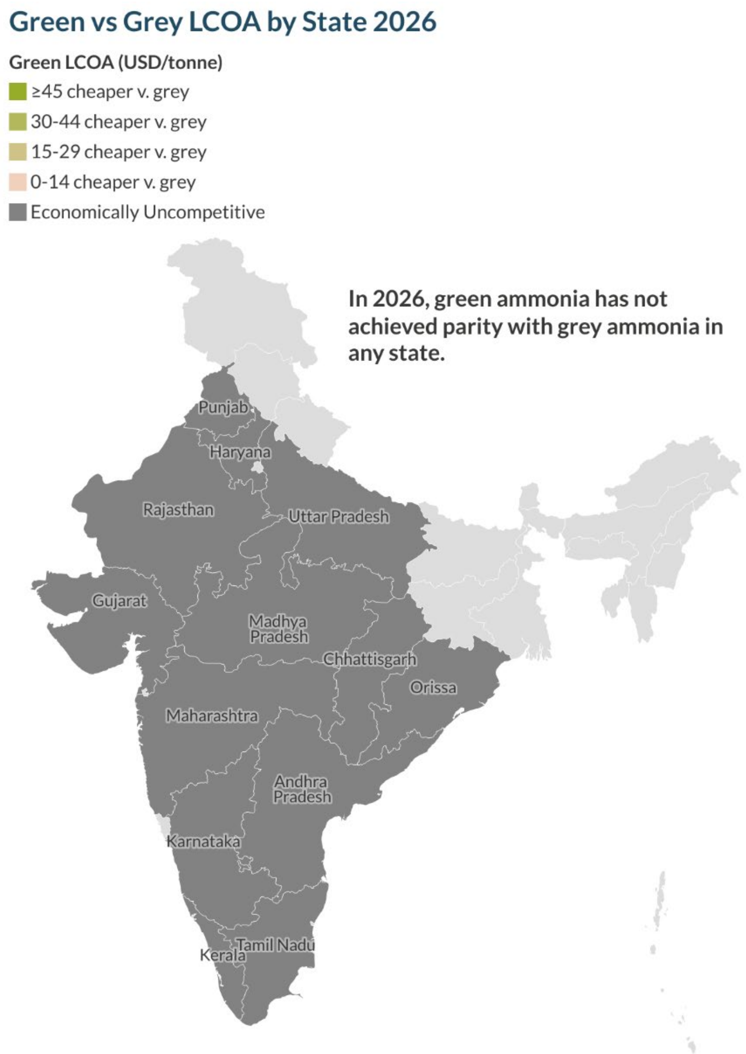
Electrolyser type is variable between alkaline and PEM systems. This analysis fixes this parameter on alkaline electrolysers, given their favoured position in the domestic market (UK India Business Council, 2023). Short to medium term domestic manufacturing is expected to be dominated by alkaline electrolyser technology given its lower capital costs and higher maturity, with decades of proven use in fertiliser production, compared to PEM electrolyser technology (Raj et al., 2022, pp. 47–48). The ammonia plant capacity is held fixed at 1000 kTPA.

To compare the findings on green LCOA for the model, we establish a baseline LCOA for grey ammonia. We hold this amount constant over 2026 and 2034 to compare with green LCOA, assuming that the production process and associated technology for grey ammonia is unlikely to see significant reductions over the next decade and costs for LNG (imports) will not change either. The Haber-Bosch process is a mature technology, having been in industrial use since the early 20th century (Erfani et al., 2024). It is well-developed and optimised, with modern plants running close to their technical limits for energy efficiency. This leaves little room for future cost reduction for grey ammonia attributable to technological improvements of this process. Instead, changes in final cost can be due to shifts in feedstock costs, energy sources, carbon pricing, and process integration. The primary driving factor in cost fluctuations for grey LCOA today is the price of LNG (Munasinghe & Krimer, 2024). The analysis assumes a static grey LCOA and fixes the price of the LNG feedstock which is the source of variation in final costs. The initial analysis does not account for the adoption of carbon pricing between 2026 and 2034, though this is explored in the price sensitivity analysis.

Renewable energy sources and ammonia production facilities are co-located in the same states for analysis. The model includes inputs for solar-derived electricity and wind-derived electricity. The analysis adjusts the renewable energy mix in each state based on the most cost-effective or resource-efficient source, or combination of sources. Lastly, we assume full grid connectivity for all facilities in the analysis. Findings from the above-mentioned bottom-up approach are further supported by an analysis of auction results covering the build out of green ammonia capacity under SIGHT.

Modelling results and analysis

State level analysis of green ammonia production

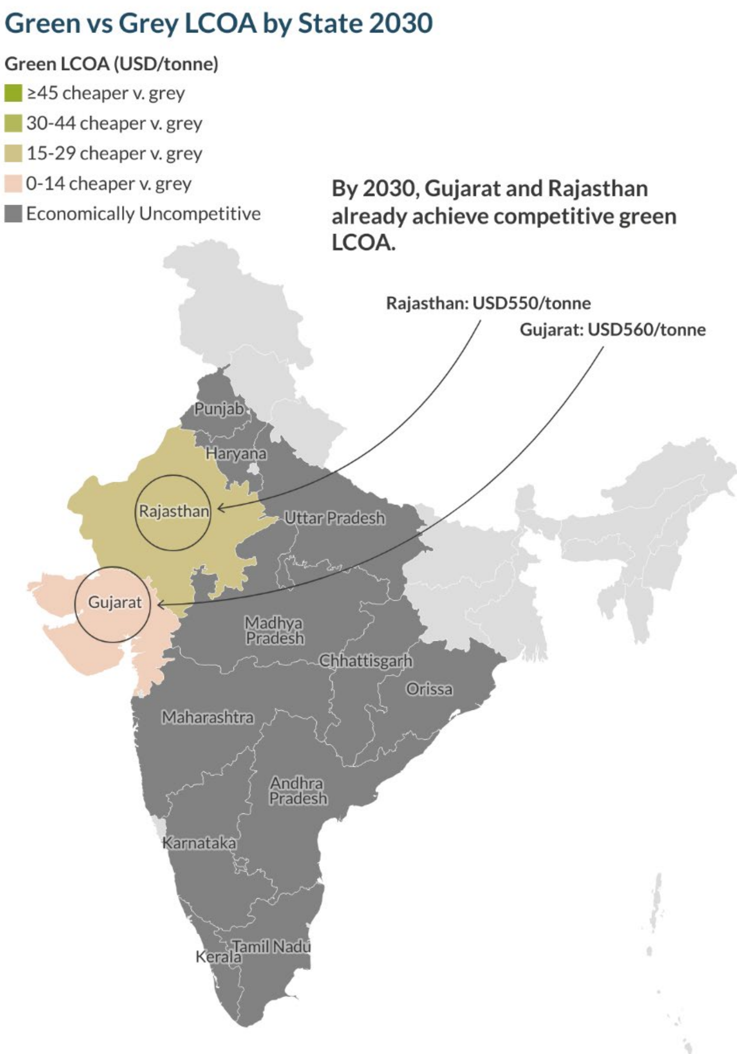


State name	LCOA (USD/tonne)
Baseline grey ammonia	573
Rajasthan	600
Gujarat	610
Chhattisgarh	640
Punjab	640
Madhya Pradesh	650
Haryana	660
Karnataka	660
Orissa	660
Maharashtra	670
Andhra Pradesh	680
Tamil Nadu	680
Uttar Pradesh	710
Kerala	760

Figure 4 Potential LCOA (2026) distribution across the thirteen states in the analysis. Values of LCOA (2026) for each state are listed in the corresponding table.

Across the 13 states of analysis, the model estimates a green LCOA range of 600 to 760 USD per tonne in 2026 (Table 2). Although Rajasthan and Gujarat have the most competitive green LCOA, no state can produce green ammonia at costs equal to or below the baseline grey LCOA in 2026.

By 2034, the LCOA for green ammonia is projected to fall for production across the whole country, becoming more economical than grey ammonia in 10 of the 13 analysed states (Table 3). Cost reductions range from 12-17% between 2026 and 2034. Consistent with the results from 2026, the 2034 projections demonstrate a correlation between lower-priced green ammonia production and locating facilities in states with the greatest renewable energy production capacity, captured by the capacity utilisation factor (UCF). Again, Rajasthan and Gujarat lead other states in 2034 for LCOA per tonne. At 21% solar, both states also have the best CUF among peers. The LCOA by 2034 is so low that cost parity with grey ammonia could be expected already within the next five years, with states such as Punjab, Chhattisgarh and Madhya Pradesh not far behind. That is critical data to consider for upcoming investment decisions, as well as policy development.



State name	LCOA (USD/tonne)
Baseline grey ammonia	573
Rajasthan	550
Gujarat	560
Chhattisgarh	580
Punjab	580
Madhya Pradesh	590
Haryana	600
Orissa	610
Karnataka	620
Maharashtra	620
Andhra Pradesh	620
Tamil Nadu	620
Uttar Pradesh	650
Kerala	690

Figure 5 Potential LCOA (2030) distribution across the thirteen states in the analysis. Values of LCOA (2030) for each state are listed in the corresponding table. States that have attained green LCOA at parity with or below grey LCOA are highlighted.

The analysis identifies renewable power generation as a key enabler to produce green ammonia at cost competitive levels. Gujarat and Rajasthan outperformed other states, which is partly attributable to the significant solar and wind energy potential in both states as well as the advantages gained from being early adopters in renewable energy deployment.[1] A recent study by Hunt and Bloomfield (2024) on the India's renewable energy potential identified Gujarat and Rajasthan as having the greatest onshore wind and solar potential in the entire country (Hunt & Bloomfield, 2024). This is reflected in existing installed capacity in both states (NITI Aayog and India Energy, 2025). Our analysis weights this heavily, contributing significantly to the lower LCOA rates in both states.

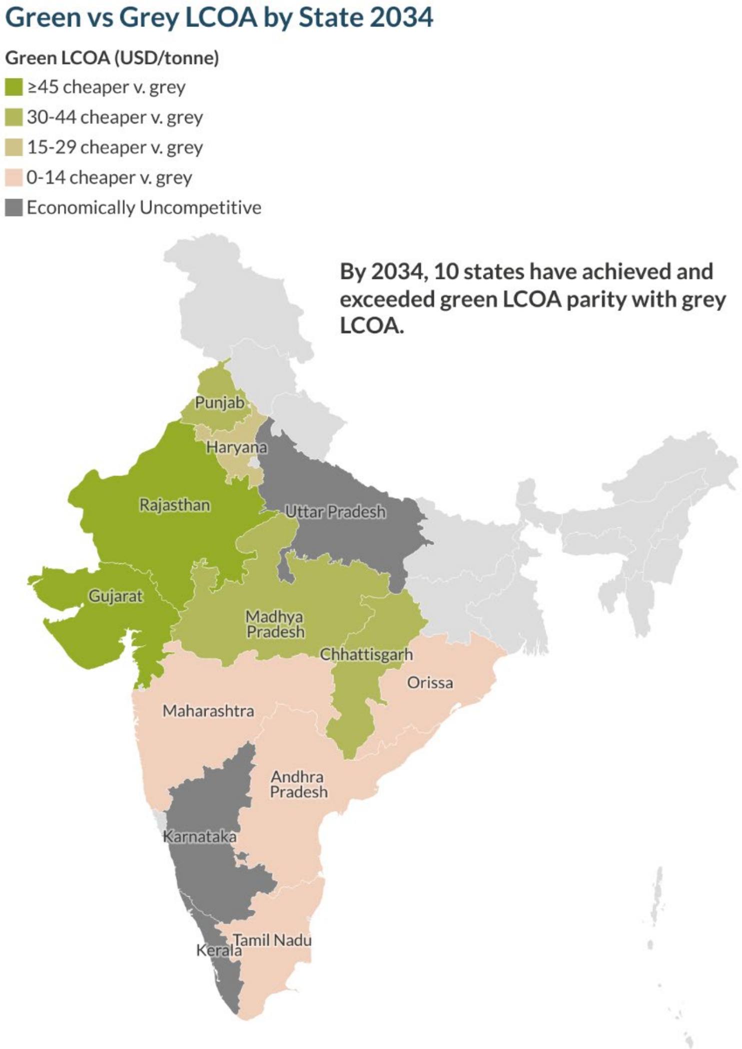
Power banking is another significant enabler (intrinsically tied to the build out of renewable energy capacity) for lowering green ammonia production costs that is configured into the model. Power banking is a policy promoted by the Ministry of Power and facilitated by the individual state electricity regulatory authorities that allows renewable electricity facilities to feed surplus electricity into the state power grid when generation exceeds demand, and withdraw an equivalent amount at a later point when demand exceeds generation. This allows renewable facilities to optimise energy usage without onsite storage by effectively using the state grid as communal battery storage.

We do not take into account how renewable energy (over)capacity in some states could power green ammonia production in other states at competitive cost levels, nor how green ammonia produced in some states at low LCOA could fuel fertiliser production in other states. It is reasonable to assume that a policy-enabling environment structured to capitalise on the energy abundance in some states and redistribute toward renewable energy-scarce states would improve the economic feasibility of green ammonia in the latter. Enhancing interstate transmission of renewable electricity could enable renewable energy-scarce states to achieve lower green LCOAs, while green ammonia producers might alternatively choose to locate their facilities in states with renewable

[1] The analysis considers onshore wind potential and installed capacity in India. While building out offshore capacity remains a stated objective of the central government, tendering for these projects has been fraught with challenges and cancelations (The Maritime Executive, 2025). As of publication, India has no installed offshore wind capacity, and buildout efforts are largely on hold. Consequently, the model is configured to only factor in onshore wind for the analysis.

energy abundance. The study by Samadi et al. on the influence of renewable energy costs for locating industrial production supports this conclusion (Samadi et al., 2023). They find that differences in renewable energy availability can shift production toward regions with cheap and abundant renewable energy, taking precedent over other factors impacting facility location.

Variations in the costs of renewable energy are a core factor for end-LCOA. Our analysis showed a significant impact of power banking policies on LCOA end levels. In the case of Gujarat and Rajasthan, power banking access accounts for over USD 300 of savings per tonne for LCOA in 2026. Without power banking access, LCOA costs in Gujarat and Rajasthan reached USD 890 and USD 930 per tonne respectively. In 2034, without power banking, the LCOA reaches USD 780 per tonne in Gujarat and USD 830 per tonne in Rajasthan. This is a difference of USD 270 and USD 320 per tonne in loss savings potential compared to results where power banking was configured into the model. These results point to the significant role power banking can play in achieving cost competitive green LCOA levels.



State name	LCOA (USD/tonne)
Baseline grey ammonia	573
Gujarat	510
Rajasthan	510
Punjab	530
Chhattisgarh	540
Madhya Pradesh	540
Haryana	550
Orissa	560
Andhra Pradesh	570
Maharashtra	570
Tamil Nadu	570
Karnataka	580
Uttar Pradesh	600
Kerala	640

Figure 2 *Potential LCOA (2034) distribution across the 13 states in the analysis. Values of LCOA (2034) for each state are listed in the corresponding table. States that have attained green LCOA at parity with or below grey LCOA are highlighted.*

Green ammonia auction results

Green LCOA figures from the modelling are corroborated by recent results from India's green ammonia auctions, run by the Solar Energy Corporation of India (SECI). SECI is the central agency responsible for implementing the NGHM, including facilitating tenders to build out the country's production capacity of green hydrogen, electrolysers, and green ammonia under the SIGHT scheme. The results from the most recent set of tender auctions are included below in Figure 7, occurring in August 2025. Through these auctions, SECI invites bids from developers to produce and supply green ammonia to fertiliser plants under long-term contracts (typically 10 years) with fixed tariffs.

Over the course of these 13 auctions, new record-low levels of pledged LCOA were achieved (including one auction which resulted in a committed green LCOA of USD 572, just below the baseline grey LCOA of USD 573). Of the winning bids, five have committed to producing green ammonia below an LCOA of USD 600/tonne (Kothadiya & Yadav, 2025). These pledged levels are consistent with the green LCOA levels that the analysis indicates are achievable by 2026. This indicates a strong trend in the reduction of costs associated with green ammonia, bringing it closer to parity with grey LCOA.

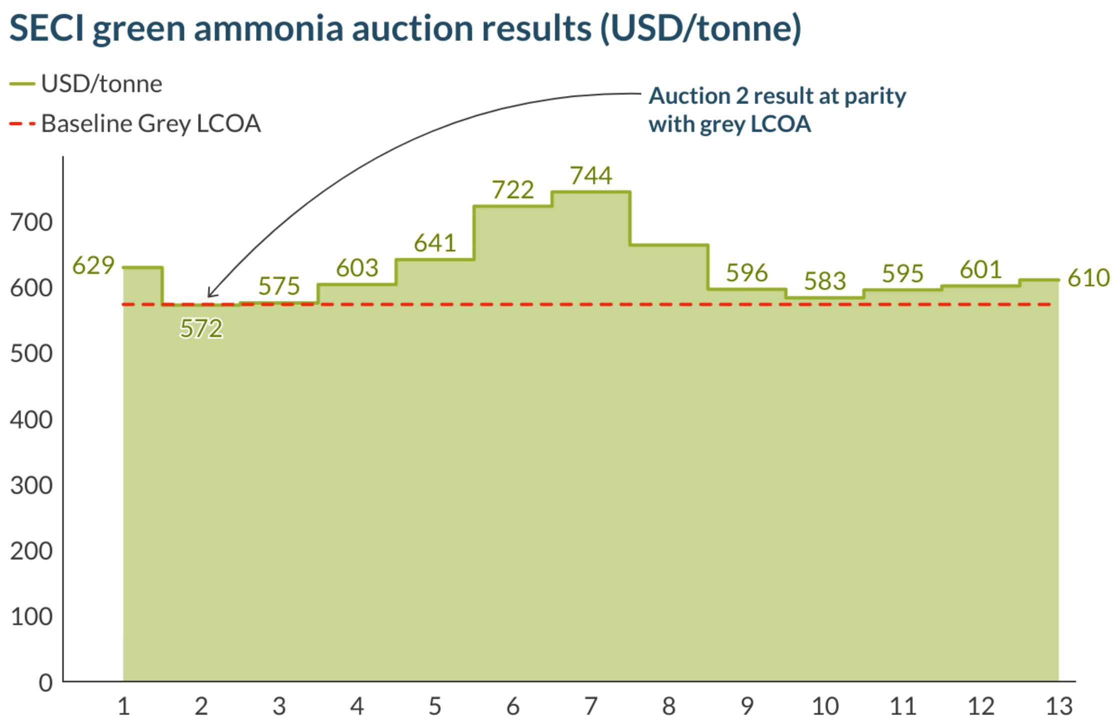


Figure 3 Winning bids from the Solar Energy Corporation of India auctions for the year of 2025 production of green ammonia (SECI, 2025).

Key driving factors

An analysis of the main components for the LCOA (for 2026) of grey, blue and green ammonia, highlight a fundamentally divergent cost structures for each method.

CAPEX and OPEX components for grey, blue and green ammonia

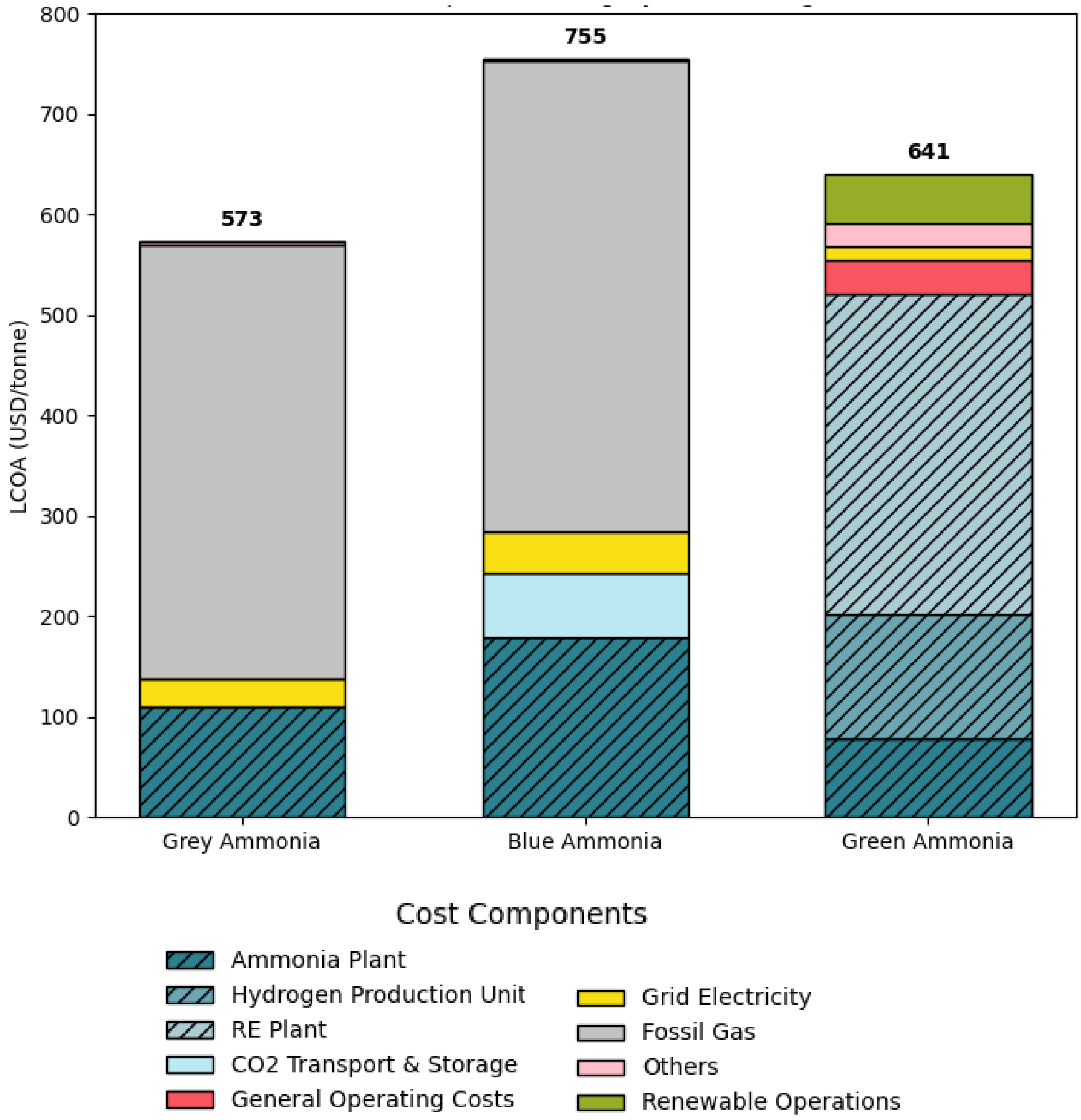


Figure 4 Comparison of cost components for LCOA.

Grey ammonia, with an LCOA of USD 573/t, is overwhelmingly dominated by OPEX, with the procurement of fossil gas (feedstock) constituting the single largest cost component at 75% of the total LCOA. CAPEX for the ammonia plant are comparatively modest, accounting for only 19% of the LCOA. This high OPEX and low CAPEX profile makes grey ammonia's economics highly sensitive to fossil fuel market volatility but financially attractive to private investors in the absence of stringent climate policy.

Green ammonia, by contrast, presents an almost inverse economic profile. With an LCOA of USD 615/t, it is only marginally more expensive than grey ammonia in this model. However, its cost is dominated by capital expenditures. The combined CAPEX for the RE plant (49%) and the hydrogen production unit (electrolyser, 20%) accounts for nearly 70% of its total LCOA. When the CAPEX for the ammonia plant (12%) is included, the total capital intensity rises to over 80%. Operational expenditures are minimal, primarily consisting of renewable operations (8%). This structure makes green ammonia highly dependent on the cost of capital but largely insulated from the price volatility of commodity feedstocks.

Blue ammonia represents a hybrid economic model and, under a zero-carbon-price regime, is the least competitive pathway with an LCOA of USD 755/t. It shares grey ammonia's dependence on fossil gas (feedstock), which comprises 62% of its LCOA. However, it also carries a significant capital burden associated with integrating carbon capture technology, reflected in a higher ammonia plant CAPEX (24%) compared to the grey pathway. Critically, it introduces a new, material operational cost: CO2 transport and storage, which accounts for 9% of the total LCOA. In a zero-carbon-price environment, blue ammonia bears the costs of decarbonisation without reaping any financial benefit, positioning it as economically unviable.

The above comparison highlights certain key enablers for driving the production costs of green ammonia. A few are listed below.

Factors influencing the production costs of green ammonia

- **Renewable electricity and electrolyser capital costs:** The primary driver for reducing green ammonia's LCOA is the continued cost decline of renewable energy and hydrogen electrolysis. Since the RE plant and hydrogen production unit constitute the vast majority of the cost, reductions in solar PV, wind turbine, and electrolyser manufacturing costs – driven by learning curves and economies of scale – will directly and substantially lower the LCOA.

- **Cost of capital (amortisation and interest rates):** As a CAPEX-heavy technology, green ammonia's financial viability is acutely sensitive to interest rates. Higher rates increase the cost of financing, leading to higher amortisation costs that can significantly inflate the LCOA. This represents a key vulnerability compared to OPEX-heavy grey ammonia projects.

- **Capacity factor:** The utilisation rate of the electrolyser and renewable assets is critical. Higher capacity factors, achieved through hybrid solar-wind farms, co-location with consistent industrial electricity demand, or advanced energy storage (putting less reliability on the grid), allow the high upfront capital costs to be amortised over a greater volume of ammonia production, thereby lowering the LCOA.

It may also be helpful to scrutinise the key driving factors of competitiveness for grey and blue ammonia. A successful climate policy will target these factors to discourage their use.

Factors influencing the competitiveness of grey ammonia

Grey ammonia's competitiveness is almost singularly tied to two external factors that define its operational environment.

- **Fossil gas Prices:** With 75% of its LCOA derived from fossil gas, the price of this feedstock is the overwhelming determinant of its economic viability. In regions with access to low-cost, stable fossil gas reserves, grey ammonia will likely remain a competitive production method for the near term. However, this also exposes it to significant commodity market volatility.

- **Carbon pricing regimes:** The data presented is for a zero-carbon-price scenario, which is the ideal condition for grey ammonia. The introduction of any meaningful carbon tax or emissions trading scheme would internalise the externality of its CO_2 emissions, adding a significant cost penalty that would rapidly erode its competitiveness against both blue and green pathways.

Factors influencing the competitiveness of blue ammonia

- **Carbon pricing:** The primary factor that makes blue ammonia competitive is the imposition of a carbon price. Its entire business case is predicated on being a lower-cost decarbonisation alternative to green ammonia when the carbon price is high enough to make unabated grey ammonia uneconomical.
- **Cost of carbon capture and storage (CCS):** Reductions in the cost of CCS technology directly improve blue ammonia's economics. This includes innovations that lower the capital cost of capture units, reduce the energy

penalty of the capture process, and decrease the costs associated with CO_2 pipeline transportation and geological sequestration.

- **Fossil gas prices:** Similar to grey ammonia, blue ammonia remains highly exposed to fossil gas price fluctuations (62% of LCOA). It cannot escape the underlying commodity risk, which can undermine its cost advantage over green ammonia even in a high-carbon-price environment.
- **Methane abatement costs:** Increasing scrutiny on upstream methane leakage from fossil gas supply chains may lead to regulations requiring costly monitoring and abatement measures, which would add to the feedstock cost and diminish blue ammonia's low-carbon credentials and economic standing.

Sensitivity analysis

Impact of reduced WACC on green ammonia LCOA

A 25% decrease in the weighted average cost of capital (WACC) results in a significant reduction in the CAPEX-related cost components of green ammonia. The overall LCOA decreases from approximately USD 617/tonne in the base case to USD 516/tonne with higher WACC, a reduction of about USD 101/tonne. This change is primarily driven by lower annualised CAPEX for the RE Plant, H_2 electrolyser, and NH_3 production units, with smaller reductions in associated OPEX components. The proportional contribution of CAPEX to total LCOA declines, while OPEX shares increase slightly. This indicates that under different financing assumptions the cost structure can change for green ammonia.

Impact of 25% lower WACC on green ammonia

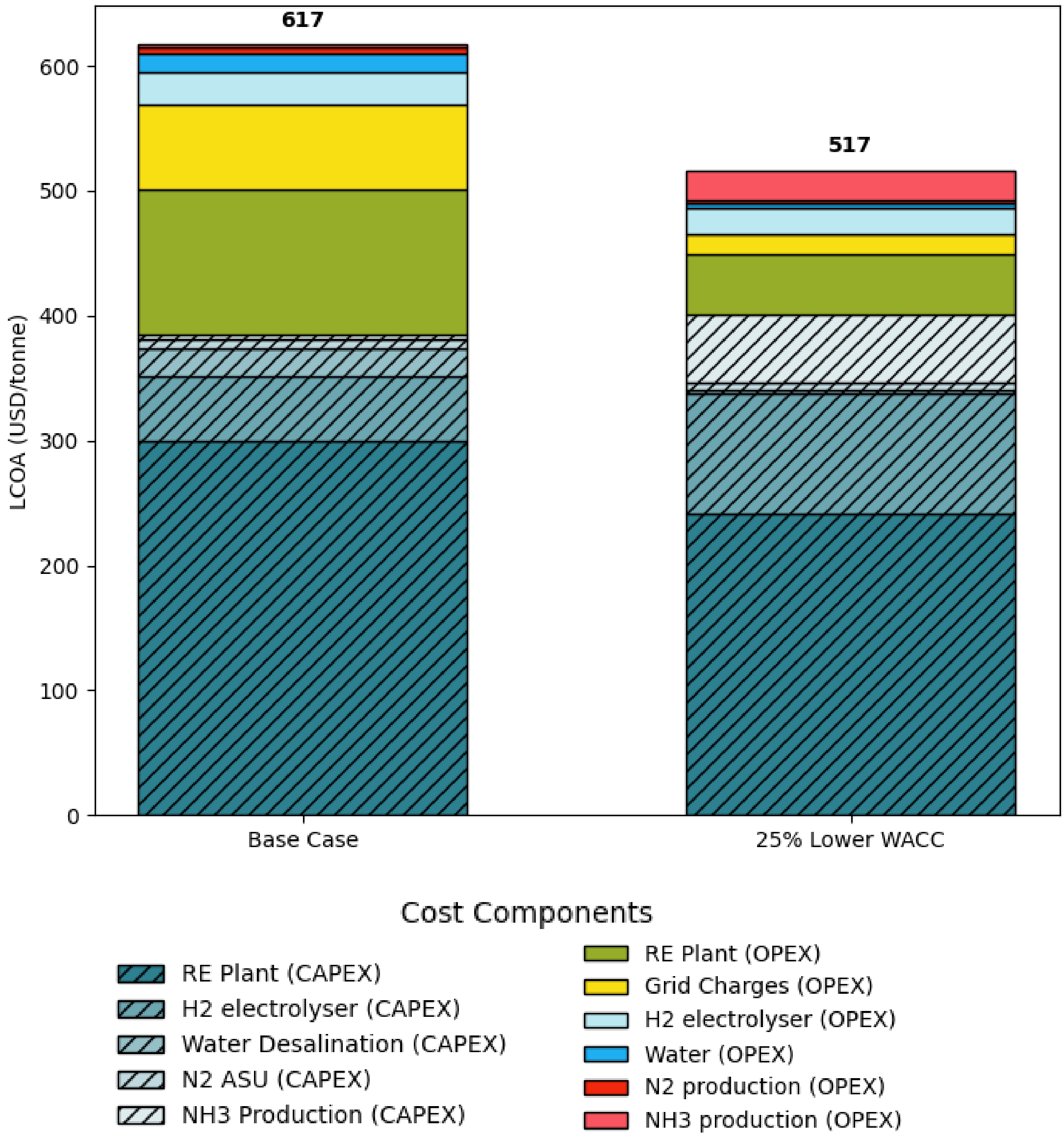


Figure 5 Component analysis of green LCOA with a reduction in WACC. The bar on the right represents a reduction of WACC by 25%

Impact of higher fossil gas price on grey and blue ammonia LCOA

A 25% increase in fossil gas prices leads to a substantial rise in the LCOA for both grey and blue ammonia. For grey ammonia, the total LCOA increases from USD 573/tonne in the base case to USD 681/tonne under higher gas prices, an increase of USD 108/tonne. For blue ammonia, the LCOA rises from USD 751/tonne to USD 807/tonne, a USD 56/tonne increase. The OPEX-NG component becomes even more dominant in both cases, especially for grey ammonia, where it constitutes the majority of the cost, while other cost components remain unchanged. This highlights the sensitivity of ammonia production costs to fossil gas price fluctuations.

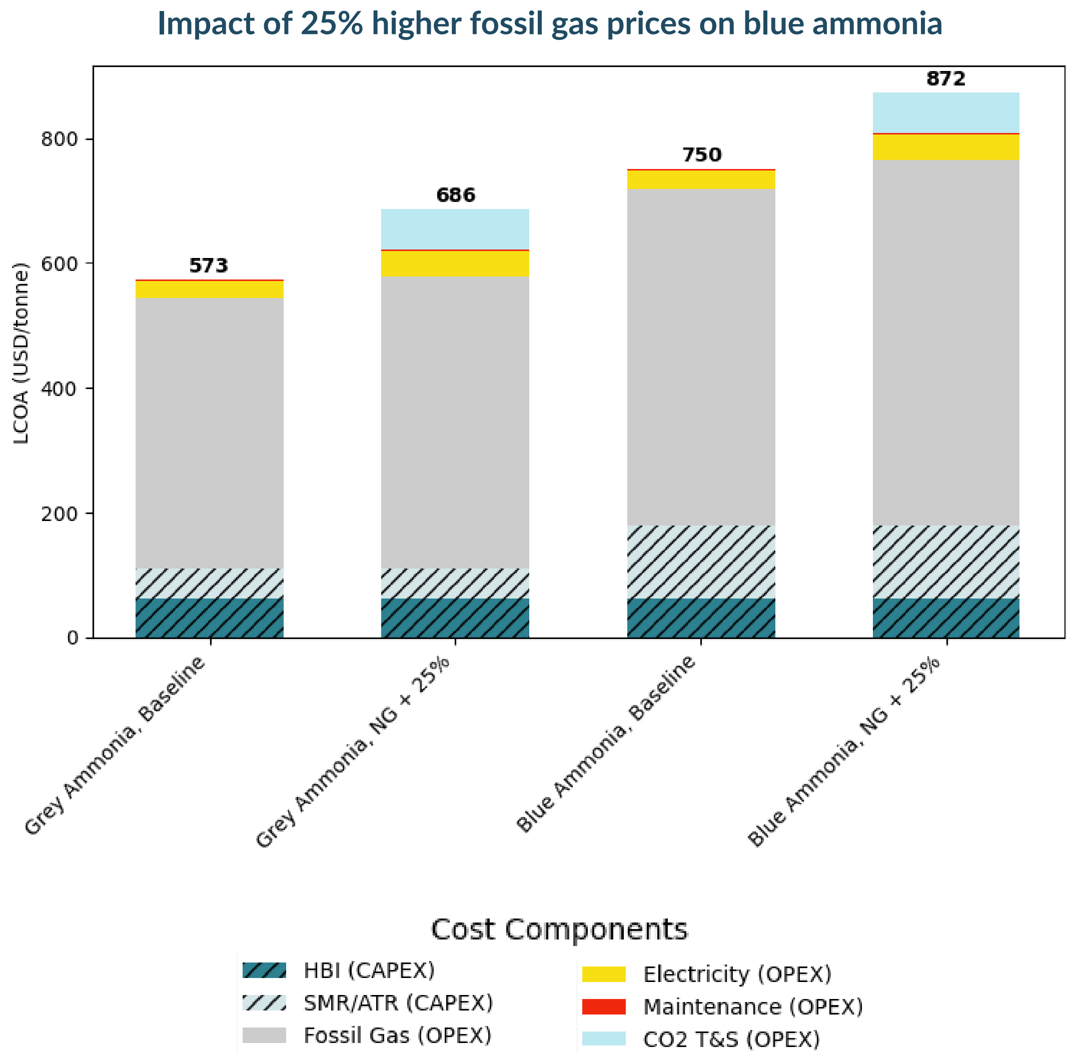


Figure 6 Analysis of fossil gas feedstock cost variability on grey and blue LCOA.

Impact of increasing CO_2 prices on grey and blue ammonia LCOA

Raising the CO_2 price from USD 0 to USD 20 and USD 100 per tonne increases the LCOA for both grey and blue ammonia. For grey ammonia, the total LCOA rises from USD 573/tonne (CO_2 USD 0) to USD 609/tonne (CO_2 USD 20) and USD 753/tonne (CO_2 USD 100), with the OPEX-emission cost component increasing from USD 0 to USD 36 and USD 180/tonne, respectively. For blue ammonia, the LCOA increases from USD 751/tonne to USD 755/tonne and USD 770/tonne, with OPEX-emission rising from USD 0 to USD 3.6 and USD 18/tonne. The impact is much more pronounced for grey ammonia, reflecting its higher direct CO_2 emissions and exposure to carbon pricing.

Impact of carbon emission pricing on blue and grey ammonia LCOA (USD/tonne)

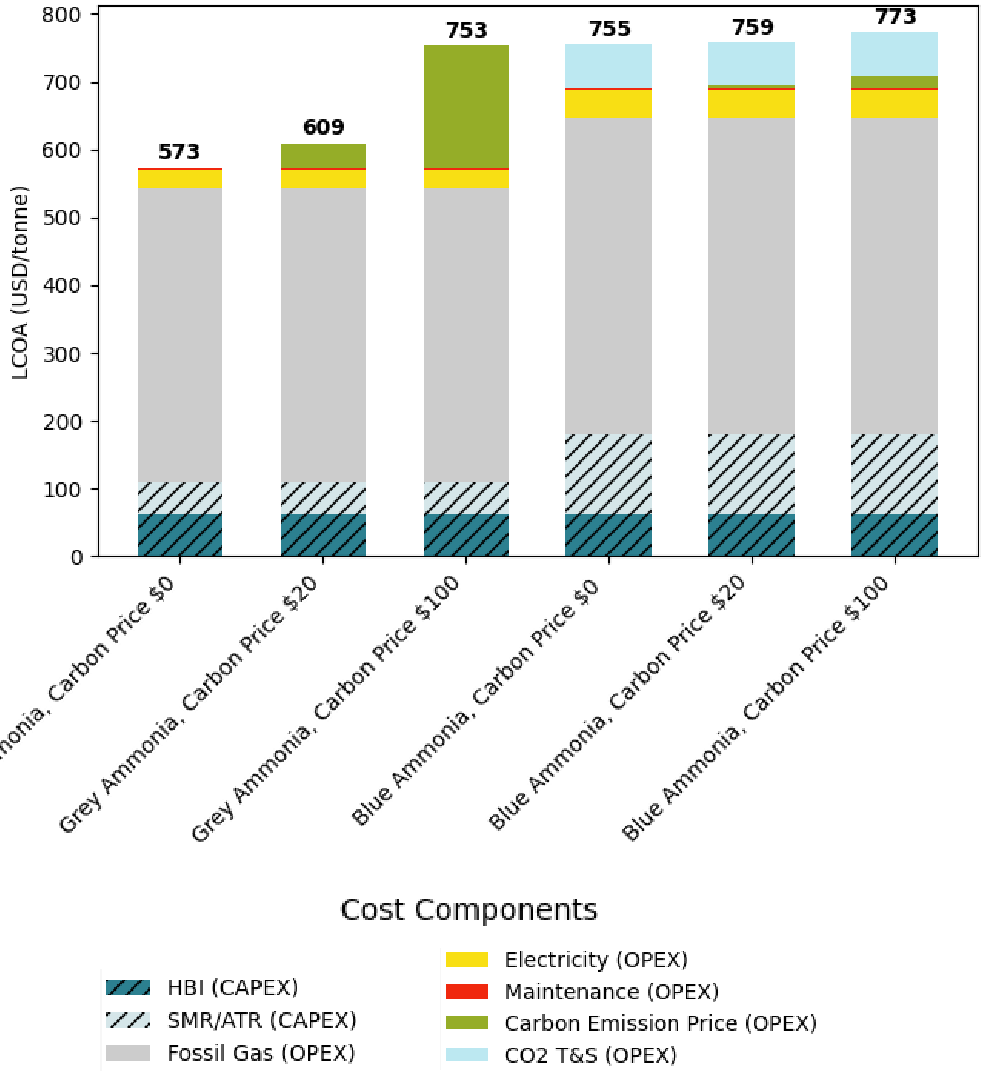


Figure 7 Analysis of variable carbon pricing on grey and blue LCOA.

Potential impact on end-use product

So far, the discussion and analysis has been limited to the comparison of ammonia production options. It is worth exploring the financial and emissions impact at the final product stage (fertiliser production). Though this is not the focus of this paper, an analysis by Yara International, a Norweigan chemical company and the world's largest producer and distributor of nitrogen-based fertilisers, has been used to give a brief overview on the impact on the final consumer (Yara International, 2022, p. 53).

Their analysis found that the use of green ammonia offers a significant reduction in CO_2 emissions to the carbon footprint of food products, yet it represents only a small fraction of the overall cost of food production. For example, a 1% increase in the cost of a loaf of bread – attributable to switching from conventional to green ammonia – can yield a 15-30% reduction in its carbon footprint. This reduction percentage would obviously increase if other parts of the supply chain of consumer products like bread are also decarbonised. This creates a strong value proposition for food brands to leverage their supply chain influence and drive the adoption of green fertilisers at the farm level, substantially reducing emissions with minimal financial impact.

Importantly, the impact on end-consumers is marginal and falls well within the range of willingness to pay for environmentally-friendly products, at least for some of India's export markets. Even if the cost of fertiliser were to double, the resulting price increase for a consumer would be negligible – only, for example, about €0.05 extra for a cup of coffee. Studies show that high-value brands can command up to a 20% premium for sustainable products, with customers willing to pay extra for food items with a lower environmental impact (Bar Am et al., 2023; PwC, 2024; SK, 2024).

Conclusion

A real zero future for India's fertiliser sector

India's fertiliser sector stands at a critical juncture, facing a dual challenge of ensuring food security for its growing population while meeting its ambitious climate goals. The current reliance on imported LNG for conventional grey ammonia production exposes the nation to volatile global energy markets, strains government finances through escalating subsidies, and generates significant GHG emissions. This analysis concludes that in a transition to real zero, green ammonia is not only environmentally essential but is rapidly becoming the most economically prudent path forward for India.

Main findings:

The techno-economic assessment reveals a clear and compelling case for green ammonia. While grey ammonia production remains marginally cheaper in the short term, the landscape is set for a dramatic shift. Key findings from the analysis include:

- **Shrinking cost gap:** The levelised cost of green ammonia is projected to fall significantly, driven by the rapidly declining costs of solar and wind power, as well as advancements in electrolysis technology. By 2034, green ammonia is forecasted to be more economical than grey ammonia in 10 of the 13 states modelled, with states like Gujarat and Rajasthan, rich in renewable resources, leading the transition.
- **Economic and strategic advantages:** A shift to green ammonia will bolster India's energy security and economic resilience by reducing dependence on LNG imports. This move will also alleviate the substantial and volatile fertiliser subsidy burden on the national budget, freeing up public funds for other development priorities.
- **Supportive policy environment:** The Indian government's 'Self-reliant India' initiative, coupled with the National Green Hydrogen Mission (NGHM) and the Strategic Interventions for Green Hydrogen Transition (SIGHT) programme, has created a powerful enabling environment. These policies are successfully catalysing private sector investment and de-risking the development of a domestic green hydrogen ecosystem.
- **Minimal consumer impact:** The transition to green fertilisers will have a negligible impact on the final price of food for consumers. The small initial

increase in fertiliser cost is a minor component of overall food production expenses, making it a highly effective and low-cost pathway to decarbonise the food supply chain.

Recommendations:

To accelerate this vital transition, the following actions are recommended:

1. **Prioritise and scale investment:** Focus public and private investment in states with the highest renewable energy potential and existing infrastructure, such as ports and industrial corridors, to develop large-scale, cost-competitive green ammonia production hubs.
2. **Strengthen policy and financial incentives:** Continue and enhance policies that support the entire green hydrogen value chain, from renewable energy generation and electrolyser manufacturing to storage and transport infrastructure. This includes financial policies to target a drop in WACC for green technology.
3. **Foster innovation and domestic manufacturing:** Promote research and development in next-generation electrolysis technologies and support the creation of a robust domestic supply chain for all critical components. This will not only reduce costs but also create skilled jobs and enhance India's technological leadership.
4. **Discourage blue ammonia production:** Implement clear policy signals to discourage investment in blue ammonia. Given its continued reliance on volatile fossil fuels and the risk of stranded assets, blue ammonia is not a viable transitional or long-term solution. Resources and incentives should be exclusively directed towards scaling up green ammonia.
5. **Develop green fertiliser markets:** Implement policies that encourage the uptake of green fertilisers by farmers and create a market for low-carbon food products, both domestically and for export. Corporations can play an important role here.

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